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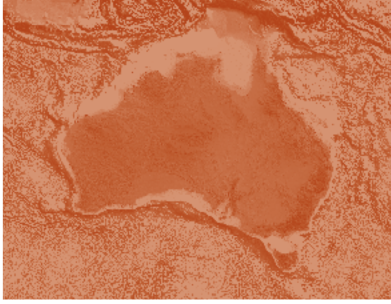

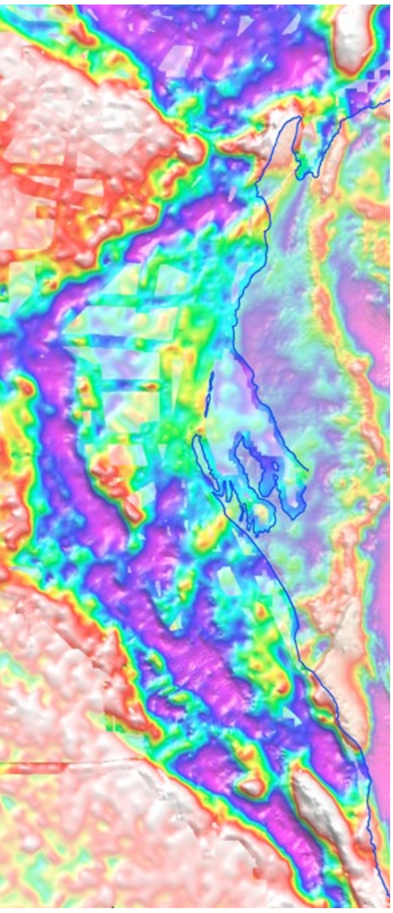

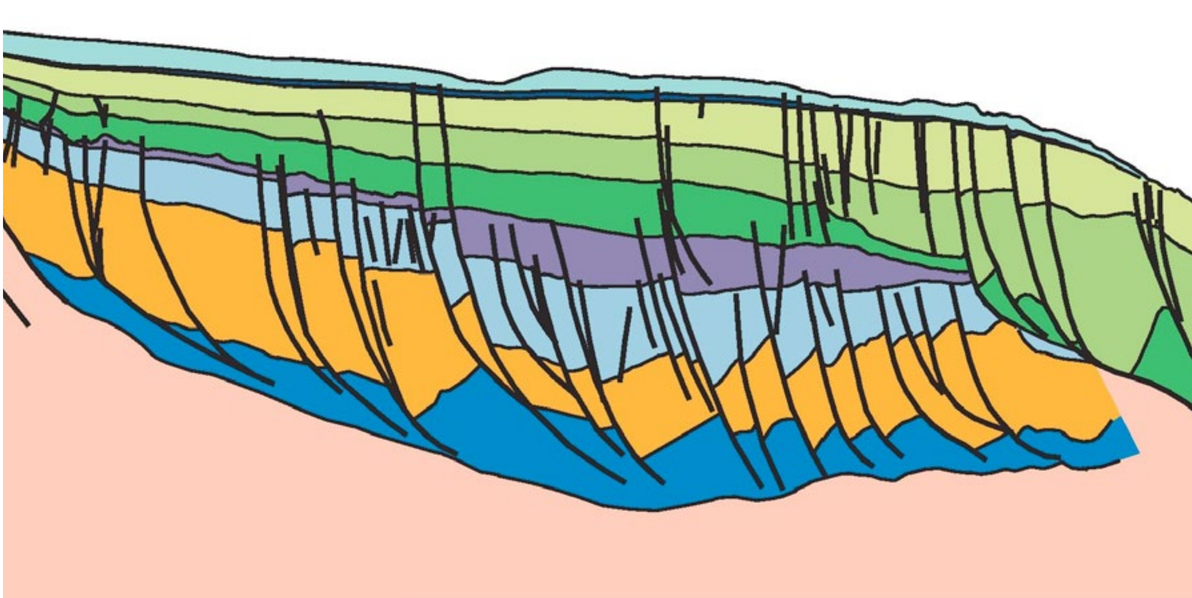

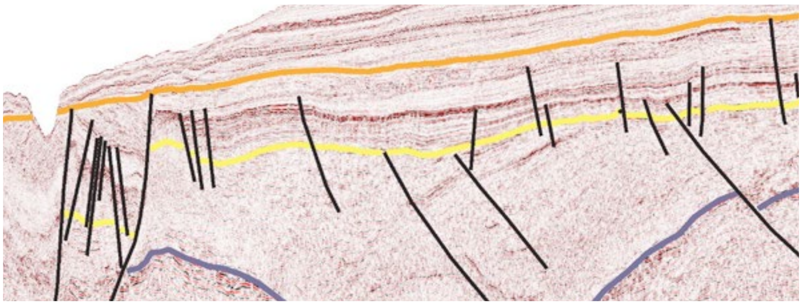

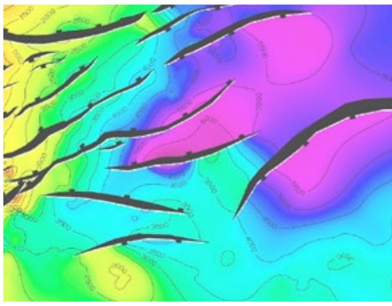

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Petroleum geology inventory of Australia's offshore frontier basins

Jennifer Totterdell, Lisa Hall, Riko Hashimoto, Kathryn Owen and Marita Bradshaw

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GEOSCIENCE AUSTRALIA
RECORD 2014/09

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Australian Government
Geoscience Australia

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Executive Summary

Oil and gas discoveries in Australia's offshore basins are concentrated on the North West Shelf (Northern Carnarvon, Browse and Bonaparte basins) and Bass Strait (Gippsland, Otway and Bass basins). While discoveries have been made in a few regions outside these areas (e.g. Perth Basin), a large proportion of Australia's offshore basins remain exploration frontiers. However, the decline in oil production from the North West Shelf and Bass Strait basins since 2000 has led to an increasing exploration interest in the frontier basins.

To improve our knowledge of the offshore frontiers and encourage exploration in these areas, from 2003–2011, Geoscience Australia was funded by the Australian Government to undertake a series of pre-competitive data acquisition and analyses programs in frontier basins around the Australian margin.

This Record presents a comprehensive inventory of the geology, petroleum systems, exploration status and data coverage for 35 frontier basins, sub-basins and provinces that draws on the results of those pre-competitive data programs, as well as exploration results and the geoscience literature. The Record also provides an assessment of the critical science questions and exploration uncertainties for each area.

The results of each basin assessment are summarised in a prospectivity ranking. The availability of data and level of knowledge in each area is reflected in a confidence rating for that ranking.

While the prospectivity of some areas is widely acknowledged to be high (e.g. Ceduna Sub-basin), the perception of prospectivity in many basins is negatively affected by the amount or quality of data available. In these basins, the acquisition of new data or targeted research could make a significant difference to the understanding of petroleum potential and likelihood of exploration success. Therefore, recommendations for future work that could assist in addressing key knowledge or data gaps are included in each basin assessment.

1 Introduction

1.1 Background

Australia's first offshore hydrocarbon discoveries were made in the 1960s in the Gippsland Basin. In some of the first offshore wells in the basin, Esso Australia and BHP Petroleum made a series of discoveries that included Australia's largest oil-field, Kingfish. These discoveries encouraged more offshore exploration, and by 1972, nearly all the major basins and petroleum systems that are now producing hydrocarbons had been found. During the following three decades, large discoveries in the Northern Carnarvon, Bonaparte and Gippsland basins moved progressively into production. However, since 2000, oil production from these basins has been in steady decline. As a result, exploration interest has increasingly turned to the frontier basins on Australia's rifted margins, and into deeper water.

The Australian Government recognised the need to improve the knowledge base of the frontier basins in order to assist exploration and from 2003 to 2011, Geoscience Australia (GA) was funded under the Australian Government's *New Petroleum* and *Offshore Energy Security* initiatives to undertake pre-competitive data acquisition and analysis programs in Australia's offshore basins. The aim of these programs was to identify new hydrocarbon provinces and encourage exploration and investment.

Under the *New Petroleum Program* (2003–2007), GA completed data acquisition activities around the Australian continental margin. The program comprised:

- Southwest margin regional 2D seismic acquisition in the Perth and Mentelle basins and the Bremer Sub-basin (2004)
- Bremer Sub-basin geological sampling survey, which resulted in a geology and prospectivity study and release of exploration acreage (2004–2005)
- a series of seepage surveys on the central North West Shelf (2005–2006)
- Arafura Basin geology and prospectivity study and seepage survey, which resulted in the release of exploration acreage (2004–2006)
- surveys in the remote eastern frontier basins to acquire 2D seismic, bathymetry, heat flow and potential field data (2006–2007)
- the Bight Basin geological sampling and seepage survey (2007).

Towards the end of the *New Petroleum Program*, GA received further funding to investigate the petroleum geology of offshore frontier basins—the *Offshore Energy Security Program* (2007–2011). Several studies undertaken under this program built on the results of the previous program. Data acquisition and studies were undertaken in the following regions:

- Bight Basin: identification and characterisation of oil-prone source rocks obtained during the 2007 geological sampling survey; this work underpinned acreage release in 2009, 2010 and 2012
- Capel and Faust basins: marine sampling survey (2007) and integrated basin study
- Offshore Canning Basin: acquisition of aeromagnetic data, followed by acreage release in 2007

- Southwest margin; 2D seismic acquisition and geological sampling surveys spanning the Mentelle, Perth and Southern Carnarvon basins and the Wallaby Plateau (2009)
- Mentelle Basin: geology and prospectivity study, followed by acreage release in 2010
- Northern Perth Basin: geology and prospectivity study including new geochemical and biostratigraphic analyses, followed by acreage release in 2011 and 2013
- Bass-Otway-Sorell region: aeromagnetic data acquisition (2008)
- Deepwater Otway–Sorell basins; geology and prospectivity study, followed by acreage release in 2012.

The programs acquired a wealth of new geological and geophysical data in Australia's offshore frontier areas, which has encouraged exploration and attracted investment, particularly on the southern and southwestern margins. These datasets, and the studies undertaken, have improved the understanding of the geology and petroleum prospectivity of Australia's continental margins.

1.2 Aims

This Record draws on the results of *New Petroleum* and *Offshore Energy Security* initiatives to provide a comprehensive inventory of the geology, petroleum systems, exploration status and data coverage for 35 frontier basins, sub-basins and regions within the Australian Maritime Jurisdiction (AMJ; Figure 1.1), and analysis of the critical exploration and geoscientific questions for these areas. Basin[1] assessments are based on the synthesis and analysis of available geoscientific data and information relevant to their petroleum prospectivity. Each frontier basin assessment is written so that it can be read as a stand-alone document, and key references and a listing of the main data sets for that area are included.

The 35 frontier basins are located on Australia's northern, northwestern, southwestern, southern, southeastern and remote eastern continental margins. The report encompasses both the frontier basins studied during the *New Petroleum* and *Offshore Energy Security* initiatives and other potentially prospective frontier basins not addressed by those work programs.

Areas not covered by this report are the northeastern continental margin, the offshore basins of the Australian Antarctic Territory, and the Australian Maritime Jurisdiction (AMJ) of the Kerguelen Plateau.

The purpose of this compilation is to provide a thorough and consistent data set that can form the basis for advice to the Australian Government regarding the exploration status and prospectivity of offshore frontier basins, underpin development of future Geoscience Australia work programs to encourage investment in offshore exploration by the petroleum industry, and provide all stakeholders with information on the geology and prospectivity of frontier basins in the Australian Maritime Jurisdiction.

[1] Although the frontier areas discussed in this Record comprise a range of province types (basin, sub-basin, plateau, rise, ridge), the term "basin" is used when referring to them collectively or in a general sense.

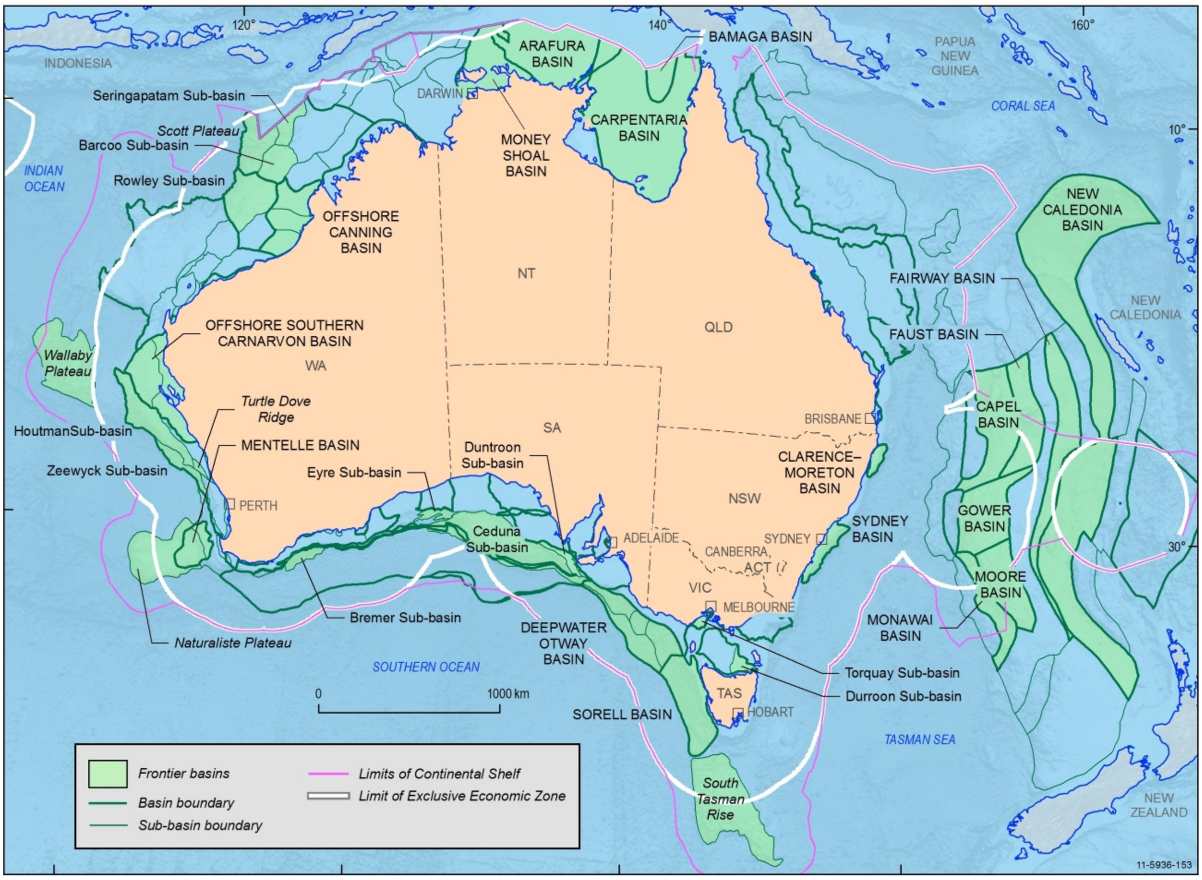

Figure 1.1: Australia's offshore frontier basins included in this Record (green shading). Basins of the northeastern margin have not been included.

1.3 Frontier basin definition

A frontier basin is a sedimentary province (e.g. basin, sub-basin) where no hydrocarbons have been discovered, but where the presence of hydrocarbon accumulations is considered possible. The level of exploration activity is variable, but low density or sparse seismic coverage and little or no well control is common.

A petroleum discovery is defined as the first well (in a new field) from which a measurable amount of oil or gas has been recovered (Geoscience Australia, 2009). In some instances, an untested well may be classified as a discovery where well logging provides a very reliable indication of the presence of producible/recoverable hydrocarbons.

1.4 Classification scheme

The petroleum prospectivity classification of basins is generally based on the presence or absence of evidence for the existence of active petroleum systems, including hydrocarbon indicators (physical or geophysical), and the identification of the petroleum system elements such as source, reservoir and seal rocks, traps, and timing of generation and migration, as well as geological factors including the age, thickness, lithology and depositional environments of the sedimentary succession. For frontier basins, where by definition hydrocarbons have not been discovered, the classification of basins in terms of their prospectivity is strongly dependent on the geological interpretation of well and seismic data. In addition, the amount and quality of data in such areas can be variable, so any prospectivity assessment must be accompanied by some indication of the confidence of that assessment. For the purposes of this Record, the prospectivity of frontier basins in Australia's Maritime Jurisdiction has been classified using the scheme shown in Table 1.1. The confidence rating for the prospectivity assessment uses a three-tiered classification (Table 1.2); the basis for those ratings provided in this table is a guide only.

Table 1.1: Frontier basin prospectivity classification.

Prospectivity class	Description
High	Hydrocarbon accumulations are likely based on sediment thickness greater than 2.5 seconds two-way-time, and identified petroleum systems elements, plays, prospects or leads; hydrocarbon generation and migration indicated in wells (shows or indications) or from indirect evidence (e.g. seeps, seismic anomalies).
Moderate	Potential for hydrocarbon accumulations based on sediment thickness greater than 2.5 seconds two-way-time, and interpreted/inferred petroleum systems elements, including evidence for potential trapping mechanisms in seismic data, and/or hydrocarbon indications in wells.
Low	Potential for hydrocarbon accumulations in regions with i) sediment thickness less than 2.5 seconds two-way-time, and evidence for potential trapping mechanisms in seismic data; or ii) sediment thickness greater than 2.5 seconds two-way time, but limited evidence for the presence of key petroleum systems elements (i.e. source, reservoir, seal, traps, timing of generation and migration)
Non-prospective	No potential for hydrocarbon accumulations based on i) sediment thickness generally less than 1 second two-way time, and no evidence for potential trapping mechanisms in seismic data (sediments may overlie oceanic crust or basement); or ii) absence of one or more key petroleum systems elements.

Table 1.2: Frontier basin data confidence rating.

Confidence rating	Basis
High	Moderate-high density of regional and exploration scale seismic data (1-15 km line spacing), more than 2 wells; +/-geological sampling data.
Medium	Moderate (5–15 km line spacing) to regional scale seismic data (15-30 km line spacing), 0-2 wells; +/- geological sampling data.
Low	Sparse seismic data, no wells.

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2 Southern margin basins

Australia's southern rifted continental margin extends over 4000 km, from a structurally complex region south of the Perth Basin in the west, to the transform plate boundary adjacent to the South Tasman Rise in the east. The margin contains a series of Middle Jurassic to Cenozoic basins that developed during the breakup of eastern Gondwana—the Bight, Otway, Sorell, Gippsland and Bass basins, and smaller depocentres on the South Tasman Rise (STR)—and which together comprise the Southern Rift System. The margin evolved through repeated episodes of extension and thermal subsidence leading up to, and following, the commencement of seafloor spreading between Australia and Antarctica. Breakup took place diachronously along the margin, starting in the west at ~83 Ma and concluding in the east at 34 Ma. In general, breakup was not accompanied by significant magmatism and the margin is classified as magma-poor.

Development of the margin was characterised by a prolonged period of lithospheric extension from the Middle Jurassic to the Late Cretaceous. Initial, Middle–Late Jurassic, upper crustal extension was focused in the Bight Basin, with the major extensional phases in the eastern basins (Otway, Sorell, Bass, Gippsland) occurring later, in the Early and Late Cretaceous.

Key references that discuss the geology and tectonic evolution of the southern margin include: Stagg et al. (1990), Willcox & Stagg (1990), Exon et al. (1997), Totterdell et al. (2000), Norvick & Smith (2001), Hill & Moore (2001), Teasdale et al. (2003), Totterdell & Bradshaw (2004), Krassay et al. (2004), Blevin & Cathro (2008).

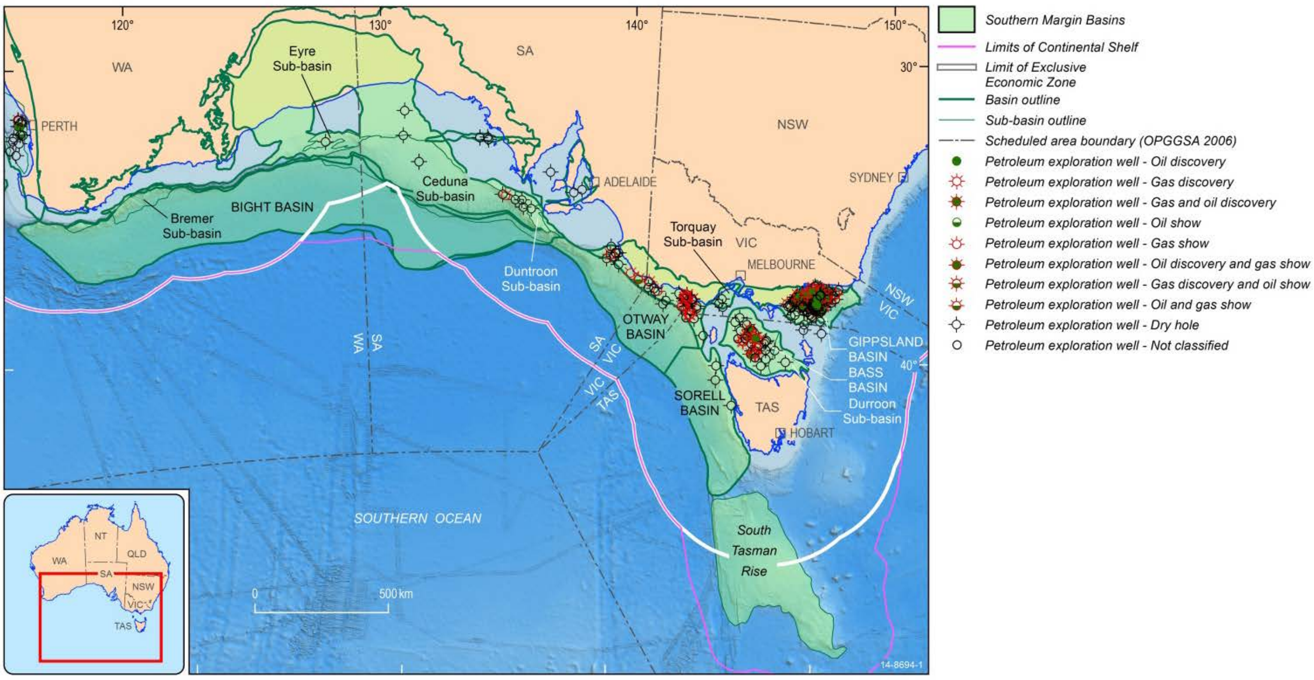

Figure 2.1: Basins of the southern Australian margin

From a petroleum exploration and production perspective, Australia's southern continental margin is a region of huge contrasts. The easternmost part of the southern margin hosts rich oil and gas resources. The Gippsland Basin is a world class petroleum province; all the petroleum systems elements and geological conditions are place and the basin contains Australia's only billion barrel oil fields. The adjacent Otway Basin is an established gas producing area, with numerous discoveries and fields located in the onshore and shelfal parts of the basin. To the south, both gas and condensate are produced from the western Bass Basin (Figure 2.1).

In contrast, the rest of the vast southern margin remains an exploration frontier. West of the Otway Basin, only a handful of wells have been drilled, with significant portions of the margin essentially undrilled (Figure 2.1).

The western two-thirds of the margin is occupied by the largest frontier basin in Australia—the Bight Basin. The basin has undergone several phases of exploration, but only 10 wells have been drilled and no discoveries have been made (Figure 2.2). Nevertheless, the thick sedimentary succession in the Bight Basin (>15 km) 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, indicates potential for the presence of multiple petroleum systems across the basin.

The Ceduna Sub-basin in the eastern Bight Basin is currently the focus of renewed exploration efforts. The key to its petroleum prospectivity is the distribution of Upper Cretaceous marine and deltaic facies. Dredging of upper Cenomanian–Turonian organic-rich marine rocks has confirmed the presence of high quality potential source rocks in this section. Work program commitments for permits granted across the Ceduna and Duntroon sub-basins in 2011 and 2013 include the drilling of nine exploration wells, which will almost double the number of wells drilled in the basin.

The Bremer Sub-basin in the westernmost part of the southern margin has been the focus of recent exploration, although wells have yet to be drilled in this prospective depocentre.

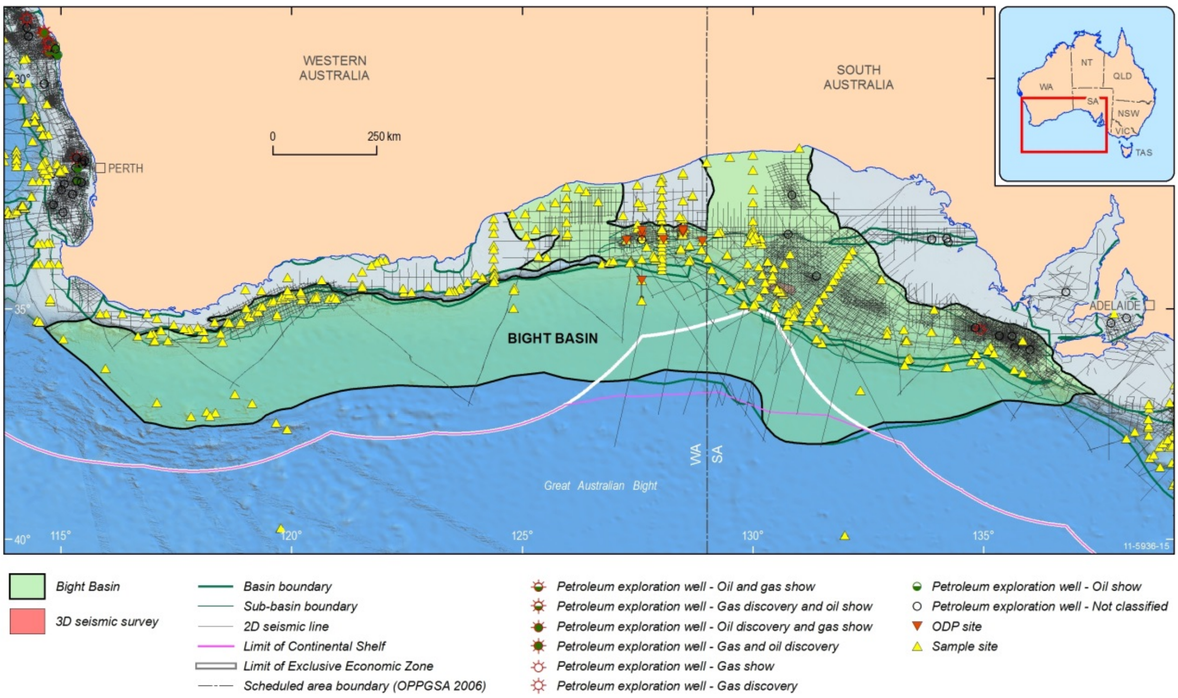

Figure 2.2: Bight Basin data coverage

This inventory includes assessment of the main Bight depocentres—the Ceduna, Duntroon, Eyre and Bremer sub-basins. The remaining Bight depocentres are not addressed here for different reasons—the poorly known and isolated Denmark Sub-basin, located 60 km west-southwest of the Bremer Sub-basin, due to its small size and lack of data, and the vast and potentially prospective deep-water Recherché Sub-basin, which lies outboard of the main depocentres, due to extreme water depths and paucity of data. The inboard Madura and Couedic shelves are not considered as they comprise thin Cretaceous successions overlying shallow basement, and are considered non-prospective. The Cenozoic Eucla Basin, which unconformably overlies the Bight Basin, is not included as it is considered to be too thin and shallow to have any significant prospectivity Two isolated depocentres underlying the Madura Shelf have also been omitted—the offshore Polda Basin, where the thin Jurassic succession is thermally immature and drilling has not provided any indications of prospectivity in the older Proterozoic–Lower Paleozoic section, and the Denman Basin, which contains a thin, immature Permian glacial succession overlying ?Lower Paleozoic sandstones with little to no permeability.

To the east, in the frontier deepwater Otway and northern Sorell basins, the keys to prospectivity are the presence/extent of marine-influenced Albian–Aptian and Turonian–Coniacian source rocks, with maturation and generation driven by accumulation of a thick Upper Cretaceous section.

In the southern Sorell Basin and South Tasman Rise, prospectivity is linked to the preservation of organic-rich rocks in restricted transtensional depocentres, and the extent of early Late Cretaceous marine environments.

Exploration frontiers also remain in the under-explored Torquay (eastern Otway Basin) and Durroon (eastern Bass Basin) sub-basins.

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2.1 Bremer Sub-basin (Bight Basin)

2.1.1 Summary

State(s)		Western Australia
Area (km^2)		~14,900
Water Depth (m)		100–4500
Maximum sediment thickness (m)		11,000
Age range		Middle Jurassic–Turonian
Basin	**Overlies**	Albany–Fraser Orogen
	Underlies	Eucla Basin
	Parent	Bight Basin
	Adjacent basins	Recherche Sub-basin
Basin type		Extensional
Depositional setting, rock types		Fluvial, lacustrine, deltaic and shallow marine clastic sedimentary rocks; ?pre-rift salt
Petroleum prospectivity		Moderate–High
Confidence		*Medium*

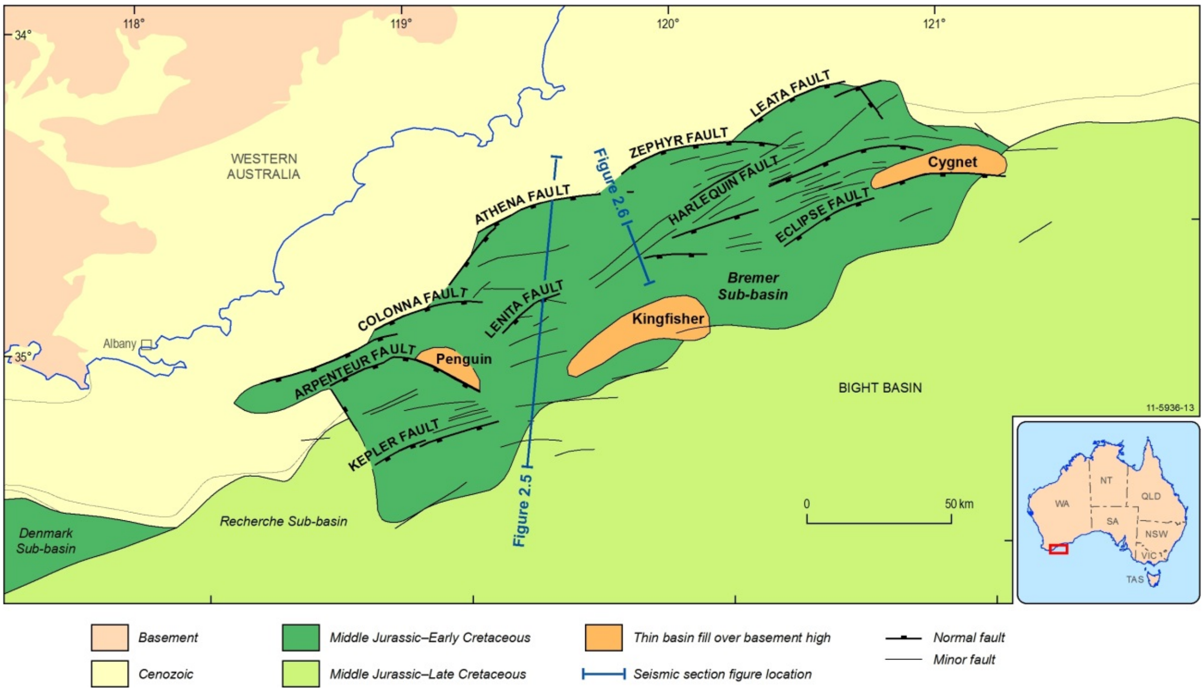

Figure 2.3: Structural elements map, Bremer Sub-basin.

2.1.2 Geology

The east-northeast-trending Bremer Sub-basin (Bradshaw et al., 2003), is located in the western part of the Bight Basin (Figure 1.1 and Figure 2.3). The sub-basin was referred to previously as the Albany Sub-basin of the Bremer Basin. However, following reassessments of the structural architecture and nomenclature of both the Eucla (Clarke et al., 2003) and Bight basins, this offshore Jurassic–Cretaceous depocentre was redefined as a sub-basin of the Bight Basin (Bradshaw et al., 2003). The sub-basin covers an area of approximately 14,900 km^2 and lies in water depths of 100–4500 m. The sub-basin has been the subject of intermittent petroleum exploration activity, but no wells have been drilled and the area remains an exploration frontier. The sub-basin is currently the focus of exploration interest and is covered by two exploration permits. There is a moderate to good 2D seismic coverage and some lithological control from dredge samples obtained from submarine canyons (Blevin, 2005; Bradshaw, 2005).

The Bremer Sub-basin consists of a series of structurally complex half graben containing up to 11 km of Jurassic and Lower Cretaceous sedimentary rocks (Figure 2.4). Basement to the sub-basin is likely to comprise Proterozoic rocks of the Albany–Fraser Orogen (Bradshaw, 2005) and a basin containing upper Proterozoic or lower Paleozoic evaporites (Cathay Petroleum & Arcadia Petroleum, 2012). A thin (~500 m) Cenozoic Eucla Basin succession, comprising cool-water carbonate and siliciclastic rocks, unconformably overlies the Bremer Sub-basin and onlaps basement rocks to the north (Hocking, 1994; Bradshaw et al., 2003; Clarke et al., 2003). On the southern margin of the sub-basin, a series of down-stepping fault blocks represents a transition from the Bremer Sub-basin to the Recherche Sub-basin.

An isolated half graben, referred to as the Denmark Sub-basin, lies 60 km west-southwest of the Bremer Sub-basin (Figure 2.3). As data coverage of this structural element is poor, this basin element has not been addressed in this Record.

2.1.2.1 Structural geology

The half graben of the Bremer Sub-basin, along with similar structures in the eastern Bight Basin, represent the earliest phase of basin development along Australia's southern rifted margin. These depocentres developed during the Middle–Late Jurassic to earliest Cretaceous as a result of northwest–southeast to north-northwest–south-southeast intracontinental extension. Interpretation of recent seismic data has indicated that the structural evolution of the sub-basin may have been influenced by salt in the pre-rift section, with salt tectonics playing a fundamental role in the structural architecture of the basin (Cathay Petroleum & Arcadia Petroleum, 2012; Bradshaw, et al., 2013).

In the Bremer Sub-basin, an east to east-northeast striking, southerly-dipping rift border fault system controlled the location and orientation of the main depocentres. This fault system comprises a number of smaller and discontinuous half-graben bounding faults that change orientation along strike, from an east–west orientation in the western part of the sub-basin, to an east-northeasterly strike in the east (Figure 2.3). The change in orientation is accompanied by significant changes in structural style from west to east (Stagg & Willcox, 1991; Bradshaw et al., 2003; Nicholson & Ryan, 2005). As for the eastern Bight Basin, basement trends appear to have had a profound influence on the structural architecture of the Bremer Sub-basin. For example, the change in structural style from the western to eastern Bremer Sub-basin coincides with a change in orientation of structural trends in the Albany–Fraser Orogen from east-northeast to northeast (Bradshaw et al., 2003; Totterdell & Bradshaw, 2004). A series of shear zones in the Albany–Fraser Orogen may also have exerted some control on the location, orientation and timing of basin forming and basin modifying structures in the Bremer Sub-basin (Bradshaw et al., 2003; Totterdell & Bradshaw, 2004).

The Bremer Sub-basin comprises five main half graben bounded to the north by the Arpenteur, Colonna, Athena, Zephyr and Leata faults (Figure 2.3; Nicholson & Ryan, 2005). The westernmost half graben are characterised by rift-flank uplift, hanging wall anticlines and truncation of strata beneath an unconformity interpreted as Turonian (Figure 2.5). Based on analysis of new seismic data, Cathay Petroleum & Arcadia Petroleum (2012) suggested that much of this deformation could be related to salt tectonics. The half graben to the east are characterised by thick divergent rift fill. In the Zephyr depocentre, well developed synthetic and antithetic faults border an intra-basin graben. Nicholson & Ryan (2005) identified two phases of extension in the sub-basin: Jurassic and Valanginian–Aptian. Cathay Petroleum & Arcadia Petroleum (2012) argued that the Berriasian–Aptian was dominated by salt tectonics and some strike-slip faulting, with salt withdrawal resulting in the formation of growth faults and depocentres. Nicholson & Ryan (2005) suggested that a period of faulting, uplift and erosion in the Turonian was associated with initial seafloor spreading on this portion of the southern margin. If this interpretation is correct, breakup adjacent to the Bremer Sub-basin at about 90 Ma pre-dated breakup in the central Bight Basin by approximately 7 m.y. Cathay Petroleum & Arcadia Petroleum (2012) have argued that breakup outboard of the Bremer Sub-basin may have commenced as early as the Aptian.

2.1.2.2 Basin evolution and depositional history

No wells have been drilled in the Bremer Sub-basin and stratigraphic information has been derived from rocks sampled by dredging strata exposed in the walls of submarine canyons (Blevin, 2005; O'Leary et al., 2005), and by analogy with the Eyre Sub-basin to the east. While sampling was by nature incomplete, biostratigraphic analyses of the dredge samples indicate that the Bremer Sub-basin contains Jurassic and Cretaceous strata, overlain by a thin Cenozoic cover of the Eucla Basin (Monteil et al., 2005). Due to the limitations of seafloor outcrop, dredge sampling was biased towards the younger, Cretaceous part of the basin succession. The older Jurassic rift fill was poorly sampled, and those samples come from thin Jurassic strata overlying shallow basement.

Using the dredge samples, interpretation of seismic data and comparison with other Bight Basin depocentres, O'Leary et al. (2005) defined six seismic stratigraphic units within the Bremer Sub-basin (Bremer 1–6) and two in the overlying Eucla Basin (Eucla 1–2; Figure 2.4) and proposed the following geological history for the sub-basin:

- Late Jurassic extension, with a syn-rift fill of fluvio-lacustrine sediments.
- Berriasian–Hauterivian thermal subsidence and extension, with bounding faults active at varying times across the basin. A thick succession of sandstone, siltstone, organic-rich claystone and coal accumulated, in fluvial, lacustrine and paralic conditions.
- Thermal subsidence continued through the Hauterivian to breakup in the Santonian and into the Maastrichtian following breakup.
- Restricted marine conditions developed in the Hauterivian to Aptian, with open marine conditions prevailing from the Aptian to Santonian after continued thermal subsidence and eustatic transgression.
- During breakup, many older faults were reactivated and some new intra-basin faults formed. Major uplift and erosion was restricted to the western Bremer Sub-basin, where rift-flank uplift produced a major angular unconformity.
- A thin succession of calcareous sediments and siliciclastics was deposited after breakup, indicating low sediment supply and low subsidence rates.
- A carbonate-dominated passive margin phase defines the overlying Eucla Basin and is associated with pronounced mid-Eocene and younger submarine canyon incision.

Recent exploration activity in the Bremer Sub-basin, including the acquisition of high resolution 2D seismic data, has resulted in a radical re-interpretation of the geology and evolution of the Bremer Sub-basin by Arcadia Petroleum & Cathay Petroleum. Their revised interpretation is based on interpretation of Proterozoic or lower Paleozoic pre-rift salt in the region, and the influence of salt tectonics on basin development (Cathay Petroleum & Arcadia Petroleum, 2012; Bradshaw, et al., 2013). In this interpretation, much of what had previously been mapped as basement, apart from those areas inboard of the rift margin faults on the continental shelf, is interpreted as pre-rift evaporites, with previously mapped basement highs now interpreted as salt-cored features. During the Berriasian–Aptian the mobilisation of this salt resulted in the formation of salt withdrawal basins, with salt walls and diapirs underlying regional and counter-regional growth faults. The new seismic data sets have imaged seafloor features interpreted as exposed salt diapirs (Figure 2.6; Cathay Petroleum & Arcadia Petroleum, 2012; Bradshaw, et al., 2013). Previously, these features had not been explained; they could alternatively be interpreted as volcanic rocks. Another key difference in the Cathay/Arcadia explanation is the interpretation of a deep lacustrine depositional setting, rather than fluvial–lacustrine conditions during the period of salt tectonics and the interpretation of high amplitude reflections in sequences Bremer 3 and 4 as deep water lacustrine deposits and lacustrine delta successions rather than the previously interpreted coaly facies.

Bradshaw et al. (2013) argued that the presence of evaporites in the section is also supported by velocity data. They noted that P-wave refraction velocities of 4.9–5.7 km/s were recorded over interpreted salt structures by the sonobuoys deployed on Geoscience Australia survey s280. These velocities are lower than typical for continental basement rocks but consistent with those through evaporites. Neoproterozoic–Cambrian salt sequences are known to occur in the offshore Polda Basin and in the Officer and Amadeus basins.

2.1.2.3 Level of knowledge

Geological understanding of the Bremer Sub-basin is based on interpretation of generally good quality, 2D seismic data, in conjunction with the results of samples from 45 dredge sites (Figure 2.7; Bradshaw et al., 2005). Pre-2009 seismic data sets have a line spacing of approximately 15–30 km. The extensive seismic data acquired by Arcadia/Cathay in WA-279-P and WA-280-P, which has recently become open-file, has reduced the overall line spacing to 5–10 km. No wells have been drilled in the Bremer Sub-basin and stratigraphic control relies on the dredge samples. Together these data sets provide a fair to good basis for understanding the stratigraphy, structure and evolution of the Bremer Sub-basin.

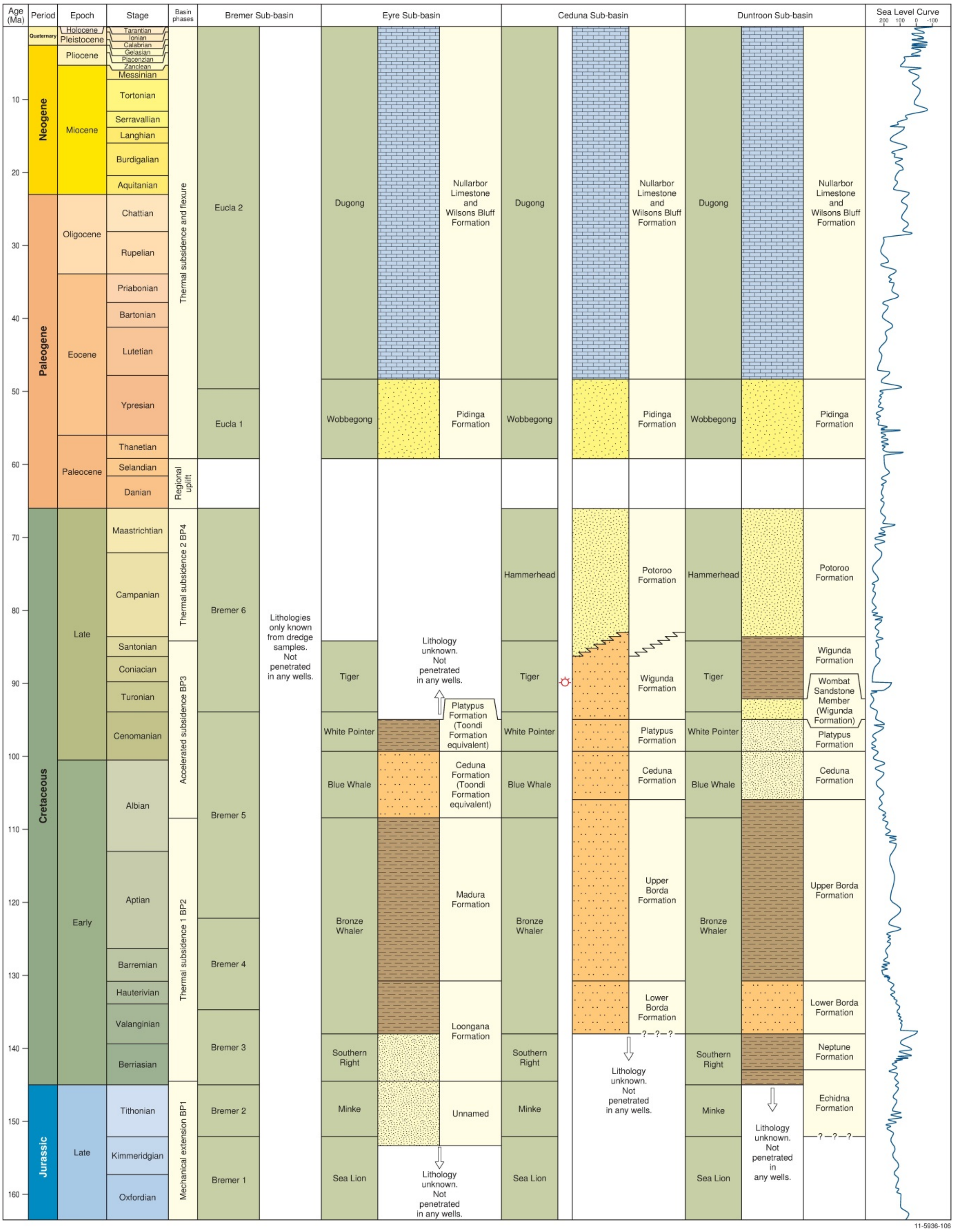

Figure 2.4: Stratigraphy of the Bremer, Eyre, Ceduna and Duntroon sub-basins, Bight Basin. Geologic time scale after Gradstein et al. (2012); sea-level curve of Haq et al (1988) calibrated to the time scale.

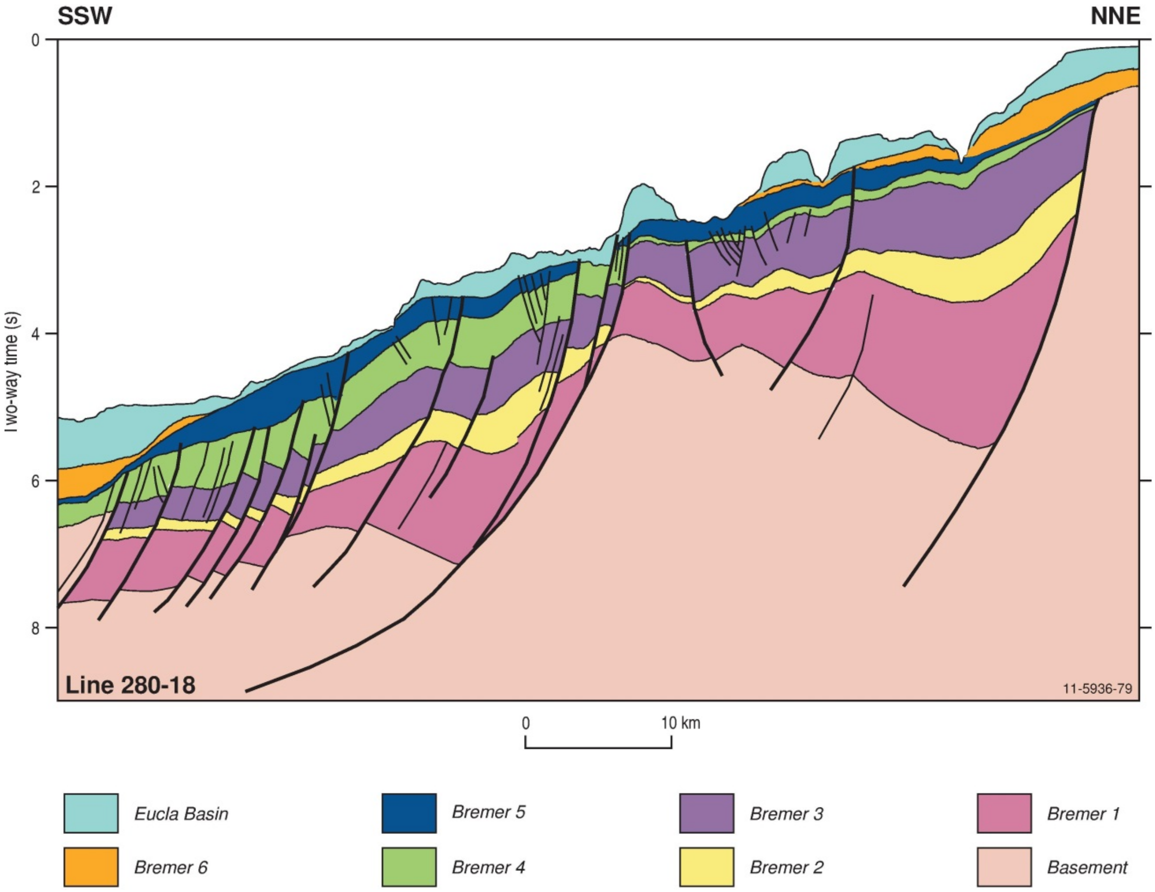

Figure 2.5: Geological cross-section across the central Bremer Sub-basin showing structural and stratigraphic relationships; based on the extensional basin model of Nicholson & Ryan (2005).

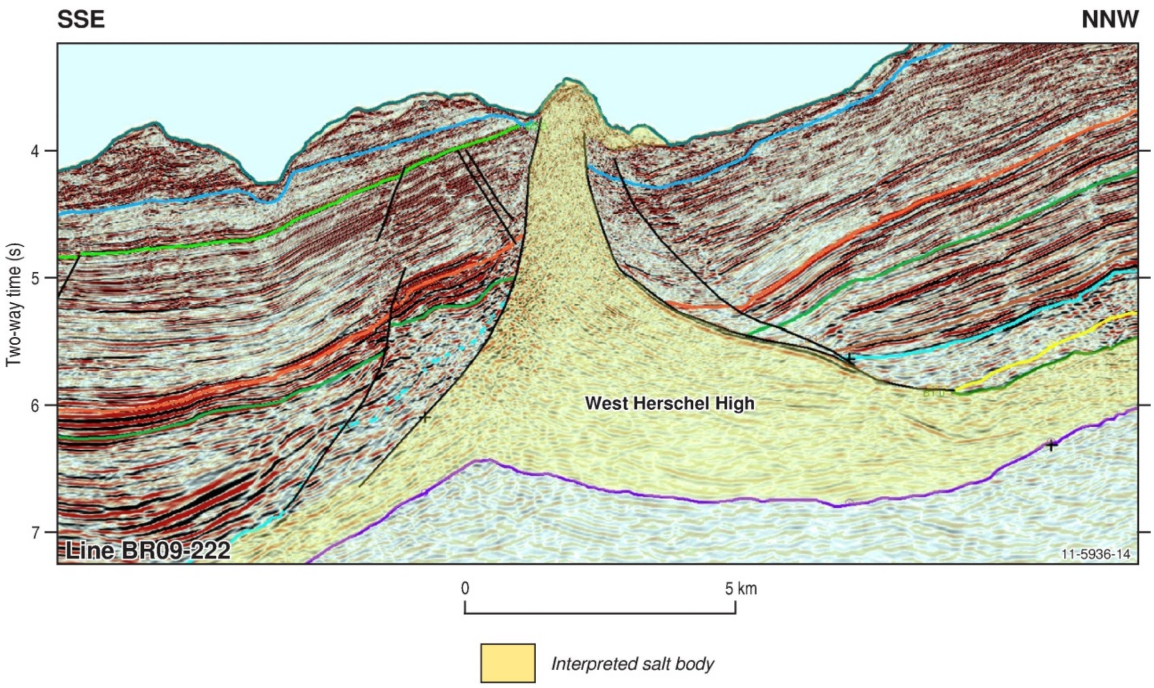

Figure 2.6: Seismic section across the western Bremer Sub-basin, showing interpreted salt diapir and salt withdrawal basin (from Cathay Petroleum & Arcadia Petroleum, 2012).

2.1.3 Petroleum systems

No wells have been drilled in the Bremer Sub-basin, so assessment of its hydrocarbon potential is dependent on the tectonostratigraphic interpretation of 2D seismic data and samples from 45 dredge sites, and comparison with similar depocentres in the eastern Bight and Perth basins. Geoscience Australia's Bremer Sub-basin study concluded that this data supported the presence of all essential petroleum systems elements, and that the sub-basin was prospective for hydrocarbons (Ryan et al., 2005).

2.1.3.1 Source Rocks

Samples recovered from seafloor dredging in early 2004 identified three oil-prone potential source rock units in the Bremer Sub-basin (Ryan et al., 2005):

- Upper Jurassic (Bremer 1) fluvio-lacustrine organic facies, with TOC values of 1–4% and HI_{ker} values of 50–170 mg HC/g TOC, are classified as Type III and considered to be gas-prone;
- Jurassic–Lower Cretaceous lacustrine organic facies (Bremer 2 and 3) are considered to have good potential for generation of oil and gas, with TOC values of 1–3.5%, and a subset of samples having HI_{ker} values of 230–300 mg HC/g TOC; these rocks are of similar facies and age to the Austral 1 petroleum system in the Otway Basin (Edwards et al., 1999).
- Lower Cretaceous (Bremer 4) lacustrine–marine organic-rich facies are considered to have very good potential for generation of oil and gas, with TOC values of 5–22%, and HI_{ker} values of 135–340 mgHc/g TOC.

The presence of potential source rocks within a Lower Cretaceous coaly unit (Bremer 3) was postulated by Ryan et al. (2005), based on seismic data. Such rocks would be an equivalent to the Austral 2 petroleum system. However, Cathay Petroleum & Arcadia Petroleum (2012) interpreted the Bremer 3 sequence to comprise deep water lacustrine sandstones and mudstones overlain by a large prograding delta complex. They proposed that this succession could contain key source and reservoir units. They also considered that the pre-rift evaporate succession may be a potential source interval.

2.1.3.2 Generation and expulsion

Most of the Geoscience Australia dredge samples are immature for hydrocarbon generation as they were obtained from the top two kilometres of a basin succession possibly 10 km thick (Ryan et al., 2005). However, burial history and 1D petroleum systems modelling suggests that predicted source rocks within the Jurassic Bremer 1 sequence are mature to overmature for hydrocarbon generation, and would have undergone a major phase of oil and gas expulsion during rapid burial in the Tithonian–Valanginian. Modelling indicates that predicted lacustrine source rocks within Bremer 2 and Bremer 3 successions are mature for oil generation in the thicker parts of the sub-basin, undergoing expulsion in the Berriasian–Turonian. Generation and expulsion late in this period would have provided the most favourable timing relative to trap generation during the Valanginian–Aptian phase of extensional and/or salt tectonics. Younger parts of the succession are generally immature for hydrocarbon generation. Support for the presence of active petroleum systems in the sub-basin is provided by the presence of oil fluorescence and oil inclusions in some dredge samples (Ryan et al., 2005), oil slicks interpreted from Synthetic Aperture Radar surveys and AVO anomalies in seismic data (Cathay Petroleum & Arcadia Petroleum, 2012).

2.1.3.3 Reservoirs and seals

Ryan et al. (2005) considered that interpreted fluvial units at the tops of Bremer 2 and 3 could contain potential reservoir facies. Cathay Petroleum & Arcadia Petroleum (2012) interpret these sections as coaly swamp and deep lacustrine turbidites associated with a prograding delta complex, respectively; turbiditic sandstone units at the top of Bremer 3, as well as the lowstand delta section at the base of Bremer 4, are considered to be the key reservoir targets in the sub-basin. Analysis of Berriasian–Hauterivian sandstones recovered in dredges confirmed the good reservoir qualities of these rocks; maximum porosities of 24 to 34% were measured using Mercury Injection Capillary Pressure analysis (Daniel, 2005; Ryan et al., 2005). Potential reservoirs are also interpreted to be present in the non-marine Bremer 1 syn-rift succession, and fluvial–coastal plain and marine facies in the younger Bremer 4 section (Ryan et al., 2005).

Potential regional and intraformational seals are present at several stratigraphic levels (Ryan et al., 2005; Cathay Petroleum & Arcadia Petroleum, 2012). Thick lacustrine shales at the bases of the Bremer 2, 3 and 4 successions are likely to provide the best seals in the basin, while mudstones within the younger Cretaceous marine section may also have seal potential.

2.1.3.4 Play types

Numerous potential play types are present in the Bremer Sub-basin including anticlines, fault blocks and combined structural/stratigraphic plays. Structural plays relate to both the early extensional faulting and the subsequent period of extension and/or salt tectonics in the Early Cretaceous. Cathay Petroleum & Arcadia Petroleum (2012) suggested that salt tectonics resulted in the formation of salt diapirs and walls, salt withdrawal basins and anticlinal structures associated with gravity-driven collapse.

2.1.3.5 Critical risks

The main risks for petroleum systems in the Bremer Sub-basin are:

- Lack of charge. As no wells have been drilled in the basin and stratigraphic/lithological information is derived solely from dredge samples, uncertainty remains about the presence and extent of high quality source rocks and their maturity. However, trace oil inclusions have been identified in several dredge samples, and seismic data and interpretation indicate the presence of thick depocentres with the sub-basin.
- Presence of good quality reservoir and seal facies, although the results of analysis of dredge samples is encouraging (Ryan et al., 2005), and AVO analysis of seismic data suggests the presence of trapped hydrocarbons (Cathay Petroleum & Arcadia Petroleum, 2012).
- Loss of early generated hydrocarbons due to Late Cretaceous structuring, uplift and erosion across the sub-basin, and breaching of accumulations by canyons.
- Interpretation uncertainty caused by paucity of direct geological control.

2.1.3.6 Overall prospectivity classification

Moderate–high

2.1.4 Exploration status

The Bremer Sub-basin is a frontier region in which no wells have been drilled. The western Bight Basin has seen two phases of exploration, in the early 1970s and during the past five years. Initial exploration in the area was undertaken by Esso Australia Limited and Continental Oil Company between 1972 and 1974. During this time, seismic and aeromagnetic data were acquired across the Bremer Sub-basin and shelfal areas to the east. Esso identified some large structures in the Bremer Sub-basin, but no further work was undertaken. During the period 2003–2005 Geoscience Australia undertook a petroleum prospectivity study of the Bremer Sub-basin that acquired seismic data and dredge samples (Bradshaw, 2005). These data underpinned the release of exploration areas in 2005. Two permits (WA-279-P and WA-280-P) were initially awarded to Plectrum Petroleum, but in 2008 the permit titles were transferred to a joint venture comprising Arcadia Petroleum and Enovation (now Cathay Petroleum). In 2009–10, the joint venture acquired over 4000 km of 2D seismic data.

2.1.5 Data

Key data sets for the Bremer Sub-basin are listed in Table 2.1–Table 2.3. The Bremer Sub-basin is well covered by generally good quality 2D reflection seismic data. Publicly available seismic data includes the reprocessed R74a survey, originally acquired by Esso, and Geoscience Australia Survey 280 (1300 km). Survey 280 also included the deployment of nine sonobuoys to acquire refraction seismic data. An extensive 2D seismic survey (BR09) acquired by Arcadia and Cathay in exploration permits WA-279-P and WA-280-P has increased the total seismic data in the sub-basin to approximately 8000 line-km and reduced line spacing to 5–10 km.

No wells have been drilled, but seafloor samples obtained by Geoscience Australia during Survey 265 provide lithological information from 45 dredge sites across the sub-basin (Blevin, 2005; Bradshaw, 2005). During Survey 265, over 6500 km of high-resolution swath bathymetry data was collected across the sub-basin. This dataset provides excellent imaging of the canyons that extend across the continental slope, and enabled accurate planning of dredge sites.

2.1.5.1 Confidence rating

Medium

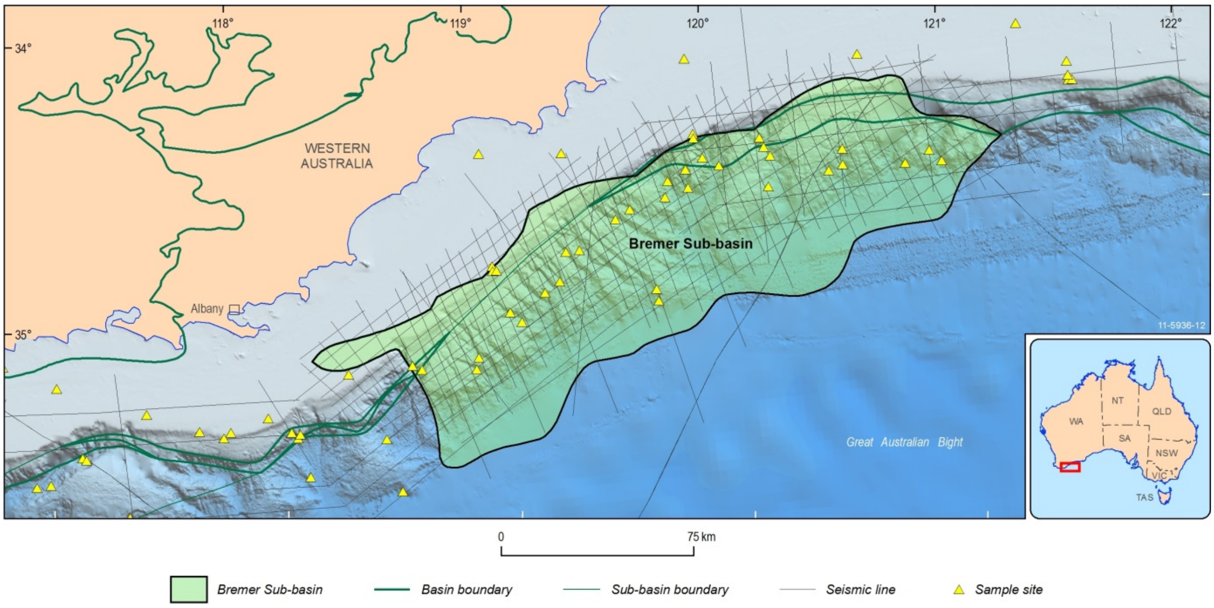

Figure 2.7: Seismic, well and sample distribution, Bremer Sub-basin.

2.1.6 Issues and remaining questions

No wells have been drilled in the Bremer Sub-basin, so geological knowledge is based on dredge samples and seismic data. As a result there is a considerable degree of uncertainty about the nature of the basin fill, including its age, lithology and the distribution of facies. While seismic data and geophysical analysis can provide a great deal of information about potential prospectivity, the full hydrocarbon potential of the sub-basin will not be well understood until more geological samples are obtained.

2.1.6.1 Recommendations

- Drilling of wells in is this sub-basin is the essential next step. While the acquisition of high quality 2D seismic data has enabled more detailed interpretation of the basin fill, only drilling will provide definitive data regarding its geology and prospectivity.
- The acquisition of 3D seismic data is critical for enabling more accurate delineation of potential prospects, assessment of the potential size of petroleum accumulations, and risks relating to structural reactivation.
- Geological and geochemical sampling, particularly in areas where salt features are interpreted to crop out at the seafloor, and in areas of potential seepage identified using the new seismic data sets, should be undertaken to provide further information about petroleum systems.
- Acquisition of new gravity and magnetic data may assist in assessing the presence of salt in the basin, or alternatively, igneous rocks.

2.1.7 References

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2.1.8 Data Tables

Table 2.1: Key seismic surveys in the Bremer Sub-basin.

Year	Survey	Operator	Line-km	Reference
1972	Petrel	Shell		
1974	R74a	Esso	2227	
2001	R74a reprocessed	Esso/Fugro	2227	
2004	Survey 280	Geoscience Australia	2700	Bradshaw, 2005
2009	BR09	Arcadia/Cathay	4443	Cathay Petroleum & Arcadia Petroleum, 2012

Table 2.2: Key geological sampling surveys, Bremer Sub-basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
2004	Survey 265	Geoscience Australia	Bremer Sub-basin	Dredge/core/grab	Jurassic and Cretaceous clastic rocks	Blevin, 2005

Table 2.3: Key swath bathymetry surveys, Bremer Sub-basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
2004	Survey 265	Geoscience Australia	6200 line-km	Blevin, 2005
2006	AUSFAIR–GAB transit	Institut Polaire Français Paul-Emile Victor		Institut Polaire Français Paul-Emile Victor, 2007

2.2 Eyre Sub-basin (Bight Basin)

2.2.1 Summary

State(s)		Western Australia, South Australia
Area (km^2)		~9200
Water Depth (m)		100–2800
Maximum sediment thickness (m)		3500
Age range		Middle Jurassic–Turonian
Basin	**Overlies**	Proterozoic basement
	Underlies	Eucla Basin
	Parent	Bight Basin
	Adjacent basins	Ceduna Sub-basin; Madura Shelf
Basin type		Extensional
Depositional setting, rock types		Non-marine, deltaic and shallow marine clastic sedimentary rocks
Petroleum prospectivity		Moderate–High
Confidence		*Medium*

2.2.2 Geology

The Eyre Sub-basin (Bein & Taylor, 1981; Stagg et al., 1990; Bradshaw et al., 2003) is located in the eastern Bight Basin and underlies the bathymetric Eyre Terrace (100–2800 m water depth). It comprises a series of Middle Jurassic–Early Cretaceous east-northeast-striking en echelon half graben (Figure 2.8). The sub-basin covers an area of approximately 9200 km^2, and contains up to 3500 m of Jurassic–Cretaceous sedimentary rocks (Figure 2.9). The Eyre Sub-basin succession is unconformably overlain by up to 1000 m of Cenozoic strata of the Eucla Basin. The Eyre Sub-basin adjoins the Ceduna Sub-basin to the southeast, and the Madura Shelf to the north, west and south. A basement high covered by a thin Madura Shelf succession separates the southern boundary of the Eyre Sub-basin from the deep-water Recherche Sub-basin.

2.2.2.1 Structural geology

The half graben of the Eyre Sub-basin, along with similar structures in the Bremer and Duntroon sub-basins and the inboard Ceduna Sub-basin, represent the earliest phase of basin development along Australia’s southern rifted margin. These depocentres developed during the Middle–Late Jurassic to earliest Cretaceous as a result of northwest–southeast to north-northwest–south-southeast intracontinental extension. In the Eyre Sub-basin, the landward margin of each half graben is clearly defined by east-northeast striking rift-border faults (Figure 2.8). The eastern end of the faults consistently strike in a more easterly direction, and fault displacements are transferred along-strike by accommodation zones between overlapping fault segments. Minor reactivation of the half-graben bounding faults and compaction-related faulting occurred during the Late Cretaceous.

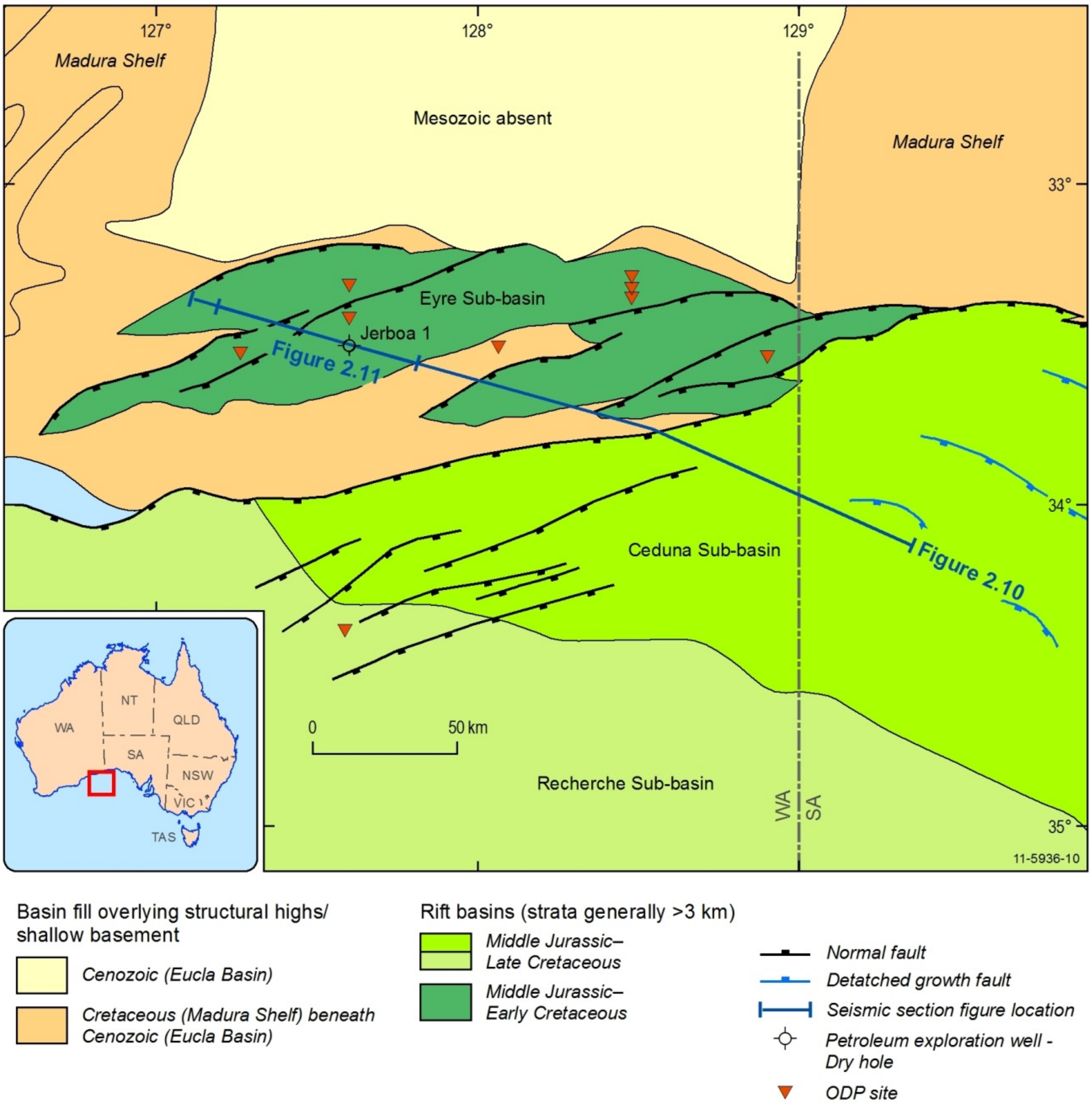

Figure 2.8: Structural elements map, Eyre Sub-basin.

2.2.2.2 Basin evolution and depositional history

In the Eyre Sub-basin, the syn-rift fill comprises fluvial–lacustrine sandstone, siltstone and claystone of the Middle Jurassic–Lower Cretaceous Sea Lion and Minke supersequences (Figure 2.10 and Figure 2.11). The overlying early post-rift succession, comprising the Lower Cretaceous Southern Right and Bronze Whaler supersequences, consists of interbedded claystone, siltstone, sandstone and coal deposited in lacustrine and fluvial environments. The early post-rift succession is overlain by marine to deltaic rocks of the Lower Cretaceous Blue Whale and White Pointer supersequences that extend beyond the half-graben boundaries and onlap basement. The Upper Cretaceous Hammerhead Supersequence and most of the Tiger Supersequence are generally absent across the Eyre Sub-basin, however the Tiger Supersequence is interpreted on seismic data across the southernmost part of the sub-basin, and both the Tiger and Hammerhead supersequences occur in onshore wells to the north. This distribution indicates a period of uplift and erosion across the sub-basin, and adjacent Madura Shelf, in the latest Cretaceous–early Paleocene.

2.2.2.3 Level of knowledge

Geological understanding of the Eyre Sub-basin is based on interpretation of a generally good quality, regional scale, 2D seismic data set, which has a line spacing of approximately 20–40 km, and the Jerboa 1 well, drilled by Esso Australia (Heubner, 1980), which provides valuable stratigraphic control and constrains seismic-based facies interpretation (Figure 2.12). Together these data sets provide a good basis for understanding the stratigraphy, structure and evolution of the Eyre Sub-basin.

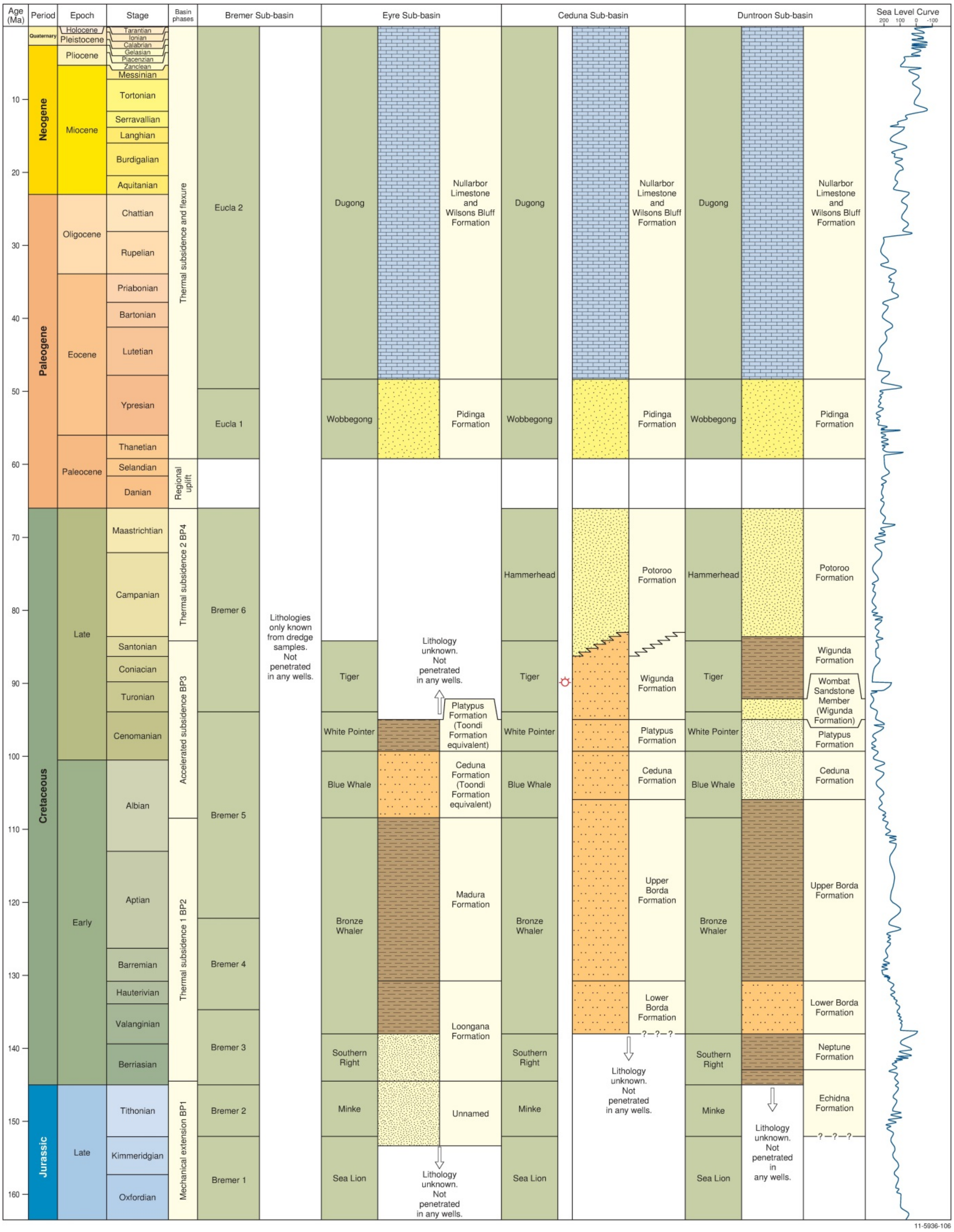

Figure 2.9: Stratigraphy of the Eyre, Ceduna and Duntroon sub-basins, Bight Basin. Geologic time scale after Gradstein et al. (2012); sea-level curve of Haq et al (1988) calibrated to the time scale.

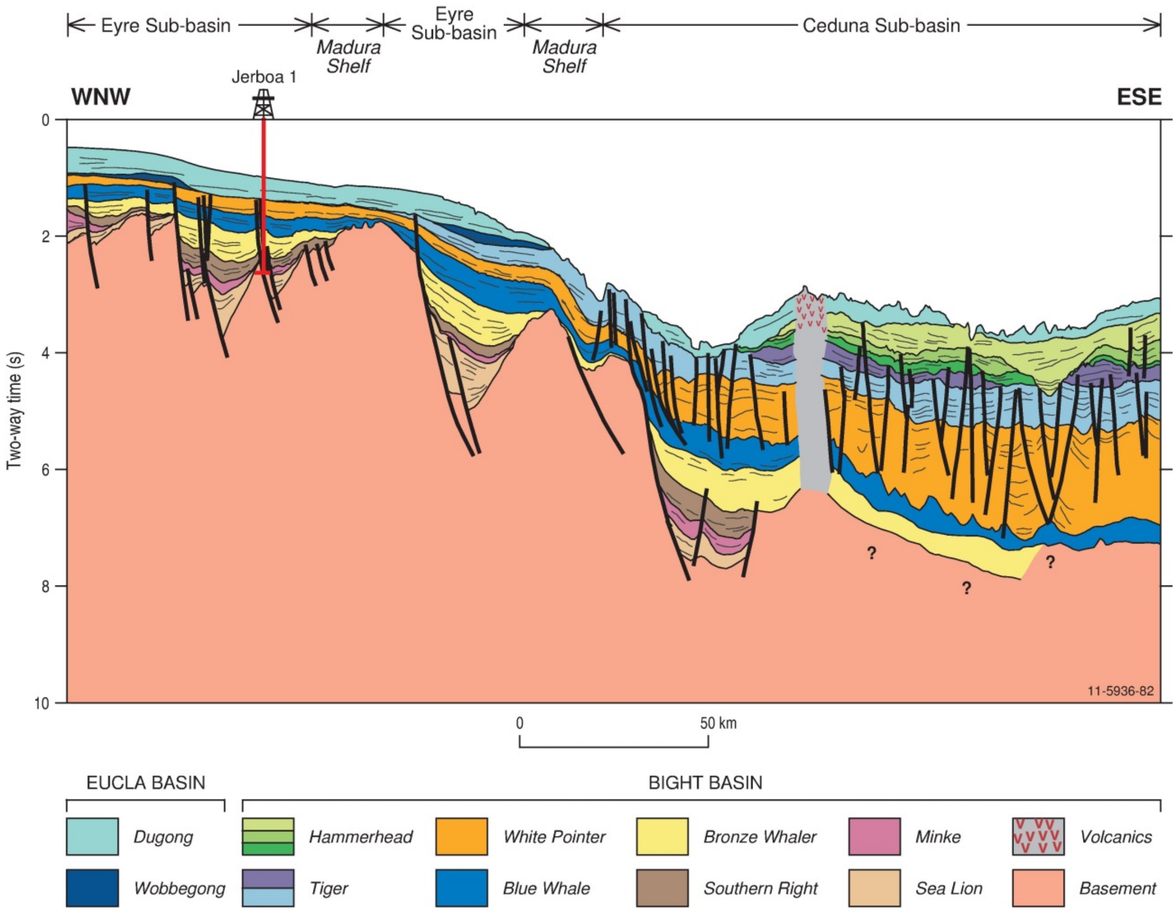

Figure 2.10: Geological cross-section(s) showing structural and stratigraphic relationships.

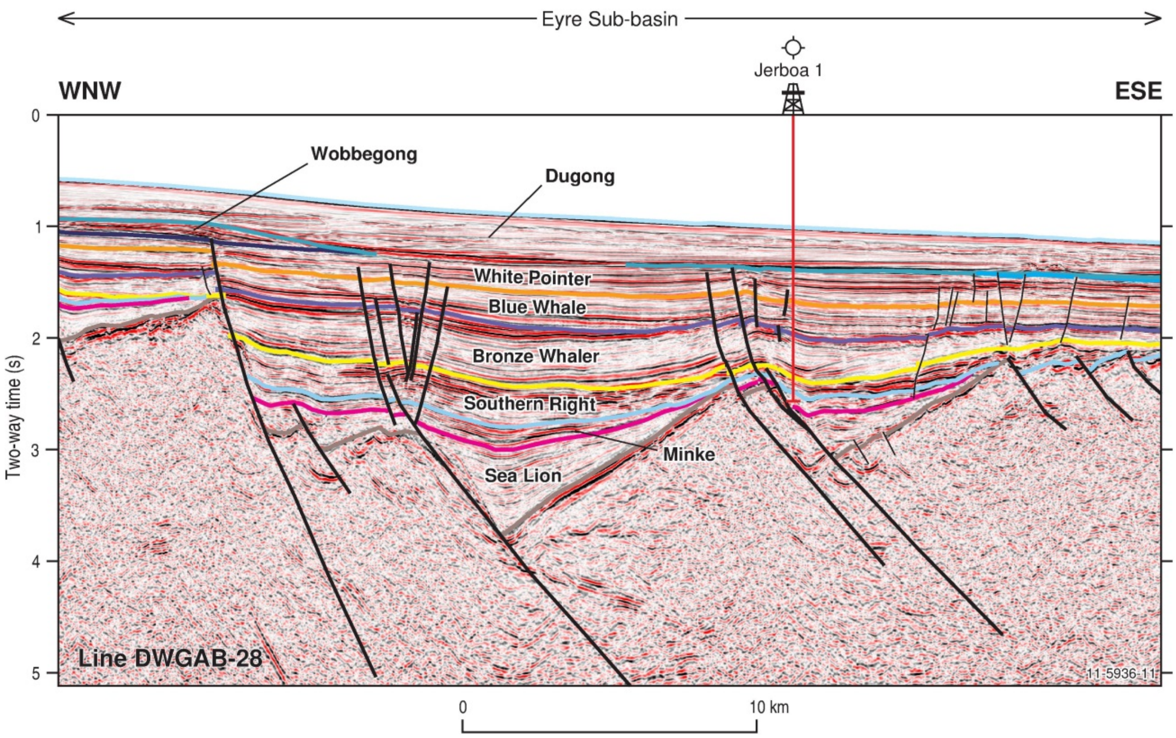

Figure 2.11: Seismic section across the Eyre Sub-basin.

2.2.3 Petroleum systems

There have been no hydrocarbon discoveries in the Eyre Sub-basin, which contains only one exploration well, Jerboa 1. The well targeted Lower Cretaceous to Jurassic strata that drape the footwall block of an intra-basinal fault. There were no significant hydrocarbon shows recorded during drilling, and the well was plugged and abandoned. However, later analysis of oil in fluid inclusions in Upper Jurassic sandstone at the base of the well resulted in the identification of a 15 m palaeo-oil column; this finding supports the interpretation of an active petroleum system in the sub-basin (Liu & Eadington, 1998; Ruble et al., 2001).

2.2.3.1 Source Rocks

In the Eyre Sub-basin, potential source rocks containing algal-rich lacustrine facies and coal are interpreted to be present within the Upper Jurassic to Lower Cretaceous Sea Lion, Minke, Southern Right and Bronze Whaler supersequences (Blevin et al., 2000; Totterdell et al., 2000). These units contain non-marine sediments deposited during the initial period of extension, and the subsequent post-rift phase.

The key potential source rocks are likely to be algal-rich lacustrine facies deposited during the Jurassic rift phase (Austral 1 petroleum system; Edwards et al., 1999), as these are the most likely to be mature for hydrocarbon generation. In Jerboa 1, the Sea Lion and Minke supersequences consist of fluvial–lacustrine sandstone and mudstone. Morgan (1999) reported that some samples from the Minke Supersequence contain high algal content (up to 17%) and may have good oil source potential. Away from the well, the rift phase succession has a generally low amplitude seismic character suggestive of uniform lithology.

The structural geology, stratal geometries, seismic facies and lithofacies observed in the Eyre Sub-basin indicate that during the Late Jurassic and Early Cretaceous (prior to the Albian), the Eyre half graben formed a series of isolated, lacustrine depocentres. This interpretation is supported by the analysis of fluid inclusion oil from Jerboa 1, which indicates that the oil came from a calcareous source rock containing primarily algal and bacterial organic material, probably deposited in a lacustrine depositional environment (Ruble et al., 2001). The structural position of Jerboa 1 on the footwall of an intra-basinal fault, the immaturity of the succession penetrated in the well, and the stratigraphic position of the palaeo-oil column near basement indicate that these hydrocarbons are likely to have migrated from lacustrine source rocks in the flanking half graben (Ruble et al., 2001).

Geochemical analysis of samples from Jerboa 1 has also demonstrated good oil potential in fine-grained lacustrine facies of the Bronze Whaler Supersequence (Struckmeyer et al., 2001). Boreham et al. (2001) also identified organic-rich (8% TOC) lacustrine rocks within the Bronze Whaler Supersequence in Gambanga 1, which is located northwest of the Eyre Sub-basin in the onshore part of the basin (Totterdell & Krassay, 2003). Coaly facies may also provide potential source rocks within the sub-basin, as high amplitude reflections on seismic data suggest that the Minke and Southern Right supersequences contain coal (Figure 2.11).

2.2.3.2 Generation and expulsion

The sequences containing potential source rocks are immature at the Jerboa 1 well (Ruble et al., 2001), but are likely to be mature to early mature where buried deeper within, and overlying, the half graben, particularly in the southeastern part of the sub-basin adjacent to the Ceduna Sub-basin. Burial history modelling of a 'pseudo-well' in the centre of the half graben adjacent to Jerboa 1 indicates that the early rift section in the deepest half graben entered the oil window during the Cretaceous, with peak hydrocarbon generation occurring ~85 Ma (Ruble et al., 2001). This coincides with the time of initial continental breakup and precedes both the structural reactivation that breached the Jerboa 1 trap and the latest Cretaceous–early Paleocene period of uplift and erosion (Ruble et al., 2001). The burial history modelling also indicates that low volumes of residual oil and gas were potentially expelled from approximately 48 Ma onward (Ruble et al., 2001).

2.2.3.3 Reservoirs and seals

In Jerboa 1, potential reservoirs are present as sandy facies at the base of each supersequence, with the basal sands of the Southern Right Supersequence having the highest measured porosity and permeability values (Quinn, 1999). Potential reservoir rocks are also present in the lowstand and highstand deposits of the Wobbegong Supersequence at the base of the overlying Cenozoic succession.

Shale facies within the upper Minke and Southern Right supersequences have the best sealing capabilities (Quinn, 1999). Quinn (1999) also assessed fault sealing capacity for the succession intersected in Jerboa 1; the results were excellent for the Bronze Whaler Supersequence and good for the Sea Lion, Minke and White Pointer sections.

2.2.3.4 Play types

Potential, untested, plays within the Eyre Sub-basin include: footwall blocks of half-graben bounding faults, similar to Jerboa 1, where compaction/reactivation faulting is absent; stratigraphic onlap onto hanging wall blocks and relay ramps; reactivation anticlines; pre-Cenozoic sub-crop plays; and stratigraphic traps within progradational sandy facies in the Wobbegong Supersequence (Blevin et al., 2000; Totterdell et al., 2000). Untested stratigraphic plays may also occur in lowstand systems tract channel sandstones and incised valleys, and transgressive sandstone bodies at the base of Blue Whale Supersequence (Totterdell et al., 2000). Prospectivity is best in areas adjacent to more deeply buried and thicker half-graben successions, and where an absence of late-stage fault reactivation has maintained trap integrity (Totterdell et al., 2000). In addition, in the southeastern part of the sub-basin, there is the potential for long-distance migration of hydrocarbons from the Ceduna and Recherché sub-basins into Lower Cretaceous reservoirs.

2.2.3.5 Critical risks

A key prospectivity risk in the Eyre Sub-basin is the lack of hydrocarbon charge in areas where the basin fill is less than 2500–3000 m. Ruble et al. (2001) argued that timing of trap formation, generation, expulsion and reactivation are all critical issues for the prospectivity. This particularly applies the timing of migration and accumulation relative to the period of uplift and erosion in the latest Cretaceous–early Paleocene. Given the localised nature of potential source kitchens, accumulation size may also be an issue in the sub-basin.

Jerboa 1 is considered to have been a valid structural test of a drape structure over a basement block; the cause of failure is likely to be breaching of the trap following the accumulation of the hydrocarbon column (Messent, 1998). Seismic data shows that a group of small faults branch upwards from the half-graben bounding fault, the result of Late Cretaceous fault reactivation (possibly related to the period of uplift), as well as compaction. Ruble et al. (2001) considered that any hydrocarbon accumulation in place at the time of reactivation would have been breached and leaked to the surface. Seismic data shows that while there are similar faulted structures elsewhere in the sub-basin, there are also structures associated with half-graben bounding faults that do not appear to have been affected by later faulting.

Another potential risk for explorers in the Eyre Sub-basin is the presence of H_2S. ODP Leg 182 wells encountered high levels of H_2S when drilling through thick Pleistocene progrades (Feary et al., 2000; Swart et al., 2000). This issue could be problematic for wells drilled into areas of the Eyre Sub-basin that are overlain by a thick Cenozoic succession.

2.2.3.6 Overall prospectivity classification

Moderate–high

2.2.4 Exploration status

There have been no hydrocarbon discoveries in the Eyre Sub-basin and the area is an exploration frontier. Exploration activity in the Eyre Sub-basin has been sparse, with permits being held in the sub-basin only once. The only well, Jerboa 1, was drilled more than 30 years ago; in the late 1970s–early 1980s, Esso Exploration and Production Australia, in joint venture with Hematite Petroleum, undertook an exploration program in the Eyre Sub-basin, acquiring seismic data and drilling the well. Since then, exploration has been limited to the acquisition of a speculative seismic survey over the Eyre Sub-basin by the Japan National Oil Corporation in the early 1990s.

2.2.5 Data

Key data sets for the Eyre Sub-basin are listed in Table 2.4–Table 2.7. Jerboa 1 is the only exploration well in the sub-basin; all open-file documentation, including the well completion report and cores and cuttings samples can be accessed through Geoscience Australia. In 1998, Leg 182 of the Ocean Drilling Program drilled a series of shallow wells in the area to investigate the evolution of a Cenozoic cool water carbonate margin (Table 2.4; Feary & James, 1998; Feary et al., 2000, 2004). Nine holes were drilled across the Eyre Terrace and onto the lower continental slope. The focus of the study was the Cenozoic section, and only one hole (Site 1126) intersected Cretaceous rocks (Feary et al., 2000, 2004).

Seismic data coverage across the Eyre Sub-basin is good given its frontier exploration status (Table 2.5). Key data sets are JNOC's 1990 survey, BMR/AGSO surveys 65 and 199, and the DWGAB and HRGAB data. Seismic data quality ranges from poor in deep water and in the vicinity of canyons, to good on the Eyre Terrace.

Several BMR/AGSO/GA marine sampling surveys have collected sea floor samples from the Eyre Sub-basin (Table 2.6). These include Survey 66 (Willcox et al., 1988), and the 2007 Bight Basin Sampling and Seepage Survey (Totterdell & Mitchell, 2009). High resolution bathymetric data was also acquired in sampling areas during the 2007 survey (Table 2.7).

2.2.5.1 Confidence rating

Medium

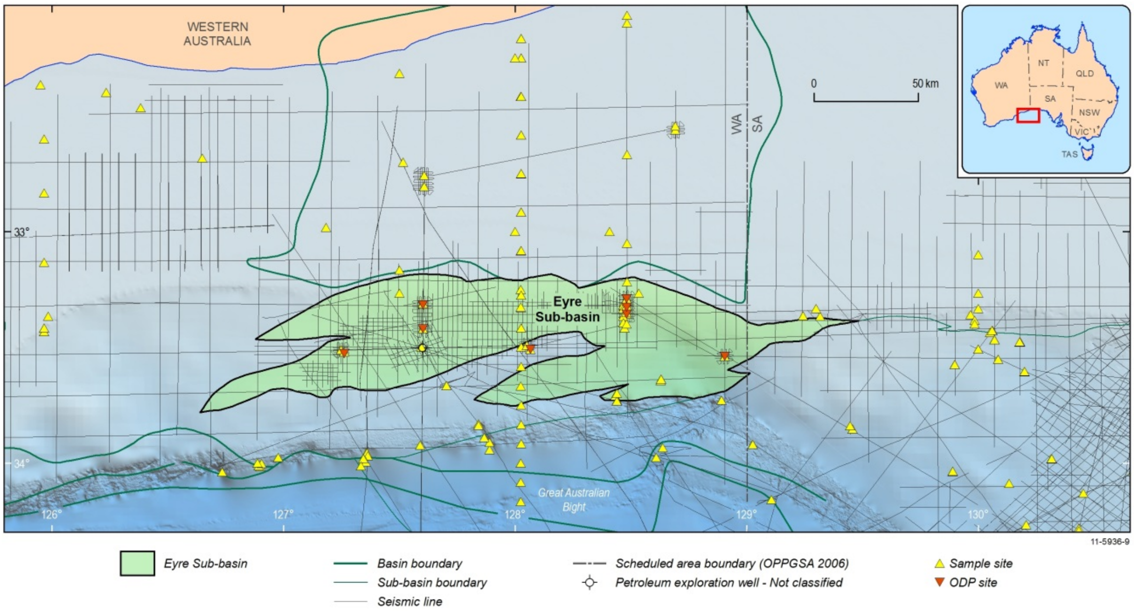

Figure 2.12: Seismic, well and sample distribution.

2.2.6 Issues and remaining questions

As only one well, Jerboa 1, has been drilled in the sub-basin, the lithology, age, and source, reservoir and seal potential of the sequences away from that well remain unknown. This profound knowledge gap limits robust assessment of the petroleum prospectivity of the sub-basin. Key uncertainties for the sub-basin are whether potential source rocks within the half graben are mature for hydrocarbon generation, and the volume of charge from lacustrine source rocks in isolated depocentres.

2.2.6.1 Recommendations

- Acquisition of high quality 2D seismic data with a line spacing of <10 km across the sub-basin, followed by targeted 3D seismic acquisition and drilling are required to address the present gaps in knowledge.
- Improved seismic data quality and density would assist in more accurately assessing: the distribution of facies; the timing, distribution and nature of fault reactivation and whether there are structures that were not at risk from reactivation during later deformation; the uplift and erosion history of the sub-basin; and the potential size of petroleum accumulations.

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2.2.8 Data Tables

Table 2.4: List of wells, Eyre Sub-basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1980	Jerboa 1	Exploration	Esso	2538	Jurassic	GOI	Huebner, 1980; Ruble et al., 2001
1998	Leg 182 (9 wells)	Stratigraphic	ODP		Cretaceous	Nil	Feary et al., 2000, 2004

Table 2.5: Key seismic surveys, Eyre Sub-basin

Year	Survey	Operator	Line-km	Reference
1972–3	Continental Margins Survey	BMR		
1972	Petrel	Shell		
1979–80	E79A and E82A	Esso/Hematite	4073	
1986	Survey 65	BMR	3500	
1990–91	JA90	JNOC	2350	
1997	Survey 199	AGSO	3911	
1998	DWGAB and HRGAB	Seismic Australia/AGSO	8294	

Table 2.6: Key geological sampling surveys, Eyre Sub-basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
1986	BMR Survey 66 (Rig Seismic research cruises 10 and 11): geology of the central GAB	BMR	Great Australian Bight	Dredging, coring	Sediments, granitic basement	Willcox et al., 1988; Davies et al., 1989
1998	Ocean Drilling Program Leg 182: Sites 1126–1134	ODP	Great Australian Bight	Stratigraphic drilling	Carbonates, minor clastic rocks	Feary et al., 2000, 2004
1991	RV Rig Seismic cruise 102 (Area B): Cool-water carbonate sedimentation, GAB	Australian Geological Survey Organisation	Great Australian Bight	Gravity cores	Bioclastic sand	Feary et al., 1993
2007	Bight Basin geological sampling and seepage survey (SS01/2007)	Geoscience Australia	Great Australian Bight	Dredge, gravity core, grab	Ooze, clastic sediments	Totterdell & Mitchell, 2009

Table 2.7: Key swath bathymetry surveys, Eyre Sub-basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
2007	Bight Basin geological sampling and seepage survey (SS01/2007)	Geoscience Australia		Totterdell & Mitchell, 2009

2.3 Ceduna Sub-basin (Bight Basin)

2.3.1 Summary

State(s)		South Australia; Western Australia
Area (km^2)		126,300
Water Depth (m)		200–5200
Maximum sediment thickness (m)		>15,000
Age range		Middle Jurassic–Late Cretaceous
Basin	**Overlies**	?Gawler Craton
	Underlies	Eucla Basin
	Parent	Bight Basin
	Adjacent basins	Eyre, Duntroon and Recherché sub-basins, Madura Shelf, Couedic Shelf; Otway Basin; Morum Sub-basin; Polda Basin
Basin type		Extensional; passive margin
Depositional setting, rock types		Non-marine, deltaic and marine clastic sedimentary rocks
Petroleum prospectivity		High
Confidence		*High–Medium*

2.3.2 Geology

The east-southeast-trending Ceduna Sub-basin is the major depocentre of the Bight Basin, extending over an area of 126,300 km^2 and containing at least 15,000 m of syn-rift and post-rift Middle Jurassic–Upper Cretaceous sediments (Figure 2.13 and Figure 2.14; Bradshaw et al., 2003). The deep-water Recherche Sub-basin adjoins the Ceduna Sub-basin and extends west along the southern margin. The Ceduna Sub-basin is flanked to the northwest by the half-graben systems of the Eyre Sub-basin. The Duntroon Sub-basin adjoins the Ceduna Sub-basin to the southeast, and consists of a series of oblique extensional depocentres. Thin platform cover areas—the Madura and Couedic shelves—are located to the north and east of the Ceduna Sub-basin respectively.

2.3.2.1 Structural geology

The Ceduna Sub-basin can be divided into three structural domains (Figure 2.15 and Figure 2.16):

- A steeply-dipping hinge zone along the northern and eastern margins of the sub-basin containing extensional and transtensional Middle Jurassic–Early Cretaceous half-graben systems.
- A broad central depocentre characterised by detached extensional faulting and fault reactivation, forming a complex series of rotated fault blocks.
- An outer basin high underlain by a zone of complex, mainly contractional, Cenomanian deformation, which was the focus of subsequent extensional faulting and shelf-margin instability.

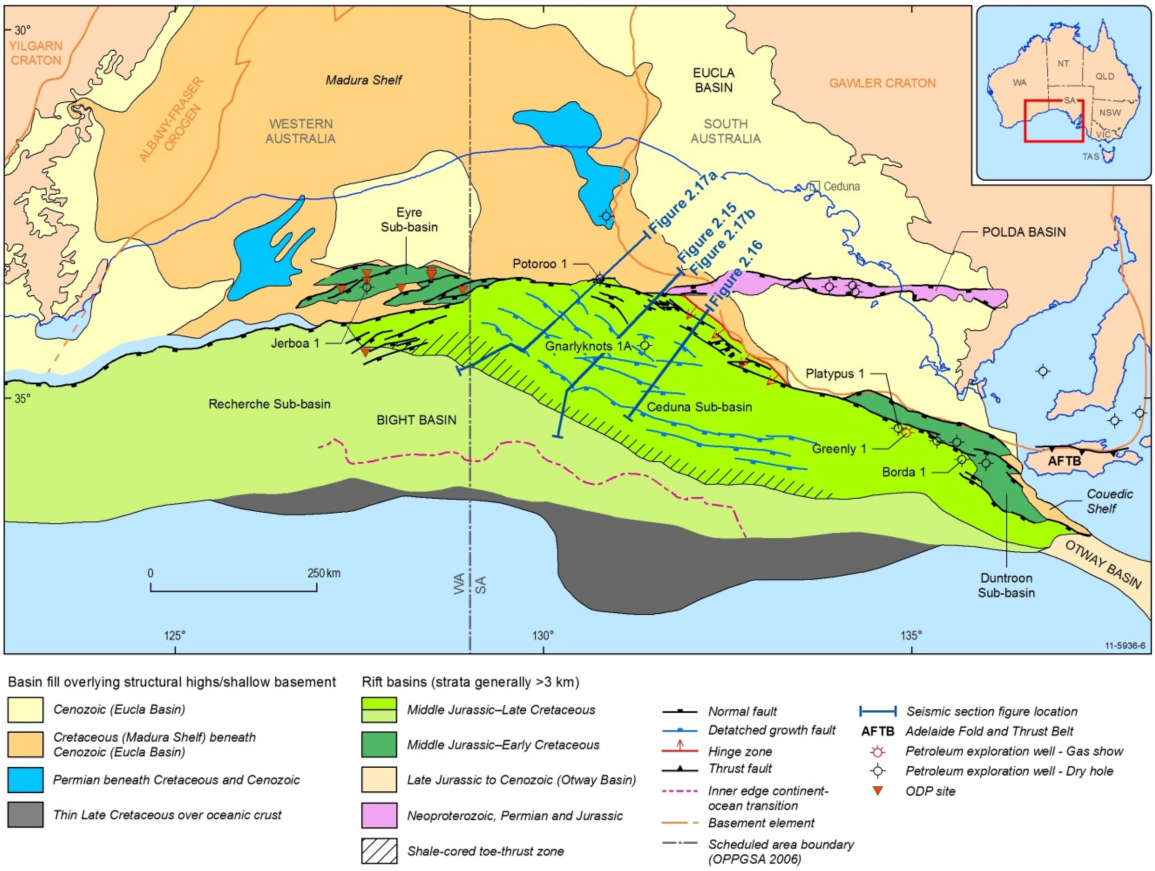

Figure 2.13: Structural elements map, eastern Bight Basin, showing location of the Ceduna Sub-basin.

The northern and eastern margins of the Ceduna Sub-basin have a steep ramp-like geometry and are characterised by Middle Jurassic–Early Cretaceous half graben (Figure 2.16). The basin thickens rapidly seaward where the succession is dominated by a thick Lower–Upper Cretaceous marine–deltaic section. Structural architecture over much of the sub-basin is controlled by a series of generally northwest–southeast oriented, listric normal faults that formed as a result of shale tectonics during deposition of a major delta system in the Cenomanian. Dominantly southwest-dipping regional faults detach onto a decollement formed in Albian–Cenomanian shales (Figure 2.15). Farther down-dip, this extension is compensated by contractional faulting and folding. A transitional zone of complex deformation lies between these extensional and contractional zones. This region coincides with an outer high at the seaward edge of the Ceduna Sub-basin (Figure 2.15). Compaction-related faulting and/or reactivation of the listric extensional faults occurred during the Turonian–Santonian prior to the initiation of sea-floor spreading in the latest Santonian. Some reactivation occurred on selected faults in the Campanian–Maastrichtian, particularly in the more outboard parts of the sub-basin. During this period, new gravity-slide structures also formed at the outer edge of the sub-basin as a result of collapse of the gravitationally unstable, palaeo-shelf margin.

2.3.2.2 Basin evolution and depositional history

The Ceduna Sub-basin developed in response to repeated periods of extension and thermal subsidence leading up to, and following, the commencement of seafloor spreading between Australia and Antarctica (Figure 2.14; Totterdell & Bradshaw, 2004). Deposition commenced during the Middle–Late Jurassic to earliest Cretaceous as a result of northwest–southeast to north-northwest–south-

southeast intracontinental extension. A series of oblique extensional and transtensional half graben formed along the northern and eastern margins of the Ceduna Sub-basin, as well as in the Bremer, Eyre and Duntroon sub-basins. This succession has not been intersected by wells drilled in the Ceduna Sub-basin, but the fill of the basal half graben imaged on seismic data is assigned to the Sea Lion and Minke supersequences by analogy with the Eyre Sub-basin. In Jerboa 1 in the Eyre Sub-basin, the rift-fill comprises a fluvial–lacustrine sandstone, siltstone and mudstone succession.

The extensional phase was followed by a period of slow thermal subsidence that lasted throughout most of the Early Cretaceous (Figure 2.14), and resulted in deposition of the Southern Right and Bronze Whaler supersequences. Depositional environments were largely non-marine, although some marine influence is evident late in this phase. The Southern Right Supersequence has not been drilled in the Ceduna Sub-basin, but is inferred to be present based on seismic interpretation and correlation with the Eyre and Duntroon Sub-basins. The Bronze Whaler Supersequence generally consists of an aggradational succession of fluvial and lacustrine sediments. Where interpreted in the Ceduna Sub-basin, the succession has an onlapping, sag-fill geometry.

An abrupt increase in subsidence rate in the mid-Albian signalled the start of the third basin phase (Figure 2.14), during which up to 10,000 m of deltaic and marine, predominantly fine-grained sediments were deposited in the central Ceduna Sub-basin. 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 2.14). This combination of factors resulted in a high rate of creation of accommodation space, the first major marine flooding event in the basin and the widespread deposition of marine silts and shales of the Albian–Cenomanian Blue Whale Supersequence. Marine conditions extended along the southern margin from the open sea in the west towards the Otway Basin in the east. Progradation of deltaic sediments (White Pointer Supersequence) into this seaway commenced in the Cenomanian. Deposition was rapid, resulting in a short-lived period of shale tectonics throughout the northern half of the Ceduna Sub-basin. The Blue Whale Supersequence is interpreted to have had a pre-deformation thickness of about 1500–2000 m (Totterdell & Krassay, 2003). The thickness of the unit is now highly variable, reaching a maximum of about 4000 m adjacent to some growth faults. The White Pointer Supersequence has a maximum thickness of approximately 5000 m within growth fault-bounded depocentres. Interpretation of seismic facies suggests that a broad band of coaly sediments is present within the White Pointer Supersequence in the inner part of Ceduna Sub-basin. The Cenomanian deltaic sediments are overlain by the marginal marine, deltaic and open marine sediments of the Turonian–Santonian Tiger Supersequence. During this time, the locus of deltaic deposition moved to the southeast (MacDonald et al., 2013). On seismic data from the northern half of the sub-basin, the supersequence has an overall flat-lying aggradational character, with some progradational seismic facies evident in its upper part. The Tiger Supersequence thickens markedly to the south where it reaches a maximum thickness of approximately 4500 m.

The start of continental breakup in the late Santonian was followed by a period of thermal subsidence and the establishment of the southern Australian passive margin (Figure 2.14). During this phase a second large deltaic system developed, represented by the latest Santonian–Maastrichtian Hammerhead Supersequence (Krassay & Totterdell, 2003). This sand-rich delta is characterised by strongly prograding stratal geometries (Figure 2.15 and Figure 2.16). The updip portion of the basal sequence boundary records widespread incision, including several large incised valley systems. The Hammerhead Supersequence has an overall progradational–aggradational character. Two lower sequence sets are strongly progradational in character, reflecting a consistently high rate of sediment supply from the late Santonian through the Campanian. The thick, stacked deltaic sequences of the upper sequence set were deposited during a period of balance between the rates of creation of accommodation space and sediment supply. The Hammerhead Supersequence reaches a maximum thickness of about 5000 m.

A dramatic reduction in sediment supply at the end of the Cretaceous saw the abandonment of deltaic deposition. A widespread angular unconformity between the Bight and Eucla basin successions on the Madura Shelf suggests regional uplift at this time. From the late Paleocene to present, the largely cool-water carbonates of the Eucla Basin accumulated on a sediment-starved passive margin. A short phase of magmatism in the middle Eocene, coinciding with the onset of rapid spreading, affected the central and eastern Ceduna Sub-basin. This magmatic phase was characterised by both extrusive volcanism (volcanoes, flows, volcanic build-ups) and the intrusion of sills, dykes and deeper igneous bodies (Schofield & Totterdell, 2008).

2.3.2.3 Level of knowledge

Geological understanding of the Ceduna Sub-basin is based largely on the interpretation of good quality 2D and 3D seismic data sets, calibrated to the five wells that have been drilled in the sub-basin and those elsewhere in the Bight Basin.

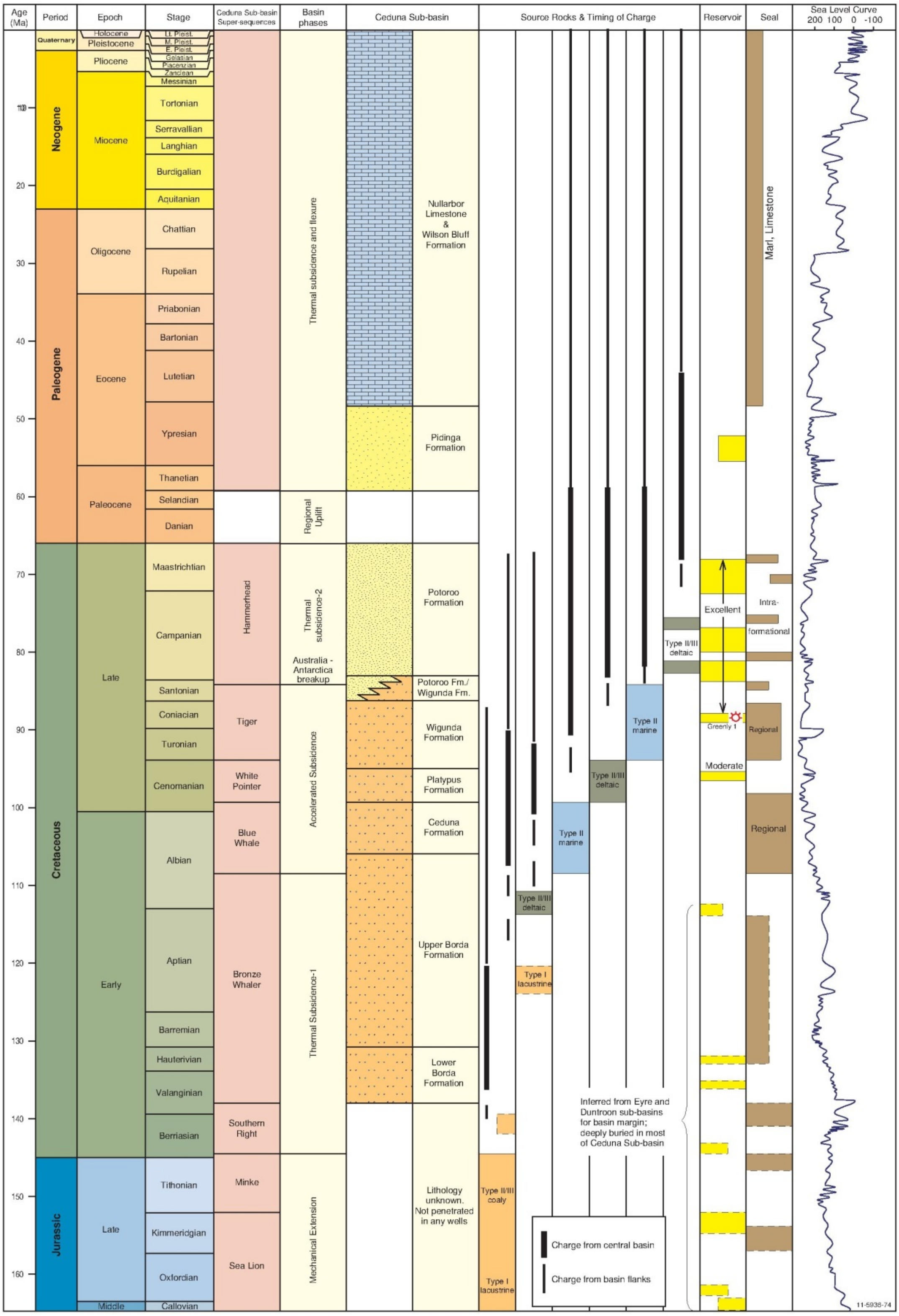

Figure 2.14: Stratigraphy and potential petroleum systems, Ceduna Sub-basin. Geologic time scale after Gradstein et al. (2012); sea-level curve of Haq et al (1988) calibrated to the time scale.

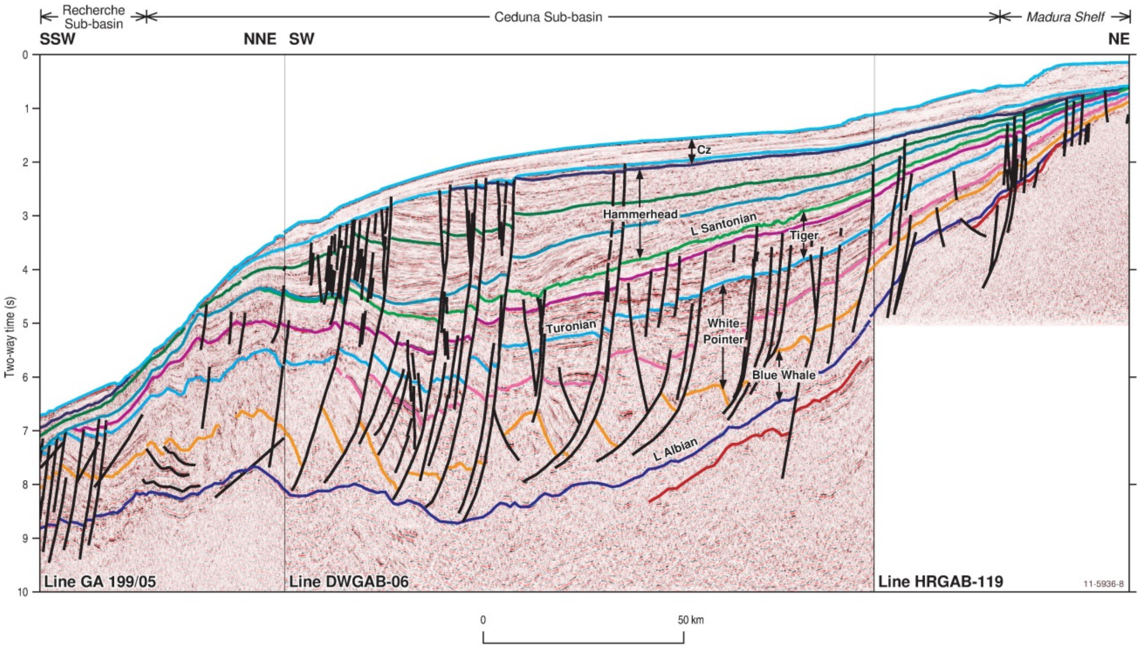

Figure 2.15: Seismic profile across northern Ceduna Sub-basin showing structural and stratigraphic relationships.

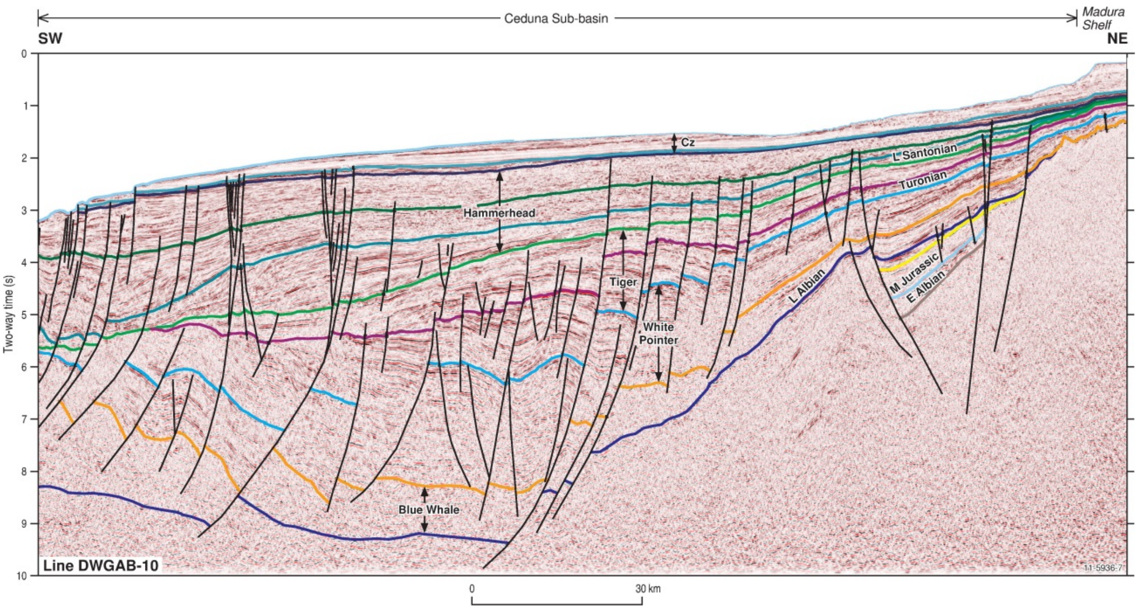

Figure 2.16: Seismic profile across central Ceduna Sub-basin showing structural and stratigraphic relationships.

2.3.3 Petroleum systems

There have been no hydrocarbon discoveries in the Ceduna Sub-basin. However the thick sedimentary succession and the evolution of the sub-basin from local extensional 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. Apart from oil and gas indications in wells of the eastern Ceduna and Duntroon sub-basins, and a palaeo-oil accumulation in the Eyre Sub-basin in the Jerboa 1 well, evidence for hydrocarbons is provided by numerous indirect indicators on seismic and remote sensing data

(Struckmeyer et al., 2002). Although the Gnarlyknots 1A well in the central Ceduna Sub-basin was unsuccessful, a number of secondary indications of charge such as fluorescent hydrocarbon-bearing inclusions, monazite grains with hydrocarbon rims and a shallow biogenic gas signal from fluid inclusion stratigraphy have been described from analyses of well samples (King & Mee, 2004). Hydrocarbon indications on seismic sections include amplitude anomalies within the Hammerhead and Tiger supersequences (King & Mee, 2004; Tapley et al., 2005). The overall prospectivity of the Ceduna Sub-basin is considered to be high. Given the amount and quality of data available, the confidence rating for this assessment is high–medium.

2.3.3.1 Source Rocks

Regional sequence stratigraphic analysis and the results of seafloor dredging indicate that several potential source intervals may be present in the Ceduna Sub-basin (Figure 2.14; Blevin et al., 2000; Totterdell et al., 2000, 2008). Key potential source rocks are marine shales of the Albian–Cenomanian Blue Whale and Turonian–Santonian Tiger supersequences, and coaly rocks of the Cenomanian White Pointer Supersequence that are interpreted on seismic data across the inner part of the Ceduna Sub-basin. While the Jurassic–Lower 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 Upper Cretaceous marine and deltaic facies.

Recent dredging of upper Cenomanian–Turonian (basal Tiger Supersequence) organic-rich marine rocks has confirmed the presence of high quality source rocks in the basin and has significantly reduced exploration risk. These rocks, obtained by dredging the succession on the western margin of the Ceduna Sub-basin, are the best potential source rocks found in the Bight Basin (Totterdell et al., 2008; Totterdell & Mitchell, 2009). In eleven samples dated as latest Cenomanian to Turonian, TOC content ranges from <2 to 6.9% and HI values range from 274 to 479 mg HC/g TOC. These data suggest good to excellent generative potential for oil. Molecular composition of the extractable organic matter shows that it was deposited in a marine environment under reducing conditions; the rocks have geochemical affinities to marine asphaltites found stranded along the southern Australian coastline (Edwards et al., 1998; Boreham et al., 2001; Boreham, 2009). Regional petroleum systems modelling (Totterdell et al., 2008) suggests that the basal Tiger Supersequence is currently mature for oil and gas generation across the greater part of the depocentre and immature along the basin margins (Figure 2.17). In the thickest part of the basin, where the overburden is between about 5000 and 5500 m thick, the basal Tiger Supersequence is gas mature.

The Albian–lower Cenomanian Blue Whale Supersequence records the first major marine flooding event in the Ceduna Sub-basin (Totterdell et al., 2000). During this time, deep water, restricted marine environments favourable to the deposition of rich marine source rocks are interpreted to have been present in the central Ceduna Sub-basin (Boreham et al., 2001; Struckmeyer et al., 2001). Organic matter content of the Blue Whale Supersequence is high (Struckmeyer et al., 2001), with TOC values ranging from 0.5 to 62%, and it typically comprises Type II/III kerogen; the higher values represent mostly coals, which have HI values up to 345 mg HC/g TOC. TOC values for the shales are 0.5–22% with HI values up to 230 mg HC/g TOC. RockEval and TOC data show that the Blue Whale Supersequence has good potential for the generation of both oil and gas. At present, the Blue Whale Supersequence lies within the oil window in the inner and outermost parts of the Ceduna Sub-basin, but is gas mature to overmature across the greater part of the sub-basin (Figure 2.17).

A considerable proportion of the organic matter analysed from the Cenomanian White Pointer Supersequence consists of coal (Struckmeyer et al., 2001). These are typically rich in vitrinite and liptinite and have HI values ranging up to 338 mg HC/g TOC. TOC values obtained from shales and siltstones are consistently above 1.0% and most are above 2%. Although a considerable proportion of the organic matter comprises Type III kerogen, over 50% of the analysed samples contain Type II/III kerogen. These data indicate that this succession contains rocks with good to excellent source potential for both oil and gas. The lower part of this thick succession is typically gas mature throughout the basin, except for the basin margins, but the upper White Pointer Supersequence lies within the oil window and wet gas window in most of the basin (Figure 2.17; Totterdell et al., 2008).

Older potential source rocks are interpreted to be present within lacustrine shales and coaly deposits of the Middle Jurassic–Lower Cretaceous Sea Lion, Minke, Southern Right and Bronze Whaler supersequences along the inboard margin of the sub-basin. Along the northern and eastern margins of the sub-basin, marginal marine to coastal plain mudstone and coal of the upper Aptian–Albian Bronze Whaler Supersequence are likely to be mature for oil and gas generation.

2.3.3.2 Generation and expulsion

Generation and expulsion from potential Jurassic source rocks of the Sea Lion and Minke supersequences occurred during the Early Cretaceous in most of the Ceduna Sub-basin (Figure 2.14). However, where the overburden is less than about 3000–4000 m, expulsion is likely to have occurred during the late Early to Late Cretaceous. Regional petroleum systems modelling suggests that expulsion from the Southern Right Supersequence occurred mainly in the Albian to Turonian, and from the Bronze Whaler Supersequence during the Cenomanian to Turonian. Most of these early generated and expelled hydrocarbons are likely to have been lost during major structuring related to breakup. However, in the inboard parts of the basin, where this structuring was less pronounced, some accumulations within reservoir units of the Bronze Whaler Supersequence may be preserved as dry gas.

Petroleum systems modelling results indicate that generation and expulsion from the Tiger Supersequence occurred continuously from about the mid-Campanian, following deposition of the lowermost Hammerhead succession, until the present day (Tapley et al., 2005; Totterdell et al., 2008). Generation and expulsion from upper White Pointer Supersequence potential source rocks is modelled to have occurred from the early Campanian. Generation and expulsion from potential source rocks of the Blue Whale Supersequence is likely to have occurred from the Turonian onwards and continues to the present-day near the basin margins. Expulsion from potential deltaic source rocks of the Hammerhead Supersequence probably commenced in the Maastrichtian.

The major regional structural gradients in the basin during the Late Cretaceous were shallowing towards the northwest and north, and the southeast and east. Some fault reactivation at the time of breakup (late Santonian) may have facilitated the vertical movement of fluids along faults, many of which terminate at the Hammerhead Supersequence boundary. Minor reactivation in the early to middle Paleocene produced steep, planar normal faults that terminate at the Wobbegong Supersequence boundary, and which may have facilitated migration of hydrocarbons from pre-existing traps.

2.3.3.3 Reservoirs

The primary reservoir units in the Ceduna Sub-basin are the deltaic and shallow marine sandstones of the upper Santonian to Maastrichtian Hammerhead Supersequence delta. Data from Potoroo 1 and Gnarlyknots 1A (King & Mee, 2004) and wells in the Duntroon Sub-basin show that sandstones from this succession are quartzose and medium- to very coarse-grained with porosities between 10 and

35%. King & Mee (2004) reported preservation of porosities >20% at depths up to about 3000 m based on petrophysical models, and regional petroleum systems modelling suggests porosities of 15% to depths of about 4000 m (Totterdell et al., 2008). Seismic facies studies of the Hammerhead Supersequence delta (Krassay & Totterdell, 2003; King & Mee, 2004) indicate that coarse-grained facies deposited in alluvial and coastal plain settings occur in the inner to central basin, while shelf deposits and turbiditic slope and basin floor sands are likely to occur in the central to outer basin.

Potential reservoir rocks also occur in the Lower Cretaceous Bronze Whaler Supersequence, the Cenomanian White Pointer Supersequence and the Turonian to Santonian Tiger Supersequence. Due to depth of burial, porosities in the Bronze Whaler Supersequence across much of the sub-basin are likely to be too low to provide an effective reservoir, but the White Pointer Supersequence is likely to have porosities of up to15% to depths of about 3000 m and of up to 20% to depths of about 2000 m. In the inboard parts of the basin, where coarse-grained facies are likely to be more abundant, this unit could be a viable reservoir interval. Results from Gnarlyknots 1A and seismic facies mapping show that the Tiger Supersequence is characterised by coarser-grained shallow marine facies in the inboard Ceduna Sub-basin. Sandy units in the middle of the Tiger Supersequence are also indicated by the presence of a clear impedance contrast at this stratigraphic level on seismic data across the basin (Totterdell et al., 2008). Predicted porosities for this unit range from 10–20% at depths of 3000–4500 m and 15–25% at depths of 2000–3500 m.

2.3.3.4 Seals

Moderate to excellent intraformational seals are probably present throughout the Cretaceous succession, with quality and thickness dependent on depositional facies. The Blue Whale Supersequence may provide a good regional seal for potential accumulations in Lower Cretaceous reservoirs in the inboard part of the basin. Marine shales of the Tiger Supersequence are likely to form an excellent regional seal for reservoir rocks of the White Pointer and Tiger supersequences (Somerville, 2001).

Seals within the Hammerhead Supersequence are mostly likely to be intraformational, although the presence of more widespread, thin, transgressive marine shales within the shallow marine to nearshore facies is also likely (King and Mee, 2004). Downlapping marine shales deposited in outer shelf to slope environments in the central to outer basin are probably the best potential seals within this unit (Krassay and Totterdell, 2003; King and Mee, 2004). Given the present-day depths of burial of regionally extensive potential sealing units such as the Tiger Supersequence, the presence of intraformational seals within the Hammerhead Supersequence, particularly in the upper aggradational parts of the section, will probably be crucial to exploration success in this part of the basin.

Marl and limestone of the middle Eocene to Holocene Dugong Supersequence may provide a regional seal for reservoirs in the upper Hammerhead Supersequence. This unit is of varying thickness and probably varying quality (Messent et al., 1996). The Dugong Supersequence is likely to have improved sealing properties beyond the present-day shelf break, where it is typically less than 500 m thick.

2.3.3.5 Play types

Regional petroleum systems modelling has shown that potential Jurassic to Cretaceous source intervals in the Ceduna Sub-basin have reached maturities adequate to generate and expel liquid and gaseous hydrocarbons (Figure 2.17; Struckmeyer et al., 2001; Totterdell et al., 2008; Struckmeyer, 2009). Sediment loading of the Upper Cretaceous succession and, in particular, the Hammerhead Supersequence, was the critical event in the maturation of successively younger systems. The major regional structural gradients in the basin during the Late Cretaceous were shallowing towards the northwest and north, and the southeast and east. Some fault reactivation at the time of breakup (late Santonian) may have facilitated the vertical movement of fluids along faults, many of which terminate at the Hammerhead Supersequence boundary (Figure 2.15). Minor reactivation in the early to middle Paleocene produced steep, planar normal faults that terminate at the Wobbegong Supersequence boundary (Figure 2.15), and which may have facilitated migration of hydrocarbons from pre-existing traps.

3D petroleum systems modelling (Struckmeyer, 2009) indicates that the sub-basin is likely to have experienced several phases of hydrocarbon generation, expulsion and accumulation. Early generated and accumulated oil and gas from potential source rocks of the Blue Whale and White Pointer supersequences (Albian to Cenomanian) are likely to have spilled from earlier structures, but may have accumulated through remigration into structures along the basin margin. Late (Neogene) generated and accumulated oil and gas from the Blue Whale/White Pointer supersequences is potentially preserved in structures in the inboard and outboard parts of the basin. Generation and expulsion from lower Turonian organic-rich rocks commenced in the Late Cretaceous, but accumulation of oil is unlikely to have occurred until the Cenozoic and is continuing to the present day. Potential accumulations related to this petroleum system probably occur in two major trends within the central Ceduna Sub-basin.

The Ceduna Sub-basin offers a wide range of play types at various stratigraphic levels (Somerville, 2001; Tapley et al., 2005). 2D and 3D petroleum systems modelling (Totterdell et al., 2008; Struckmeyer, 2009) predicts several major play trends:

- The inner basin-margin trend is located up-dip from main northward-migrating drainage paths. Accumulations here are likely to have been sourced from mostly Blue Whale and White Pointer organic-rich rocks. They are likely to contain both light oil and gas accumulated during the Cenozoic, but may also contain some remnant hydrocarbons from earlier accumulation phases.
- In the central basin, the Springboard and Gnarlyknots trends (Tapley et al., 2005; Totterdell et al., 2009), are predicted to contain light oil sourced mostly from Cenomanian–Turonian (Tiger Supersequence) organic-rich rocks, as well as remnant oil and gas from earlier accumulations charged from Blue Whale and White Pointer source rocks.
- Modelled flow paths and the geometry of the basin suggest the presence of a major play trend along the outer margin high. These are most likely to contain oil and gas from both Blue Whale and Tiger marine organic-rich rocks, and Cenomanian deltaic facies, accumulated during the Cenozoic. The main liquids charge for these accumulations is likely to have occurred from the Neogene to Holocene.

The Gnarlyknots Trend (Tapley et al., 2005) comprises fault-related hanging wall and footwall traps with either rollovers or dip closures and targets in Cenomanian to Santonian reservoirs (White Pointer and Tiger supersequences). These plays typically lie at depths of 3.5–5.0 seconds two-way time (TWT), and would be charged laterally from a mature Tiger Supersequence source to the west or vertically and laterally from mature marine shales of the Blue Whale Supersequence and coaly source rocks of the White Pointer Supersequence.

The Springboard Trend occurs in the outer part of the sub-basin and comprises both lowside and highside fault-related traps, with targets in Campanian Hammerhead Supersequence deltaic facies, charged by Turonian and older source rocks.

In addition to these trends is a set of plays associated with Middle Jurassic–Early Cretaceous half graben, which occur along the northern and eastern margins of the Ceduna Sub-basin. These half graben are generally more deeply buried than the half graben of the Eyre Sub-basin; while the most deeply buried half graben are likely to be overmature (Figure 2.17), others are likely to be mature for oil and gas generation.

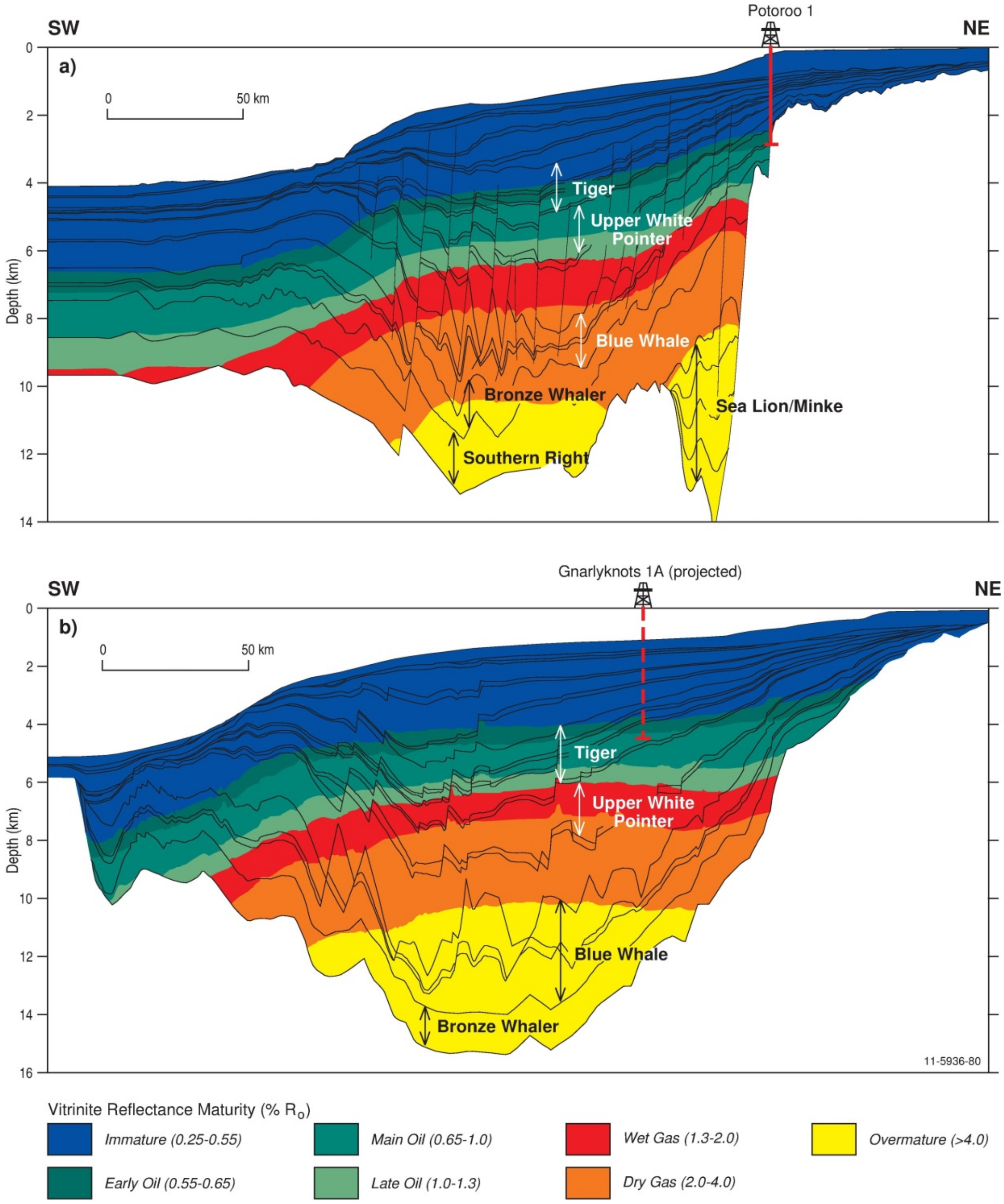

Figure 2.17: Modelled present-day maturity zones (% Ro) for two 2D maturity profiles through Potoroo 1 and Gnarlyknots 1A (projected). Supersequences are labelled. The locations of the profiles are shown in Figure 2.13(after Totterdell et al., 2008).

2.3.3.6 Critical risks

One of the key risks identified prior to the most recent exploration phase was the possible lack of an effective source rock and thus adequate hydrocarbon charge (Somerville, 2001). This risk has been significantly reduced by the sampling and identification of a high quality marine source rock of Cenomanian to Turonian age (Totterdell et al., 2008; Totterdell & Mitchell, 2009), and the identification of a number of encouraging bright amplitude anomalies (King & Mee, 2004; Tapley et al., 2005). Burial depth and thermal maturity calibrated by data from the Potoroo 1 and Gnarlyknots 1A wells suggest that this potential source rock is thermally mature for oil and gas generation across much of the basin depocentre.

Another risk is the presence of an effective seal, as shown by the high net to gross ratio encountered in Gnarlyknots 1A. However, seismic facies mapping suggests that prodelta shales are likely to exist at various levels within the Cenomanian–Turonian section. The majority of plays are structural and, as such, are dependent on cross-fault seal. In the outboard basin this is probably less of a risk, because of the very likely presence of thick basinal shales in the Tiger Supersequence, and outer shelf to slope fine-grained sediments within the lower part of the Hammerhead Supersequence (Krassay & Totterdell, 2003; King & Mee, 2004). These could provide excellent cross fault seals for hydrocarbons in intra-Tiger Supersequence reservoirs and basal Hammerhead Supersequence turbidite reservoirs. Tapley et al. (2005) suggested that net to gross ratios are probably lower in the middle to lower Tiger Supersequence (i.e. below TD of the Gnarlyknots 1A well) and cross fault seals are likely to be present.

The presence of volcanic and intrusive rocks within and overlying the Upper Cretaceous succession presents a potential risk to petroleum systems, particularly in the central and eastern Ceduna Sub-basin. Schofield & Totterdell (2008) mapped the location of a suite of volcanoes, sills and dykes in the Ceduna Sub-basin and overlying Eucla Basin related to a short-lived period of igneous activity in the Middle Eocene. Igneous activity can have both negative and positive impacts on potential petroleum systems (Schutter, 2003). These impacts relate to local and regional heat flow, maturation, reservoir quality/porosity, seals and traps (Schutter, 2003; Schofield & Totterdell, 2008). The presence of high-level igneous bodies is also an issue of concern for seismic data acquisition programs.

2.3.3.7 Overall prospectivity classification

High

2.3.4 Exploration status

There have been no hydrocarbon discoveries in the Ceduna Sub-basin and the area is an exploration frontier.

Petroleum exploration in the Ceduna Sub-basin has occurred in three major cycles—the late 1960s to early 1970s, the early 1990s and 2000–present (O'Neil, 2003). In nearly 50 years of exploration in the offshore Bight Basin, approximately 100,000 line-km of seismic data have been acquired and only 10 petroleum exploration wells have been drilled. With the exception of Gnarlyknots 1/1A, all the wells were drilled in relatively shallow water near the basin margin and the deeper part of the sub-basin remains largely untested (Figure 2.18).

During the 1960s and 1970s, exploration was carried out by Shell Development (Australia) (Shell) and Outback Oil. Seismic, shipboard magnetic and aeromagnetic data were acquired. Several prospects were developed from these activities and three exploration wells were drilled, Echidna 1 and Platypus 1 in 1972 and Potoroo 1 in 1975. By 1977, Shell had surrendered all of its Bight Basin exploration petroleum permits. The early 1980s was a period of relatively lacklustre exploration in the central Ceduna Sub-basin, with exploration efforts concentrating on shallower, flanking depocentres. Outback Oil and BP undertook exploration in the Duntroon Sub-basin, resulting in the drilling of Duntroon 1, while Esso Exploration and Production Australia (Esso), in joint venture with Hematite Petroleum (Hematite), focused their exploration efforts on the Eyre Sub-basin, acquiring seismic and drilling Jerboa 1.

In early 1990, BP flew an Airborne Laser Fluorosensor (ALF) survey that covered the inboard Bight Basin. The initial results were poor, but reprocessing and reinterpretation of the data resulted in the identification of 941 confident fluors (Cowley, 2001). In 1991, BHP Petroleum (Australia) (BHP) commenced an exploration program focusing on the eastern Ceduna and Duntroon sub-basins. BHP drilled three wells in 1993—Borda 1 and Greenly 1 (Ceduna Sub-basin), and Vivonne 1 (Duntroon Sub-basin). Although all were plugged and abandoned, their results vastly improved knowledge of the basin succession, and gas shows and oil indications in Greenly 1 provided some exploration encouragement.

The latest phase of petroleum exploration commenced in 2000, when three petroleum exploration permits were awarded to a joint venture comprising Woodside Energy (operator), Anadarko Australia and PanCanadian Petroleum (now EnCana). The permits, EPP28, EPP29 and EPP30 covered much of the northern and central Ceduna Sub-basin. The joint venture acquired a large quantity of 2D seismic data and drilled an exploration well, Gnarlyknots 1/1A. In early 2006, 1250 km^2 of 3D seismic data (Trim 3D Seismic Survey) was acquired over EPP29; however, in 2007 Woodside surrendered its permits. Also during this period, permits were held in the eastern Bight Basin (Duntroon Sub-basin and adjacent portion of the Ceduna Sub-basin) by the Woodside-Anadarko-EnCana joint venture and Santos Offshore. Approximately 2300 km of seismic data was acquired during the exploration programs in these permits, which were both surrendered in 2007.

In 2009, six areas in the central Ceduna Sub-basin were released for bidding, followed in 2010 by the release of two exploration areas in the eastern Ceduna–Duntroon sub-basin. In January 2011, BP Exploration was awarded 4 permits (EPP37–40) in the central Ceduna Sub-basin. The guaranteed work program for the permits includes 4 exploration wells and ~12,000 km^2 of 3D seismic data. In 2013, Statoil farmed-in to the BP permits, taking a 30% interest. Bight Petroleum was awarded the two Ceduna–Duntroon permits (EPP41 and EPP42) in June 2011: the 3-year work program includes one well.

Building on this renewed interest in the Ceduna Sub-basin, the Government released three large exploration areas in 2012. All three received competitive work program bids and exploration permits were awarded in October 2013. Permit EPP43 was awarded to a joint venture between Murphy Australia Oil Pty Ltd (Operator) and Santos Offshore Pty Ltd with a work program that includes the acquisition and processing of 3D seismic survey in the primary term and the drilling of one well in the secondary term. Permits EPP44 and 45 were awarded to Chevron Australia New Ventures Pty Ltd with a guaranteed work program that includes the drilling of two exploration wells in each permit in the primary term and acquisition of 21,000 km^2 of 3D seismic data.

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 28,000 line-km of regional 2D seismic data. GA's 2007 Bight Basin Geological and Sampling Survey (Totterdell et al., 2008; Totterdell & Mitchell, 2009) targeted and sampled potential source rocks of late Cenomanian to early Turonian age from the northwestern edge of the Ceduna Sub-basin.

2.3.5 Data

Key data sets for the Ceduna Sub-basin are listed in Table 2.8–Table 2.11. Only ten petroleum exploration wells have been drilled in the eastern Bight Basin, five of those in the Ceduna Sub-basin (Figure 2.18; Table 2.8). All except Gnarlyknots 1/1A have been drilled in relatively shallow water near the basin margin and the deeper part of the sub-basin remains largely untested. Gnarlyknots 1/1A, drilled in approximately 1300 m of water and reaching a depth of 4736 mRT within the upper part of the Tiger Supersequence, provides a key stratigraphic calibration point and important hydrocarbon indications. Potoroo 1, which lies on the northeastern margin of the sub-basin, is also a key stratigraphic control point for the Ceduna Sub-basin succession. Gas shows and oil indications in Greenly 1 in the eastern Ceduna Sub-basin may indicate the presence of active petroleum systems in the area; Edwards et al. (1999) assigned these hydrocarbons to the Austral 1 and 2 petroleum systems.

Seismic coverage ranges from excellent to poor, and comprises a mixture of vintages ranging from the 1970s through to 2012. Between 1967 and 1977, Shell acquired over 14,500 line-km of seismic data across the Ceduna Sub-basin, while at about the same time the Bureau of Mineral Resources (BMR, now GA) acquired approximately 15,000 line-km of 2D data across the Bight Basin. Two deep seismic (16 s TWT) transects across the Great Australian Bight, together with deep seismic data across the South Australian Abyssal Plain and Recherche Sub-basin, were acquired by the Australian Geological Survey Organisation (AGSO, now GA) in 1997. Seismic Australia, in joint venture with AGSO, acquired 8500 line-km of regional seismic data across the Ceduna Sub-basin during 1998–99 (HRGAB and DWGAB surveys). Woodside Energy Ltd acquired the Flinders 2D Seismic Survey in 2001 and the Trim 3D Seismic Survey in 2006 as part of their work program commitments. The Flinders 2D Seismic Survey comprises 15,636 line-km of closely spaced 2D seismic data; magnetic and gravity data was recorded concurrently. The seismic grid ranges from 4 x 4 km in the west to 4 x 8 km in the northern and eastern portions of the survey area.

Recently, two very large seismic datasets have been acquired in the Ceduna Sub-basin. In 2009 ION-GXT acquired the BightSPAN regional seismic survey, which comprises 4957 line-km of deep 2D seismic data and covers the entire Ceduna Sub-basin. In 2012, BP acquired approximately 12,000 km^2 of 3D seismic data (Ceduna 3D) over their central Ceduna Sub-basin permits. Neither data set is open-file at present (2014).

Many of the earlier seismic datasets were reprocessed by Fugro Multi Client Services in 1999 and 2004 and a data product comprising reprocessed seismic, new potential field data and satellite SAR seep data over the Ceduna Sub-basin is also currently available.

2.3.5.1 Confidence rating

High–medium.

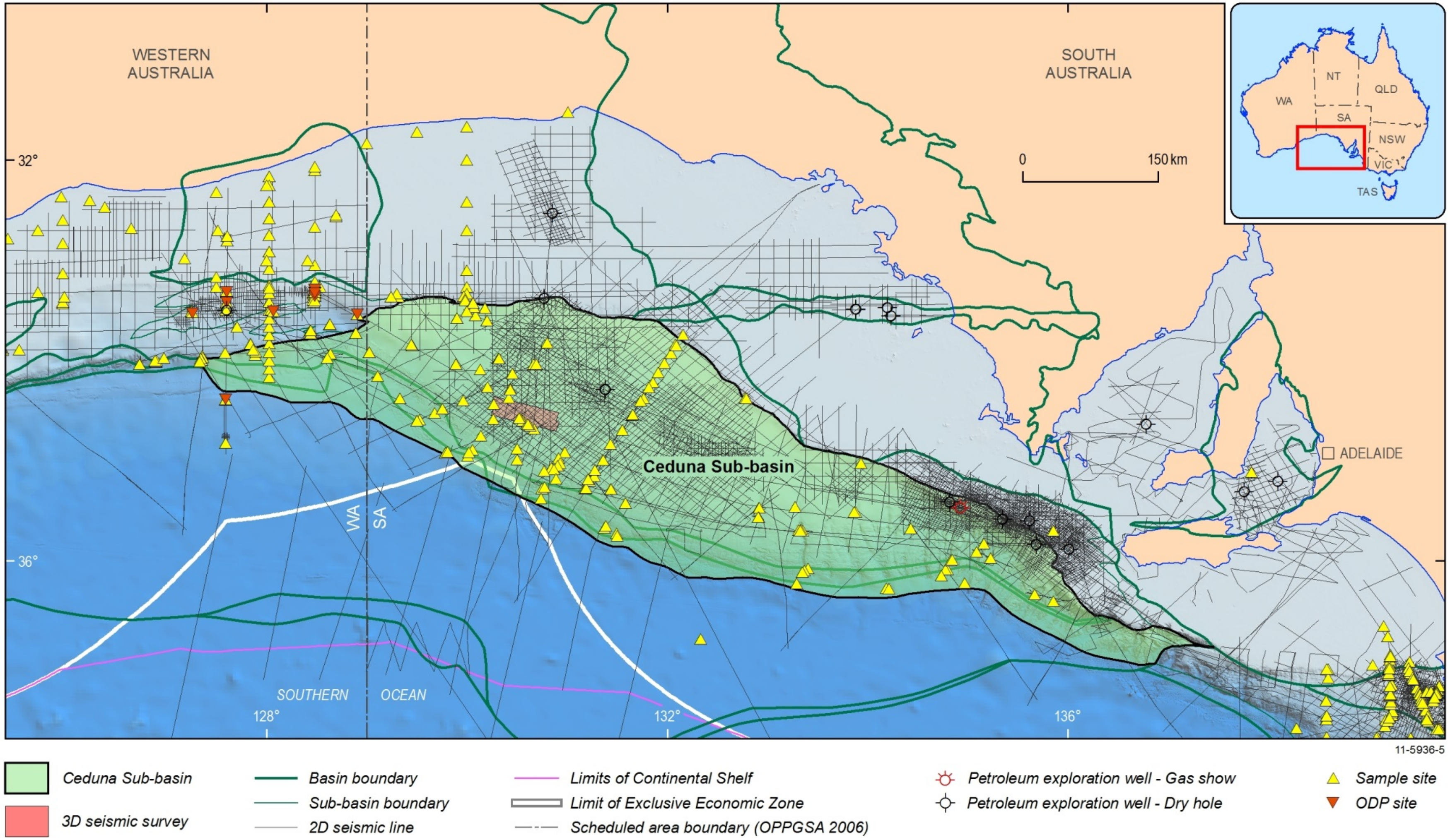

Figure 2.18: Seismic, well and sample distribution, Ceduna Sub-basin.

2.3.6 Issues and remaining questions

2.3.6.1 Stratigraphy

The present state of knowledge of the petroleum prospectivity of the Ceduna Sub-basin is derived largely from the interpretation of seismic data. Although this interpretation is broadly constrained by the few wells in the area, the amount of well data available is extremely limited. As a result, there is a degree of uncertainty about the geological/stratigraphic interpretation, particularly for the deeper, pre-Turonian section. While high-resolution seismic data, including 3D data, will help to further constrain interpretation, a higher degree of certainty about the stratigraphy of the basin, and the nature of the basin fill and key petroleum systems elements, will only be provided by drilling. This issue will begin to be addressed over the next 3–5 years, as the Ceduna Sub-basin is currently the focus of renewed exploration activity. Primary work programs in the northern–central Ceduna Sub-basin include four wells in BP Exploration/Statoil permits EPP37–40, and four wells in Chevron permits EPP44 and 45. Further east, Bight Petroleum's guaranteed work program includes the drilling of one well in EPP41–42 (eastern Ceduna–Duntroon sub-basins). These wells will provide vital information about the geology and petroleum potential of the Cretaceous delta system.

2.3.6.2 Petroleum systems

The key unanswered question in the Ceduna Sub-basin is whether or not the area contains significant active petroleum systems and petroleum accumulations. In coming years this will be addressed by the BP/Statoil, Chevron, Murphy/Santos and Bight Petroleum work programs, which include the drilling of nine wells and extensive seismic acquisition, including 21,000 km^2 of 3D seismic data in EPP44 and EPP45.

Other work programs that may assist in addressing this question include targeted seepage surveys in areas previously identified as potential seepage sites, such as the northern margin of the Ceduna Sub-basin (Totterdell & Mitchell, 2009). To improve on previous surveys, it is recommended that such surveys utilise AUV and ROV equipment and sophisticated hydrocarbon sensor technologies.

A key uncertainty in petroleum systems modelling in the region, particularly in the outer parts of the Ceduna Sub-basin, is thermal history. Due to a lack of either good seismic imaging of deep structure or refraction data, the overall structure of the lithosphere is poorly understood; this prevents a detailed understanding of the timing and processes of crustal thinning and hence the heat flow history of the margin/basin. Acquisition of refraction seismic data on several profiles (sonobuoy or Ocean Bottom Seismometers) across the sub-basin and adjacent margins is recommended.

2.3.6.3 Data gaps

The eastern Ceduna Sub-basin (between approximately 133º and 137ºE) is an area of relatively poor seismic data coverage and quality, compared with the northern and central parts of the sub-basin. Factors affecting data quality include the presence of Cenozoic volcanic and high-level intrusive rocks, and closely spaced faulting. These factors have also influenced perceptions of exploration risk and lower prospectivity in this area of the basin. The acquisition of high-resolution 2D and/or 3D seismic data, along with detailed fault risk and seepage studies, could assist in addressing these issues.

2.3.6.4 Recommendations

- drilling

- 3D or high resolution 2D seismic data to improve understanding of stratigraphy, facies, age, structural geology, and to fill data gaps
- targeted seepage surveys utilising AUV, ROV and sophisticated hydrocarbon sensing tools
- a comprehensive refraction seismic data acquisition program across the Ceduna Sub-basin and adjacent margin to assist understanding of the tectonic subsidence history and petroleum systems modelling.

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2.3.8 Data Tables

Table 2.8: List of wells, Ceduna Sub-basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1972	Platypus 1	Exploration	Shell Development (Australia)	3893	Albian	Trace gas	Shell Development, 1972
1975	Potoroo 1	Exploration	Shell Development (Australia)	2815	Proterozoic	Trace gas	Shell Development, 1975
1993	Greenly 1	Exploration	BHP Petroleum	4860	Cenomanian	Gas shows, oil indications	Wong, 1994a
1993	Borda 1	Exploration	BHP Petroleum	2800	Campanian	None	Wong, 1994b
2003	Gnarlyknots 1	Exploration	Woodside Energy	1824	?Maastrichtian	None	Woodside, 2004
2003	Gnarlyknots 1A	Exploration	Woodside Energy	4736	Santonian	Fluorescence and cut	Woodside, 2004

Table 2.9: Key seismic surveys in the Ceduna Sub-basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1971	Great Australian Bight South Australian Seismic Deepwater Survey 1970	Shell Development (Aust) P/L	3837	
1974	South Australia R-8 Marine Seismic Survey, and Great Australian Bight R-9 Marine Seismic Survey	Shell Development (Aust) P/L	2691	
1976	R-10 Marine Seismic Survey	Shell Development (Aust) P/L	795	
1981	South Australia S81 Marine Seismic Survey EPP16	BP Petroleum Development Australia	935	
1982	South Australia EPP16 1982 Marine Seismic Survey	BP Petroleum Development Australia	1190	
1982	GSI -82 EPP-19 Marine Seismic Survey	Outback Oil	1360	
1986	BMR survey 65	Bureau of Mineral Resources	3500	Willcox et al., 1988
1997	Survey 199; Law of the Sea - Great Australian Bight	Australian Geological Survey organisation	3911	Robertson Research, 1999
1999	Great Australian Bight Marine Seismic Survey (DWGAB and HRGAB)	Seismic Australia/AGSO	8294	Totterdell et al., 2000
2000	Flinders 2D Marine	Woodside Energy	15,636	Somerville, 2001; King & Mee, 2004

Year	Survey	Operator	Line-km/Area (km^2)	Reference
2006	Trim 3D	Woodside Energy	1250 km^2	Tapley et al., 2005
2009	BightSPAN	Ion-GXT	4957	Ion Geophysical, 2014
2012	Ceduna 3D	BP	~12,000 km^2	

Table 2.10: Key geological sampling surveys, Ceduna Sub-basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
1986	BMR Survey 66	BMR	Great Australian Bight	Dredge, gravity core, heat flow	Siliciclastic rocks, lithified and semi-lithified pelagic limestone, volcanic rocks, igneous basement rocks	Davies et al., 1989
1991	Southern margin sampling program (Rig Seismic cruise 102)	AGSO	Ceduna and Eyre sub-basins, Eucla shelf	Dredge, gravity core	Siliciclastic rocks, calcareous rocks and ooze.	Feary et al., 1993
2000	AGSO cruise 224 (SS01/00)	AGSO	GAB Marine Protected Area	Dredge, gravity and box core, grab	Nannofossil ooze, carbonaceous mudstone	Harris et al., 2000; Hill et al., 2001
2007	Bight Basin geological sampling and seepage survey	Geoscience Australia	Ceduna Sub-basin, Eyre Terrace	Dredge, gravity core, grab	Siliciclastic rocks, carbonate rocks and ooze	Totterdell & Mitchell, 2009

Table 2.11: Key swath bathymetry surveys, Ceduna Sub-basin

Year	Survey	Operator	Line-km/Area (km^2)	Reference
2000	AUSTREA 1	AGSO		Hill et al., 2000, 2001
2003	AUSCAN	Geoscience Australia		Hill & De Deckker, 2004
2006	AUSFAIR–GAB transit	Institut Polaire Français Paul-Emile Victor		Institut Polaire Français Paul-Emile Victor, 2007
2007	Bight Basin geological sampling and seepage survey	Geoscience Australia	~4600	Totterdell & Mitchell, 2009

2.4 Duntroon Sub-basin (Bight Basin)

2.4.1 Summary

State(s)		South Australia
Area (km²)		9800
Water Depth (m)		100–1000
Maximum sediment thickness (m)		7000
Age range		Middle Jurassic–Late Cretaceous
Basin	**Overlies**	Gawler Craton, Adelaide Fold and Thrust Belt
	Underlies	Eucla Basin
	Parent	Bight Basin
	Adjacent basins	Ceduna Sub-basin, Couedic Shelf
Basin type		Extensional
Depositional setting, rock types		Fluvial–lacustrine clastic sedimentary rocks; late shallow marine and deltaic influence
Petroleum prospectivity		Moderate
Confidence		*Medium*

2.4.2 Geology

The Duntroon Sub-basin (Figure 2.19; Bradshaw et al., 2003) is located in the eastern Bight Basin. The Duntroon Sub-basin of Bradshaw et al. (2003) superseded the former Duntroon Basin of Stagg et al. (1990), and is approximately equivalent to the “Inner Basin” of the Duntroon Basin (Whyte, 1978; Smith & Donaldson, 1995).

The Duntroon Sub-basin extends over an area of 9800 km^2 in water depths of 100–1000 m, and contains up to 7000 m of Jurassic–Cretaceous sedimentary rocks (Figure 2.20). The sub-basin succession is unconformably overlain by up to 500 m of Cenozoic strata of the Eucla Basin. The Duntroon Sub-basin adjoins the eastern Ceduna Sub-basin to the southwest, and the sub-basins are separated by a complex series of major extensional faults that correspond to the “Late Cretaceous Hinge” of Smith & Donaldson (1995).

2.4.2.1 Structural geology

The Duntroon Sub-basin is an extensional depocentre that developed as a result of oblique extensional or transtensional deformation during the initial stages of southern margin extension in the Middle Jurassic–Early Cretaceous (Figure 2.20). Gibson et al. (2012) proposed that the Duntroon Sub-basin formed along a northwest–southeast oriented continental transform originally identified by Willcox & Stagg (1990). The Duntroon Sub-basin is bounded by major faults with the same approximately northwest orientation (Totterdell & Bradshaw, 2004) and occupies a long, narrow embayment in the Gawler Craton. Gibson et al. (2012) argued that the shape and orientation of the sub-basin are consistent with the geometry expected of a basin developed at the releasing bend of a continental transform fault.

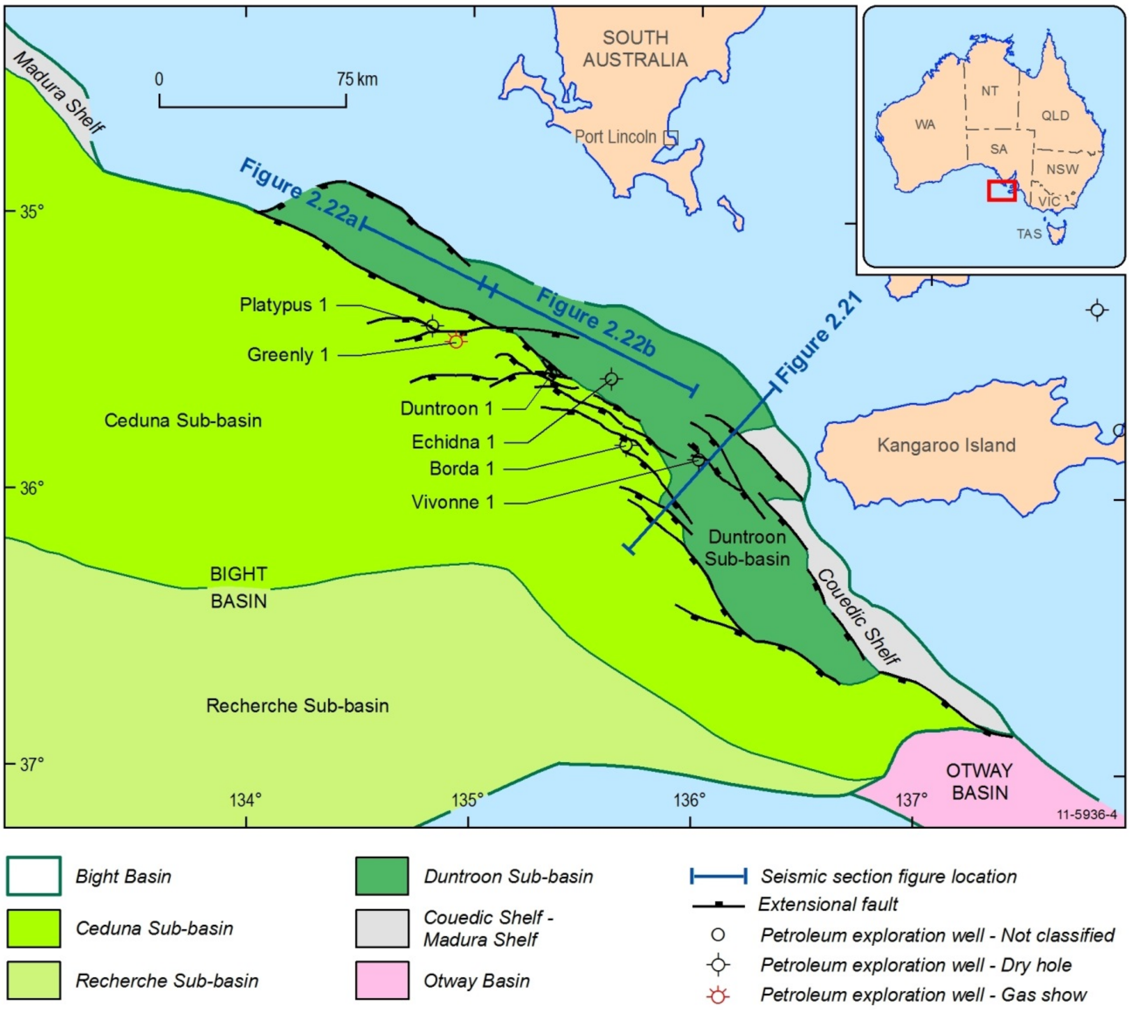

Figure 2.19: Structural elements map, Duntroon Sub-basin (from Bradshaw et al., 2003).

The sub-basin consists of a series of half graben (Cockshell, 1990; Thomas, 1990; Stagg et al., 1990; Messent, 1995; Messent et al., 1995; Smith & Donaldson, 1995; Bradshaw et al., 2003), which change orientation along strike (Figure 2.19). The northern west-northwest–east-southeast-trending rift basin contains at least two half graben, while the southern part of the sub-basin consists of one deep, northwest–southeast-trending half graben (Figure 2.21). The change in orientation of the rift structures may be related to underlying basement as it appears to coincide with the westerly projection of the east–west-trending Kangaroo Island Shear Zone, which marks the boundary between the Proterozoic Gawler Craton and the Proterozoic–Lower Paleozoic Adelaide Fold-Thrust Belt (Flöttmann et al., 1995).

The Duntroon Sub-basin is characterised by complex, generally southwest-dipping, rift border fault systems and west–east to northwest–southeast striking intra-basin faults. Half graben were mildly deformed during a period of Late Cretaceous inversion and uplift—probably related to the final phases of rifting and the commencement of breakup—and crestal collapse faults have developed in some hanging wall blocks (Figure 2.21; Bradshaw et al., 2003).

2.4.2.2 Basin evolution and depositional history

The lithostratigraphic nomenclature of Hill (1991) is used here as it is the stratigraphic scheme generally used by industry in this area. Where considered appropriate, the sequence stratigraphic units of Totterdell et al. (2000) are used or the equivalent supersequences noted. Figure 2.20 shows the relationships between these schemes.

Deposition in the Duntroon Sub-basin commenced in the Middle Jurassic–Early Cretaceous during the initial stages of rifting on the southern margin (Figure 2.20). The oldest syn-rift part of the basin fill has not been intersected by drilling, but is imaged on seismic data. The oldest section penetrated by drilling is a late rift or early post-rift succession intersected in Echidna 1. Based on a comparison with the section in the Eyre Sub-basin, the Duntroon Sub-basin syn-rift succession is assigned to the Middle Jurassic–earliest Cretaceous Sea Lion and Minke supersequences (approximately equivalent to the Echidna Formation and underlying unnamed Polda Formation equivalent of Hill (1991)). A key difference between the Eyre and Duntroon sub-basins is that the rift and post-rift section in the Duntroon Sub-basin is more than twice as thick as the comparable section in the Eyre Sub-basin. This may reflect more rapid subsidence in a transcurrent tectonic regime during the early rifting phase.

The upper part of the rift phase succession that was intersected in Echidna 1 is dominated by carbonaceous shales deposited in isolated lacustrine environments (Hill, 1991; Smith & Donaldson, 1995). A high algal content (40–50% *M. evansii*) indicates significant hydrocarbon source potential (Smith & Donaldson, 1995).

The Lower Cretaceous post-rift (thermal subsidence phase) succession consists of over 2000 m of aggradational fluvial channel, floodplain and lacustrine deposits assigned to the Neptune and Borda formations (approximately equivalent to the Southern Right and Bronze Whaler supersequences; Figure 2.20). Palynological data suggest an intermittent marine influence during deposition in the Aptian (Morgan, 1986). This dominantly non-marine section is overlain by a thin fluvio-deltaic to marginal marine succession comprising the Ceduna, Platypus and Wigunda formations (Blue Whale, White Pointer and Tiger supersequences). Volcaniclastic and lithic sediments dominate this part of the basin fill. The Ceduna and Platypus formations are dominantly sandy and represent deposition in lower and upper delta plain environments. The overlying, dominantly marine, Wigunda Formation is more mud-rich.

The Duntroon Sub-basin depocentres are dominated by the Middle Jurassic–Lower Cretaceous succession (Borda Formation and older), and upper Lower Cretaceous and Upper Cretaceous rocks are either very thin or absent (particularly in the eastern part of the sub-basin; Figure 2.21; Smith and Donaldson, 1995). As in the Eyre Sub-basin, a period of structural deformation in the late Santonian, coinciding with the commencement of breakup, resulted in inversion, uplift, and erosion across the Duntroon Sub-basin. The locus of extension moved further basinward, and deposition was focused in the adjacent Ceduna Sub-basin (the “Outer Basin” of Smith & Donaldson, 1995).

The Santonian unconformity is overlain in parts of the sub-basin by a thin Upper Cretaceous Potoroo Formation (Hammerhead Supersequence) section comprising marine and deltaic mudstone, siltstone and sandstone.

The Duntroon Sub-basin is overlain by a carbonate-dominated Eucla Basin succession. A thin basal veneer of Paleocene–Eocene shallow marine sediments (Wobbegong Supersequence/Pidinga Formation) is preserved in places, and the sub-basin is covered by a southwestward thickening wedge of Eocene and younger carbonates (Figure 2.21). On the western margin of the sub-basin, the Cenozoic section is characterised by the fill of successive channel or canyon forming events (Ormerod, 1993; Messent et al., 1996).

2.4.2.3 Level of knowledge

Geological knowledge of the Duntroon Sub-basin is based on interpretation of a generally closely-spaced 2D seismic data set, and six wells—three in the sub-basin and three in the adjacent Ceduna Sub-basin. However, considerable variations in the quality of seismic data across the sub-basin, caused largely by the presence of a thick Cenozoic carbonate succession that obscures the underlying seismic data, provide a significant constraint on interpretation.

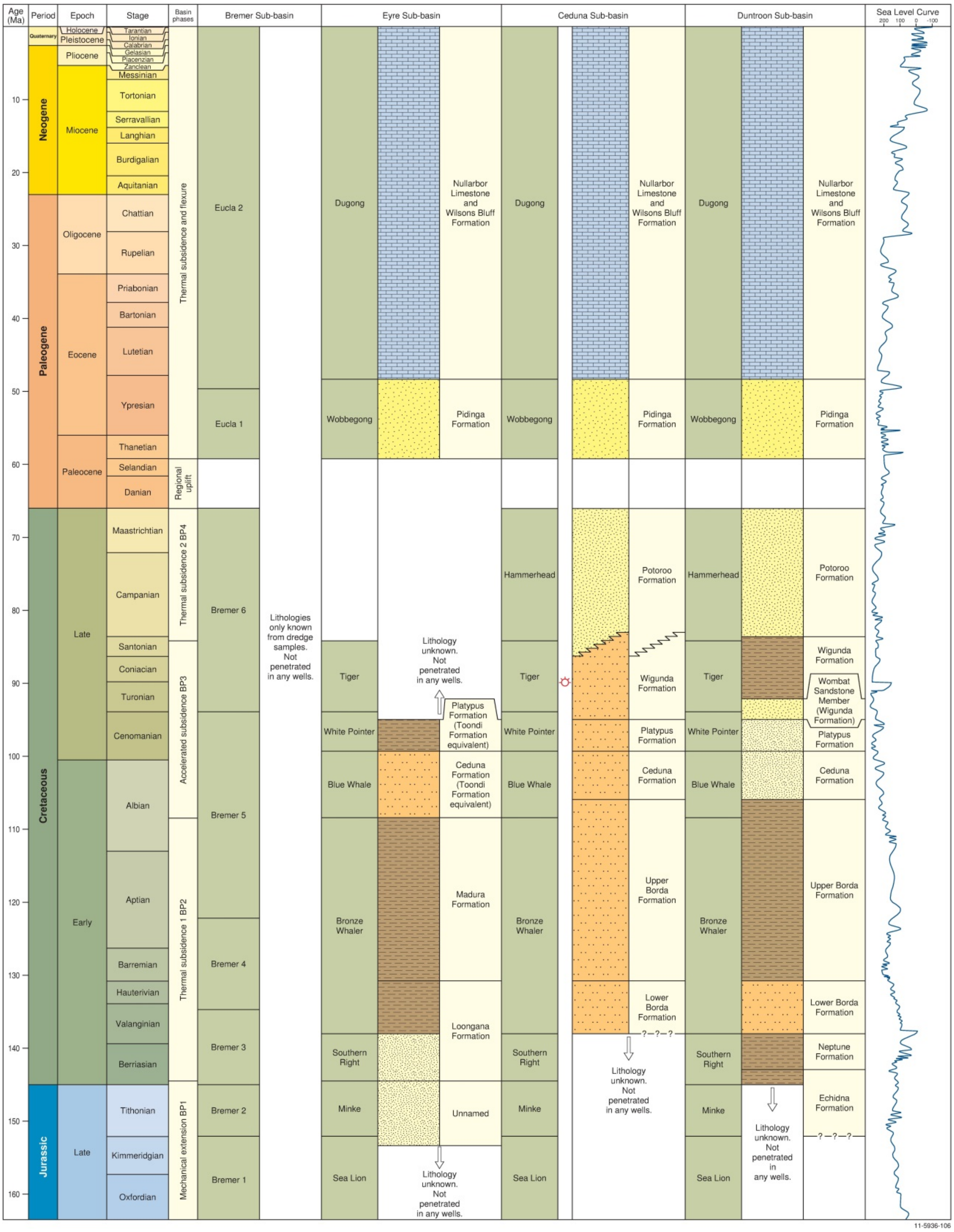

Figure 2.20: Stratigraphy of the Eyre, Ceduna and Duntroon sub-basins, Bight Basin. Geologic time scale after Gradstein et al. (2012); sea-level curve of Haq et al (1988) calibrated to the time scale.

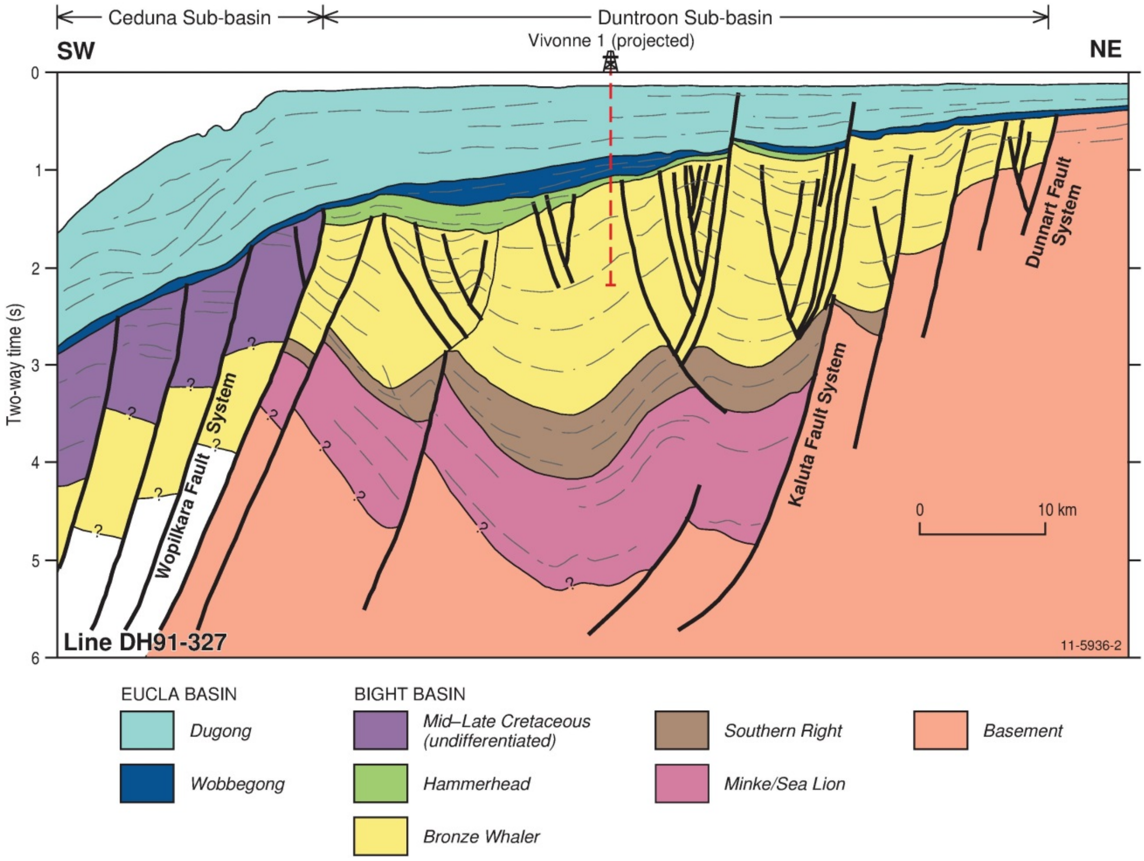

Figure 2.21: Geological cross-section showing structural and stratigraphic relationships.

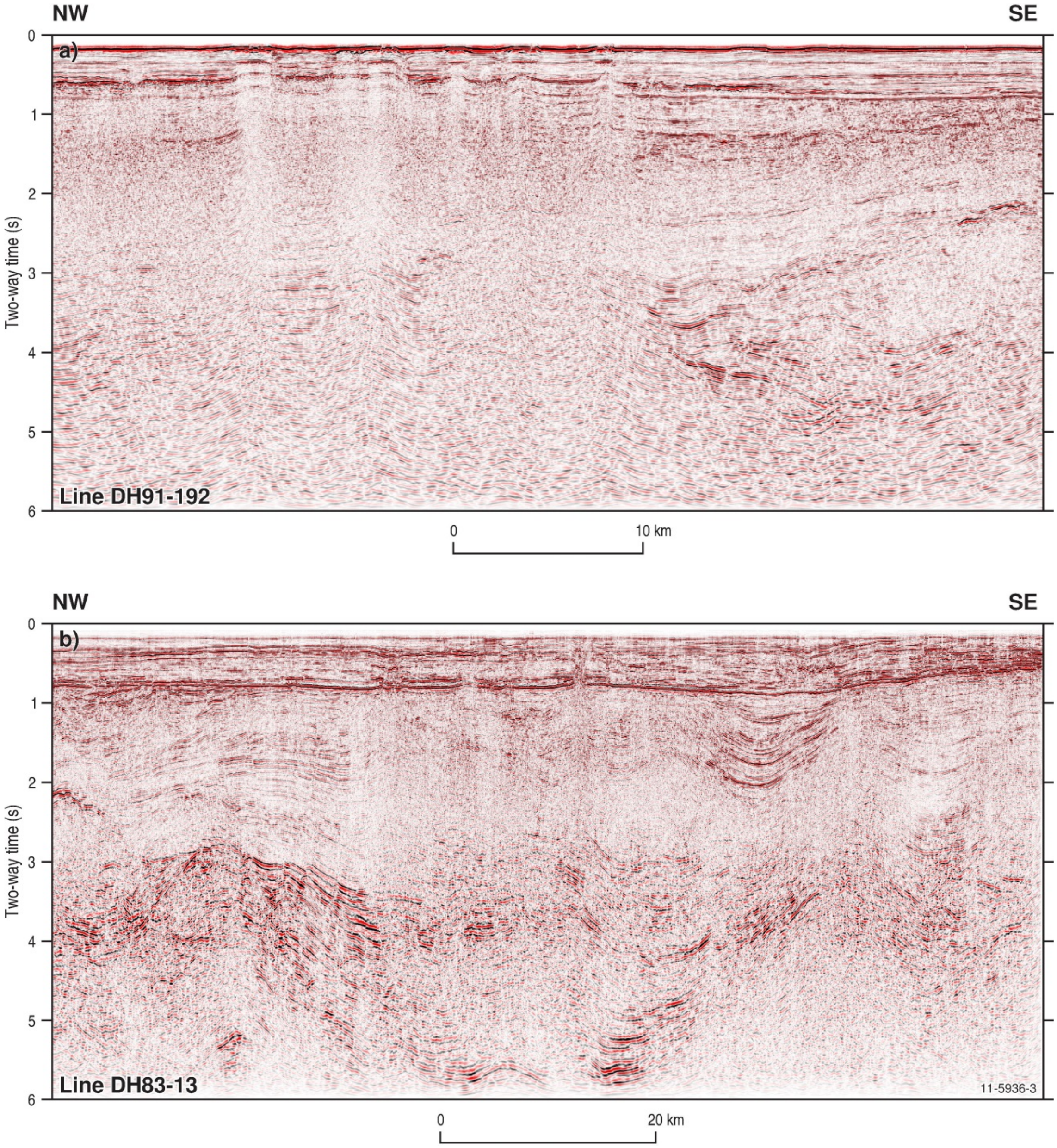

Figure 2.22: Examples of Duntroon Sub-basin seismic data, illustrating typical data quality issues.

2.4.3 Petroleum systems

2.4.3.1 Source Rocks

The key potential source rocks in the Duntroon Sub-basin are the algal-rich, lacustrine, black shales of the basal rift succession (Echidna Formation and older; Austral 1 petroleum system of Edwards et al., 1999), which are likely to contain good quality oil-prone source rocks and are predicted to be gas mature in the deeper depocentres (Smith & Donaldson, 1995; Morgan, 1999).

The Lower Cretaceous, non-marine to coastal plain, upper Borda Formation represents the richest and most oil-prone interval penetrated in the Duntroon Sub-basin–eastern Ceduna Sub-basin wells (Smith & Donaldson, 1995; Struckmeyer et al., 2001). Data presented by Smith & Donaldson (1995) indicates that this section is generally not mature for oil and gas generation in the Duntroon Sub-basin (their "Inner Basin"), but is mature in the adjacent Ceduna Sub-basin. This source rock is therefore important for Duntroon Sub-basin prospectivity as the source of hydrocarbons migrating from the Ceduna Sub-basin into traps along the western margin of the Duntroon Sub-basin. Coals interbedded within the claystone dominated succession commonly have HI values between 150 and 323 mg HC/g TOC and TOC values up to 57% (Struckmeyer et al., 2001). By comparison, claystones have average HI values in the range 120 to 170 mg HC/g TOC and TOC values up to 5.5%. Pyrolysis studies indicate that the coaly material in the upper Borda Formation is more oil-prone than the organic matter in the mudrocks (Preston, 1992). Variations in source richness for this unit are apparent, and source rock quality and quantity increases basinward into the southeastern Ceduna Sub-basin. The oil and gas shows encountered in Upper Cretaceous rocks in Greenly 1 (in the adjacent Ceduna Sub-basin), are likely to have been sourced from the Borda Formation/Bronze Whaler Supersequence (Smith & Donaldson, 1995) and/or older, Austral 1, source rocks (Edwards et al., 1999).

Potential source intervals are present in the coal-prone lower delta plain facies of the Ceduna Formation (Blue Whale Supersequence) and the fluvio-deltaic facies of the Platypus and Wigunda formations (White Pointer–Tiger supersequences), however, these intervals are only likely to be mature for hydrocarbon generation in the adjacent Ceduna Sub-basin.

2.4.3.2 Generation and expulsion

Generation and expulsion from potential Jurassic–Lower Cretaceous source rocks of the early rift phase succession is modelled to have occurred during the Early Cretaceous in the Duntroon Sub-basin, with peak generation being reached in the Late Cretaceous just prior to the main structuring event (Smith & Donaldson, 1995). There is a risk that some early-generated hydrocarbons may have been lost from early formed structures, however there is also the possibility of tertiary migration into structures formed during that deformation. Structures formed during the Late Cretaceous deformation would also have been in place to receive later generated charge.

Generation and expulsion from source rocks in the upper Borda Formation in the adjacent Ceduna depocentre is modelled to have commenced during the Campanian, with potential traps in place prior to the commencement of generation (Smith & Donaldson, 1995). While the upper Borda Formation potential source units are not considered to be mature for hydrocarbon generation across much of the Duntroon Sub-basin (Smith & Donaldson, 1995), interpretational uncertainty means that it is possible the lower parts of this unit may be buried deeply enough (>3000 m) in some of the thicker half graben, particularly in the southern depocentre.

In contrast to other areas of the Bight Basin, particularly the Ceduna Sub-basin, deposition of the thick wedge of Cenozoic carbonates is likely to have driven late hydrocarbon charge in the sub-basin (Bight Petroleum, 2011).

2.4.3.3 Reservoirs

Reservoir quality in the Duntroon and southeastern Ceduna sub-basins varies from poor to excellent and is dependent on palaeoenvironment and depth of burial (Blevin et al., 2000; Somerville, 2001). The Neptune and Borda formations generally have poor to moderate reservoir potential due to their depth of burial, below 10 km, throughout much of the southeastern Bight Basin. Upper Borda Formation sandstones generally consist of fine-grained well-sorted feldspathic litharenites. Petrographic analysis of upper Borda Formation sandstones in Duntroon and southern Ceduna sub-basin wells showed that diagenetic processes had eliminated nearly all primary intergranular porosity in these clay-choked and compacted sandstone units (Martin, 1992; Smith & Donaldson, 1995). The porosity data presented in Smith & Donaldson (1995) shows a clear trend of porosity degradation with depth consistent with changes in reservoir facies and provenance. As the wells studied are on the western edge of the sub-basin or in the adjacent Ceduna Sub-basin, it is possible that reservoir quality may be better in more inboard parts of the Duntroon Sub-basin, where burial depth is much less.

Sandstones in the Ceduna Formation are also dominated by volcaniclastic material, however, early formed carbonate cements appear to have protected the sands from compactional effects during burial, and later partial dissolution of these cements has resulted in some intergranular secondary porosity (Martin, 1992; Smith & Donaldson, 1995).

Rocks with the best reservoir properties are the Upper Cretaceous Platypus, Wigunda and Potoroo formations. In wells from this region, these units have average log porosities between 15–30% and moderate permeabilities (Santos Australia Exploration, 2006). However, in the Duntroon Sub-basin the distribution of these units is limited to the western margin of the sub-basin, adjacent to the “Late Cretaceous Hinge”, and northernmost parts of the sub-basin (Smith & Donaldson, 1995; Santos Australia Exploration, 2006; Woodside, 2006).

The Paleocene–Eocene Pidinga Formation (Wobbegong Supersequence), which contains shallow marine and shoreface sandstones, has good reservoir characteristics with porosities of 19–21% in Borda 1 (Messent et al., 1995).

2.4.3.4 Seals

The sedimentary succession in the Duntroon Sub-basin is mudstone-dominated, and potential seal facies are present throughout the Lower Cretaceous succession, particularly in the Borda and Neptune formations. Prodelta mudstones of the Upper Cretaceous Wigunda Formation are likely to provide an effective seal above the highly porous sands of the Ceduna and Platypus formations. Laterally extensive claystone units (up to 100 m thick) within the Potoroo Formation may provide excellent intraformational seals.

Marls of the Cenozoic Dugong Supersequence may provide seal for reservoirs in the Campanian–Maastrichtian and Paleocene–Eocene section; across the region, the seal is of varying thickness (~500–1000 m) and probably varying quality (Messent et al., 1996). Messent et al. (1996) argued that there was a relationship between higher argillaceous content and improved seal potential. They proposed that seal risk was lowest in areas where Cenozoic channels were present as fine grained clastic facies within the channel systems improved seal quality.

Overall, the abundance of mudstone in the Duntroon Sub-basin succession may be a significant risk for petroleum systems, as thick mudstone units overlying potential source rocks may act as a barrier to migration of hydrocarbons into reservoir facies (Santos Australia Exploration, 2006).

2.4.3.5 Play types

The Duntroon Sub-basin contains several potential play types. These include:

- structural traps (including faulted, rotated and collapsed anticlinal structures, tilted fault blocks) with intraformational sandstone reservoirs sealed within the mudstone-dominated Borda Formation, and hydrocarbons sourced from Upper Jurassic–Lower Cretaceous organic-rich lacustrine and coaly facies; may rely on trapping of hydrocarbons generated/migrated after the late Santonian deformation

- thick transgressive marls at the base of the Cenozoic Dugong Supersequence providing a trapping mechanism in Upper Cretaceous–Eocene reservoirs for late-generated hydrocarbons sourced from Upper Jurassic–Lower Cretaceous organic-rich lacustrine and coaly facies
- migration of hydrocarbons from mature Lower and Upper Cretaceous source rocks (particularly the upper Borda Formation) in the adjacent Ceduna Sub-basin into fault-related structural traps with Upper Cretaceous reservoirs and intra-formational seals on the western margin of the Duntroon Sub-basin.

2.4.3.6 Critical risks

The main risks for petroleum systems in the Duntroon Sub-basin include:

- reservoir quality, particularly in the Lower Cretaceous section. The volcaniclastic nature of sandstones in this succession has resulted in the development of diagenetic clays that have eliminated primary porosity (Martin, 1992; Smith & Donaldson, 1995). However, as most wells are located on the western margin of the sub-basin, there is little information on the reservoir quality of this succession across much of the sub-basin
- migration pathways: the abundance of mudstone in the basin fill may be a significant risk for petroleum systems, as the presence of thick mudstone units overlying potential source rocks may act as a barrier to migration of hydrocarbons into reservoir facies (Santos Australia Exploration, 2006)
- distribution and quality of potential Cenozoic seals
- loss of early generated hydrocarbons due to Late Cretaceous structuring, uplift and erosion across the sub-basin. This risk may be mitigated to some extent by the presence of a thick Cenozoic carbonate wedge, which would have driven generation of hydrocarbons from the good quality Lower Cretaceous potential source rocks during the Cenozoic
- interpretation problems caused by variable seismic data quality (Figure 2.22).

2.4.3.7 Overall prospectivity classification

Moderate

2.4.4 Exploration status

Petroleum exploration in the Ceduna and Duntroon sub-basins occurred in four major cycles—the late 1960s to early 1970s, the early 1980s, the early 1990s and, most recently, from 2000–2007. In nearly 50 years of exploration in the offshore Bight Basin, less than 100,000 line-km of seismic data have been acquired and only 10 petroleum exploration wells have been drilled. The majority of these wells were drilled in water depths of less than 250 m along the margins of the basin, where the source rock quality of upper Lower to Upper Cretaceous marine deposits has been reduced by the influx of terrigenous organic matter into proximal depositional facies. Six wells have been drilled in the eastern Ceduna–Duntroon sub-basin region. Three wells have been drilled within the currently defined limits of the Duntroon Sub-basin—Duntroon 1, Echidna 1 and Vivonne 1. The other three—Platypus 1, Greenly 1 and Borda 1—are located just to the west of the Duntroon Sub-basin, in the eastern Ceduna Sub-basin (Figure 2.19 and Figure 2.23).

The first petroleum exploration permits held in the Duntroon Sub-basin area were granted to Shell Development (Australia) Ltd (Shell) in 1966. OEL38 covered most of the eastern Bight Basin and was converted to a number of exploration petroleum permits (EPP) between 1968 and 1969. Between

1966 and 1976, Shell carried out seven seismic surveys (R4 to R10) over these permits, acquiring over 14,500 line-km of 2D seismic reflection data. Magnetic data was also recorded along most of the deep water lines. In 1966, Shell, in conjunction with Outback Oil Co. NL (Outback), recorded 16,000 km of regional aeromagnetic data over OEL33 and 38. Several prospects were developed from these activities and three exploration wells were drilled, Echidna 1 and Platypus 1 in 1972 and Potoroo 1 (in the northern Ceduna Sub-basin) in 1975. By 1977, Shell had surrendered all of its Bight Basin exploration permits.

The early 1980s was a period of relatively lacklustre exploration in the Bight Basin. During this period EPP16, 17 and 19, covering the inboard parts of the eastern Bight Basin, were held by BP Petroleum Development Pty Ltd (BP) and Hematite Petroleum Pty Ltd, a consortium headed by Sterling Petroleum NL, and Outback Oil Co. NL respectively. EPP19 partly covered the Duntroon Sub-basin. In 1982, Outback acquired 539 line-km of seismic in EPP19, with the contractor Geophysical Service Inc. recording an additional 827 line-km of data in adjacent permits on a non-exclusive basis (O'Neil, 2003). However, interest in the area was so low that most of the data was left unprocessed and by 1984 all the permits had been surrendered (Stagg et al., 1990).

In 1982, EPP21, which was located over the central Duntroon and eastern Ceduna sub-basins, 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 reflection 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, and led to the drilling of Duntroon 1 in early 1986. The well was dry and subsequent mapping indicated that it had been 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, under the auspices of a Scientific Investigation Authorisation. The survey covered the entire inboard Bight Basin and was conducted as part of a regional evaluation prior to an expected release round. A total of 27,624 line-km of data were recorded at a line spacing of 5 km over an area of approximately 108,508 km^2 (Mackintosh & Williams, 1990). The initial results were poor with only two definite, but weak fluors detected. However, reprocessing and reinterpretation of the data recorded a total of 941 confident fluors (Cowley, 2001). The fluors are concentrated in three regions, including one in the vicinity of Greenly 1.

A new phase of exploration began in 1991, when BHP Petroleum (Australia) Pty Ltd (BHP) was awarded EPP25 and 26 covering the eastern Ceduna and Duntroon sub-basins. In 1991, 1046 line-km of seismic data acquired by the EPP21 joint venture was reprocessed and three new seismic surveys (DH91, DH92 and HD95) acquired high quality 2D seismic data from 1991 to 1995. These new data indicated that all prior drilling had been sited on invalid structures (O'Neil, 2003). BHP drilled three wells in 1993; Borda 1 and Greenly 1 lie within the Ceduna Sub-basin (Bradshaw et al., 2003), while Vivonne 1 was drilled in the Duntroon Sub-basin. Although all were plugged and abandoned, their results are encouraging and emphasise the highly unpredictable stratigraphy and complex structural history of the basin. Gas shows and oil indications recorded in Greenly 1 represented the first major indication of hydrocarbons in the basin, identifying the presence of a valid source rock and thus considerably upgrading the prospectivity of the basin.

The latest phase of petroleum exploration in the Duntroon Sub-basin region commenced in 2001. Exploration permit EPP31, located partially over the Ceduna 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 1769 line-km of 2D seismic data (Whidbey 2D Marine Seismic Survey) between

December 2004 to January 2005 and also reprocessed 4455 line-km older 2D seismic data over the permit. The adjacent permit, EPP32, was awarded to Santos Offshore Pty Ltd in late 2002, who acquired 556 line-km of 2D seismic data in 2003 (2003 Duntroon Basin, EPP32 Marine Seismic Survey) and also reprocessed 2531 line-km of existing 2D seismic data. Both permits were surrendered in 2007.

In 2010, two exploration areas were released in the eastern Ceduna–Duntroon sub-basin. In June 2011, Bight Petroleum was awarded the two Ceduna–Duntroon permits (EPP41 and 42); the 3-year work program includes one well.

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 28,000 line-km of regional 2D 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 models predict numerous potential petroleum systems in Jurassic and Cretaceous 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, 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; Totterdell & Mitchell, 2009).

2.4.5 Data

Key data sets for the Duntroon Sub-basin are listed in Table 2.12–Table 2.15. Six wells have been drilled in the eastern offshore Bight Basin; three in the Duntroon Sub-basin (Duntroon 1, Echidna 1 and Vivonne 1), and three in the immediately adjacent eastern Ceduna Sub-basin (Platypus 1, Greenly 1 and Borda 1; Figure 2.19). Oil and gas shows were recorded in Greenly 1, while other wells have recorded oil and gas indications. No commercial hydrocarbons have been discovered in either the Duntroon or Ceduna sub-basins.

Seismic coverage over most of the Duntroon Sub-basin ranges from very good (~1 km line spacing) to moderate (~10 km line spacing), although there is little or no data in the northwestern and southeastern corners of the sub-basin (Figure 2.23). Seismic data comprises a mixture of vintages ranging from the 1970s through to recently acquired data. The most significant older seismic data sets are the DH91, DH92A and HD95 surveys acquired by BHP in the early 1990s. Seismic Australia, in joint venture with Australian Geological Survey Organisation (AGSO), acquired 8500 line-km of regional seismic data across the Ceduna Sub-basin during 1998–99 (HRGAB and DWGAB surveys). The easternmost lines of that survey extend into the Duntroon Sub-basin.

Many of the earlier seismic datasets were reprocessed by Fugro Multi Client Services in 1999 and 2004 and a new data product comprising reprocessed seismic, new potential field data and satellite SAR seep data over the Ceduna Sub-basin is also currently available.

The Woodside-Anadarko-EnCana joint venture acquired 1769 line-km of 2D seismic data (Whidbey 2D Marine Seismic Survey) between December 2004 to January 2005 and also reprocessed 4455 line-km of older 2D seismic data over EPP31 in the southern Ceduna and Duntroon sub-basins. The adjacent permit, EPP32, was awarded to Santos Offshore Pty Ltd in late 2002, who acquired 556 line-km of 2D seismic data in 2003 (2003 Duntroon Basin, EPP32 Marine Seismic Survey) and also reprocessed 2531 line-km of existing 2D seismic data. Both permits were surrendered in 2007.

Additional publications, reports and data covering the Duntroon Sub-basin and broader Bight Basin are available from Geoscience Australia (GA) and the Energy and Resources Division of the South Australian Department of Manufacturing, Innovation, Trade, Resources and Energy (DMITRE). Data and analyses include gravity, magnetic and bathymetry grids, depth-time functions, results of SAR (Struckmeyer et al., 2002) and ALF seepage surveys, company reports and related publications.

Despite the abundance of seismic data in the region (Figure 2.23), seismic data quality is an issue of concern in the Duntroon Sub-basin and adjacent eastern Ceduna Sub-basin. Data quality on the shelfal areas (i.e. in the Duntroon Sub-basin) is generally fair to poor due to the presence of a westward-thickening wedge of Cenozoic carbonates (Woodside, 2006). Beneath the carbonate wedge, data quality deteriorates and imaging is more difficult due to increased noise levels and lack of penetration (Figure 2.22; Woodside, 2006; Santos Australia Exploration, 2006). On the western margin of the sub-basin, shelf edge canyons and complex extensional faulting patterns lead to seismic imaging and depth conversion issues that are unlikely to improve with further acquisition or processing of 2D seismic data (Woodside, 2006; Santos Australia Exploration, 2006).

2.4.5.1 Confidence Rating

Medium

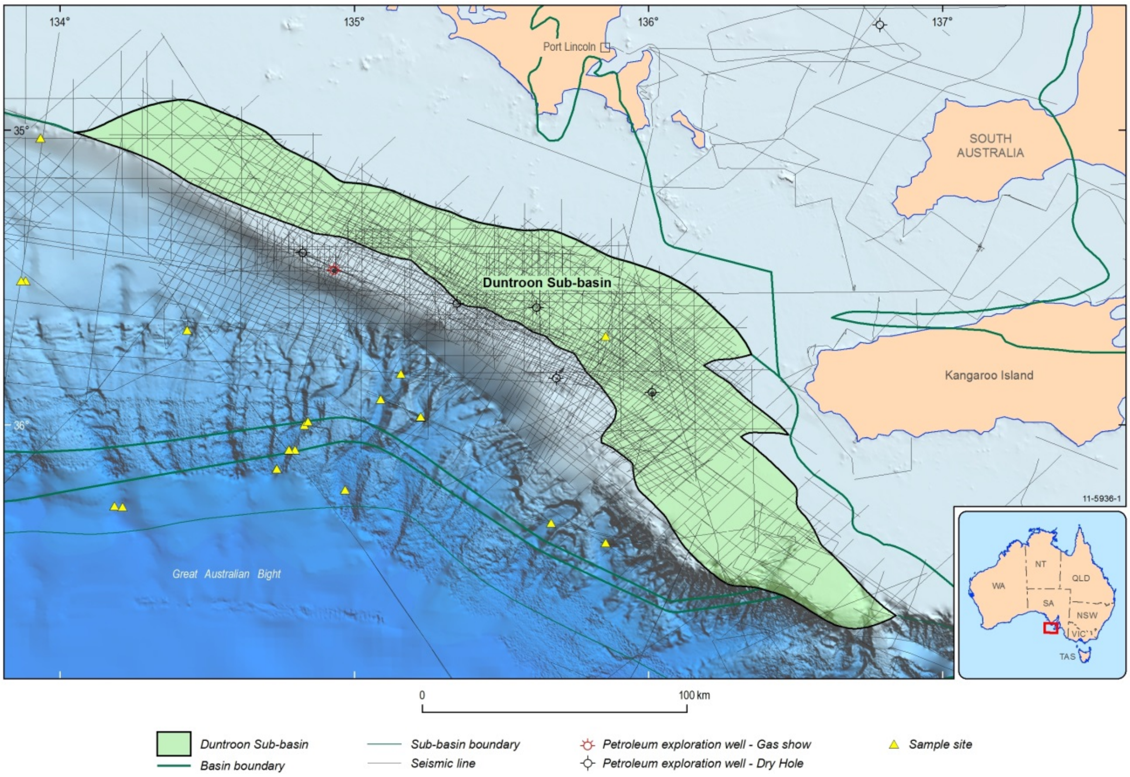

Figure 2.23: Seismic, well and sample distribution.

2.4.6 Issues and remaining questions

Advances in our understanding of the Duntroon Sub-basin are likely to be made in the near future, as Bight Petroleum's current exploration program in EPP41 and 42 includes the acquisition of 3D seismic and the drilling of one well as part of the guaranteed work program; however, drilling may focus on the Ceduna Sub-basin rather than the Duntroon Sub-basin. In general, there are two main areas of concern, the presence of viable petroleum systems and data quality.

2.4.6.1 Petroleum systems

While high quality source rocks and adequate seal facies are likely to be present in the Duntroon Sub-basin, the following petroleum systems elements are issues of concern:

- the presence of good quality reservoirs. The mudstone-dominated nature of the succession means that thick sandstone units are not abundant in the few wells that have been drilled. However, the paucity of drilling in the sub-basin means that there is considerable uncertainty about the presence and distribution of sandstone units away from the western margin of the sub-basin. Porosity in potential reservoir units is an issue of concern, as studies on wells in the area have shown that diagenetic processes have eliminated primary porosity in volcaniclastic-rich Lower Cretaceous sandstones. The potentially isolated nature of hydrocarbon-bearing sandstones may have implications for the economic viability of discoveries
- the presence of viable migration pathways in the dominantly mudstone section
- preservation of accumulations, i.e. the timing of generation and migration relative to the major structuring event in the late Santonian.

The understanding of these critical issues will be improved through further drilling and the acquisition of 3D seismic data. Improved knowledge of the distribution and nature of potential reservoir units and the structural geology of the sub-basin could inform robust regional petroleum systems models that could more accurately address the relative timing of generation, migration, trap formation and structuring.

2.4.6.2 Data quality

Seismic data in the Duntroon Sub-basin is abundant but of highly variable quality (Figure 2.22). The westward thickening wedge of Cenozoic carbonates strongly influences seismic data quality across the basin, particularly in the west where the Cenozoic section also contains numerous large channels and canyons. These data quality issues lead to significant interpretational uncertainty.

Seismic acquisition and processing programs that are specifically designed to address the issue of shallow carbonates are required in the area. Woodside (2006) recommended reprocessing of 2D seismic data in the Duntroon Sub-basin ("shelfal areas") followed by the acquisition of 3D data to address interpretation uncertainties.

2.4.6.3 Recommendations

- Drilling; one well is guaranteed in Bight Petroleum's EPP41–42 work program.
- Acquisition of 3D seismic data to improve understanding of stratigraphy, facies, age, structural geology.
- Seismic acquisition and processing designed to address data problems caused by shallow carbonates.
- Petroleum systems modelling.

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2.4.8 Data Tables

Table 2.12: List of wells, Duntroon Sub-basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1972	Echidna 1	Exploration	Shell Development (Australia) Pty Ltd	3832	Berriasian	Fluorescence and cut	Shell, 1972
1986	Duntroon 1	Exploration	BP Petroleum Development Ltd	3510	Aptian	Dry	Templeton & Peattie, 1986
1993	Vivonne 1	Exploration	BHP Petroleum Pty Ltd	3000	Barremian	Dry	Wong, 1994

Table 2.13: Key seismic surveys in the Duntroon Sub-basin.

Year	Survey	Operator	Line-km	Reference
1983	Duntroon Basin EPP21 Marine Seismic Survey D83	Getty Oil	2102	O'Neil, 2003
1984	Duntroon Seismic Survey D84	Getty Oil	1019	O'Neil, 2003
1991	Duntroon Seismic Survey, EPP25 and EPP26 DH91	BHP Petroleum	7564	O'Neil, 2003
1992	Duntroon Seismic Survey, EPP25 and EPP26 DH92	BHP Petroleum	1458	O'Neil, 2003
1995	HD95 Seismic Survey HD95	BHP Petroleum	1557	O'Neil, 2003
1999	Great Australian Bight Marine Seismic Survey (DWGAB and HRGAB)	Seismic Australia/AGSO	8294 (most in Ceduna Sub-basin)	
2003	DS03 (EPP32) Seismic Survey DS03	Santos	556	Santos, 2006
2004	Whidbey 2D Marine Seismic Survey	Woodside	1769	Woodside, 2006

Table 2.14: Key surveys involving geological sampling surveys, Duntroon Sub-basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
1986	BMR Survey 66	BMR	Great Australian Bight	Dredge, gravity core, heat flow	Siliciclastic rocks, lithified and semi-lithified pelagic limestone, volcanic rocks, igneous basement rocks	Davies et al., 1989
1994	Southern Australian margin: cool-water carbonates and geological history (FR 06/94)	CSIRO	Great Australian Bight	Dredges, benthic sled	Carbonate	Bone et al., 1994

Table 2.15: Key swath bathymetry surveys, Duntroon Sub-basin

Year	Survey	Operator	Line-km/Area (km^2)	Reference
2000	AUSTREA 1	AGSO		Hill et al., 2000, 2001
2003	AUSCAN	Geoscience Australia/ANU		Hill & De Deckker, 2004
2006	AUSFAIR–GAB transit	Institut Polaire Français Paul-Emile Victor		Institut Polaire Français Paul-Emile Victor, 2007

2.5 Deepwater Otway Basin

2.5.1 Summary

State(s)		South Australia, Victoria, Tasmania
Area (km²)		~92,500
Water Depth (m)		200–5400
Maximum sediment thickness (m)		~8000
Age range		Early Cretaceous–Holocene
Basin	**Subdivisions**	Morum, Nelson and Hunter Sub-basins, Discovery Bay High
	Parent	Otway Basin
	Adjacent basins	“Inner Otway Basin”, Bight and Sorell basins
Basin type		Extensional; passive margin
Depositional setting, rock types		Fluvio-lacustrine, deltaic and marine clastic sedimentary rocks, cool-water carbonate rocks
Petroleum prospectivity		Moderate
Confidence		*Medium–low*

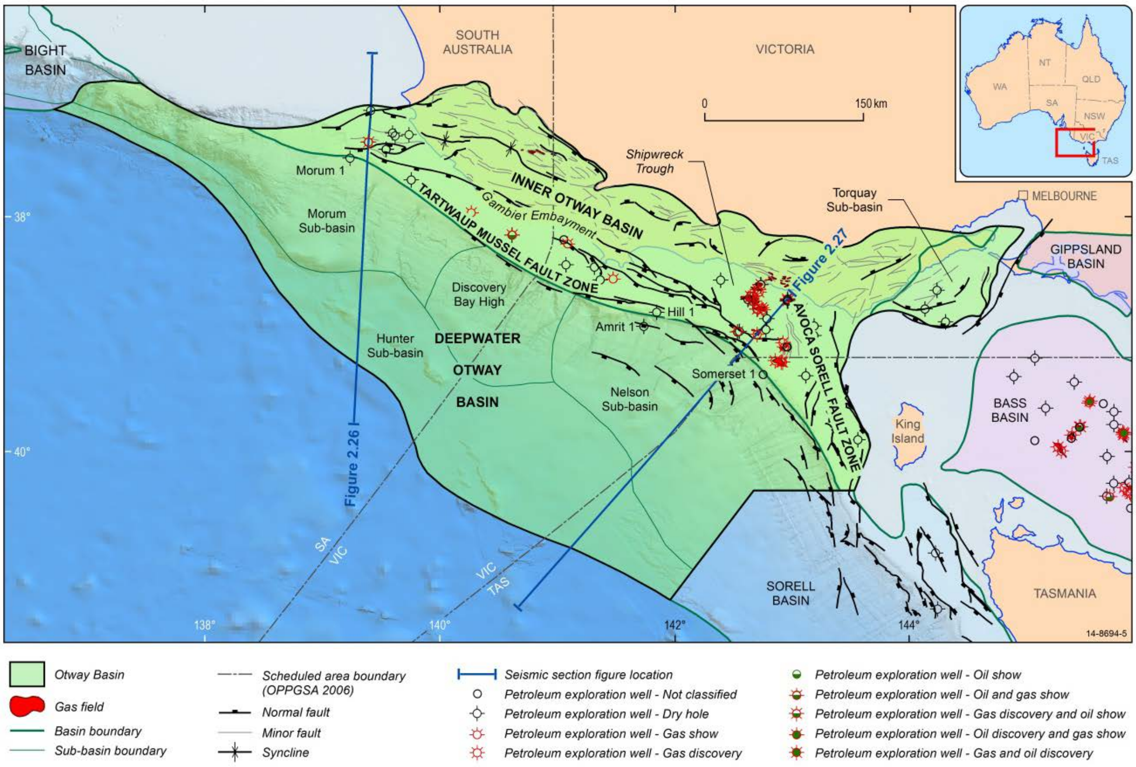

Figure 2.24: Structural elements map, Otway Basin.

2.5.2 Geology

The Otway Basin is a northwest-trending passive margin rift basin that extends from southeastern South Australia to a boundary with the contiguous Sorell Basin west of King Island (Figure 2.24). The basin covers an area of 150,000 km^2, 80% of which lies offshore in water depths ranging from <50 m to 5400 m. The Otway Basin contains a Lower Cretaceous to Cenozoic siliciclastic and carbonate sedimentary succession (Figure 2.25) that accumulated within two major depocentres. The "Inner Otway Basin", which occupies onshore and shelfal areas, is characterised by a thick Lower Cretaceous sedimentary section. Farther offshore, basinward of a large fault system in part mapped as the Tartwaup–Mussel Fault Zone, the region referred to herein as the "deepwater Otway Basin" includes the Late Cretaceous depocentres of the Morum, Nelson and Hunter sub-basins, and the Discovery Bay High (Figure 2.24).

The Otway Basin is a well-established gas producing region, but discoveries have been confined to onshore and shallow water offshore areas of the basin. No discoveries have been made in the relatively poorly explored deepwater part of the basin; hence this part of the basin is classified as frontier.

2.5.2.1 Structural geology

The Otway Basin developed during the latest Jurassic to Cenozoic as a result of rifting and continental separation between Australia and Antarctica (Willcox & Stagg, 1990; Stagg & Reading, 2007; Blevin & Cathro, 2008). The basin overlies deformed Proterozoic and Paleozoic rocks of the Delamerian and Lachlan fold belts, which appear to have influenced the location and orientation of later basin-forming structures (Miller et al., 2002; Moore, 2002; Bernecker & Moore, 2003; Gibson et al., 2012). The complex structural and depositional history of the basin also reflects its location in the transition from an orthogonal–obliquely rifted continental margin in the west to a transform continental margin to the southeast (Totterdell et al., 2012).

The deepwater Otway Basin consists of two main depocentres—the Morum and Nelson sub-basins—separated by the Discovery Bay High, all of which are flanked basinward by the Hunter Sub-basin (Figure 2.24). The inboard boundary of the deepwater Otway Basin approximately coincides with a large fault system (in part mapped as the Tartwaup–Mussel Fault Zone) and a corresponding hinge zone, basinward of which the Upper Cretaceous succession thickens dramatically.

The westernmost element of the deepwater Otway Basin is the Morum Sub-basin. In this report, the Morum Sub-basin includes the narrow, highly faulted Beachport Sub-basin of Moore et al. (2000), which links the Otway Basin with the Ceduna Sub-basin of the Bight Basin. The narrow, neck-like nature of this part of the basin may reflect its position adjacent to a transform segment of the continent-ocean boundary.

The Morum Sub-basin contains at least 5 s TWT (~8 km) of Cretaceous sediments overlain by a thin Cenozoic section. The sub-basin is characterised by intense faulting that affects the entire Cretaceous succession (Figure 2.26; Moore et al., 2000). The faults are typically high-angle, particularly in the inboard fault zone underlying the upper continental slope. Lower-angle listric faults are common farther basinward.

The Morum Sub-basin is separated from the thick section in the Nelson Sub-basin to the east by the Discovery Bay High (Moore et al., 2000), a complex structural high across which the Cretaceous succession thins to about 2.5 s TWT (~4 km) and the Cenozoic section is thin or absent. This part of the basin is referred to by some authors as the Bridgewater High or Arch (e.g. Reid et al., 2001; Krassay et al., 2004). The Cretaceous section on the Discovery Bay High is of relatively uniform thickness, and only mildly deformed, suggesting this area underwent only moderate subsidence during the Cretaceous (Moore et al., 2000).

The Nelson Sub-basin, like the Morum Sub-basin, contains up to 5 s TWT (~8 km) of Cretaceous sediments overlain by a thin Cenozoic section. However, both the structural style and sedimentary architecture are very different to that seen in the Morum Sub-basin (Figure 2.27). The inboard boundary of the sub-basin is marked by the broad Tartwaup–Mussel Fault Zone, across which the Lower Cretaceous section is offset basinwards by about 4 km (Moore et al., 2000). The basal section, interpreted to comprise the Lower Cretaceous Crayfish and Eumeralla supersequences, is closely faulted, although fault offsets are generally small. In comparison, the thick, overlying Upper Cretaceous succession is much less affected by faulting. Late Cretaceous faulting is concentrated in the Tartwaup–Mussel Fault Zone, with faults becoming more widely spaced farther basinward. Structural control on deposition is evident for the basal Upper Cretaceous succession. The overlying Cretaceous section comprises a thick progradational succession that is only mildly structured. This section onlaps an outer basement high that is interpreted to represent exhumed sub-continental lithospheric mantle (Totterdell et al., 2012). The Nelson Sub-basin is contiguous with the Sorell Basin to the southeast.

The Morum and Nelson sub-basins are flanked farther outboard by the Hunter Sub-basin, which is located in water depths of 3300–5400 m. The Hunter Sub-basin is contiguous with the Recherche Sub-basin of the Bight Basin to the west. The Hunter Sub-basin contains a thin Cretaceous and Cenozoic succession; the outer part of the sub-basin is interpreted to overlie highly extended continental crust and rocks of the ocean–continent transition (Totterdell et al., 2012; Moore et al., 2000). The Hunter Sub-basin is considered to have insufficient sedimentary section (generally less than 1 s TWT) to be prospective for hydrocarbons and will not be considered further in this discussion.

2.5.2.2 Basin evolution and depositional history

Middle–Late Jurassic intracontinental extension across the western and central parts of the southern margin resulted in the formation of a series of extensional and transtensional half graben from the Bremer Sub-basin in the west, across the eastern Bight Basin, to at least the western Otway Basin in the east (Totterdell & Bradshaw, 2004; Norvick & Smith, 2001). By the Early Cretaceous, upper crustal extension was focused in the eastern part of the southern margin. The oldest rift-fill sediments in the Otway Basin are latest Jurassic–Early Cretaceous (Figure 2.25). During that time, the locus of rifting and deposition was in the onshore parts of the basin where a series of west to northwest-trending extensional depocentres formed (Krassay et al., 2004). Interpretation of seismic data suggests that a thin, extensional Lower Cretaceous succession is also present in the deepwater Otway Basin (Figure 2.27). This succession is interpreted to comprise fluvial and lacustrine rocks of the Crayfish and Eumeralla supersequences (Figure 2.25). In the eastern Nelson Sub-basin, deposition during this time was strongly influenced by the north–south oriented Avoca–Sorell fault system.

A period of compression and structural inversion affected most of the Otway Basin during the Cenomanian (Norvick & Smith, 2001; Krassay et al., 2004), resulting in kilometre scale uplift and exhumation in some areas of the basin (e.g. Otway Ranges region; Holford et al., 2011), and non-deposition or erosion of much of the Cenomanian succession across most of the basin. Due to the limitations of seismic data and the lack of wells, its impact in the deepwater Otway Basin is less clear.

Extension recommenced in the Late Cretaceous, with the locus of deposition moving to the south, basinward of the Tartwaup–Mussel Fault Zone and equivalent faults farther west (Reid et al., 2001; Krassay et al., 2004). This resulted in the development of a series of northwest-trending depocentres beneath the present day outer shelf and slope in the Morum and Nelson sub-basins; the inboard fault-controlled depocentre is commonly referred to as the Voluta Trough (e.g. Reid et al., 2001). Deposition throughout the Late Cretaceous was dominated by the fluvio-lacustrine, deltaic and marine sediments of the Shipwreck and Sherbrook supersequences (equivalent to the Sherbrook Group; Krassay et al., 2004). Initial deposition of the Shipwreck Supersequence, particularly in the Nelson Sub-basin, appears to have been strongly fault controlled, with that control diminishing through time. In hydrocarbon producing areas of the Otway Basin, the Shipwreck Supersequence includes the economically important reservoirs of the Waarre and Flaxman formations, and the "Thylacine Sandstone Member" of the Belfast Mudstone.

The Sherbrook Supersequence consists of a thick, basinward-thickening progradational succession of coastal plain, deltaic and marine sediments up to 5 km thick. There is evidence of localised fault control on deposition, particularly around the Tartwaup–Mussel Fault Zone (Figure 2.27), and further basinward where listric growth faults are observed in seismic data.

The Late Cretaceous culminated in the commencement of breakup in the Otway Basin at around 65 Ma (Krassay et al., 2004). Regionally, the base of the Cenozoic is marked by uplift and erosion. A thin Cenozoic succession overlies the Sherbrook Supersequence in the deepwater Otway Basin (Figure 2.26 and Figure 2.27). These sediments represent deep water equivalents of the progradational coastal plain–open marine siliciclastic and carbonate sediments of the Wangerrip, Nirranda and Heytesbury groups preserved on the continental shelf.

2.5.2.3 Level of knowledge

Geological understanding of the deepwater Otway Basin is based on three wells and a limited grid of 2D and some 3D seismic reflection data, which are tied to wells and and seismic data in shelfal areas of the basin. The expansion of the Upper Cretaceous succession across the fault systems marking the inner boundary of the sub-basins, poor seismic data quality beneath the continental shelf break and in the deepest, most heavily structured parts of the basin, plus the paucity of direct well control add a considerable degree of uncertainty to seismic interpretation in the deepwater basin.

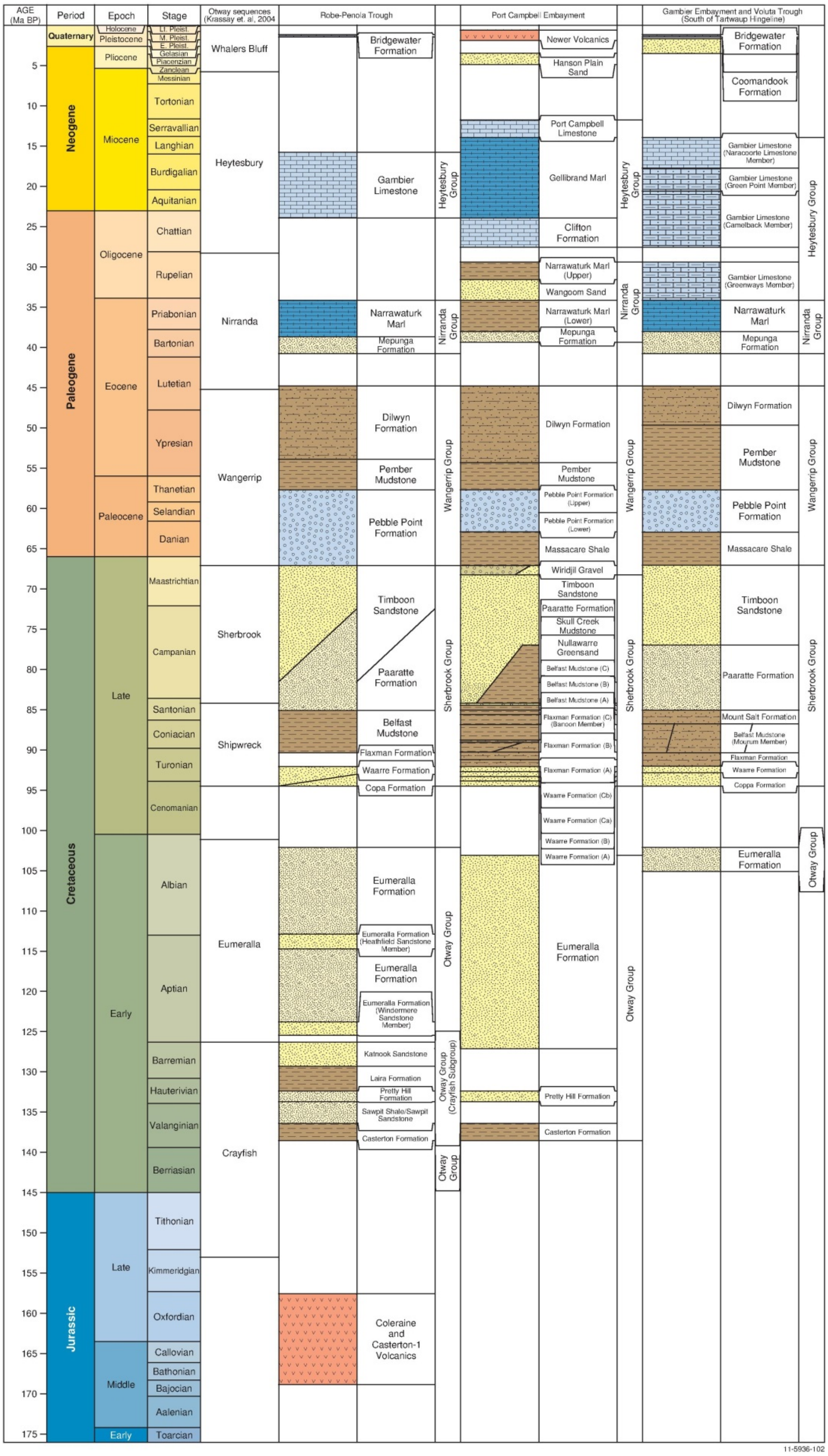

Figure 2.25: Stratigraphy of the offshore Otway Basin. Geologic time scale after Gradstein et al. (2012).

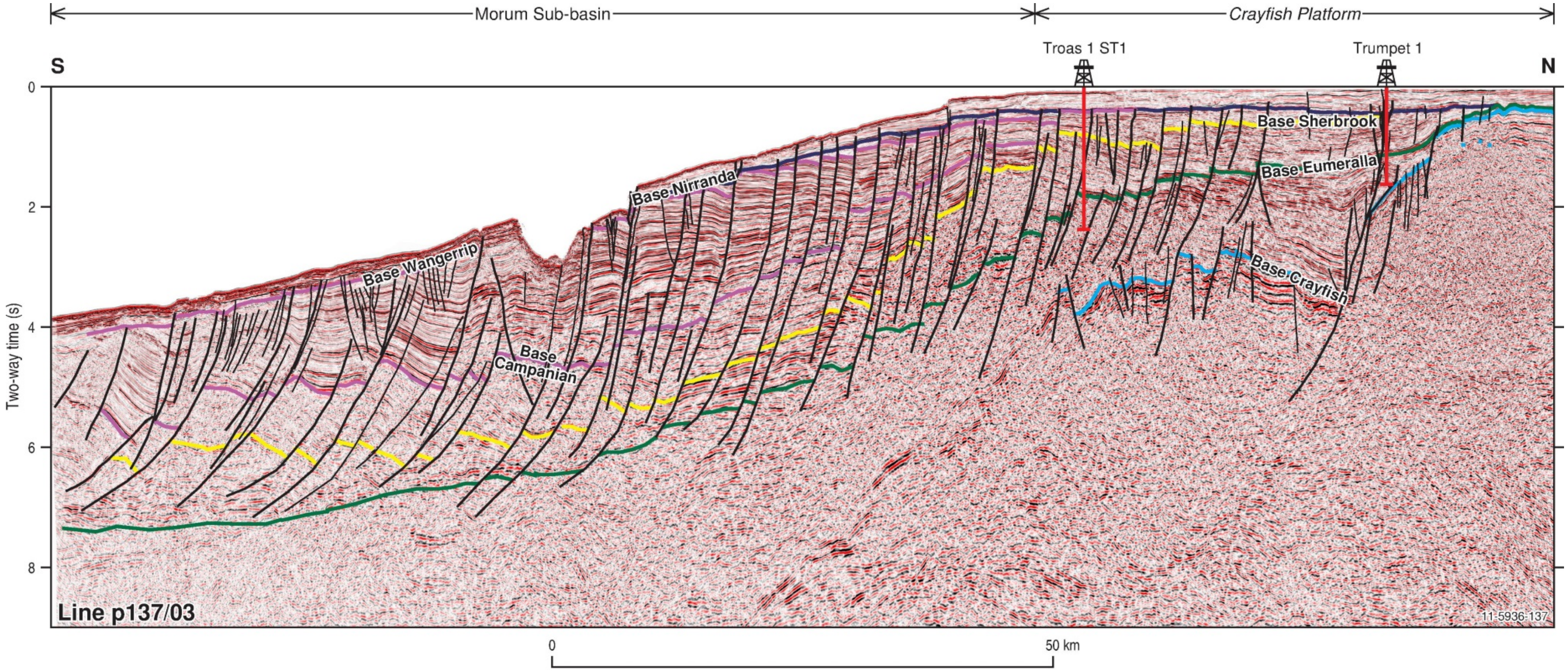

Figure 2.26: Geological cross-section based on composite seismic profile across the Morum Sub-basin, western Otway Basin (after Krassay et al., 2004).

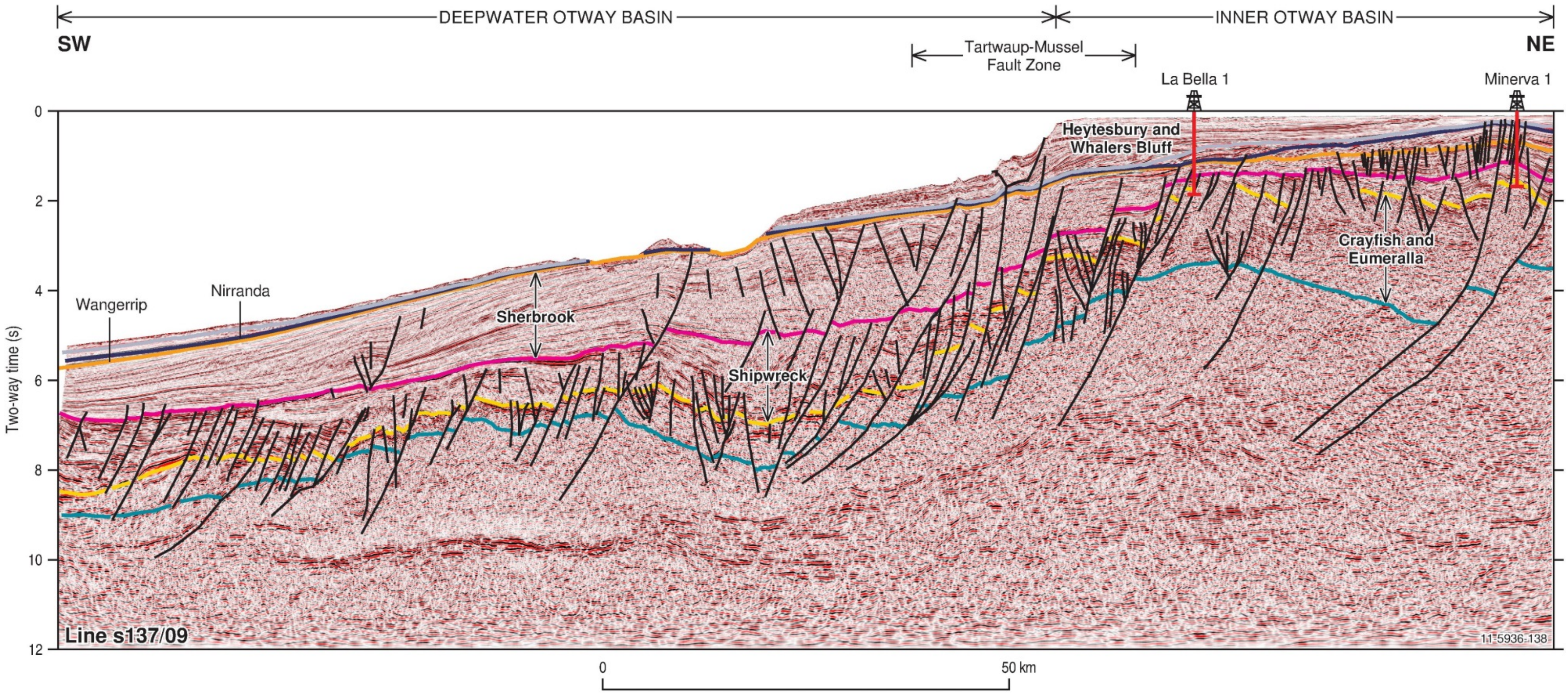

Figure 2.27: Seismic section across the Nelson Sub-basin (after Stacey et al., 2013).

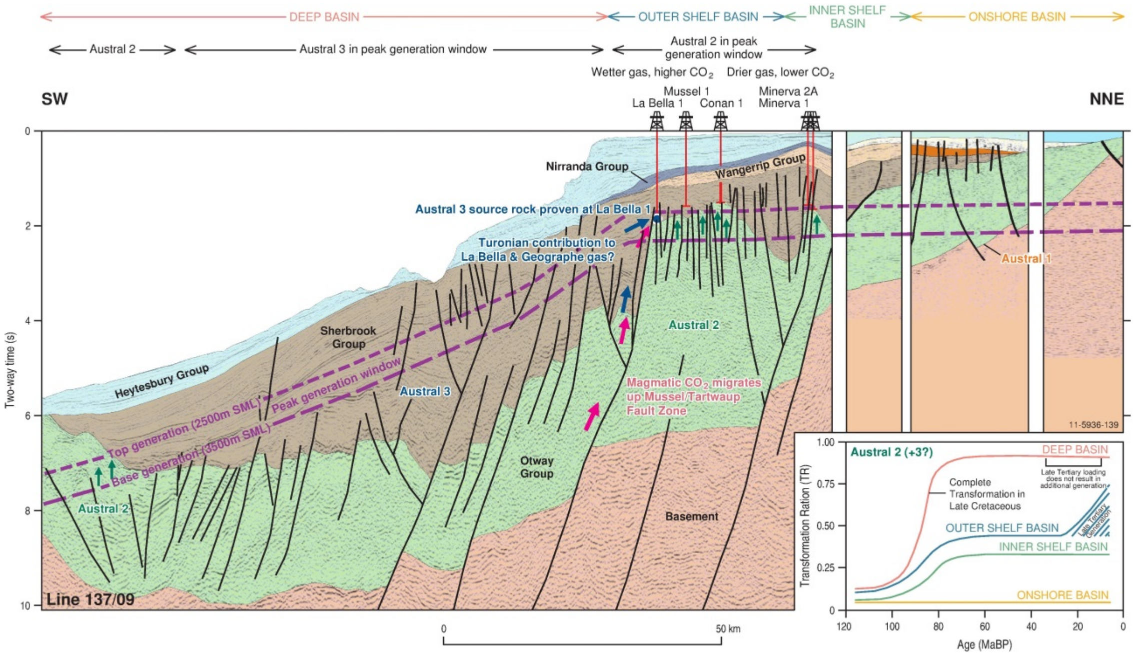

Figure 2.28: Interpreted seismic profile across the Nelson Sub-basin and Inner Otway Basin, showing hydrocarbon migration model for Austral 2 and 3 petroleum systems (after O'Brien et al., 2009).

2.5.3 Petroleum systems

Only three petroleum exploration wells (Morum 1, Amrit 1 and Somerset 1) have been drilled in the deepwater Otway Basin, and all were dry. Austral 2 source rocks are modelled as being overmature across much of the Late Cretaceous depocentre (O'Brien et al., 2009); however, the presence of a thick, dominantly marine Upper Cretaceous succession, and geochemical indications suggesting the influence of Austral 3-sourced hydrocarbons in outboard wells (O'Brien et al., 2009), provide some encouragement that active petroleum systems are present in the deepwater basin.

2.5.3.1 Source Rocks

Hydrocarbon discoveries on the Australian southern margin are assigned to the Austral Petroleum Supersystem (Bradshaw, 1993; Summons et al., 1998; Edwards et al., 1999), in which three subsystems are recognised:

- Austral 1: Upper Jurassic to lowest Cretaceous fluvio-lacustrine shales (Crayfish Supersequence);
- Austral 2: Lower Cretaceous fluvial and coaly facies (Crayfish and Eumeralla supersequences); and
- Austral 3: Upper Cretaceous to lowest Cenozoic fluvio-deltaic facies (Shipwreck and Sherbrook supersequences).

The nature of potential source rocks basinward of the Tartwaup–Mussel Fault Zone in the Otway Basin is not well understood, but interpretation of seismic data indicates the Lower and Upper Cretaceous depositional sequences that contain Austral 2 and 3 source rocks elsewhere in the basin (Boreham et al., 2004), are also likely to be present in the deepwater Otway Basin (Figure 2.28). Seismic interpretations indicate that Lower Cretaceous sequences thin basinward into the deepwater

Otway Basin; conversely, the Upper Cretaceous Shipwreck and Sherbrook supersequences thicken considerably basinward of the controlling Late Cretaceous faults systems (Figure 2.26 and Figure 2.27).

Given the thickness of the Upper Cretaceous section, potential Austral 2 source rocks (coaly sediments of the Eumeralla Supersequence) are modelled to be overmature across much of the deepwater basin (Figure 2.28; Reid et al., 2001; O'Brien et al., 2009). Consequently, exploration success in the deepwater basin is likely to be dependent on the presence of Turonian or younger (Austral 3) source rocks in the Shipwreck and Sherbrook supersequences (Figure 2.28; O'Brien et al., 2009). A possible exception to this is in the innermost part of the Morum Sub-basin, where the Lower Cretaceous succession is not as deeply buried and is modelled to have potential (Figure 2.26; Duddy et al., 2003). In this region, the basinward-thickening Upper Cretaceous section is interpreted to overlie potential Aptian–Albian source rocks that are postulated to include, not only the coaly source rocks of the Eumeralla Supersequence, but also organic-rich oil-prone marine sediments (Boult et al., 2006).

In the inner Otway Basin, the Turonian Waarre and Flaxman formations at the base of the Shipwreck Supersequence and the overlying Coniacian–Campanian Belfast Mudstone contain marine, marginal marine and coastal plain sediments. Farther basinward, the Turonian–Campanian section is likely to comprise prodelta and open marine facies, which have the potential to contain high-quality source rocks (O'Brien et al., 2009). The Cenomanian–Turonian and Coniacian–Santonian were times of global anoxia and source rock accumulation (Oceanic Anoxic Events (OAE) II and III; Arthur et al., 1990; Jenkyns, 2010), which further enhances the potential for the presence of good-quality Austral 3 source rocks in distal marine facies in the deepwater basin (Gallagher et al., 2005; O'Brien et al., 2009). The dredging of Cenomanian–Turonian potential source rocks with excellent liquids potential from the Ceduna Sub-basin of the Bight Basin further to the west (Totterdell et al., 2008), provides support for this hypothesis. In addition, O'Brien et al. (2009) identified organic enrichment in Turonian rocks in wells located along the outer margin of the basin, near the Tartwaup–Mussel Fault Zone. Those results support the concept that the basal parts of the Sherbrook Group became increasingly rich in organic matter basinward, as the system became more fully marine in the Late Cretaceous.

Hydrocarbons have not been definitively linked to Austral 3 source rocks in the Otway Basin, however most of the wells drilled in the basin have been located on inner shelf areas or onshore where the Sherbrook Group has not reached sufficient maturity for significant hydrocarbon generation. O'Brien et al. (2009) reported that gas discoveries in wells drilled on the outer shelf adjacent to the Tartwaup–Mussel Fault Zone (La Bella, Geographe and Thylacine) are significantly wetter than discoveries on the inner shelf, where the Austral 2 system comprises the sole hydrocarbon charge. Migration of Austral 3-sourced wet gas from the deepwater basin up the Tartwaup–Mussel Fault Zone was suggested by O'Brien et al. (2009) as a possible mechanism to explain this difference (Figure 2.28).

2.5.3.2 Generation and expulsion

Significant sediment loading took place in the deepwater Otway Basin during the Late Cretaceous (Shipwreck and Sherbrook supersequences). Petroleum systems modelling using the thermal history model of Duddy (1997), which includes elevated heat flow in the Cenomanian diminishing over time, suggests that in most of the Nelson Sub-basin, both the Austral 2 and basal Austral 3 source rock intervals had undergone complete organic matter transformation, and had generated and expelled hydrocarbons by 82 Ma (Figure 2.28; O'Brien et al., 2009). Given the amount of Late Cretaceous structuring in the basin, particularly prior to breakup in the latest Maastrichtian, preservation of these early-generated hydrocarbons could be problematic. O'Brien et al. (2009) also reported that in a narrow zone around the Tartwaup–Mussel Fault Zone, where the Upper Cretaceous section is not as thick, much of the Sherbrook Group is currently at peak maturity (Figure 2.28), which enhances the prospectivity of this zone.

In the Morum Sub-basin, modelling by Duddy et al. (2003), suggests that generation from Austral 2 (Eumeralla) source rocks ceased at about 45 Ma, and that migration, which commenced in the Late Cretaceous, continues to the present day.

2.5.3.3 Reservoirs and seals

In the offshore Otway Basin, the primary reservoir facies occur in the Sherbrook Group (Shipwreck and Sherbrook supersequences). In the Victorian part of the Otway Basin, the Turonian Waarre Formation is the major regional reservoir interval. The Flaxman Formation and a sandy facies ("Thylacine Sandstone Member"; Cliff et al., 2004) at the base of the Belfast Mudstone are also significant exploration targets. The Campanian–Maastrichtian Paaratte Formation, intersected by many wells in South Australia, is also known to contain good quality reservoir intervals. However, the extent to which these reservoir facies are developed in the deepwater Otway Basin is not known. Both the deepwater Otway well Amrit 1 and Hill 1, located on the shelf break 15 km to the northeast, targeted the Paaratte Formation, and good quality reservoir facies were intersected in both wells (Subramanian, 2004, 2005). In Amrit 1, petrophysical analyses indicated 42.5 m of net sand with an average porosity of 16.2%.

In the shelfal areas of the Otway Basin, the most widely distributed sealing facies is the Belfast Mudstone, which provides a reliable regional top seal for reservoirs in the Waarre and Flaxman formations. In addition, shales within the Flaxman Formation may act as intraformational seals. In the deepwater Otway Basin, the Upper Cretaceous succession is predicted to contain fine-grained prodelta and marine facies (Krassay et al., 2004), which could provide good quality seals. Drilling at Amrit 1 proved the presence of reservoir quality sandstone units and an overlying seal facies in mudstones coeval with the more proximal Timboon Sandstone (Subramanian, 2005).

2.5.3.4 Play types

Sandstones within the Shipwreck Supersequence (Sherbrook Group; Waarre and Flaxman formations) sealed by the Belfast Mudstone and charged by Austral 2 source rocks are the most successful exploration targets inboard of the Tartwaup–Mussel Fault Zone. In the deepwater Otway Basin rapid sediment loading in the Late Cretaceous resulted in Austral 2 source rocks undergoing complete organic matter transformation by 82 Ma (O'Brien et al., 2009). Therefore plays in much of the deepwater Otway Basin are likely to be reliant on charge from unproven Austral 3 source rocks (Geary & Reid, 1998; Reid et al., 2001; O'Brien et al., 2009), charging Paaratte Formation equivalent sandstones with top and cross-fault seal provided by distal marine mudstones. The most promising exploration targets in the deepwater Otway Basin lie in faulted anticlines and tilted fault blocks immediately outboard of the Tartwaup–Mussel Fault Zone. Amrit 1 targeted an inboard intra-Paaratte play sourced from the Belfast Mudstone. While the well confirmed the presence of reservoir quality sands and overlying seal facies (Subramanian, 2005), no significant hydrocarbons were encountered and the play remains unproven. Minor hydrocarbon indications observed in the upper part of the Paaratte Formation could be interpreted as providing some evidence for the presence of an active petroleum system, but raise doubt over the volumes of generated hydrocarbons (Subramanian, 2005).

In the inboard parts of the deepwater Otway, there is potential for plays charged by early-generated, Austral 2-sourced, hydrocarbons; however, as noted previously, preservation of such accumulations is problematic. O'Brien et al. (2009) proposed that the best opportunities for preservation of early-generated hydrocarbons were in fault-independent anticlines with four-way dip closure, and in fault-dependent plays on faults with low dip and/or strike that tends towards east–west rather than northwest–southeast.

In the Morum Sub-basin, Duddy et al. (2003) suggested that migration from Eumeralla source rocks continues to the present day and therefore there is potential for accumulations in suitable trapped Upper Cretaceous reservoirs.

2.5.3.5 Critical risks

The critical exploration issues and petroleum systems risks for deepwater Otway Basin relate to the presence and maturity of source rocks, and preservation of accumulations, including the presence of effective seals and fault seal integrity.

2.5.3.5.1 Maturity of source rocks

The major exploration risk in the deepwater areas of the Otway Basin is the presence and maturity of Austral 3 source rocks. Maturation modelling undertaken by O'Brien et al. (2009) shows the basal, Turonian Austral 3 petroleum system is likely to be overmature across the deep water basin except in a narrow band adjacent to the Tartwaup–Mussel Fault Zone. Successful plays in the deepwater Otway Basin are therefore likely to rely on younger and shallower Austral 3 source rocks.

2.5.3.5.2 Preservation and size of accumulations

Petroleum systems modelling indicates that Austral 2 and basal Austral 3 source rocks in the deepwater Otway Basin had completely generated and expelled hydrocarbons by 82 Ma. Preservation of these early-generated hydrocarbons is problematic (O'Brien et al., 2009) given the amount of structuring and changes in basin geometry since that time.

In general, poor fault-seal is a risk for fault-related traps across the basin. The Morum Sub-basin in particular is closely faulted, with widespread reactivation of Early Cretaceous faults, the formation of new faults occurring in the latest Cretaceous and continued reactivation during the Cenozoic. The inboard Nelson Sub-basin is less affected by Late Cretaceous and Cenozoic faulting and faults are less closely spaced. Subramanian (2005) noted that in the Amrit 1 area, faulting had largely ceased by the end of the Cretaceous and few faults cut the overlying Cenozoic section. In the present-day stress field, traps bound by steeply dipping, northwest-trending faults are considered the least likely to retain hydrocarbons (O'Brien et al., 2009).

Cross-fault seal is a risk in the inboard part of the deepwater Otway, due to the interbedded nature of the largely deltaic sediments; however, a likely increase in shale content basinward would provide a mitigating factor. The failure of Hill 1, located on the shelf break, was attributed to cross-fault seal issues, with sand-on-sand juxtaposition across the main fault (Subramanian, 2004).

Closely spaced faulting and cross-fault seal issues in parts of the inboard deepwater Otway Basin both impact the size of potential traps.

2.5.3.5.3 Interpretation uncertainty

The expansion of the Upper Cretaceous succession across the fault systems marking the inner boundary of the sub-basins, poor seismic data quality beneath the continental shelf break and in the deepest, most heavily structured parts of the basin, and paucity of direct geological control lead to a large degree of interpretation uncertainty.

2.5.3.6 Overall prospectivity classification

Moderate

2.5.4 Exploration status

The deepwater Otway Basin is one of the least explored of the major southeast Australian offshore sedimentary basins. While a few exploration wells have been drilled along the shelf-edge, the slope and deepwater areas are relatively unexplored.

Exploration in the region dates back as far as 1892, when coastal bitumen strandings led to the drilling of an exploration well in the South Australian Otway at Kingston. The first wells in the Victorian part of the Otway Basin were drilled in the 1920s to 1940s in the Anglesea and Torquay areas (Sprigg, 1986). In 1959, Port Campbell 1 was drilled into Upper Cretaceous sediments and intersected the first hydrocarbon column in the basin. Drilled by the Frome-Broken Hill consortium, it flowed at a rate of 4.2 MMcf/d from Waarre Formation sandstones. This was followed by further exploration success in the Port Campbell area, as well gas discoveries in the Penola Trough in the South Australian portion of the onshore Otway Basin.

In the offshore Otway Basin, gas was discovered by BHP at Minerva 1 (in 1993) and La Bella 1 (in 1994) on the flanks of the Shipwreck Trough. The relatively small size of offshore hydrocarbon discoveries, and poor gas markets, led to a hiatus in exploration activity during the remainder of the 1990s. In the early 2000s, a major exploration program by the Woodside Energy Ltd joint venture, which included the acquisition of 3D seismic, resulted in the large (approx. combined 1.3 Tcf GIP) Geographe and Thylacine gas discoveries. In 2002, another commercial offshore gas discovery was made by Strike Oil with the Casino 1 well, drilled some 20 km southwest of the Minerva field on the western flank of the Shipwreck Trough. This was followed in 2005 by the nearby Henry 1 gas discovery by Santos.

In recent years, the unsuccessful wells Amrit 1 and Somerset 1 were drilled in the deepwater Otway Basin.

2.5.5 Data

Deepwater Otway Basin wells and key seismic, sample and swath bathymetry data sets are listed in Table 2.16–Table 2.19.

Only three wells have been drilled in the deepwater Otway Basin. Morum 1 was drilled in the Morum Sub-basin in 1975, and the Voluta Trough of the Nelson Sub-basin was tested by Amrit 1 (in 2004) and Somerset 1 (in 2009); all wells were dry. The oldest unit penetrated in deepwater Otway drilling is the Turonian Waarre Formation, which was reached in Morum 1 (Esso Australia, 1975).

Seismic coverage is best in the inboard part of the Nelson Sub-basin, where there is a moderately good 2D seismic data coverage (including the Fugro DS01 and DS02 surveys), and three 3D seismic surveys—OS02 (Santos), Aragorn (Woodside) and Brandt (Santos). Data is extremely sparse further basinward (Figure 2.29). Seismic data coverage is also very sparse in the Morum Sub-basin. A key seismic data set for the deepwater Otway Basin is Geoscience Australia's 1998 regional Otway Basin survey 137, which provides a series of long, deep crustal (12 s TWT) seismic profiles across the basin (Moore et al., 2000; Krassay et al., 2004). Geoscience Australia and its predecessor organisations have undertaken numerous geophysical and geological sampling surveys across the region, which are listed in Table 2.17–Table 2.19.

2.5.5.1 Confidence rating

Medium–low

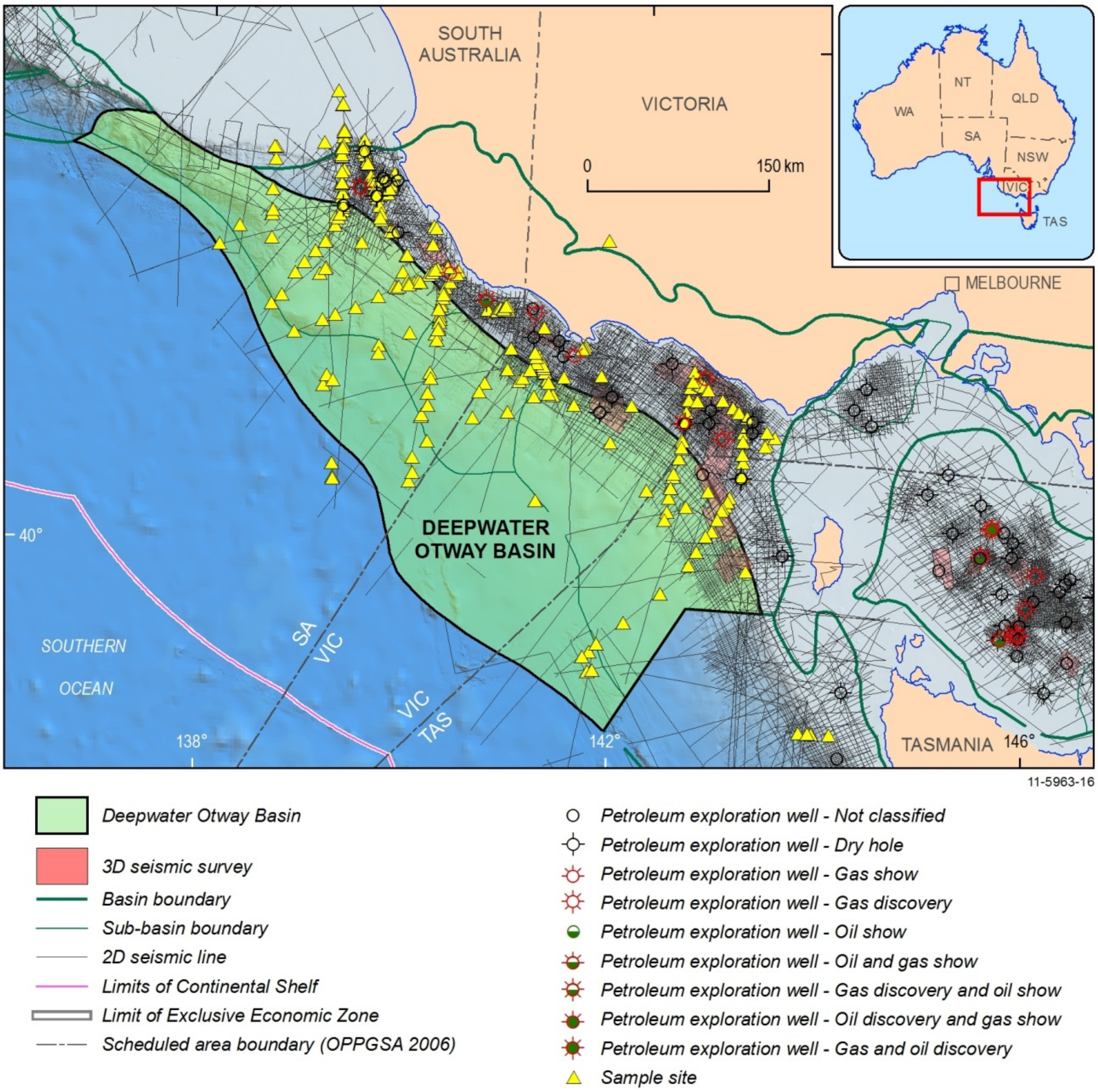

Figure 2.29: Seismic, well and sample distribution, deepwater Otway Basin.

2.5.6 Issues and remaining questions

2.5.6.1 Petroleum systems and prospectivity

The key issues regarding petroleum systems in the deepwater Otway basin are:

- presence and distribution of potential Austral 3 source rocks
- generation, expulsion and migration from deeply buried Austral 2 and basal Austral 3 source rocks, and the thermal history controlling this.
- charge and hydrocarbon phase
- fault seal/preservation of hydrocarbons.

In much of the deepwater Otway Basin, Austral 2 source rocks are modelled to be overmature (O'Brien et al., 2009) and Waarre reservoirs are too deeply buried to be exploration targets (Walker, 2007). However, in the inboard parts of the deepwater basin, particularly the Morum Sub-basin, where the Upper Cretaceous succession thickens basinward across a complex fault zone, Austral 2 source rocks may still have some potential. The potential for the accumulation of Austral 3 source rocks (Turonian and younger) in the Upper Cretaceous section of the deepwater Otway Basin is also not well understood. Understanding of the geology and petroleum systems of this part of the Otway Basin will be improved by further drilling, but acquisition of new data and improvements in the quality of seismic data could also provide valuable insights. Detailed interpretation of this data would provide the basis for petroleum systems models that could more accurately address the relative timing of generation, migration, trap formation and structuring, and hence the prospectivity of both traditional Austral 2 source rocks and a range of postulated Austral 3 source rocks.

To better understand the potential for liquid hydrocarbons in this part of the basin, and following on from the work of O'Brien et al. (2009), further geochemical analysis of hydrocarbons from outboard wells is required to determine whether a contribution from younger (Austral 3), more liquids-rich source rocks in the deepwater Otway Basin can be identified.

A key uncertainty in petroleum systems modelling in the deepwater Otway Basin is thermal history. The overall structure of the lithosphere in this region is poorly understood due to a lack of good seismic imaging of deep structure and refraction data. This prevents a detailed understanding of the timing and processes of crustal thinning and hence the heat flow history of the margin and basin. Acquisition of refraction seismic data on several profiles (sonobuoy or Ocean Bottom Seismometers) could help in addressing these uncertainties. Acquisition of direct heat flow measurements would also help assessment of maturity and modelling of generation and expulsion. While new velocity and heat flow data and models may not substantially change the risks associated with preservation of accumulations, it would be worthwhile to investigate a reasonably constrained set of scenarios.

Walker (2007) noted that potential Paaratte Formation (and equivalents) and younger Cenozoic plays in the deepwater basin appear to be high risk due to significant cross-fault leakage potential and likely biodegradation in shallow/cool reservoirs. In addition, the preservation of hydrocarbons generated early from Austral 2 source rocks is likely to be compromised by later structuring (O'Brien et al., 2009). Improved and robust fault seal evaluation of potential traps is required to better assess the risk to both early (O'Brien et al., 2009) and later generated hydrocarbons. Depth processing as well as acquisition of new data seismic sets would assist such structural analyses.

2.5.6.2 Data coverage and quality

The recently acquired OS02, Aragorn and Brandt 3D seismic surveys provide valuable data sets in the Nelson Sub-basin, but high resolution seismic data sets in the deepwater Otway Basin are generally scarce. In the inboard part of the deepwater Otway Basin, seismic data quality is affected by the shelf/slope break, a steep seafloor and variable degrees of faulting. The acquisition of better quality, higher resolution seismic data would allow testing and improvement of stratigraphic and structural interpretation basinward of the shelf break, and could constrain petroleum systems and fault seal models. Depth processing of seismic data is essential for better understanding the structural and stratigraphic architecture.

Away from the shelf break/upper slope, sparse seismic data coverage limits understanding of the fundamental stratigraphy and structure of the deepwater Otway Basin. New long-offset, deep record 2D reflection seismic data is also required to address this data gap.

2.5.6.3 Recommendations

- drilling
- detailed geochemical analysis of accumulations in outboard shelfal areas to better understand the potential for oil in the basin
- analysis of recent drilling results as wells become open file
- acquisition and/or reprocessing of high resolution 2D and 3D seismic data to improve understanding of stratigraphy, facies, age, structural geology in the inboard parts of the basin, and to underpin a predictive, sequence stratigraphic, model for the distribution of source, reservoir and seal facies in the deeper water parts of the basin; depth processing/reprocessing essential
- acquisition of regional scale, long-offset 2D reflection seismic data to better understand the structure and stratigraphy of the basin
- a comprehensive refraction seismic data acquisition program across the offshore Otway Basin and adjacent margin to assist understanding of the tectonic subsidence history and petroleum systems modelling
- acquisition of heat flow data, using deep-water probes
- dredge and core sampling of distal, deep-water succession.

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2.5.8 Data Tables

Table 2.16: List of wells, deepwater Otway Basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1975	Morum 1	Exploration	Esso Exploration and Production, Australia	2439	Late Cretaceous	Nil	Esso Australia, 1975
2004	Amrit 1	Exploration	Santos	2979	Late Cretaceous	Nil	Subramanian, 2005
2009	Somerset 1	Exploration	Woodside Energy	2912	Late Cretaceous	N/A	Sturrock, 2010

Table 2.17: Key seismic surveys, deepwater Otway Basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1972	Petrel Roving	Shell		
1985	Survey 48	BMR	3700	
1995	Survey 137	AGSO	2525	Blevin et al., 1995; Moore et al., 2000; Krassay et al., 2004
2001	Otway Sorell Part 1 (DS01)	Fugro/Woodside	3754	
2002	OS02 3D	Santos	760 km^2	
2002	OS02 2D MSS	Santos	1156	
2002	Otway Sorell Part 2 (DS02)	Fugro/Woodside	2044	
2003	SS03 2D MSS	Santos	1336	
2004	OEP04	Essential Petroleum	999	
2004	KMG04 2D MSS	Santos	1262	
2006	Aragorn 3D	Woodside	2221 km^2	
2006	OEP06A 2D MSS	Essential Petroleum	303	
2008	Brandt 3D	Santos	621 km^2	
2008	Trocopa 2D MSS	CGG Veritas	1145	

Table 2.18: Key geological sampling surveys, deepwater Otway Basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
1985	Rig Seismic Research Cruise 3	BMR	Otway Basin	Dredge	Cenozoic calcareous sediments	Exon et al., 1987
1987	BMR Cruise 67: Otway Basin and West Tasmanian Sampling	BMR	Otway and Sorell basins	Grab, core, dredge, heat flow	Cenozoic carbonates, calcareous siltstone; Upper Cretaceous siliciclastic rocks; ooze and unconsolidated sediments	Exon et al., 1992

Table 2.19: Key swath bathymetry surveys, deepwater Otway Basin

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1994	TASMANTE	AGSO/Ifremer		Exon et al., 1994
1999–2000	AUSTREA-1	AGSO		Hill et al., 2001
2003	AUSCAN	Geoscience Australia/ANU		Hill & De Deckker, 2004
2006	AUSFAIR–GAB transit	Institut Polaire Français Paul-Emile Victor		Institut Polaire Français Paul-Emile Victor, 2007

2.6 Torquay Sub-basin (Otway Basin)

2.6.1 Summary

State(s)		Victoria, Tasmania
Area (km^2)	**Offshore**	~4500
	Onshore	~500
Water Depth (m)		<80
Maximum sediment thickness (m)		~7000
Age range		Early Cretaceous–Holocene
Basin	**Parent**	Otway Basin
	Adjacent basins	Inner Otway Basin
Basin type		Extensional; sag
Depositional setting, rock types		Fluvio-lacustrine, coastal plain and marine clastic sedimentary rocks, cool-water carbonate rocks
Petroleum prospectivity		Moderate–low
Confidence		*Medium*

2.6.2 Geology

The Otway Basin is a northwest-trending passive margin rift basin that extends from southeastern South Australia to a boundary with the contiguous Sorell Basin west of King Island (Figure 2.30). The basin covers an area of 150,000 km^2, 80% of which lies offshore. The Otway Basin contains a Lower Cretaceous to Cenozoic siliciclastic and carbonate sedimentary succession up to 7 km thick. The Torquay Sub-basin is a largely offshore depocentre situated in the northeastern part of the Otway Basin (Figure 2.30). It is bounded to the west by the Otway Ranges and to the east by the Mornington Peninsula–King Island High. It contains a Lower Cretaceous section similar to that seen elsewhere in the Otway Basin, and a thin post-rift Upper Cretaceous succession that has affinities closer to that of the Bass Basin (Figure 2.31; Trupp et al., 1994; Blevin & Cathro, 2008).

The Otway Basin is a well-established gas producing region, with numerous discoveries in the onshore and shallow-water offshore areas of the inner Otway Basin. No hydrocarbon discoveries have been made in the Torquay Sub-basin.

2.6.2.1 Structural geology

The Otway Basin developed during the latest Jurassic to Cenozoic as a result of rifting and continental separation between Australia and Antarctica (Willcox & Stagg, 1990; Stagg & Reading, 2007; Blevin & Cathro, 2008). The basin overlies deformed Proterozoic and Paleozoic rocks of the Delamerian and Lachlan fold belts, which appear to have influenced the location and orientation of later basin-forming structures (Miller et al., 2002; Moore, 2002; Bernecker & Moore, 2003; Gibson et al., 2012). The complex structural and depositional history of the basin also reflects its location in the transition from an orthogonal–obliquely rifted continental margin in the west to a transform continental margin to the southeast (Totterdell et al., 2012).

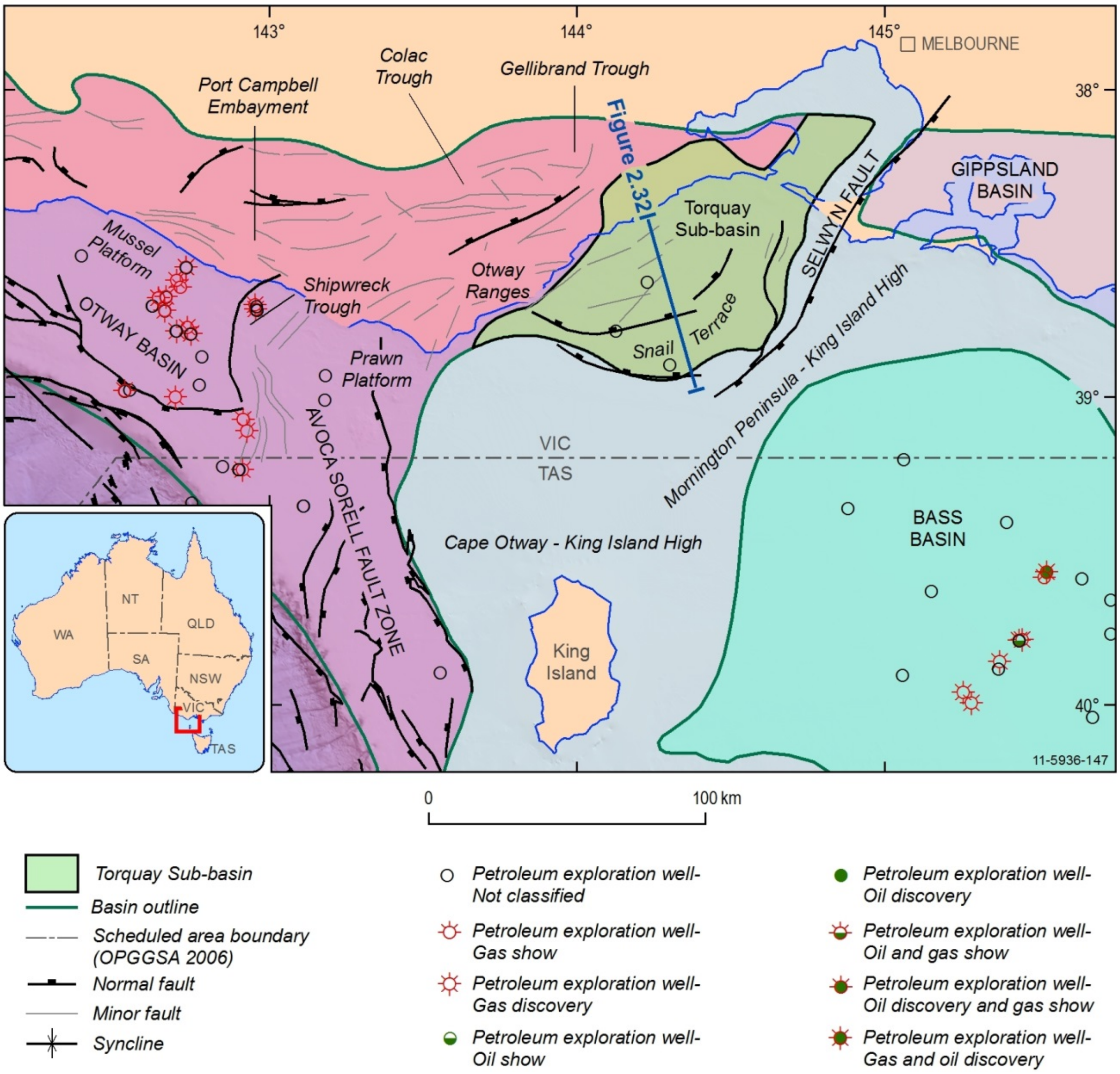

Figure 2.30: Structural elements map, eastern Otway Basin, showing location of Torquay Sub-basin.

The northeast-trending Torquay Sub-basin contains 5–7 km of Lower Cretaceous to Cenozoic sedimentary rocks (Trupp et al., 1994). The main structural feature of the Torquay Sub-basin is the east-northeast-trending Nerita Trough, which is bound on its southern margin by the northerly dipping Snail Fault. Extensional growth on this fault system was limited to the Early Cretaceous; as a result, the Nerita Trough is characterised by thick Otway Group growth wedges (Crayfish and Eumeralla supersequences of Krassay et al., 2004; Figure 2.32). A period of contractional deformation affected much of the Otway Basin in the Cenomanian resulting in inversion on Early Cretaceous faults and uplift of the Otway Ranges. Uplift and erosion is evident in the Torquay Sub-basin where much of the Albian–middle Campanian (*C. paradoxa*–*T. lilliei*) succession is missing. Holford et al. (2010, 2011b) proposed that at Nerita 1, approximately 1200 m of sediments were eroded from the top of the Eumeralla Supersequence during this event. The sub-basin is increasingly deformed to the west, culminating in the uplifted Otway Ranges (Trupp et al., 1994).

The Lower Cretaceous rift-fill is unconformably overlain by a Campanian–Cenozoic section that has an overall sag geometry (Figure 2.32). The Late Cretaceous extension seen in the rest of the Otway Basin is not apparent in the Torquay Sub-basin; Late Cretaceous faulting is limited to minor northwest–southeast-oriented faults on the Snail Terrace to the south of the main depocentre, and some minor growth against the western bounding fault system (Cooper & Hill, 1997; Blevin & Cathro, 2008). The sub-basin was affected by a series of compressional events during the Oligocene and Miocene–Pliocene, which resulted in the formation of several large inversion anticlines, and uplift and erosion (Blevin & Cathro, 2008; Holford et al., 2011a). A prominent low-angle mid-Miocene unconformity between variably folded Torquay Group sediments and flat-lying Pliocene–Holocene strata is interpreted to represent approximately 1 km of uplift and exhumation (Holford et al., 2011b).

2.6.2.2 Basin evolution and depositional history

Middle–Late Jurassic intracontinental extension across the western and central parts of the southern margin resulted in the formation of a series of extensional and transtensional half graben from the Bremer Sub-basin in the west, across the eastern Bight Basin, to at least the western Otway Basin in the east (Norvick & Smith, 2001; Totterdell & Bradshaw, 2004). By the Early Cretaceous, upper crustal extension was focused in the eastern part of the southern margin. During the Late Jurassic–Early Cretaceous, the locus of rifting and deposition was in the inboard parts of the basin where a series of west to northwest-trending extensional depocentres formed (Krassay et al., 2004). In the Torquay Sub-basin, only the upper part of this succession, the Eumeralla Supersequence, has been drilled; a thick underlying Crayfish Supersequence/undifferentiated Otway Group is interpreted on seismic data (Figure 2.32). Deposition in the Torquay Sub-basin is interpreted to have commenced in the latest Jurassic–earliest Cretaceous with accumulation of lacustrine sediments and volcanic rocks (Casterton Formation). These are overlain by a thick Lower Cretaceous growth section interpreted to contain fluvial sediments of the Crayfish Supersequence, overlain by the volcaniclastic, fluvio-lacustrine shales and coals of the Eumeralla Supersequence. Bernecker et al. (2004) proposed that subsequent Cenomanian uplift of the Otway Ranges area resulted in isolation of the Torquay Sub-basin from the rest of the Otway Basin.

Deposition resumed in the Campanian in what was by then effectively a northwest extension of the Bass Basin (Trupp et al., 1994; Bernecker et al., 2004). The lower coastal plain sandstones, siltstones and coals of the Campanian–lower Eocene Eastern View Formation, which cover much of the Bass Basin, were also deposited across the Torquay Sub-basin. The section is generally thin (<200 m) but thickens over the Early Cretaceous half graben (Figure 2.32). The Eastern View Formation is overlain unconformably by the marine shelfal sediments of the middle Eocene–upper Oligocene Demons Bluff Group, which includes the basal transgressive sands of the Boonah Formation and the potential seal facies of the Anglesea Formation. The Demons Bluff Group is overlain by the shallow marine carbonates of the upper Oligocene–upper Miocene Torquay Group.

2.6.2.3 Level of knowledge

Geological understanding of the offshore Torquay Sub-basin is limited as it based on three wells and a grid of 2D seismic reflection data of variable vintage and quality, tied to a few onshore wells. The last well drilled in the Torquay Sub-basin was Wild Dog 1, drilled in 1993. Knowledge of the pre-Eumeralla section is based on analogy with the more well-explored areas of the Otway Basin. The oldest sediments intersected are late Aptian in age (*C. hughesii* biozone; Morgan, 1987).

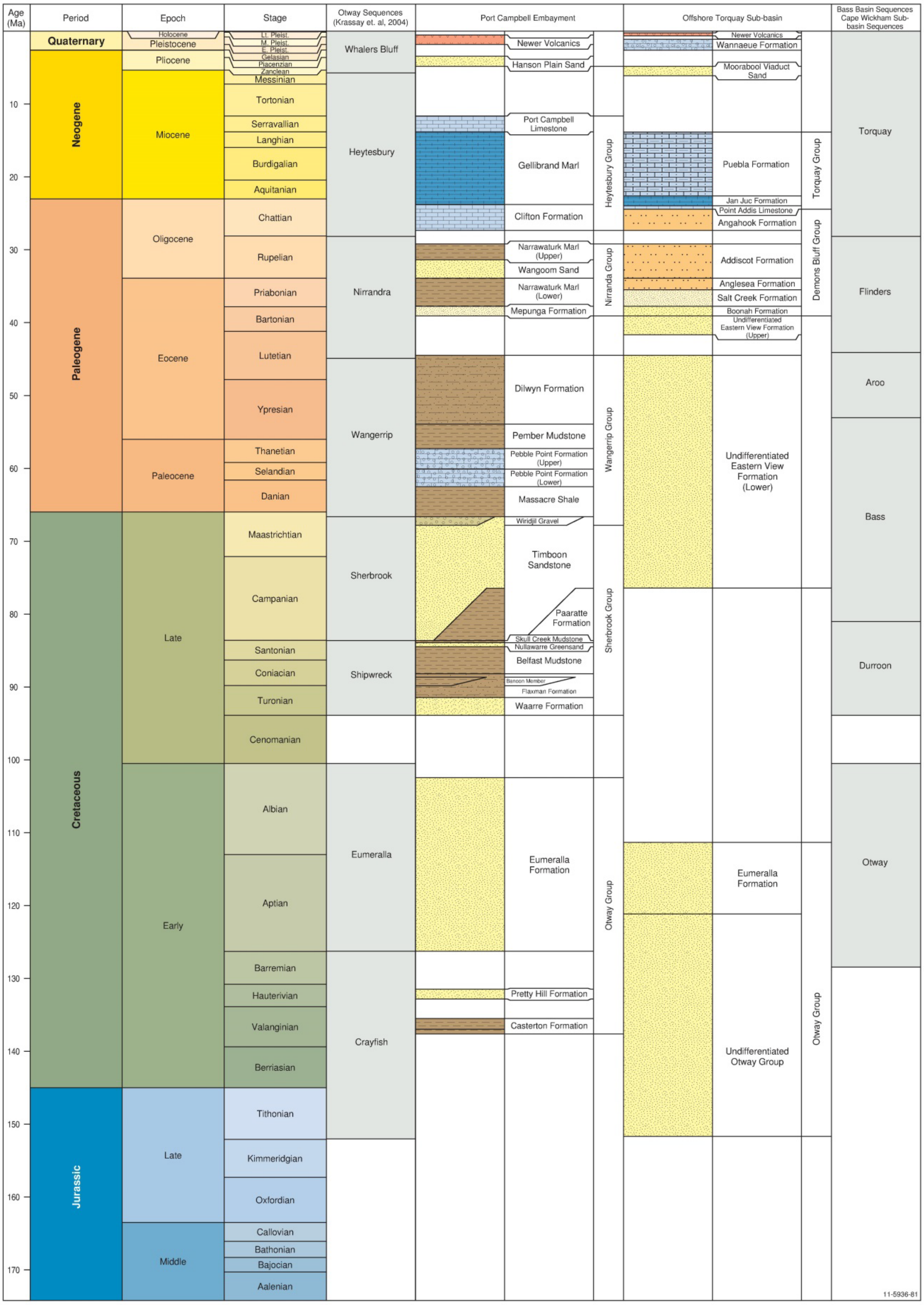

Figure 2.31: Stratigraphy of the eastern Otway Basin. Geologic time scale after Gradstein et al. (2012).

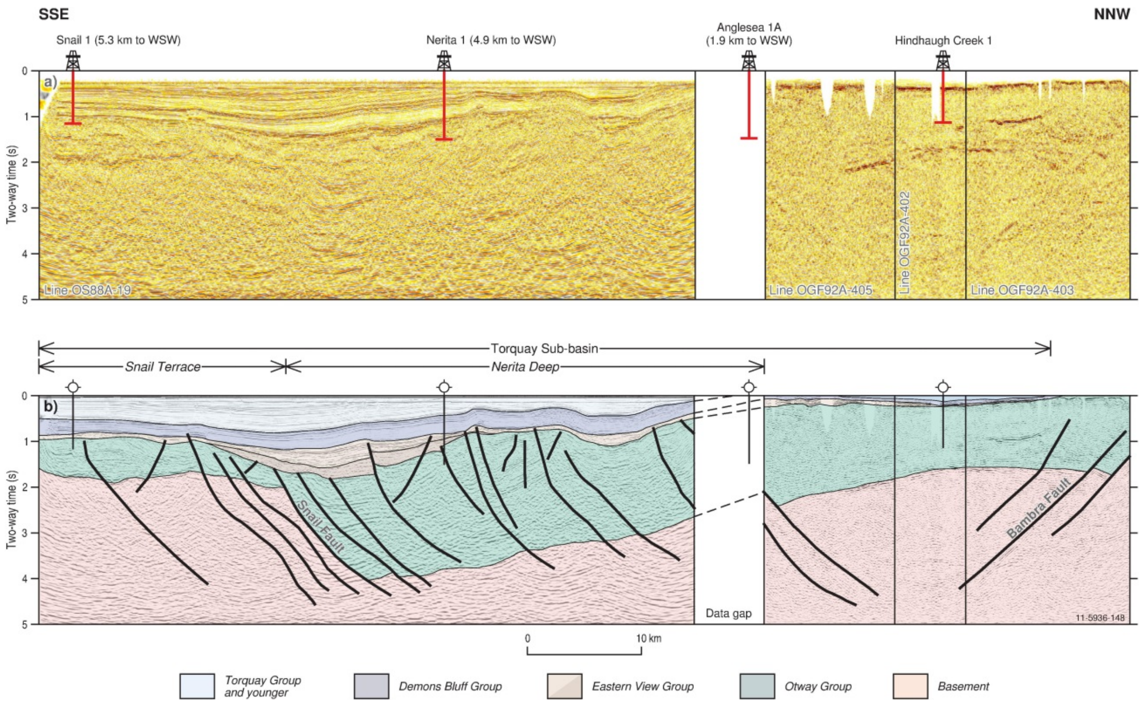

Figure 2.32: Geological cross-section across the onshore and offshore Torquay Sub-basin (after Bernecker et al., 2004).

2.6.3 Petroleum systems

Only three petroleum exploration wells (Nerita 1, Snail 1 and Wild Dog 1) have been drilled in the Torquay Sub-basin. These wells targeted Eocene reservoirs in Miocene and Oligocene structures, but all were dry. Trupp et al. (1994) noted that exploration potential in the sub-basin is probably limited to deeper, Cretaceous plays.

2.6.3.1 Source Rocks

The best potential source rocks in the Torquay Sub-basin are Upper Jurassic to lowest Cretaceous fluvio-lacustrine shales of the Casterton Formation and Crayfish Supersequence (Austral 1; Edwards et al., 1999; Boreham et al., 2004) and Lower Cretaceous fluvial and coaly facies of the Crayfish and Eumeralla supersequences (Austral 2; Edwards et al., 1999; Boreham et al., 2004). Although the Eastern View Formation provide the source for hydrocarbons in the Bass Basin (Blevin et al., 2005; Boreham et al., 2003), in the Torquay Sub-basin the unit is thermally immature and not capable of generating hydrocarbons.

In Nerita 1, source potential ranges from good in the Eastern View Formation to moderate in the Eumeralla Formation. TOC values of up to 48.6% were measured in coal cuttings at the top-Eastern View Formation level and within the Eumeralla Formation a sample was measured at 5.95%.

2.6.3.2 Generation and expulsion

In Nerita 1, VR readings of up to 0.54%Ro and T_{max} values of up to 435°C were recorded from the Eumeralla Formation, placing the sediments just within the early mature range of hydrocarbon generation. Values for the hydrogen index and the S2/S3 ratio suggest source rocks are gas-prone to marginally oil-prone.

Trupp et al. (1994) reported that for Type II source rocks, the top of the oil window lies at approximately 2200 m across the Nerita Trough, while the top of the oil window for Type III source rocks is at 3000 m; the top of the gas window is reached at about 4500 m. The modelled maturity profile presented by Trupp et al. (1994) suggests that Casterton Formation source rocks would be marginally oil mature on the Snail Terrace, but overmature for oil and gas generation in the deepest parts of the sub-basin, having expelled all hydrocarbons by 90 Ma. The only traps available during the main phase of expulsion would be within the Crayfish section, which they considered to be below the reservoir floor. In addition, their timing of generation (101 Ma) relative to the Cenomanian deformation event (95–90 Ma) would not be appear to favour preservation of accumulations. Trupp et al. (1994) also suggested that Eumeralla Formation source rocks are currently mature in the main depocentre. However, recent modelling by Holford et al. (2010), suggests that maximum post-depositional temperatures for the Otway Group in Nerita 1 were reached in the Early Cretaceous. They reported that the combined effects of deeper burial (by an additional 1200 m) and elevated heat flow during the Early Cretaceous resulted in hydrocarbon generation from Lower Cretaceous source rocks prior to the 100–90 Ma uplift and erosion.

Pockmarks associated with gas seeps of possible thermogenic origin have been recorded from seabed locations in the Torquay Sub-basin; this may provide some support for the presence of migrating gas, either through structural disturbance of older traps during recent tectonic movements, or from renewed generation arising from the Cenozoic loading (O'Brien & Heggie, 1990; Smith et al., 2003).

2.6.3.3 Reservoirs and seals

The primary objectives in the three offshore wells drilled were the Eocene Boonah Formation and the Upper Cretaceous–Eocene Eastern View Formation. The reservoir properties of these units in all wells were reported as fair to excellent. Potential for two deeper Cretaceous units is also predicted; the Pretty Hill Formation (in the Crayfish Supersequence) and the Eumeralla Supersequence (Bernecker et al., 2004).

Fine to coarse grained unconsolidated sands with excellent reservoir properties were encountered in the Boonah Formation in Wild Dog 1.

Sandstone units in the Eastern View Formation were deposited in a meandering river environment, becoming increasingly marginal marine towards the top of the formation. Meander belt sandstones in Wild Dog 1 yielded excellent reservoir properties, as did marginal marine sandstone units at the top of the Eastern View Formation in Snail 1. Overall net/gross for the Eastern View Formation is approximately 25–30%, with porosities of about 30% (Trupp et al., 1994). Permeability data is not available, but comparison with the Bass Basin suggests that permeability of 1 Darcy could be expected (Trupp et al., 1994).

Data from the top of the Eumeralla Formation in Snail 1 indicate some good reservoir potential (porosity 30%, permeability up to 700 mD), however the sandstone intervals are reported to be thin and potentially not laterally extensive. No other reservoir quality sandstones were intersected within the Eumeralla Supersequence (Trupp et al., 1994). Based on results elsewhere in the Otway Basin, there may be potential for cleaner, reservoir quality sandstones deeper in the section.

Based on results elsewhere in the Otway Basin, there is potential for good reservoir development in the Crayfish Supersequence, particularly the Pretty Hill Formation. However, Trupp et al. (1994) argued that regional porosity and permeability data suggest the reservoir floor for the Crayfish Supersequence to be around 2500 m; it would therefore not be an exploration target in the Nerita Trough. Despite this, a large Pretty Hill Formation play has been identified in 3D seismic data by current permit holders in the sub-basin (Rogers, 2013).

The potential reservoir units are all likely to have corresponding seals. The Boonah Formation is sealed by the regionally extensive Anglesea Formation, the Pretty Hill Formation is sealed by the Eumeralla Formation and intra-formational seals are likely within the Eastern View Formation and Eumeralla Formation.

Results from Wild Dog 1 confirmed the seal capacity of the Anglesea Formation (Bernecker et al., 2004). Intra-formational fluvial plain to deltaic claystones and mudstones within the Eastern View Formation may have sealing potential; however, the proposed sealing units are rarely greater than 10–20 m in thickness and are consequently susceptible to fault leakage. Mercury Injection Capillary Pressure (MICP) analysis from the Bass Basin indicates mudstones from the intra-Eastern View Formation are extremely competent seals (Blevin, 2003). Shales of the lower Eumeralla Formation have not been penetrated in the Torquay Sub-basin. However MICP measurements of core samples from the lower Eumeralla Formation in the Fergusons Hill 1 well (located immediately to the west of the Otway Ranges) confirmed this unit to have good sealing potential (Bernecker et al., 2004).

2.6.3.4 Play types

The following list of play types in the Torquay Sub-basin is derived from Trupp et al. (1994) and Bernecker et al. (2004):

- Miocene anticlines, similar to those in the Gippsland Basin, with an Eocene reservoir sealed by the Anglesea Formation
- Oligocene inversion anticlines also with an Eocene reservoir
- Early Cretaceous fault blocks and faulted anticlines; potential Pretty Hill Formation and Eumeralla Supersequence reservoirs sealed by Eumeralla Formation shales both laterally and vertically
- onlaps onto basement highs; potential Pretty Hill Formation and/or basal Eumeralla Formation reservoirs that onlap onto basement in the eastern portion of the Torquay Sub-basin and along the Snail Terrace.

2.6.3.5 Critical risks

The critical exploration issues and petroleum systems risks for the Torquay Sub-basin relate to the presence and maturity of source rocks, the timing of generation relative to trap formation, and access to charge.

Potential source rocks in the Eastern View Formation are immature, therefore plays within the Torquay Sub-basin would be dependent on hydrocarbons generated from Lower Cretaceous source rocks. Trupp et al. (1994) have demonstrated that the depth of potential source rocks within the Lower Cretaceous section is critical. Their modelling showed that for basal Eumeralla source rocks at 4000 m within the Nerita Trough, almost all generation preceded the two main phases of trap formation, in the Cenomanian and the Oligocene–Miocene, whereas source rocks at 3000 m underwent peak generation during the Neogene. More recent studies of burial history in the Torquay Sub-basin have shown that at Nerita 1, approximately 1200 m of additional Eumeralla section was removed during Cenomanian uplift and erosion (Holford et al., 2010, 2011b). This suggests not only that peak generation for basal Eumeralla source rocks may have been even earlier than the previous modelling implied, but that peak generation from potential source rocks throughout the Otway Group may have occurred prior to Cenomanian uplift.

Another risk relates to the preservation of late generated and remigrated hydrocarbons as a result of potential trap breach during Miocene uplift, which Holford et al. (2011b) estimated at about 1000 m.

The lack of potential migration pathways other than faults from basal Eumeralla source rocks is also a potential risk (Trupp et al., 1994), because of the paucity of reservoir or carrier units in the overlying section.

2.6.3.6 Overall prospectivity classification

Moderate–low.

2.6.4 Exploration status

The Torquay Sub-basin has seen only moderate levels of exploration activity, and only three wells have been drilled in the offshore basin. Exploration in the sub-basin commenced in the 1960s, when Shell drilled the Nerita 1 well (Shell Development, 1967). The well was designed to test Boonah Formation reservoirs in a Miocene anticline, but was dry.

In the early 1970s, Hematite was awarded permits in the sub-basin. They acquired seismic data and drilled the Snail 1 well (Hodgson & Mellins, 1973). The aim was to test the Eastern View Formation in a tilted fault-block closure on the Snail Terrace to the south of the main depocentre. Excellent reservoirs were intersected in the Boonah Formation, but no hydrocarbons were encountered.

During the late 1980s to early 1990s, Shell undertook an exploration campaign in the basin that included the acquisition of geophysical data sets (Gravity, magnetic and seismic) and culminated in the drilling of Wild Dog 1 (Trupp et al., 1993). As for the previous two wells, Wild Dog 1 drilled a Cenozoic structure—an asymmetric Oligocene inversion anticline, with closure in the Eastern View Formation—but failed to encounter hydrocarbons.

A permit covering much of the Torquay Sub-basin was granted to Trident Energy in 2005. In 2011, Loyz Energy farmed-in to the permit and in 2013 acquired a 3D seismic survey in the area to the east of Wild Dog 1. The partners have identified numerous leads, including an un-tested structural play in the Lower Cretaceous Pretty Hill Formation (Rogers, 2013).

2.6.5 Data

Torquay Sub-basin wells and key seismic, sample and swath bathymetry data sets are listed in Table 2.20–Table 2.22. The following summary is derived from Bernecker et al. (2004).

Prior to 1988 the only multifold seismic data in the sub-basin was limited to the Hematite 1972 HO-1 survey and several 1982 regional lines acquired by the Bureau of Mineral Resources (BMR). In 1988 Shell acquired the 1554 km regional OS88A seismic survey across the entire area of exploration permit VIC/P28 on a 5 x 10 km grid. In 1990 Shell acquired 1190 km of the OS90A infill seismic data covering specific leads with a 1 x 4 km grid. In 1996 the BMR and Victorian Department of Natural Resources acquired six regional lines across the Torquay Sub-basin that were processed together with selected lines from the Shell surveys in early 2000.

Generally seismic quality is at its best over the Snail Terrace and poor in the Nerita Trough north of the Snail Fault and to the east of the sub-basin. Data quality within the Otway Group is particularly poor within the Nerita Trough, where thick coals within the overlying Eastern View Formation attenuate the deeper reflections. Despite these limitations, data is of sufficient quality to map horizons down to the top of the Eastern View Formation.

2.6.5.1 Confidence rating

Medium

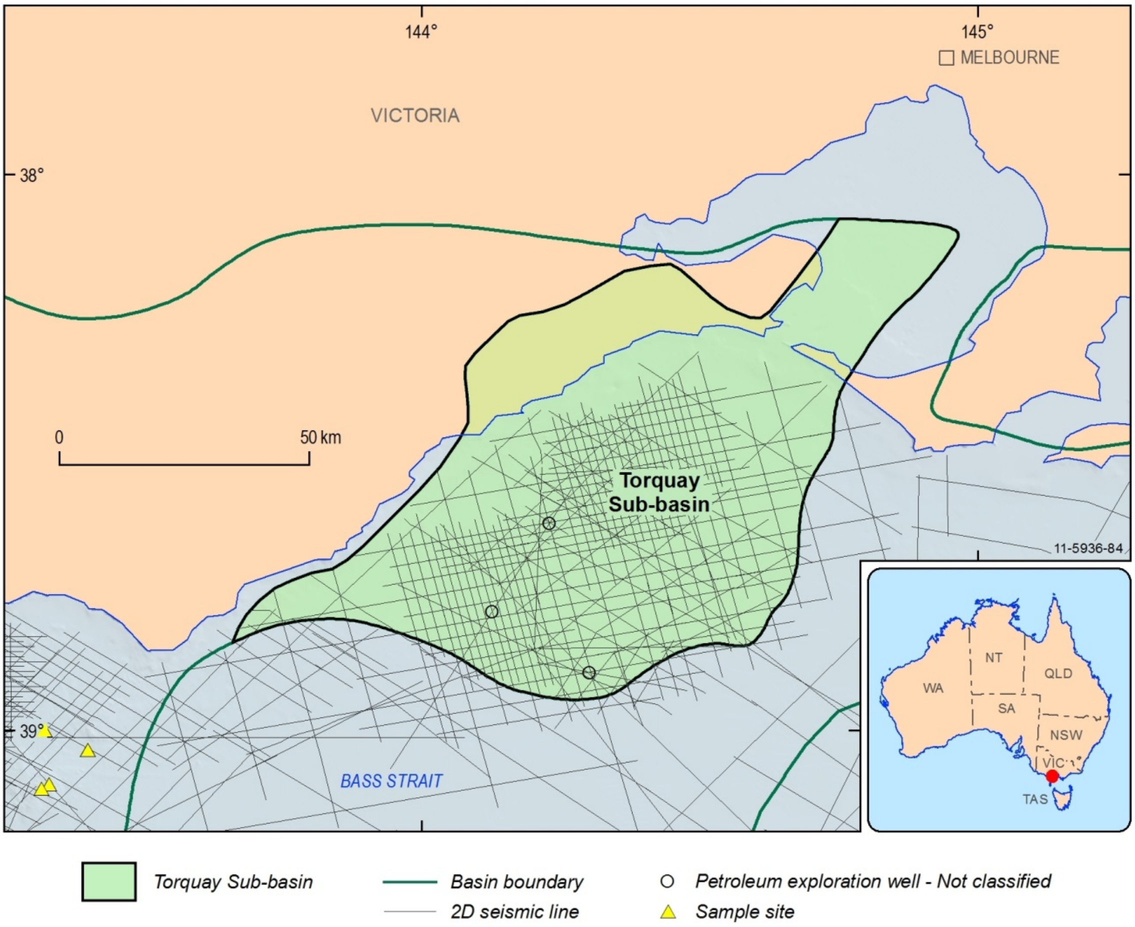

Figure 2.33: Seismic, well and sample distribution, Torquay Sub-basin.

2.6.6 Issues and remaining questions

The key issues regarding petroleum systems in the Torquay Sub-basin are:

- generation, expulsion and migration from Austral 1 and Austral 2 source rocks
  - what is the potential for hydrocarbons generated from Lower Cretaceous source rocks to be preserved in Early Cretaceous structures?
- the timing of generation relative to trap-formation and deformation/uplift events
  - what was the impact on maturation history of the presence of an additional Eumeralla Formation section across the basin (additional 1200 m in the main depocentre), and the timing of generation relative to the removal of that section in the Cenomanian, and later deformation events?
  - can variations in the thickness of the eroded section across the basin be better constrained through detailed analysis and interpretation of seismic data?

- because of the paucity of drilling and the limitations of the existing seismic coverage, the stratal architecture and facies of the Eumeralla Formation and underlying Otway Group, and hence distribution of potential reservoir and seal units, is poorly understood.

2.6.6.1 Recommendations

- drilling
- acquisition of high resolution 2D and 3D seismic data to improve understanding of stratigraphy, facies, age, structural geology, and to assist in estimation of the amount of section removed by uplift and erosion.
- 2D and 3D structural restoration to provide insights into the amount of section removed through uplift and erosion.
- a screening study to identify and sample potential source rocks in the Casterton, Pretty Hill, Laira and Eumeralla formations elsewhere in the Otway Basin, followed by analysis of the compositional kinetics of these rocks to better constrain the maturation and generation history of Austral 1 and Austral 2 source rocks.
- petroleum systems modelling that uses the results of recent thermal history and uplift and erosion studies, and any new geochemical characterisations/kinetics data, to better understand the maturation, generation and expulsion history of potential Lower Cretaceous Austral 1 and 2 source rocks.

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2.6.8 Data Tables

Table 2.20: List of wells, Torquay Sub-basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1967	Nerita 1	Exploration	Shell Development (Australia)	2042	Early Cretaceous	Dry	Shell Development, 1967
1972	Snail 1	Exploration	Hematite Petroleum	1235	Early Cretaceous	Dry	Hodgson & Mellins, 1973
1993	Wild Dog 1	Exploration	Shell Company of Australia	1222	Early Cretaceous	Dry	Trupp et al., 1993

Table 2.21: Key seismic surveys, Torquay Sub-basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1971–72	Torquay Embayment 2D MSS	Hematite Petroleum	225	
1982	BMR Bass Strait	BMR	3200	
1988	OS88A 2D MSS	Shell	1554	
1990	OS90A 2D MSS	Shell	1186	
1990	Shell 1990 Bass Strait	Shell	2119	
2010	OTE 10 2D MSS	Trident	492	
2013	OTE 12 3D	Loyz/Trident	245 km^2	Not open-file

Table 2.22: List of key surveys involving geological sampling, Torquay Sub-basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
1990	Direct Hydrocarbon detection, Torquay Sub-basin	BMR	Torquay Sub-basin	Geochemical sampling	Water column	O'Brien & Heggie, 1990
1992	Rig Seismic Survey 104	BMR	Torquay Sub-basin, eastern Otway Basin, Gippsland Basin, Durroon Sub-basin	Geochemical sampling, vibrocores, seismic	Surficial sediments	Bishop et al., 1992

2.7 Sorell Basin

2.7.1 Summary

State(s)		Tasmania
Area (km^2)		~84,600
Water Depth (m)		50–4800
Maximum sediment thickness (m)		~6000
Age range		Early Cretaceous–Holocene
Basin	**Subdivisions**	King Island, Sandy Cape, Strahan, Port Davey and Toogee Sub-basins
	Adjacent basins	Otway Basin
Basin type		Transtensional; passive margin
Depositional setting, rock types		Fluvial, lacustrine, deltaic and shallow marine clastic sedimentary rocks, cool water carbonate rocks
Petroleum prospectivity		Moderate–low
Confidence		*Medium–low*

2.7.2 Geology

The Sorell Basin is a large transtensional basin that lies offshore western Tasmania and King Island (Figure 2.34) in water depths of 50–4500 m (Moore et al., 1992; Conolly & Galloway, 1995; Hill et al., 1997, 2000; Hill & Exon, 2004; Boreham et al., 2002; O'Brien et al., 2004; Gibson et al., 2011, 2012; Stacey et al., 2013). It is bounded by the contiguous Otway Basin to the north, oceanic seafloor to the west, and the South Tasman Rise to the south. The basin contains a Lower Cretaceous to Holocene, largely siliciclastic succession (Figure 2.35). The Sorell Basin is one of the least explored basins on the southern margin. Limited exploration activity has been focused entirely on the northern part of the basin, in the King Island, Sandy Cape and Strahan sub-basins. The southern part of the basin is essentially unexplored; very sparse regional-scale seismic data has allowed the identification of two depocentres—the Port Davey and Toogee sub-basins (Figure 2.34)—but the geology of this part of the basin is extremely poorly understood. The limited seismic data that does exist suggests that away from these depocentres the section is thin. In general, sediment thickness in the basin decreases to the south and maximum thicknesses vary from approximately 6000 m in the Sandy Cape and Strahan sub-basins, to 3000 m in the Port Davey Sub-basin.

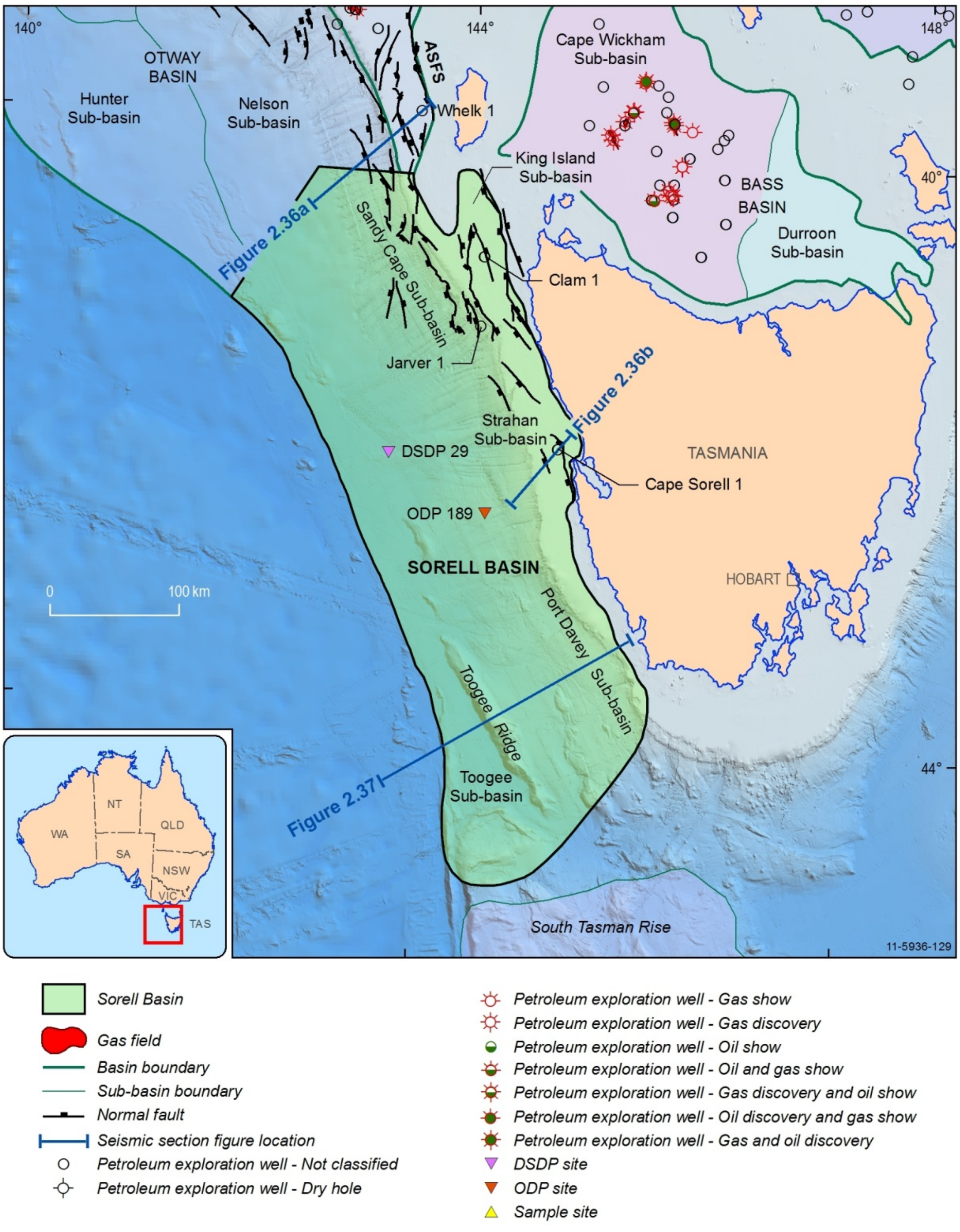

Figure 2.34: Structural elements map, northern Sorell Basin. ASFS : Avoca–Sorell Fault System

2.7.2.1 Structural geology

The Sorell Basin is structurally and stratigraphically contiguous with the Otway Basin. The structure of the eastern Otway and Sorell basins has been strongly influenced by the architecture and roughly north–south structural fabric of the underlying Proterozoic–early Paleozoic basement. This basement structure provided a fundamental control on the architecture of the southeastern part of the rifted margin and the northwest–southeast transition from extension, through transtension, to a predominantly strike-slip regime (Gibson et al., 2011). This basement control and the variations in structural regime are reflected in the architecture of the basins, particularly the narrow fault-controlled depocentres of the King Island and Strahan Sub-basins, the along-margin changes in extensional fault strike (from east–west in the Nelson Sub-basin of the Otway Basin to predominantly north–south in the vicinity of the Avoca–Sorell Fault System; Figure 2.34), and the north to south diachroneity of extension (Stacey et al., 2013).

The Sandy Cape Sub-basin is the largest structural element in the basin. The main depocentre is located west of the approximately north–south striking, basement-involved Avoca–Sorell Fault System and contains up to 4.0 s TWT of fill (Figure 2.36a; Gibson et al., 2011; Stacey et al., 2013). In the southern part of the sub-basin, the depocentre axis steps to the east-southeast across a series of faults. Early Cretaceous deposition was controlled by west-dipping extensional faults, which were reactivated during the Late Cretaceous. The Upper Cretaceous succession is also characterised by east-dipping antithetic faults (Figure 2.36a) and, locally, gravity-driven growth faulting. A period of structural inversion in the latest Cretaceous resulted in minor folding of the basin fill, and associated uplift and erosion. The overlying Cenozoic succession is relatively undeformed and onlaps pre-rift basement that consists of Paleozoic or older metamorphosed sediments. A series of north-northwest–south-southeast-oriented transtensional depocentres, including the King Island Sub-basin, lie to the east of the Sandy Cape Sub-basin; these comprise elongate and relatively isolated half graben.

The Strahan Sub-basin, located west of Macquarie Harbour (Figure 2.34), contains up to 4.5 s TWT of ?Lower Cretaceous to Paleocene sediments. Cretaceous to early Cenozoic sedimentation was controlled by a large (40–50 km) arcuate fault system that forms the northern and eastern boundaries of the sub-basin (Figure 2.36b). This fault system and the half-graben fill are interpreted to have formed in a north–south oriented transtensional or strike-slip stress regime (Stacey et al., 2013). The northern, east–west striking segment of the fault has a releasing bend, pull-apart geometry. The overlying post-rift Cenozoic section is relatively undeformed and onlaps basement.

The deepwater parts of the Sorell Basin, which are contiguous with the Nelson and Hunter sub-basins of the Otway Basin and lie to the west of the Sandy Cape and Strahan sub-basins, have a poor data coverage and sub-basins have not been defined.

The Port Davey Sub-basin, in the southern part of the basin, is a narrow northwest-trending half graben bounded by landward-dipping faults (Figure 2.34 and Figure 2.37). Based on analogy with the Strahan Sub-basin to the north, the half-graben fill is interpreted to be Late Cretaceous–Cenozoic in age. An additional depocentre, the Toogee Sub-basin, was identified by Exon et al. (1997) on the lower continental slope southwest of the Port Davey Sub-basin (Figure 2.37). This depocentre, which is interpreted to contain a largely Cenozoic section, lies landward of a large northwest–southeast oriented strike-slip fault that has a strong seafloor expression (Toogee Ridge).

2.7.2.2 Basin evolution and depositional history

From the Early Cretaceous to the Paleogene, the Sorell Basin evolved from a series of transtensional fluvio-lacustrine depocentres to an open seaway between Australia and Antarctica. The basin fill comprises five distinct and regionally mappable basin phases (Figure 2.35; Stacey et al., 2013); the Otway Basin sequence stratigraphy of Krassay et al. (2004) has been adopted for the Sorell Basin as it is contiguous with the Otway Basin:

- Early Cretaceous extension and subsidence (Crayfish and Eumeralla Supersequences)
- Late Cretaceous extension (Shipwreck Supersequence)
- Late Cretaceous subsidence/extension (Sherbrook Supersequence)
- Cenozoic subsidence/extension (Wangerrip Supersequence)
- Cenozoic subsidence and inversion (Nirranda, Heytesbury and Whalers Bluff Supersequences)

The basal Sorell Basin succession has not been intersected by drilling, but is interpreted to comprise Lower Cretaceous fluvial and lacustrine rocks, including coaly facies of the Eumeralla Supersequence (Figure 2.35). These rocks were deposited across much of the northern part of the basin, with deposition strongly influenced by the north–south oriented Avoca–Sorell Fault System. At this time, depocentres along the eastern margin of the basin were small and isolated. A period of structural inversion that affected most of the Otway Basin during the Cenomanian (Norvick & Smith, 2001; Krassay et al., 2004), resulted in only minor deformation in the Sandy Cape Sub-basin. No inversion is observed in the Strahan Sub-basin, where rifting was continuous.

Renewed extension in the early Late Cretaceous resulted in the deposition of fluvial and deltaic facies, and an increasing marine influence. During the Campanian–Maastrichtian a marginal marine to fluvio-deltaic succession accumulated throughout the northern Sorell Basin; coaly sediments of this age were intersected by Cape Sorell 1 in the Strahan Sub-basin. Correlation of the Port Davey Sub-basin succession with the Strahan Sub-basin suggests that the syn-rift fill is also Late Cretaceous, although some authors have suggested this section is possibly Paleocene and younger (Moore et al., 1992).

The Late Cretaceous culminated in the commencement of breakup in the Otway Basin to the north. Regionally, the base of the Cenozoic is marked by uplift and erosion followed by a prolonged period of subsidence. The significant Cretaceous–Cenozoic unconformity seen in the Otway Basin can also be observed in the Sandy Cape Sub-basin, but in the Strahan Sub-basin, half-graben growth wedges indicate that extension continued up until the early Eocene, at which time a local inversion event occurred (Figure 2.35 and Figure 2.36b). The structural history seen in the Strahan Sub-basin is consistent with continuation of a transtensional regime inboard of the developing transform margin. The Eocene inversion event may be related to the proximity, and passing, of the spreading ridge at this time.

Australian–Antarctic clearance and establishment of an open seaway between the continents occurred during the Eocene (Exon et al., 2001a, 2004), with estimates of the exact timing ranging from 43 Ma (Holford et. al, 2011; Norvick & Smith 2001) to 33.7 Ma (Exon et al., 2001a). The Eocene to Holocene section in the Sorell Basin consists of a series of aggradational to progradational marine successions. Shallow-marine sandstones, marls and limestones of the Nirranda Supersequence are truncated by a major mid-Oligocene unconformity and overlain by upper Oligocene and younger shelfal marls and limestones of the Heytesbury and Whalers Bluff supersequences.

2.7.2.3 Level of knowledge

Geological understanding of the Sorell Basin is based on interpretation of a highly variable, in both quality and coverage, 2D reflection seismic data set, in conjunction with data from three petroleum exploration wells, two deep sea drilling wells and a limited number of dredge samples. The oldest sediments penetrated by drilling are of Late Cretaceous age. Two of the wells bottom in or close to basement emphasising their proximal location within the basin. The most recent well, Jarver 1, was drilled in 2008. Where data coverage is fairly good, in the northernmost part of the basin and over parts of the Strahan Sub-basin, the level of knowledge is fair. Elsewhere, the geology of the basin is poorly understood.

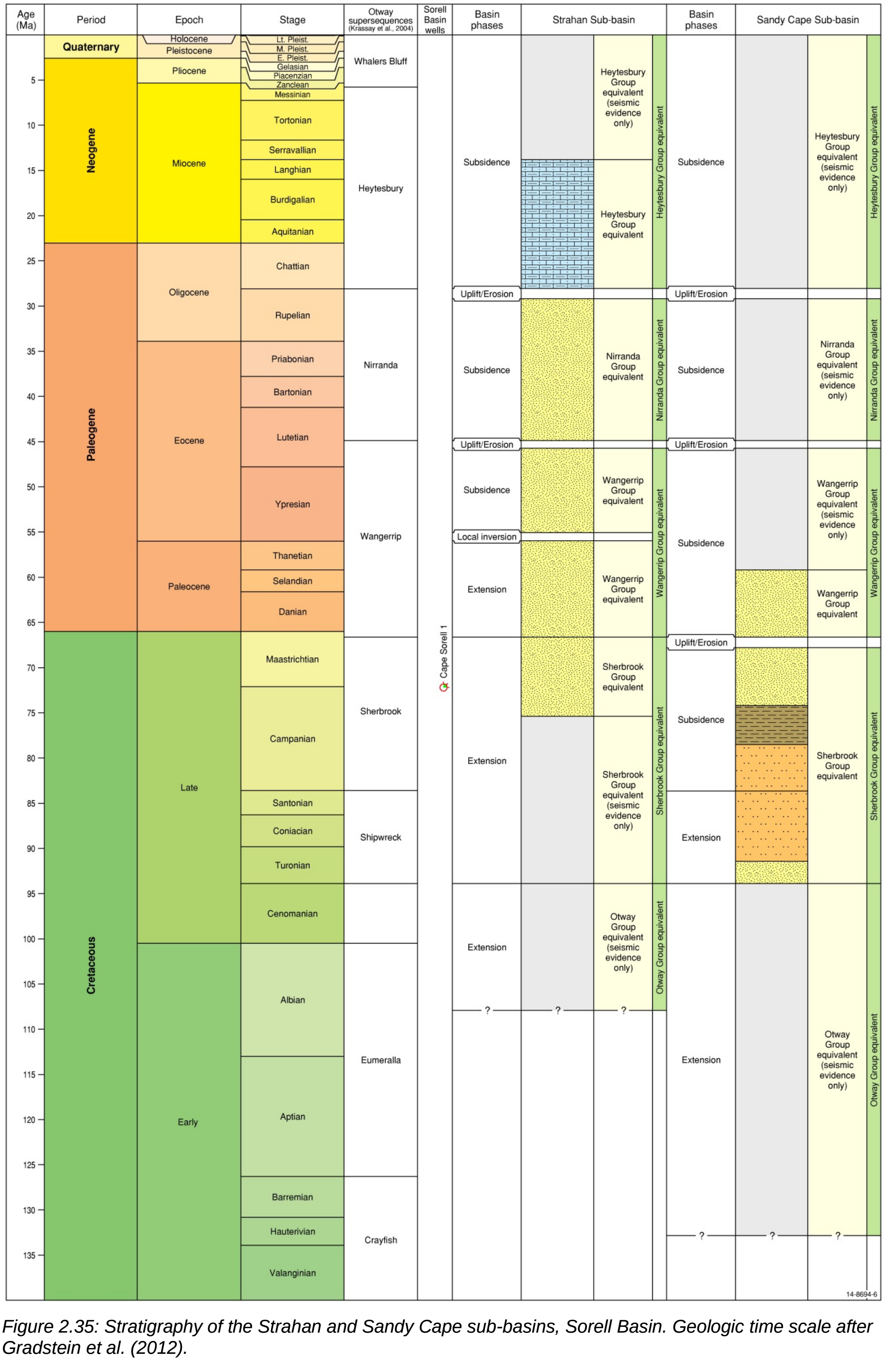

Figure 2.35: Stratigraphy of the Strahan and Sandy Cape sub-basins, Sorell Basin. Geologic time scale after Gradstein et al. (2012).

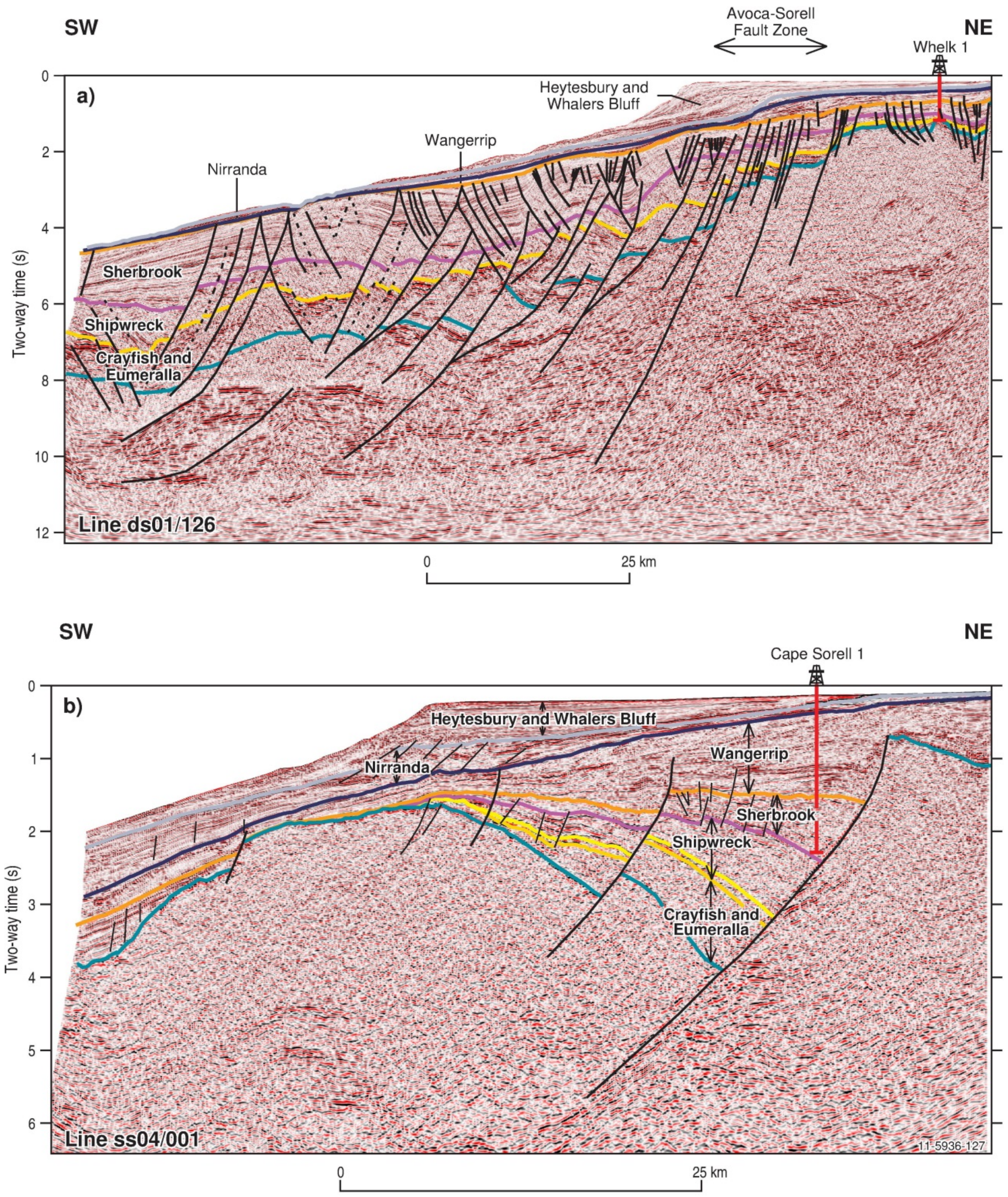

Figure 2.36: Seismic sections across the a) southern Otway basin and northern Sandy Cape Sub-basin, and b) Strahan Sub-basin (from Stacey et al., 2013).

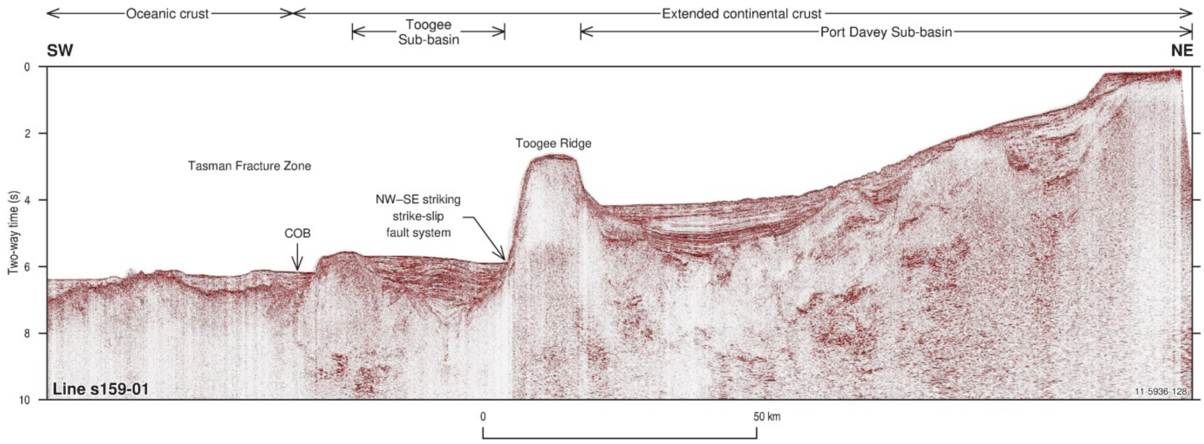

Figure 2.37: Seismic section across the southern Sorell Basin (after Totterdell et al., 2012).

2.7.3 Petroleum systems

Only three petroleum exploration wells have been drilled in the Sorell Basin, and all were dry. However, the presence of a Cretaceous basin fill up to 6000 m thick, which is interpreted to contain organic-rich coaly, deltaic and marine facies that are mature for hydrocarbon generation in much of the basin, as well as minor oil indications in one well (Cape Sorell 1), indicate that active petroleum systems could be present in the basin.

2.7.3.1 Source Rocks

Recent seismic interpretation by GA indicates the depositional sequences hosting active Austral 2 and 3 petroleum systems in the producing areas of the Otway Basin are also likely to be present in parts of the Sorell Basin (Stacey et al., 2013). The Austral 2 petroleum system contains potential source rocks of the Lower Cretaceous Eumeralla Supersequence, which typically comprise Type III kerogen and were deposited in fluvio–lacustrine environments. The Austral 3 petroleum system is based on potential source rocks of the Upper Cretaceous Shipwreck and Sherbrook supersequences that were deposited in fluvio-deltaic to marine environments.

In the Strahan Sub-basin, lower Maastrichtian (Austral 3) potential source rocks were intersected in Cape Sorell 1 in the lower Sherbrook Supersequence. Measured Total Organic Carbon (TOC) ranging from less than 1% to 18.6% and Hydrogen Index (HI) values indicative of Type II/III and Type III kerogen, suggest good potential for both oil and gas (Lodwick et al., 1999; Boreham et al., 2002). The maturity of these lower Maastrichtian potential source rocks has been assessed as immature–marginally mature (Boreham et al., 2002; Stacey et al., 2013). Cape Sorell 1 was not deep enough to intersect potential source rocks of the Austral 2 petroleum system; however, modelling for the Strahan Sub-basin indicates that if these source rocks are present, they are gas to oil mature in the main half graben (Stacey et al., 2013). Minor amounts of free oil were recorded in the Sherbrook Group in Cape Sorell 1. Whether the oil was generated locally or from deeper Sherbrook or Otway groups is uncertain, but its presence is encouraging evidence of an active Cretaceous petroleum system in the Strahan Sub-basin (Boreham et al., 2002).

Little is known about potential source rocks in the Sandy Cape Sub-basin or in the deepwater regions to the west; the only well drilled in the Sandy Cape Sub-basin (Jarver 1) terminated in conglomeratic basement overlain by a Flaxman Formation equivalent at the base of the Shipwreck Supersequence. Seismic interpretation suggests that a coaly Eumeralla Supersequence, similar to the section that hosts Austral 2 source rocks in the Otway Basin, is present in the sub-basin. In addition, the Upper

Cretaceous succession is well developed across the northern part of the Sorell Basin, raising the potential for the presence of marine-influenced Austral 3 source rocks.

2.7.3.2 Generation and expulsion

Petroleum systems modelling in the northern Sorell Basin, has revealed that, if source rocks are present at the predicted levels, generation and expulsion would have commenced in the Albian and ceased in the Paleocene (Stacey et al., 2013). A proportion of accumulated hydrocarbons are likely to have been lost as a result of the latest Cretaceous–Paleocene structural event, however, migration and accumulation continued throughout the Cenozoic and the model predicts present-day accumulations in mostly fault-related traps.

Petroleum systems modelling in the Strahan Sub-basin indicates that, if Austral 2 and 3 source rocks are present at the predicted levels, generation and expulsion would have occurred from the Late Cretaceous onwards and more or less ceased in the Eocene (Stacey et al., 2013). A proportion of accumulated hydrocarbons are likely to have been lost as a result of Paleocene/Eocene uplift and erosion, however, migration, remigration and accumulation continued throughout the Cenozoic.

Hydrocarbons have been reported from seafloor samples acquired in the Sandy Cape and Strahan sub-basins, and deeper water locations in the basin (Hinz et al., 1985; Exon et al., 1989; O'Brien et al., 2004). Initial analyses indicated that the hydrocarbons were thermogenic and represented seepage, however, the geochemistry of the low concentrations of headspace gases in these samples suggests that they are more consistent with background levels of hydrocarbons (Abrams 2005; Abrams & Dahdah, 2011) and an origin cannot be confidently inferred (C. Boreham, Geoscience Australia, pers. comm. January 2013).

2.7.3.3 Reservoirs and seals

By analogy with the offshore Otway Basin, the primary reservoirs in the Sorell Basin are likely to be sandstones in the Shipwreck (Waarre Formation, Flaxman Formation and the "Thylacine Member" at the base of the Belfast Mudstone) and Sherbrook supersequences, and Eocene and Paleocene sandstones of the Wangerrip Supersequence. In wells drilled on the flanks of the sub-basins, the dominantly sandy Sorell Basin succession lacks the mudstones that seal and separate sandstone reservoirs of the Otway Basin (Lodwick et al., 1999); however, results from Jarver 1 suggest that such sequences may be better developed to the west, away from the flanks of the sub-basins (Stacey et al., 2013).

Petroleum systems modelling in the northern part of the Sorell Basin, where no wells have been drilled, suggests that porosity at the Waarre Formation level could be a major risk in distal parts of the sub-basin; however, good porosities at this level are expected on the platform and terrace region on the eastern side of the basin.

Jarver 1, in the southern Sandy Cape Sub-basin, targeted potential reservoir units in the "Thylacine Member" at the base of the Sherbrook Group sealed by the Belfast Mudstone, as well as the Paaratte Formation, with top seal provided by intra-formational seals. However, the porosities encountered were poor to very poor and the well was dry (Pitman, 2008). A thick (344 m) claystone, siltstone and sandstone unit was intersected overlying the basal Upper Cretaceous sandstones. This unit, which can be interpreted on seismic data away from the well, may provide a regional seal for any hydrocarbon accumulation within the Waarre Formation, Flaxman Formation or "Thylacine Member" reservoirs. The marls and fine-grained limestone in the Heytesbury Group could also provide seals to Nirranda and Wangerrip group reservoirs.

In the Strahan Sub-basin, Cape Sorell 1 intersected a generally sandy section with few potential seals. Porosities in the Wangerrip Group are excellent (20–>30%), but the lack of seal limits their reservoir potential (Conolly & Galloway, 1995). Porosity decreases with depth, falling to <15% near the base of the well. Shaly interbeds up to 20 m thick in the Wangerrip Group indicate that potential intraformational seal facies may be present near the sub-basin margin. It is important to note that as the well was drilled close to the basin-bounding fault, the lithofacies encountered in the well are unlikely to be representative of the rest of the sub-basin, which is likely to be more shale-prone further to the west. Basinward of the well, a potential sealing facies in the Wangerrip Group may be formed by an Eocene flooding surface overlain by downlapping progrades (O'Brien et al., 2004). The relatively thin marls and fine-grained limestones in the Neogene Heytesbury Group could also be potential seals.

2.7.3.4 Play types

In the Strahan Sub-basin, petroleum systems modelling suggests that migration pathways are updip towards the western edge of the basin, where the most likely trap scenarios are high-side fault blocks, stratigraphic pinch-outs and, to a lesser extent, small rollover anticlines with updip closure (Stacey et al., 2013). Fault-block traps are predicted in the basal Shipwreck Supersequence (Waarre Formation) and at the base of the Wangerrip Group, charged by both Austral 2 and 3 source rocks. A pinch-out play is present along the western edge of the sub-basin where the sediments thin across the hinge of the half graben; such stratigraphic traps are likely to be charged by Austral 2 and 3 sources. Other potential traps in the sub-basin include rollover closures associated with major bounding faults, drape anticlines over canyons and fault blocks in the Wangerrip Group, and stratigraphic traps associated with Paleocene–early Eocene canyons.

The Sandy Cape Sub-basin partly underlies the continental shelf and attains a maximum thickness of approximately 6000 m. Similar sediment thicknesses underlie large areas of the continental slope in the southward deep water continuation of the adjacent Otway Basin (Nelson Sub-basin). These continental slope depocentres represent a vast, downdip, kitchen area where, if present, oil-prone Austral 3 source rocks are likely to be in the peak generation window (O'Brien et al., 2004). Petroleum systems modelling in the northern part of the basin indicates accumulations are most likely developed in structural traps (high-side fault traps and faulted anticlines) in the Waarre Formation and Sherbrook Groups (Stacey et al., 2013). Prospectivity of the deepwater basin is considered to be reliant on reservoir and seal pairs being present within the Sherbrook Supersequence, however, if these are at shallow depths, biodegradation may be a risk (Stacey et al., 2013). Paleocene–early Eocene canyons like those mapped in the Strahan Sub-basin also occur in the Sandy Cape Sub-basin, where they have the potential to form substantial stratigraphic traps if suitable seals are present. The canyons may also act as conduits for migrating hydrocarbons generated in the thick depocentres under the continental slope.

2.7.3.5 Critical risks

The main risks for petroleum systems in the Sorell Basin are:

- presence of charge. The key risk for the Sorell Basin relates to the quality, volume and maturity or source rocks, and the generation and expulsion of hydrocarbons. The Sorell Basin contains no proven petroleum systems and interpretation of their presence is largely by analogy with the Otway Basin. Interpretation of seismic data suggests that the depositional sequences that host active petroleum systems in the Otway Basin are present in the Sorell Basin. However, in large parts of the basin the section is relatively thin (<2.5 s TWT or approximately 3000 m) and compartmentalised, so there is considerable uncertainty regarding the extent, quality and maturity of potential source rocks (Walker, 2007). Potential source rocks were intersected in Cape Sorell 1 and the presence of trace amounts of free oil in the well is encouraging evidence of an active Cretaceous petroleum system in the Strahan Sub-basin (Boreham et al., 2002). Petroleum systems modelling suggests that key potential source rocks are mature for oil and gas generation in the Sandy Cape and Strahan sub-basins, however the paucity of wells means that understanding of the thermal history of the basin is limited.

- presence of good quality seal facies. Wells drilled on the inboard part of the shelf are dominated by sandstone with poor seal development; however, the presence of a thick mudstone succession in Jarver 1 suggests that seal facies are better developed further basinward. Nevertheless, given the lack of drilling, little is known about the nature of lithofacies in much of the basin.
- biodegradation. Petroleum systems modelling has shown that in the main depocentre of the northern Sorell Basin, prospectivity is reliant on the presence and quality of reservoirs in the Sherbrook Group, due to potential depth-related porosity issues for Waarre Formation reservoirs. However the modelling also indicates that biodegradation is a potential risk in areas of the basin where the reservoirs are shallow and temperatures are below 80ºC. Similarly, shallow reservoirs in the Wangerrip Group are also at risk of biodegradation.
- preservation of accumulations (fault seal issues/loss of hydrocarbons due structuring). Much of the basin is heavily faulted, with widespread reactivation of Early Cretaceous faults and the formation of new faults in the latest Cretaceous. Petroleum systems modelling suggests that a proportion of accumulated hydrocarbons is likely to have been lost as a result of the latest Cretaceous–Paleocene structuring, uplift and erosion.
- interpretation uncertainty caused by paucity of direct geological control. This problem is highlighted by the results of Jarver 1, where the stratigraphic units were encountered 100–200 m higher than predicted.

2.7.3.6 Overall prospectivity classification

Moderate–Low

2.7.4 Exploration status

The Sorell Basin is one of the least explored of Australia's southern margin basins. This frontier basin contains only three petroleum exploration wells—Clam 1, Cape Sorell 1 and Jarver 1 (Figure 2.38). Deep Sea Drilling Project (DSDP Leg 29 Site 282) and Ocean Drilling Program (ODP Leg 189 Site 1168) stratigraphic wells were drilled on the lower continental slope west of the Sorell Basin (Exon et al., 2001b). The focus of exploration has been on the northern sub-basins, where the three petroleum exploration wells have been drilled.

The exploration history of the Sorell Basin has been reported by numerous authors (e.g. Hill et al., 1997; Lodwick et al., 1999) and succinctly summarised by O'Brien et al. (2004). Petroleum exploration began in the late 1960s, when Esso Exploration and Production Australia (Esso) and Magellan Petroleum Australia (Magellan) obtained reconnaissance seismic data on the west Tasmanian margin (O'Brien et al., 2004). Esso drilled three wells: Clam 1 (1969) in the King Island Sub-basin while Prawn A1 (1967) and Whelk 1 (1970) were drilled in the adjacent Otway Basin to the northwest. All wells were dry and were plugged and abandoned.

There was a relative hiatus in exploration activity during the 1970s. During this time, reconnaissance seismic surveys by the Bureau of Mineral Resources, Geology and Geophysics (BMR, now Geoscience Australia [GA]) and Shell International along the western margin of Tasmania were the only major studies undertaken.

A new phase of exploration began in 1981 when Amoco Australia Petroleum Company (Amoco) carried out a seismic survey in the Strahan Sub-basin, followed by the drilling of Cape Sorell 1 in 1982. This well tested a rollover structure and recorded minor amounts of free oil and residual oil traces, despite being drilled off structure (Amoco Australia Petroleum Company, 1982). In 1990, Maxus Energy Corporation (Maxus) acquired a dense seismic grid in the Strahan Sub-basin. Although Maxus (1993) identified a number of drilling prospects, it failed to attract farm-in partners and the permit was relinquished (O'Brien et al., 2004).

Multi-beam swath mapping of the seabed was carried out by the Australian Geological Survey Organisation (AGSO; now GA) in 1994 (Exon et al., 1994), followed by regional seismic surveys (Survey 148 and Survey 159) in 1995 and 1996, respectively. In early 2000, AGSO undertook seafloor swath mapping and seismic reflection profiling along the upper continental slope using the RV *L'Atalante* (AUSTREA 1; Hill et al., 2000).

In 2001, Seismic Australia and Fugro-Geoteam AS acquired 3612 and 2034 line-km of non-exclusive seismic data over the deepwater Otway and northern Sorell basins (DS01 and DS02 surveys respectively), rekindling interest in the area. Santos had a major presence in the region from 2002 operating permits T/32P, T/33P, T/36P and T/48P, drilling the dry hole, Jarver 1 in T/33P during 2008 (Pitman, 2008). During this phase of exploration, Santos reprocessed the Maxus seismic and acquired a 2D infill and a 3D survey over the Strahan Sub-basin as well as acquiring several 2D infill surveys over the Sandy Cape Sub-basin. Subsequently, all of the Santos permits were relinquished with the exception of T/32P, where the Santos share was taken over by Perenco (SE Australia) Pty Ltd in 2010. In 2011, Perenco acquired 1000 km^2 of 3D seismic over the Wolseley prospect, but surrendered the permit in 2014. The are no permits currently operating in the Sorell Basin.

2.7.5 Data

Sorell Basin wells and key seismic, sample and swath bathymetry data sets are listed in Table 2.23–Table 2.26. Seismic coverage in the Sorell Basin is a mixture of government and industry data. The northern part of the basin is well covered by a mixture of regional industry 2D grids, 2D infill grids and two recent 3D surveys—one acquired by Santos in the Strahan Sub-basin in 2008, and one by Perenco in the Sandy Cape Sub-basin in 2011 (Figure 2.38). Key 2D seismic data sets include the Fugro DS-01 survey in the Sandy Cape Sub-basin, and the Maxus and Santos SS04 surveys in the Strahan Sub-basin. In comparison, seismic coverage south of the Strahan Sub-basin is extremely sparse; most of the seismic lines in this area shown in Figure 2.38 comprise shallow, low resolution data collected during research cruises in the 1980s (e.g. Hinz et al., 1985; Exon et al., 1989). There is a greater than 100 km gap between industry seismic surveys in the Strahan Sub-basin and GA line 159-01, which transects the Port Davey Sub-basin (Figure 2.37). Several potential field datasets are available for the area. Pre-2008 gravity data was mostly acquired in conjunction with seismic surveys and, as for the seismic coverage, is sparse towards the south of the basin. In 2008, over 70,000 line-km of new aeromagnetic data was acquired by Geoscience Australia and Mineral Resources Tasmania (MRT) over the western Tasmanian margin (Morse et al., 2009). These data were merged with onshore aeromagnetic datasets to create a near continuous coverage of southeastern Australia (Morse et al., 2009).

2.7.5.1 Confidence rating

Medium–low

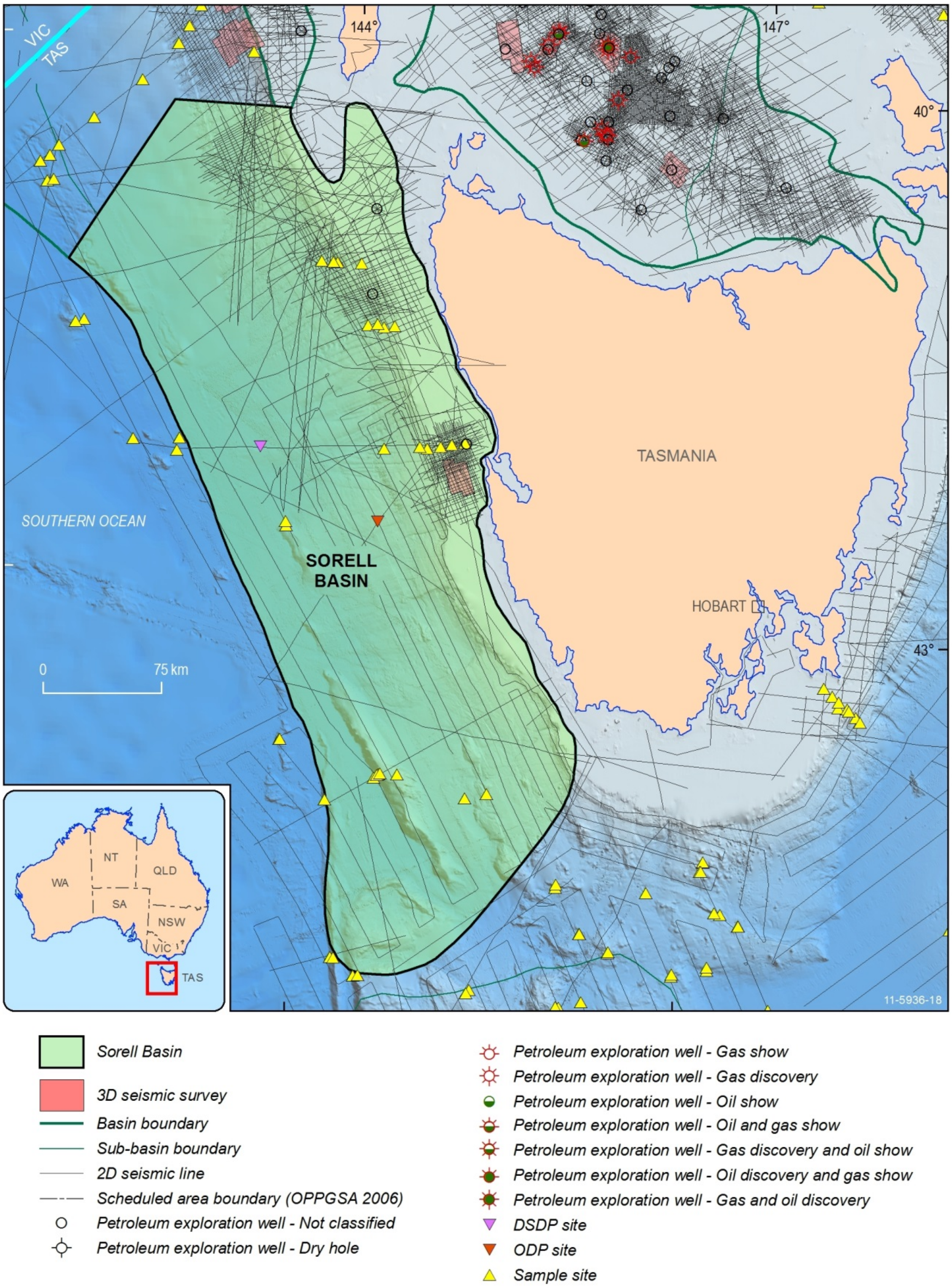

Figure 2.38: Seismic, well and sample distribution, Sorell Basin.

2.7.6 Issues and remaining questions

2.7.6.1 Petroleum systems and prospectivity

The three wells drilled in this basin were located in shallow water, proximal parts of the basin. Consequently geological knowledge of the distal and thicker parts of the basin is limited. This gap in knowledge can only be addressed by further drilling together with acquisition of more closely-spaced 2D and/or 3D seismic data. Improved seismic data quality and density would lead to a better understanding of the distribution and nature of source, reservoir and seal facies. The potential size of petroleum accumulations, and risks relating to structural reactivation could also be assessed.

While adequate reservoir facies are likely to be present in the northern Sorell Basin, the following petroleum systems elements are issues of concern:

- the presence and volume of good quality source rocks. Seismic data suggests the presence of coaly Eumeralla Supersequence facies throughout much of the Sandy Cape Sub-basin and deepwater parts of the northern Sorell Basin, but the presence of good quality Upper Cretaceous source rocks is likely to be dependent on the extent of marine influence during that time, and the degree of dilution caused by the influx of siliciclastic sediments from uplifted areas to the east. Given the compartmentalised nature of Sorell Basin depocentres, source rock volume is also an issue of concern, particularly south of the thick, outboard portion of the Sandy Cape Sub-basin.
- the presence of good quality seals. While seal has been identified as an issue in proximal parts of the basin, Stacey et al. (2013) postulated that seal quality should improve basinward away from the eastern margin of the basin. The presence of thick seal units at Jarver 1 provides some support for this prediction.
- preservation of accumulations, particularly the timing of generation and migration relative to the major structuring event in the latest Cretaceous–Paleocene.

2.7.6.2 Southern Sorell Basin

At present the geology of the southern part of the Sorell Basin is very poorly known. Seismic data is extremely limited and regional in scale. As a result it is impossible to assess prospectivity of this part of the basin.

2.7.6.3 Recommendations

- Understanding of the critical petroleum systems issues will be improved by further drilling and the acquisition of high resolution 2D and 3D seismic data. Improved knowledge of the distribution, nature and age of potential source, reservoir and seal units, and the structural geology of the sub-basin could inform robust regional petroleum systems modelling, leading to a better understanding of the relative timing of generation, migration, trap formation and structuring.
- In the southern Sorell Basin, acquisition of a comprehensive 2D seismic grid with a line spacing of no greater than 20 km, would allow a regional-scale assessment of prospectivity, and identification of areas (if any) that would benefit from more detailed data acquisition.

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2.7.8 Data Tables

Table 2.23: List of wells, Sorell Basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1969	Clam 1	Exploration	Esso	1622	Paleozoic		Esso, 1969
1982	Cape Sorell 1	Exploration	Amoco	3528	Maastrichtian	Oil indications	Boreham et al., 2002
2008	Jarver 1	Exploration	Santos	3062	?Paleozoic		Pitman, 2008
1973	DSDP Leg 29 (Site 282)	Stratigraphic	DSDP	310.5	Paleocene		Kennett et al., 1975
2000	ODP Leg 189 (Site 1168)	Stratigraphic	ODP	883.5	Late Eocene		Exon et al., 2001b

Table 2.24: Key seismic surveys in the Sorell Basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1972	Petrel	Shell		
1981	W81	Amoco	753	
1990	MXT90	Maxus	736	
1996	S159	AGSO	445	
2001	DS01	Fugro Geoteam/Seismic Australia	3754	
2002	SS02	Santos	1256	
2004	SS04	Santos	638.5	
2011	Wolseley 3D	Perenco	~1000 km^2	

Table 2.25: List of key surveys involving geological sampling.

Year	Survey	Operator	Region	Type	Rock types	Reference
1985	SO-36C (RV Sonne)	BGR	West Tasmanian margin	Dredge/core/grab	Cenozoic ooze, clastic and carbonate rocks, Cretaceous clastic rocks	Hinz et al., 1985;
1987	Survey 67	BMR	West Tasmanian margin	Dredge/core/grab/heat flow	Upper Cretaceous clastic rocks, Cenozoic carbonates and ooze	Exon et al., 1992
1988	Survey 78	BMR	West Tasmanian margin	Dredge/core/grab/heat flow	Upper Cretaceous clastic rocks, Cenozoic carbonates and ooze	Exon et al., 1989
1995	Survey 147 (Tasman Rises)	AGSO	West Tasmanian margin	Dredge/core	Basalt, metamorphic rocks and ooze	Exon et al., 1995

Table 2.26: Swath bathymetry surveys

Year	Survey	Operator	Line-km	Reference
1994	Tasmante Survey 125 (L'Atalante)	AGSO	13,600 km (STR and western Tasmanian margin)	Exon et al., 1994
2000	AUSTREA 1	AGSO		Hill et al., 2000
2003	AUSCAN	Geoscience Australia		Hill & De Deckker, 2004

2.8 South Tasman Rise

2.8.1 Summary

State(s)	Tasmania
Area (km²)	~135,250
Water Depth (m)	750–4000+
Maximum sediment thickness (m)	~5500
Age range	?Late Cretaceous–Holocene
Basin Overlies	Continental basement
Basin type	Transtensional, strike-slip
Depositional setting, rock types	Marginal to shallow marine clastic sedimentary rocks; pelagic carbonates
Petroleum prospectivity	Low
Confidence	*Low*

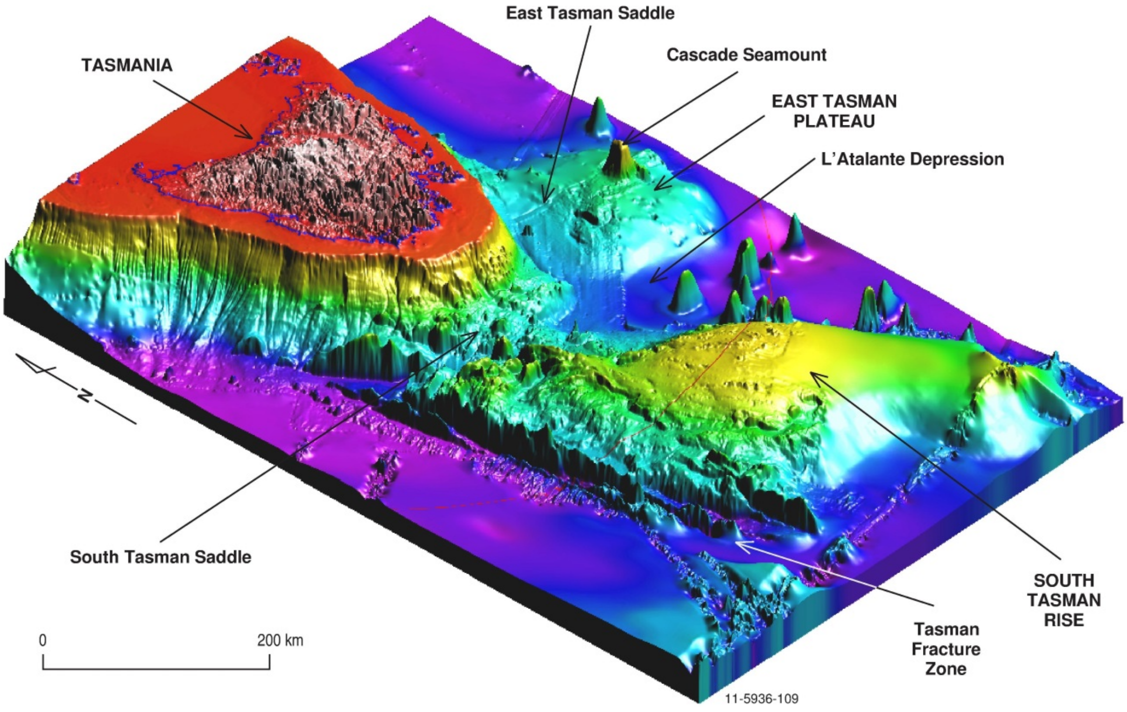

Figure 2.39: 3D perspective of the sea floor showing the South Tasman Rise, western Tasmanian margin and East Tasman Plateau (from Hill & Moore, 2001).

2.8.2 Geology

The South Tasman Rise (STR) is a large submerged landmass to the south of Tasmania that forms the southernmost part of the Australian continent (Figure 2.39). It covers an area of about 135,250 km² and lies in water depths of 750 m to more than 4000 m. The STR is surrounded by oceanic crust to the east, south and west. The western edge of the STR is a continental transform margin and is defined by a series of sheared parallel approximately north-northwest–south-southeast-oriented highs including the Tasman Escarpment, the northern prolongation of the Tasman Fracture Zone that extends south to Antarctica (Exon et al., 1997). The northeastern, southern and southwestern margins of the rise appear to be structurally controlled (Hill & Moore, 2001). The STR is separated from Tasmania by the northwest–southeast-trending South Tasman Saddle, which is underlain by extended continental crust. The STR is underpinned by continental basement comprising metamorphic and intrusive rocks. Numerous fault-bounded sedimentary basins containing up to several kilometres of fill lie within, and on the margins of, the STR. The fill is likely to comprise Upper Cretaceous to Eocene clastic rocks overlain by Neogene marine mudstones and oozes (Figure 2.40). The younger (Cenozoic) part of the sedimentary section has been intersected by drill holes from the Ocean Drilling Program (ODP) and Deep Sea Drilling Project (DSDP), but the older, inferred Cretaceous successions have not been penetrated. A paucity of well and high quality seismic data limits understanding of the hydrocarbon prospectivity of the region. High geothermal gradients of up to 60°C/km suggest that if suitable source rocks are present, oil maturation could occur at relatively shallow depths.

2.8.2.1 Structural geology

The tectonic history and development of the STR has been the subject of much debate. This inventory is focused on the basins that are present on the STR, so readers are referred to Royer & Rollet (1997), Hill & Moore (2001) and Hill & Exon (2004) for more detailed discussions of the evolution of the STR.

2.8.2.1.1 Tectonic Evolution

Intracontinental extension between Australia and Antarctica during the Jurassic and Early Cretaceous resulted in the formation of a series of rift basins, the Southern Rift System (SRS; Stagg et al., 1990), along the southern margin of Australia. During the Early Cretaceous, the area south of Tasmania was located on a southern branch of the SRS (Willcox & Stagg, 1990; Norvick & Smith, 2001). Strong northwest structural trends, consistent with major strike-slip movements, are observed across this region. Willcox & Stagg (1990) proposed that a large northwest-oriented shear zone that extended from the Bight Basin to the STR accommodated early extension between Australia and Antarctica. Hill & Moore (2001) observed that the degree to which strike-slip-related structures developed in the region at this time has not been determined and noted that Lower Cretaceous sediments have not yet been identified.

Continued lithospheric extension eventually led to the commencement of breakup, both east and west of the STR, at about 83 Ma. Seafloor spreading adjacent to the East Tasman Plateau and eastern STR was in a southwest–northeast direction (Hill & Moore, 2001). Meanwhile, to the west, ultra-slow spreading along the southern margin occurred on a northwest–southeast azimuth.

By the Paleocene, a shift in relative motion between the Antarctic and Australian plates to a more north–south direction (Tikku & Cande, 1999) led to onset of seafloor spreading off western Tasmania (Hill et al., 1997). There is general agreement (Royer & Rollet, 1997; Hill & Moore, 2001; Hill & Exon, 2004; Gibson et al., 2012) that at around 55 Ma, the western part of the STR transferred from the Antarctic plate and became attached to the eastern STR block, resulting in the present configuration of the composite STR. At this time, or possibly earlier, seafloor spreading began at the southern margin of the STR (Pyle et al., 1995; Cande et al., 2000; Norvick & Smith, 2001), and ceased soon after in the Tasman Basin (Hill & Moore, 2001).

Fast north–south seafloor spreading in the Southern Ocean, commencing at ~44 Ma, led to separation of the STR from Antarctica along the Tasman Fracture Zone, producing a major 500 km long escarpment along the western STR. The STR and Antarctica cleared each other at the southwestern tip of the STR at ~35 Ma, resulting in the opening of the Tasmanian Gateway (Norvick & Smith, 2001), which had profound effects on regional sedimentation (Hill & Moore, 2001).

2.8.2.1.2 Structural geology of STR basins

A key feature of the STR is the prominent northwest–southeast structural trend that delineates the northeastern margin of the STR and extends along much of the western Tasmanian margin (Figure 2.39). Various authors have attributed this feature to strike-slip movement associated with either initial development of the SRS (Willcox & Stagg, 1990), or a shear zone active in the Late Cretaceous–early Cenozoic (Hill & Moore, 2001).

The STR can be divided into two major terranes; a marked change in structural style, from a structurally complex western block to a less complex eastern block, occurs across a north–south oriented feature at 146°15'E (Royer & Rollet 1997; Exon et al., 1996; Hill & Exon, 2001). The western terrane contains basement blocks and intervening basins with very varied trends (Hill & Moore, 2001). The eastern terrane is characterised by basement blocks and intervening strike-slip basins that trend 300–340°. Hill & Moore (2001) argued that the more complex nature of the western terrane is related to deformation during its transfer from the Antarctic to the Australian plate in the Paleogene, and subsequent north–south strike-slip deformation associated with transform movement along the Tasman Fracture Zone.

Sedimentary basins, containing at least several kilometres of possibly Cretaceous–Cenozoic sediment fill, lie within and on the margins of the STR (Figure 2.41 and Figure 2.42; Hill & Moore, 2001; Exon et al., 2004). Though basin development is extensive, depocentres are generally small and structurally complex (Hill & Moore, 2001). Seismic data indicate that the depocentres are generally controlled by north- to northwest-trending, mostly strike-slip faults, with throws of up to several thousand metres (Exon et al., 1997). Cretaceous sediments are interpreted to be present at depth in the depocentres with a relatively thick overlying Paleogene sequence and thin Neogene and Quaternary sequence (Exon et al., 1997, 2004). The interpreted Late Cretaceous age of rift basin formation on the STR indicates that the area continued to experience transtensional and/or strike-slip deformation as breakup propagated eastwards across the southern margin, and during development of the transform margin.

Basin architecture varies across the STR. Beneath the western STR, individual depocentres are relatively small (less than 25 km wide) and often rhomboid in shape, while on the flanks of the central STR, the northwest–southeast basins are deep and narrow (20–25 km wide). In the South Tasman Saddle and southeastern margin of the STR, potentially deep basins are masked in the seismic data by igneous rocks.

The most significant sedimentary province in the STR is the Ninene Basin, which consists of an extensive series of depocentres located on the western STR (Figure 2.43). The Ninene Basin is characterised by northerly-trending high basement slivers and intervening graben and half graben that contain 1.5–2 s TWT of sediments with up to 3 s TWT in places. The basin is up to 135 km wide and contains a maximum known sediment thickness of about 4 s (~5.5 km; Exon et al., 1997).

2.8.2.2 Basin evolution and depositional history

The stratigraphy of rift basins on the STR is derived from DSDP and ODP drilling, and cores and dredges obtained during sampling cruises (Figure 2.40). In general, rifts containing probable Upper

Cretaceous to Eocene clastic rocks are overlain by Neogene and Quaternary marine mudstones and oozes. The Neogene and Quaternary sequences are generally flat-lying, whereas the older strata are variably affected by faulting and minor deformation. Cenozoic basaltic volcanic rocks are common on the northern and northeastern STR (Exon et al., 1995; Crawford et al., 1997; Hill & Moore, 2001), forming low-relief volcanic edifices up to 1500 m high.

DSDP Site 281, located in the southern part of the STR, intersected a dominantly calcareous ooze/chalk succession before reaching TD in Carboniferous metamorphic rocks (Figure 2.40; Hill & Moore, 2001). Across the STR, a prominent unconformity at the Eocene–Oligocene boundary marks a change in sedimentation patterns associated with the opening of the Tasmanian Gateway (Figure 2.41 and Figure 2.42; Hill & Moore, 2001). Generally, this unconformity marks a change from deposition of siliciclastic sediments (Maastrichtian–Eocene) to pelagic carbonates (Figure 2.40). The oldest sedimentary rocks drilled on the STR are from the base of ODP Site 1171 on the southwestern margin of the STR, and consist of Paleocene organic silty claystones. Seismic data shows that there is up to 2 s TWT of older, presumably Cretaceous, fill in some rifts (Figure 2.42). ODP Site 1172 drilled on the East Tasman Plateau intersected shallow, restricted marine Maastrichtian claystone at the base of the well (Brinkhuis et al., 2004; Exon et al., 2004). Based on the results of Site 1172, it is assumed that the deeper section within rifts on the STR is also Late Cretaceous in age. The Upper Cretaceous section penetrated in Cape Sorell 1 in the Sorell Basin was deposited in a coastal plain–marginal marine environment (Boreham et al., 2002).

Sampling and ODP drilling (Exon et al., 2001b) in the STR region show that prior to the late Eocene, siliciclastic sediments (mainly silty claystones) were being deposited in a relatively warm sea on broad, tranquil shelves in a deltaic environment (Hill & Moore, 2001). The establishment of cool surface currents by the late Eocene, led to the deposition of glauconitic sediments. By the early Oligocene the Tasmanian Gateway had opened, intensifying circum-Antarctic circulation and cutting off warm currents from the tropics (Kennett et al., 1975b; Exon et al., 2001a). Siliciclastic sedimentation ceased and was replaced by biogenic carbonate deposition (Hill & Moore, 2001). Modern sediments are now entirely deep-sea pelagic carbonates (foraminiferal and nannofossil oozes).

2.8.2.3 Level of knowledge

Geological understanding of the South Tasman Rise is based on interpretation of very widely spaced (10s of km) regional-scale 2D seismic lines, a closer-spaced grid of shallow, high-speed seismic data of variable quality, and four ODP/DSDP drill holes. The wells provide some stratigraphic control for the shallow part of the section. However, given the shallow penetration of the wells and spacing between them of 70–160 km, there is insufficient data to confidently assess the age and nature of the sedimentary succession, or the presence and distribution of potential source, reservoir and seal units.

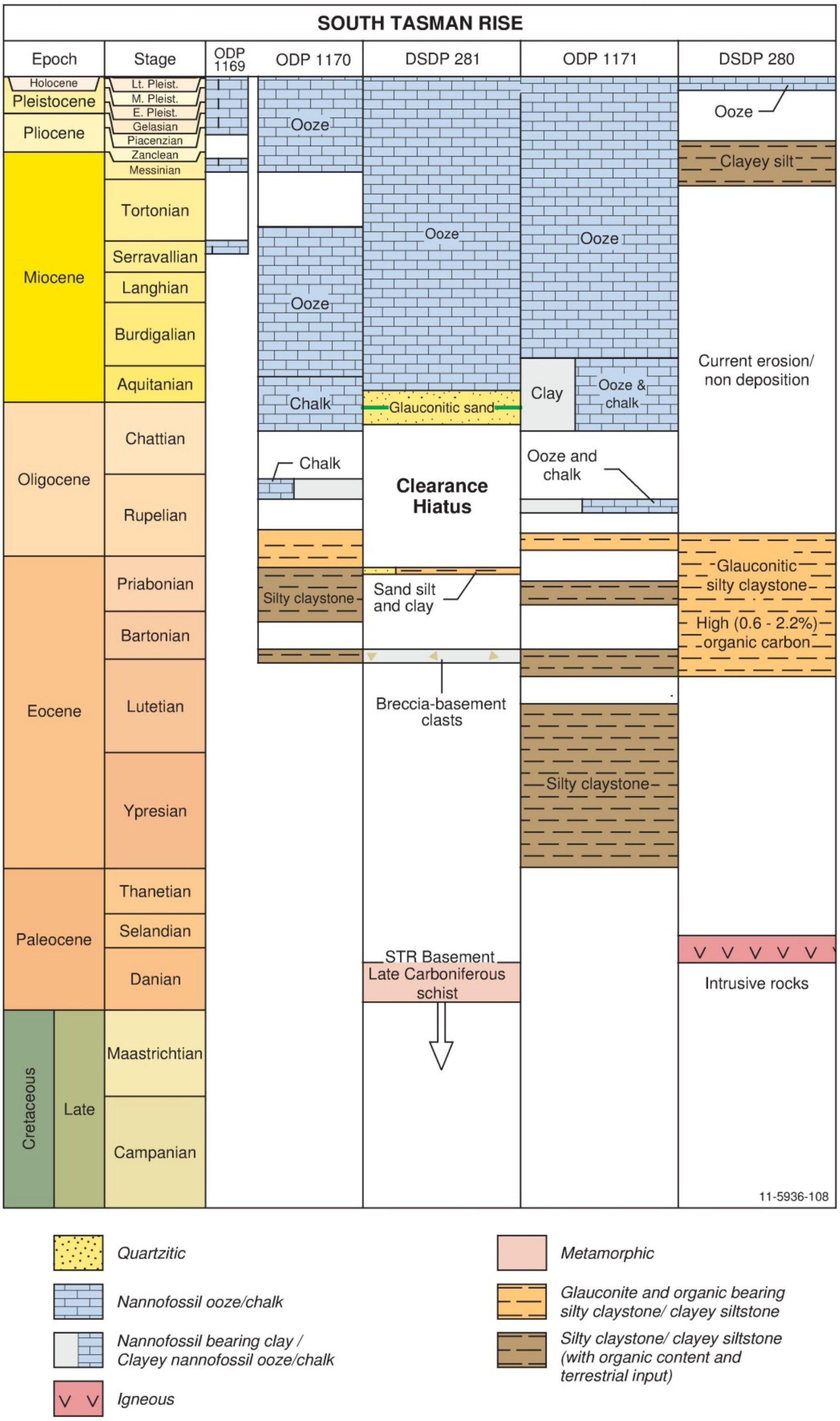

Figure 2.40: Stratigraphy of the South Tasman Rise (after Hill & Moore, 2001) .

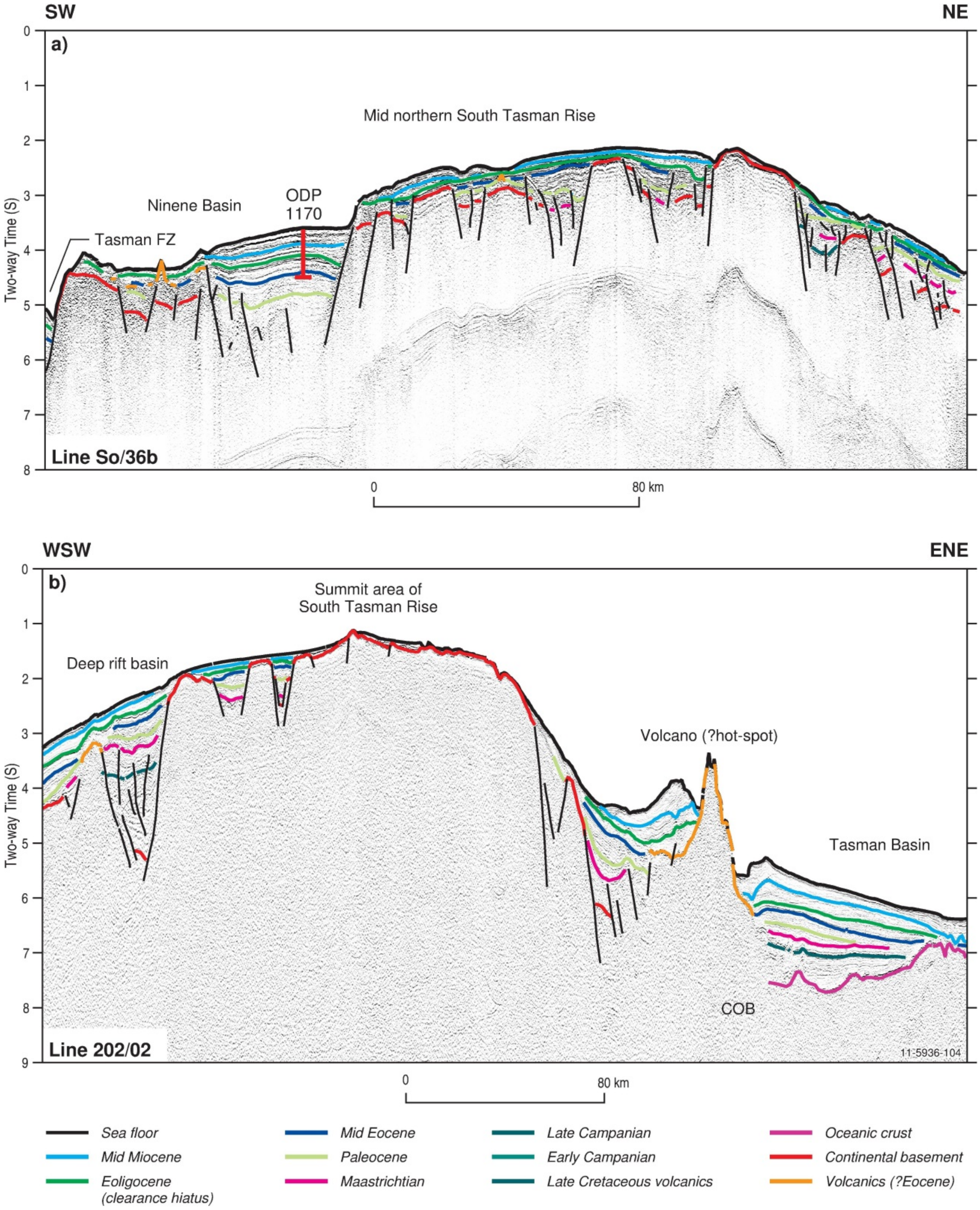

Figure 2.41: Seismic cross-section across the South Tasman Rise (from Hill & Moore, 2001).

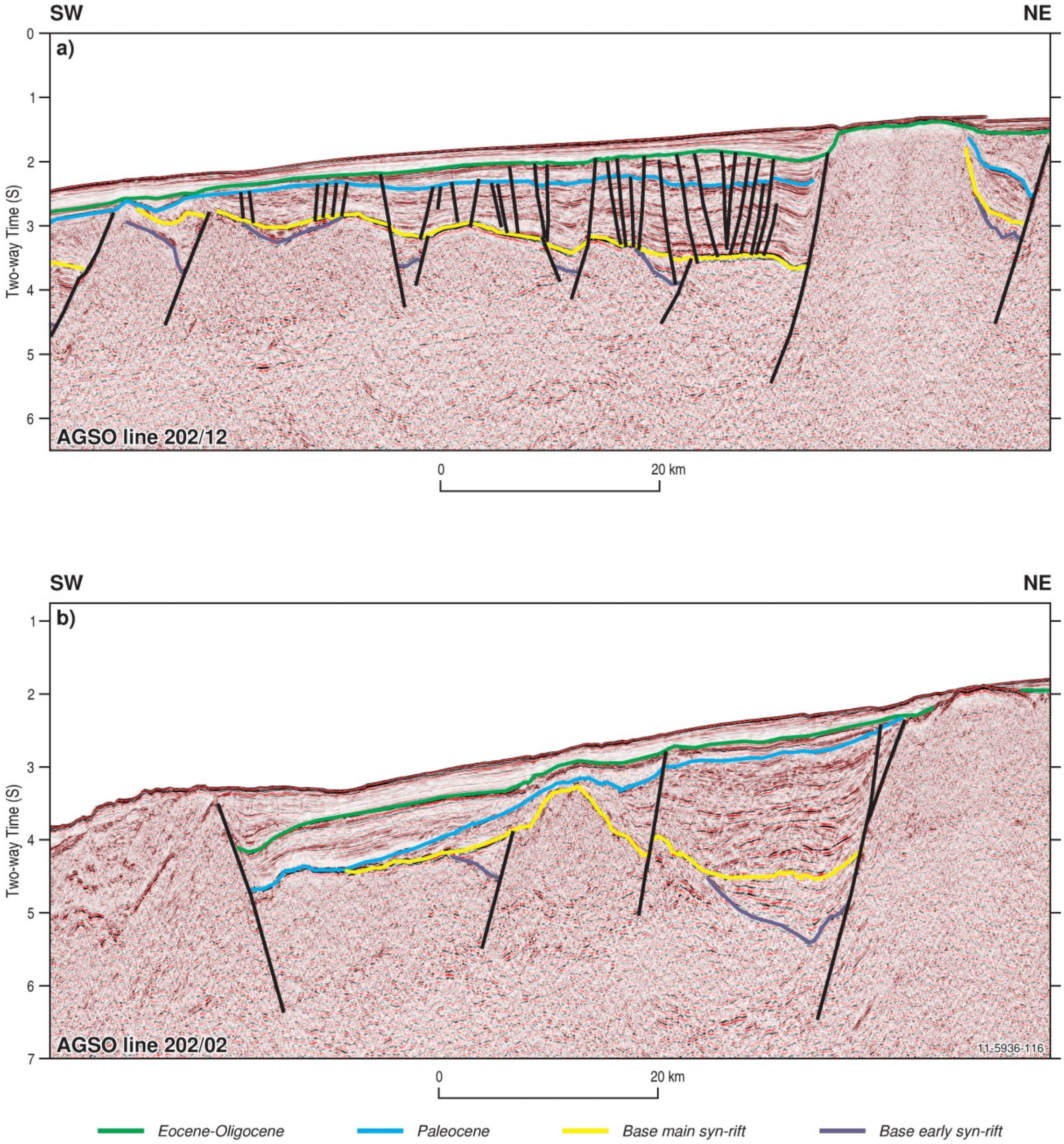

Figure 2.42: Seismic sections, central South Tasman Rise.

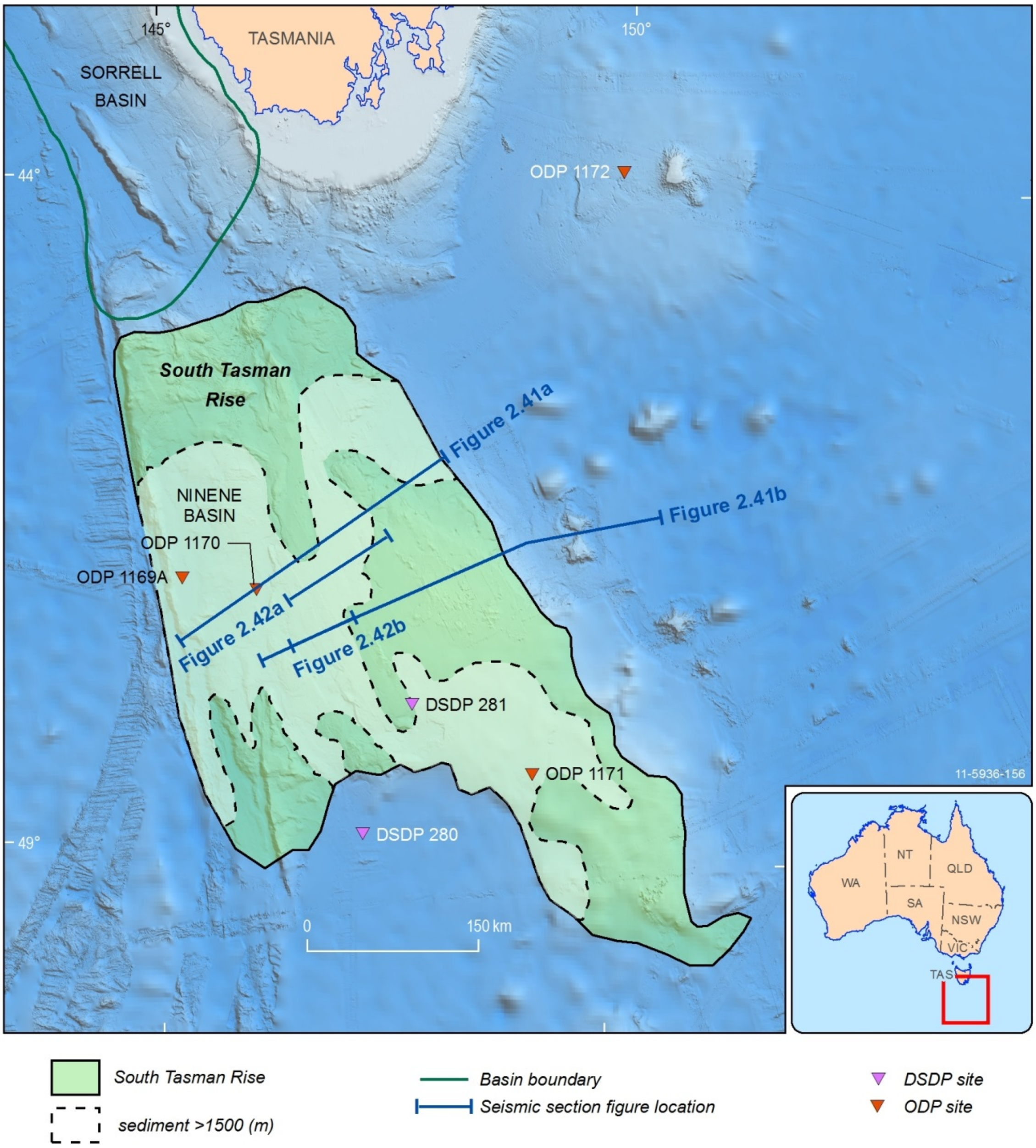

Figure 2.43: Location map, South Tasman Rise.

2.8.3 Petroleum systems

The STR contains numerous strike-slip and extensional basins. Some of these basins contain several kilometres of sedimentary section, and the deepest of these depocentres may have the potential to host petroleum systems. However, given the low level of geological knowledge of the basins, the remote and inhospitable nature of the region and the generally deep water (800–4000 m), the STR has yet to attract any hydrocarbon exploration.

The most prospective section in these basins is likely to be the undrilled pre-Oligocene clastic rift-fill, however, only the thickest rifts (up to 3 s TWT) would have any potential for hosting mature source rocks. Similarly, reservoir facies are likely to be limited to the rift successions.

2.8.3.1 Source Rocks

Eocene sediments from ODP Leg 189 wells drilled on the STR recorded TOC values ranging from 0.5–3.0% (Hill & Moore, 2001). The hydrocarbon potential of Eocene sediments from DSDP Site 280 was also reported by Whiticar et al. (1985; Figure 2.40). These rocks provide some evidence to suggest that conditions suitable for the deposition of organic-rich facies existed prior to the development of the Tasmanian Gateway (Exon et al., 2001c).

2.8.3.2 Generation and expulsion

Temperature measurements made during ODP Leg 189 indicate moderately high terrestrial heat flow in the region (55–72 mW/m^2), with geothermal gradients of ~50–60°C/km (Exon et al., 2001b; Hill & Moore, 2001). None of the DSDP and ODP holes in the region were deeper than a kilometre, and the successions penetrated were thermally immature to marginally mature (Hill & Moore, 2001).

2.8.3.3 Reservoirs and seals

The potential for sealed reservoirs in the Cretaceous section is unknown, but shallow marine clastic sediments and pelagic claystones and oozes in the Cenozoic succession may provide regional seals. Siliciclastic sediments drilled were generally silty mudstones, so sediments with reservoir potential have not been sampled; the deeper rift sections may contain suitable reservoir facies.

2.8.3.4 Play types

Seismic data reveals both complex structuring and complex stratigraphic geometries within STR depocentres, providing a range of potential structural and stratigraphic traps for generated hydrocarbons.

2.8.3.5 Critical risks

The main exploration risks in the South Tasman Rise relate to data and geology, and location.

The paucity of good seismic data and virtually no well control for the pre-Eocene section severely limits understanding of the petroleum prospectivity of the region. The limited data that does exist indicates that rift basins are present across, and on the flanks of, the STR, but the age, thickness and nature of the basin fill is poorly constrained. Limited seismic data suggests that some deep depocentres are present, but there is a risk that these basins are potentially too small or thin to have significant hydrocarbon potential.

Two critical issues for exploration on the STR are the water depths in which the basins occur and the remoteness of the region. Rift basins in the western STR and on the margins of the eastern part of the rise generally lie in water depths of 2000–3000 m, while some of the thicker depocentres on the flanks of the central STR high lie in relatively shallower water depths of 1000–1500 m.

The centre of the STR lies approximately 500 km south of Hobart, at latitude 47°20'S. Oceanic and meteorological conditions in the Southern Ocean and at these latitudes are notorious and would have a considerable impact on exploration activities.

2.8.3.6 Overall prospectivity classification

Low

2.8.4 Exploration status

There has been no hydrocarbon exploration on the STR.

2.8.5 Data

Two DSDP sites 280 and 281 were drilled in 1973 on the southwestern flank of the STR. OPD sites 1169, 1170 and 1171 were drilled in 2000 on the western and southern flanks of the STR (Table 2.27; Hill & Moore, 2001). See Figure 2.44 for locations of DSDP and ODP sites.

Seismic data coverage comprises a northwest–southeast oriented grid of high speed seismic data and a few, widely-spaced, mainly shallow seismic lines of varying vintage and quality. In 1998, as part of AGSO's Law of the Sea Program, a network of deep seismic lines was acquired over the east Tasman Plateau and STR. Two of these lines transect the southern part of the STR and provide the only good quality seismic data in the region; portions of these lines across two of the larger depocentres on the STR are shown in Figure 2.42 (locations are shown in Figure 2.43).

Numerous marine geological sampling and geophysical surveys have been conducted on the STR since the late 1960s; key surveys are listed in Table 2.28–Table 2.30.

2.8.5.1 Confidence rating

Low

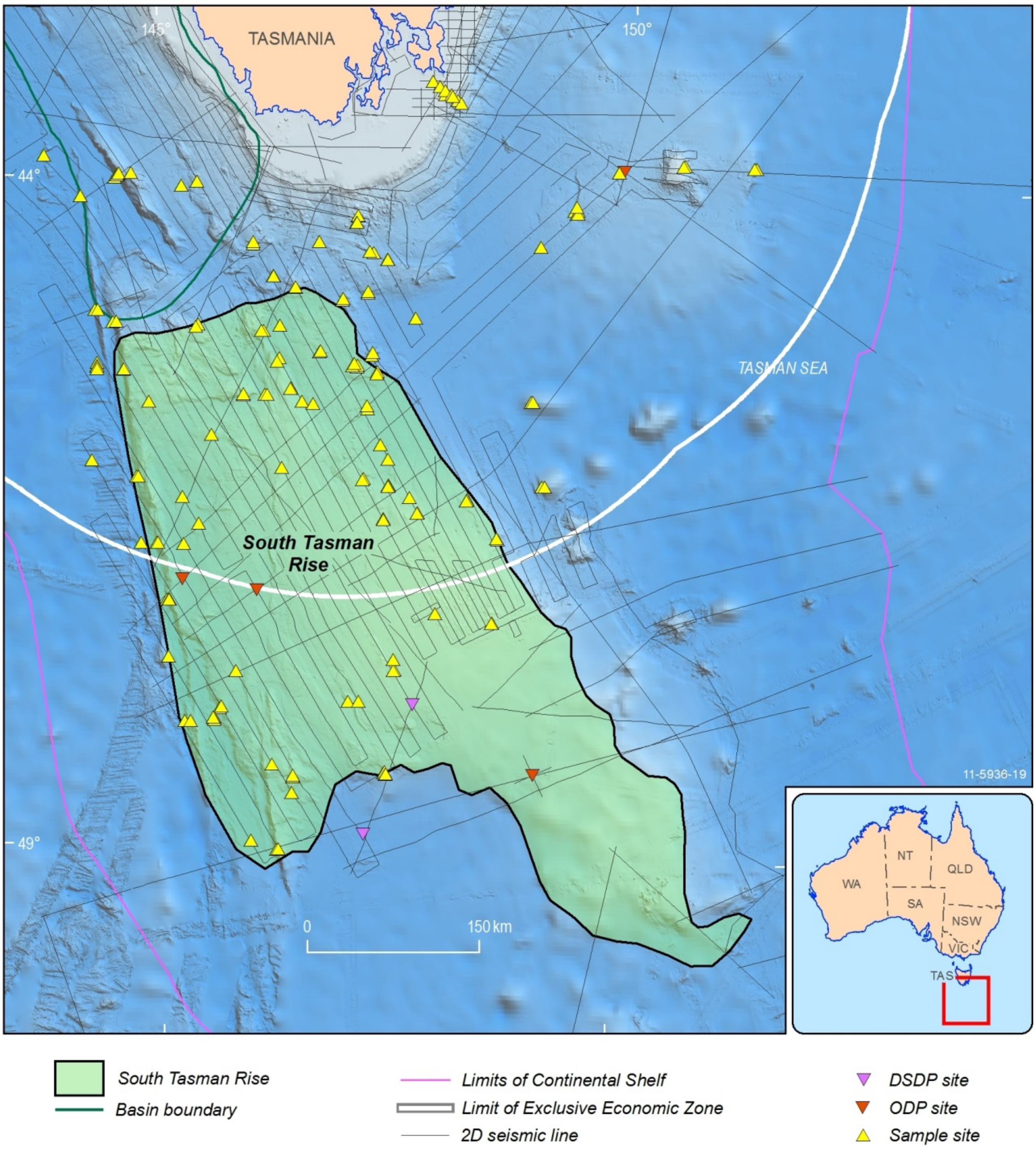

Figure 2.44: Seismic, well and sample distribution.

2.8.6 Issues and remaining questions

The South Tasman Rise is an exploration frontier and despite numerous research cruises and DSP/ODP drilling, questions still remain about the geology of the region, particularly that of its basins. In order to improve our understanding of the geology and resource potential of the region, new, high quality and high resolution geophysical data and deep stratigraphic drilling are required.

2.8.6.1 Recommendations

- Crucially, there is a lack of high quality, deep seismic data over the STR region. More closely spaced 2D reflection seismic data is required in order to better understand the nature of the depocentres on the STR and their potential prospectivity. The acquisition of both regional-scale data (10–20 km line spacing), to improve understanding of the distribution and size of depocentres, and higher resolution, more closely spaced lines over some of the larger depocentres is recommended. In addition, acquisition of seismic refraction data is required to constrain crustal structure and depth to basement.

- Present data sets suggest that the interpreted Cretaceous rift section does not outcrop at the seafloor; as a result, targeted dredging surveys would not necessarily obtain any older samples. Therefore, deeper drilling is considered to be the only way to obtain geological samples from the potentially prospective Cretaceous section.
- While bathymetric data coverage is good across the STR, the existing coverage of magnetic data is relatively patchy. However, while new aeromagnetic data would be undoubtedly useful, the distance of the STR from Tasmania is most likely to be prohibitive.

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2.8.8 Data Tables

Table 2.27: List of wells, South Tasman Rise.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1975	DSDP Leg 29 Site 280	Stratigraphic	DSDP	524	Middle Eocene	nil	Kennett, Houtz et al., 1975a
1975	DSDP Leg 29 Site 281	Stratigraphic	DSDP	169)	Late Eocene	nil	Kennett, Houtz et al., 1975a
2001	ODP Leg 189 Site 1169	Stratigraphic	ODP	246.3	Middle Miocene	nil	Exon et al., 2001a, 2001b
2001	ODP Leg 189 Site 1170	Stratigraphic	ODP	779.8	Middle Eocene	nil	Exon et al., 2001, 2001b
2001	ODP Leg 189 Site 1171	Stratigraphic	ODP	958.8	Late Paleocene	nil	Exon et al., 2001a, 2001b

Table 2.28: Key seismic surveys, South Tasman Rise.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1973	Shell *Petrel*	Shell		
1985	*Sonne* SO-36B	BMR/BGR		Hinz et al., 1985
1994	*Tasmante* AGSO Survey 125	AGSO		Exon et al., 1994
1995	TASGO AGSO Survey 148/159	AGSO		Hill et al., 1995
1998	AGSO Survey 202	AGSO		Bernardel, 1999
2000	*Polar Duke* PD00	BGR		

Table 2.29: List of key geological sampling surveys, South Tasman Rise.

Year	Survey	Operator	Region	Type	Rock types	Reference
1985	SO-36C *Sonne*	BGR	West Tasmanian margin and South Tasman Rise	Dredge/core/grab	Cz ooze, clastic and carbonate rocks, Cretaceous clastic rocks	Hinz et al., 1985;
1995	Survey 147 (Tasman Rises)	AGSO	West Tasmanian margin and South Tasman Rise	Dredge/core/grab	Upper Cretaceous and Cenozoic mudstone and sandstone; Neogene carbonate rocks; ?Paleozoic clastic rocks; granites, gneiss and basalt	Exon et al., 1995
1998	TASQWA; SO136 *Sonne*	BGR	South Tasman Rise	Gravity and box cores		Thiede et al., 1999

Table 2.30: Swath bathymetry surveys, South Tasman Rise

Year	Survey	Operator	Line-km	Reference
1994	Tasmante (*L'Atalante*)	AGSO	13,600 km (STR and western Tasmanian margin)	Exon et al., 1994;
2000	AUSTREA (AGSO surveys 222, 223)	AGSO		Hill et al., 2000, 2001; Bernardel et al., 2000

2.9 Durroon Sub-basin (Bass Basin)

2.9.1 Summary

State(s)		Tasmania
Area (km^2)		~9800
Water Depth (m)		30–60
Maximum sediment thickness (m)		~7000
Age range		Early Cretaceous–Holocene
Basin	**Overlies**	Tasman Orogen
	Parent	Bass Basin
	Adjacent basins	Cape Wickham Sub-basin
Basin type		Extensional
Depositional setting, rock types		Non-marine and shallow marine clastic sedimentary rocks
Petroleum prospectivity		Low–Moderate
Confidence		*Medium*

2.9.2 Geology

The Durroon Sub-basin forms the eastern part of the Cretaceous–Cenozoic Bass Basin, a northwest-trending, intracratonic rift basin that underlies the Bass Strait between northern Tasmania and southern Victoria (Figure 2.45). The Bass Basin is separated from the Otway and Sorell basins to the west by the King Island High, and from the Gippsland Basin to the northeast by Flinders Island and the Bassian Rise. The Bass Basin is divided into the Cape Wickham Sub-basin in the west and the Durroon Sub-basin in the east (Blevin et al., 2005). The Cape Wickham Sub-basin is a proven hydrocarbon province, hosting several gas discoveries and a producing gas and condensate field (Yolla). In comparison, the Durroon Sub-basin is underexplored, and no discoveries have been made in this portion of the Bass Basin (Figure 2.45).

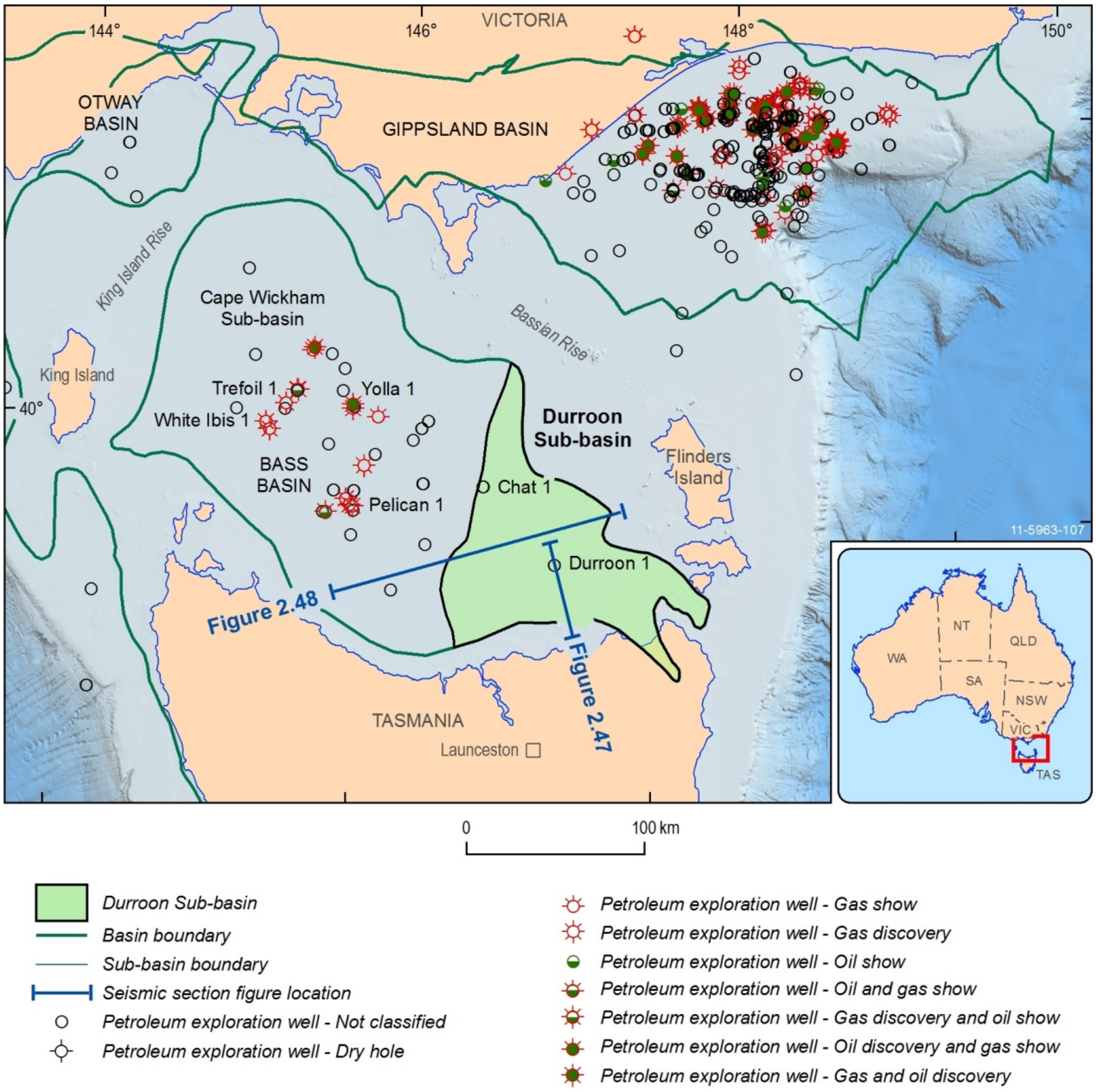

Figure 2.45: Structural elements map, Bass Basin.

2.9.2.1 Structural geology

Intracontinental extension between Australia and Antarctica during the Jurassic and Early Cretaceous resulted in the formation of a series of rift basins along the southern margin of Australia—the Southern Rift System (SRS; Stagg et al., 1990). The Bass Basin, which forms the easternmost element of the SRS, was initiated in the Early Cretaceous. Extension in the Bass Basin preceded eventual breakup between Australian and Antarctic (Blevin, 2003), which commenced in the Bight Basin to the west in the latest Santonian–earliest Campanian (83 Ma; Sayers et al., 2001). To the east, commencement of breakup in the Tasman Basin in the Campanian was approximately coeval with breakup along the southern margin (Symonds et al., 1996; Blevin, 2003). Blevin (2003) argued that the location of the Bass Basin at the junction between two Cretaceous rift systems (the Southern Rift System and Tasman Basin) had a strong control on the evolution of the basin and resulted in the area experiencing multiple periods of deformation. Although extension progressed to breakup and seafloor spreading in the adjacent Southern Ocean and Tasman basins, the Bass Basin remained a 'failed rift' basin where breakup did not occur (Blevin, 2003).

The Bass Basin is an extensional basin characterised by generally northwest–southeast oriented half graben (Blevin 2003; Blevin et al., 2005; Cummings et al., 2004; Smith, 1986; Etheridge et al., 1985; Williamson et al., 1985). The Cape Wickham and Durroon sub-basins are separated by the north-northeast-striking Chat Accommodation Zone. Blevin (2003) suggested that the location of this feature and the structural architecture of the two sub-basins are likely to have been controlled by the underlying basement fabric, with the Durroon Sub-basin overlying the deformed sediments and granites of the Lachlan Fold Belt, and the Cape Wickham Sub-basin overlying an older fold belt terrane. The Durroon Sub-basin is characterised by a series of northwest-trending half graben bounded by northeast-dipping faults, which are generally narrower and more intensely faulted than those in the western part of the basin (Blevin, 2003). The sub-basin contains a Cretaceous–Cenozoic rift and post-rift succession up to 7000 m thick (Baillie & Pickering, 1991).

2.9.2.2 Basin evolution and depositional history

Two Early Cretaceous rift phases can be identified in the Durroon Sub-basin (Figure 2.46). The first, in the Barremian–earliest Cenomanian, was coeval with extension in the adjacent Otway Basin and resulted in deposition of the non-marine Otway Megasequence (Blevin, 2003). Stratal geometries of this unit suggest that it was deposited during a period of slow subsidence, prior to the main phase of rifting (Figure 2.47; Blevin et al., 2005). The Otway Megasequence was intersected in Durroon 1, where it comprises stacked fluvial channel sands interbedded with thin, coaly overbank–floodplain shales (Blevin et al., 2005). The sediments are volcanogenic, similar to the correlative Eumeralla Formation in the Otway Basin (Blevin, 2003).

A second phase of extension affected the basin during the Turonian–Campanian, driven by Tasman Basin rifting to the east (Cummings et al., 2002). Half graben initiated in the previous rifting phase continued to develop and expand, forming a systems of linked depocentres (Blevin et al., 2005). The rift-fill (Durroon Megasequence) shows strong syn-tectonic growth against the bounding faults (Figure 2.47 and Figure 2.48). At Durroon 1, the Durroon Megasequence comprises interbedded shale, siltstone and sandstone overlying a basalt. Thick shales within the megasequence are interpreted to have been deposited in deep, freshwater lacustrine environments (Blevin et al., 2005; Partridge, 2002). Footwall uplift and erosion of upper Otway Megasequence sediments prior to, or coeval with, deposition of the Durroon Megasequence, is evident in the southeastern part of the sub-basin, including at Durroon 1 (Hill et al., 1995; Duddy, 1992).

Extension in the Durroon Sub-basin ceased in the mid-Campanian (Blevin, 2003). From the mid-Campanian to late early Eocene, deposition of the Bass Megasequence took place within an internal drainage basin, with fluvial systems feeding into the slowly subsiding depocentres from the uplifted basin flanks (DITR, 2004). Where intersected by drilling, the Bass Megasequence consists of fluvio-deltaic sandstones interbedded with thin overbank/delta plain shales and thin coal beds. In the Durroon Sub-basin, the Bass Megasequence is variably truncated beneath an unconformity at the base of the overlying Flinders Sequence (Figure 2.47). As a result, the upper Paleocene–lower Eocene coaly succession that is known to have sourced hydrocarbon accumulations in the Cape Wickham Sub-basin (Boreham et al., 2003) is either poorly developed or absent in the Durroon Sub-basin.

The overlying middle Eocene–lower Oligocene Flinders Sequence is an overall transgressive–regressive succession deposited in shallow bay to open marine environments (Blevin et al., 2005). At Durroon 1 and Chat 1, massive sandstone units near the top of the sequence are assigned to the Boonah Formation, which is generally considered the top reservoir unit across most of the Bass Basin.

The uppermost unit of the Flinders Sequence, the “Demons Bluff Shale”, forms a westward-thickening wedge across the basin and is regarded as the regional seal (Figure 2.47); in the Durroon Sub-basin it is generally thin and relatively coarse-grained (Blevin et al., 2005).

The Flinders Sequence is overlain unconformably by the upper Oligocene–Holocene Torquay Sequence, a succession of marine mudstones, marl and calcarenite that ranges in thickness from less than 200 m to 900 m. The Durroon Sub-basin was only mildly affected by the Oligocene and younger magmatic events that characterise the Cape Wickham Sub-basin (Blevin et al., 2005).

2.9.2.3 Level of knowledge

Geological understanding of the Durroon Sub-basin is based on interpretation of a relatively closely-spaced (<1 to >10 km) grid of 2D seismic data of variable quality and vintage, and two wells (Durroon 1 and Chat 1). The wells provide good stratigraphic control but because they are located approximately 50 km apart, there is insufficient data to resolve the variations in lithofacies and source, reservoir and seal units and their distribution.

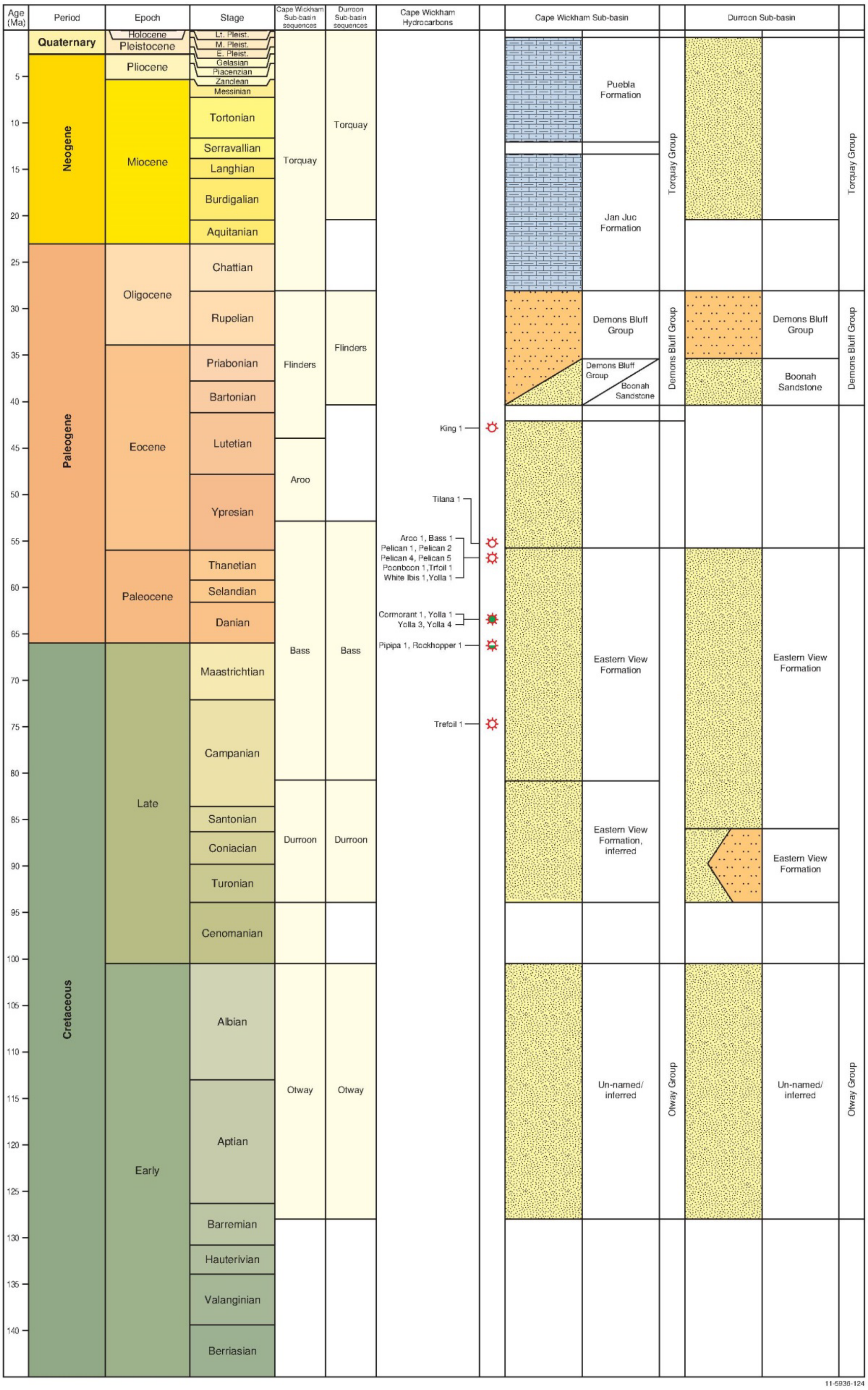

Figure 2.46: Stratigraphy of the Bass Basin. Geologic time scale after Gradstein et al. (2012).

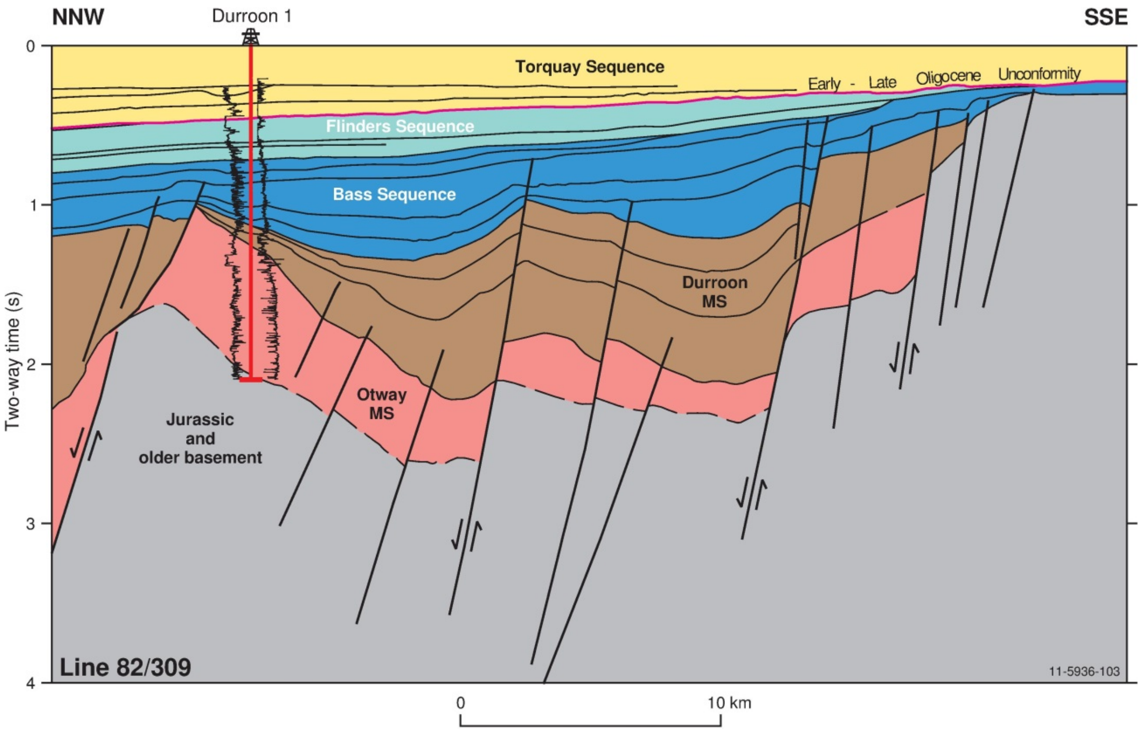

Figure 2.47: Geological cross-section across the eastern Durroon Sub-basin showing structural and stratigraphic relationships (after Blevin, 2003).

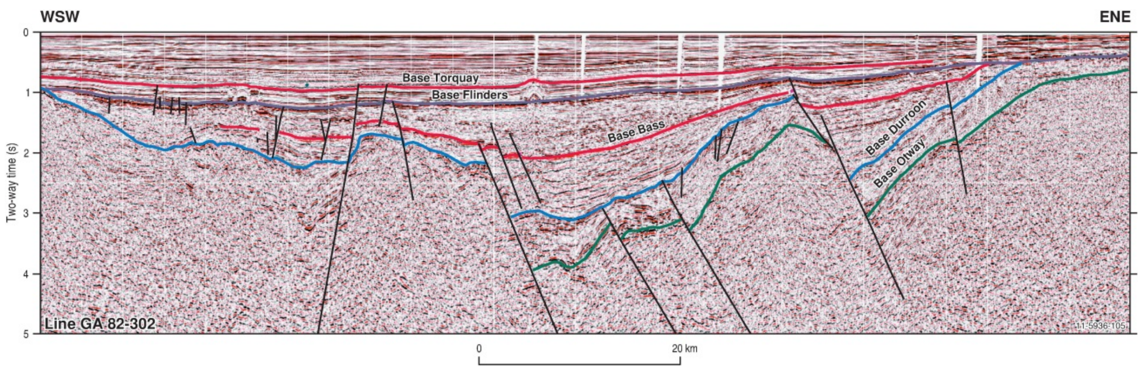

Figure 2.48: Seismic section across the Durroon Sub-basin (from Blevin et al., 2005).

2.9.3 Petroleum systems

Hydrocarbons have been discovered in the Cape Wickham Sub-basin of the Bass Basin at the Yolla, Pelican, White Ibis and Trefoil fields and gas and liquids are currently produced from the Yolla field. There have been no hydrocarbon discoveries in the Durroon Sub-basin, which contains only two exploration wells—Durroon 1 which is located in the centre of the sub-basin, and Chat 1, located on the western margin of the sub-basin. Durroon 1 recorded minor gas indications in mid-Cretaceous–lower Paleocene sediments, and Chat 1 was dry (Trigg et al., 2003).

2.9.3.1 Source Rocks

Hydrocarbon discoveries on the Australian southern margin are assigned to the Austral Petroleum Supersystem (Bradshaw, 1993; Summons et al., 1998; Edwards et al., 1999), in which three subsystems are recognised:

- Austral 1: Upper Jurassic to lowest Cretaceous fluvio-lacustrine shales
- Austral 2: Lower Cretaceous fluvial and coaly facies
- Austral 3: Upper Cretaceous to lowest Cenozoic fluvio-deltaic facies.

The hydrocarbon accumulations discovered in the Cape Wickham Sub-basin are assigned to the Austral 3 subsystem. Boreham et al. (2003) demonstrated that these hydrocarbons were sourced by Paleogene, particularly lower–middle Eocene, coals. Paleogene coals are abundant in the central and western Bass Basin, however, in the Durroon Sub-basin, the equivalent section is either missing or the facies are sand-prone (DITR, 2004). In this part of the basin, potential source rocks are likely to be older, occurring within the Barremian–Maastrichtian section.

Coaly facies of Barremian–Albian age (Otway Megasequence) were penetrated at Durroon 1, with some coals in this section up to 10 m thick. These coals have significant petroleum generation potential, with Hydrogen Index values between 200 and 300 mg HC/g TOC (Trigg et al., 2003). The coaly Otway Megasequence section in Durroon 1 is equivalent in age to the Eumeralla Formation of the Otway Basin, which is known to have sourced gas and condensate accumulations in the Shipwreck Trough and forms the basis of the Austral 2 petroleum system (Edwards et al., 1999; Geoscience Australia & GeoMark Research, 2002). The overlying Durroon Megasequence appears to have low source potential, although only one well (Durroon 1) has fully tested the sequence (Blevin, 2003).

Maastrichtian–lower Paleocene (Austral 3) coals with source rock potential were penetrated at Chat 1. Geochemical analyses of these sediments suggest good source richness, with TOC values consistently greater than 2% (Trigg et al., 2003). Potential good quality source intervals with oil-prone organic matter (Hydrogen Index >300 mg HC/g TOC) are present in this section. However, vitrinite reflectance (<0.65% Ro) and Rock Eval T_{max} (<440°C) data, together with low Production Index (PI) values, indicate that sediments to total depth at Chat 1 are immature for oil and gas generation (Trigg et al., 2003).

2.9.3.2 Generation and expulsion

The basin-wide onset of oil generation, as calculated by vitrinite reflectance (0.65% Ro), occurs at depths of between 1.6 to 2.4 km below seafloor, while the depth to the oil expulsion window (0.75% Ro) varies between 2.3 to 3.0 km below seafloor (Cummings & Tingate, 2003).

The section penetrated in Chat 1 is immature for hydrocarbon generation. Burial history modelling by Cummings & Tingate (2003) showed that while sediments at the base of Durroon 1 just reached the oil generation window, maturity levels sufficient for expulsion of oil and gas occur below the total depth of the well (>3000 m). Therefore, the numerous gas shows recorded at Durroon 1 are likely to have been sourced from mature organic-rich intervals down-dip in the more deeply buried parts of the half graben. Modelling suggests that potential source rocks in the Otway Megasequence entered the oil and gas generation window during rapid deposition of the overlying Durroon Megasequence (Cummings & Tingate, 2003).

2.9.3.3 Reservoirs and seals

As a result of the predominantly terrestrial nature of sedimentation in the Bass Basin until the middle Eocene, most reservoir and seal facies occur as inter-fingering and interbedded units (DITR 2004). Potential reservoir facies in the Bass Megasequence and Flinders Sequence are likely to be sealed by shales within the Flinders and Torquay sequences in the western part of the Durroon Sub-basin. However, these shaly units thin and become coarser-grained to the east, so potential reservoirs in the upper Flinders Sequence (e.g. the Boonah Formation) are unlikely to have adequate seal in this part of the basin. In Durroon 1, potential reservoir facies are present deeper in the section, within the Otway and Durroon megasequences. Lithic sandstones in the upper Otway Megasequence have average measured porosities of 17.6% and permeabilities of 39.1 mD. Porosity and permeability analyses of sandstones deeper in the section in Durroon 1 indicate poorer reservoir quality (porosity of 13.3%, but little or no permeability; Esso, 1973). At Chat 1, good to very good porosities (19.6–29.2%) were reported within the Campanian–Eocene succession (Bass Megasequence and Flinders Sequence; Bridge Oil, 1986; Trigg et al., 2003). Potential sealing faces in the Cretaceous syn-rift section include thick deep-water lacustrine shales in the Durroon Megasequence, and overbank shales in the Otway Megasequence (Daniel et al., 2003).

2.9.3.4 Play types

The Durroon Sub-basin is an intracratonic, largely terrestrial rift basin. Play types in the basin include rotated faults blocks with structural closure extending upward into onlapping and overlying strata, with charge provided by mature source rocks in the deepest and thickest parts of the half graben. Stratigraphic traps are also possible in sandy facies along the basin margin (alluvial fans), and lacustrine deltaic and turbidite facies associated with the “Durroon Lake” near the base of the Durroon Megasequence. Mature source rocks are likely to occur in Eumeralla Formation-equivalent coals in the Otway Megasequence. Potential long-range migration from the western Bass Basin is also possible given the westward-thickening, wedge-like geometry of Upper Cretaceous and younger strata across the basin (DITR, 2004).

2.9.3.5 Critical risks

The main exploration risks in the Durroon Sub-basin relate to maturity of source rocks, hydrocarbon charge, preservation of accumulations, and the presence of good quality reservoir and seal facies.

A key prospectivity risk in the Durroon Sub-basin is the maturity of potential source rocks in areas where the basin fill is less than 3000 m thick. Mature source rocks are likely to be present only within the deepest parts of the half graben. Given the compartmentalised nature of the Early Cretaceous depocentres where potential source rocks accumulated, and likely early generation and expulsion from those source rocks, the volume and timing of charge are also considered to be key exploration risks. Cummings & Tingate (2003) suggested that generation and expulsion from potential source rocks within the Otway Megasequence was driven by rapid deposition of the Durroon Megasequence in the Turonian–Campanian. Although the sub-basin has not undergone significant deformation since that time, uplift and erosion associated with the Durroon Unconformity (early–middle Eocene) may have implications for the preservation of early accumulations. Biodegradation of accumulations in shallow middle–upper Eocene reservoirs is also a potential risk.

Due to the paucity of drilling, the extent, distribution and quality of intraformational reservoir and seal facies within the Otway and Durroon megasequences are poorly understood.

2.9.3.6 Overall prospectivity classification

Low–Moderate

2.9.4 Exploration status

There have been no hydrocarbon discoveries in the Durroon Sub-basin and, despite several phases of industry activity, the area remains an exploration frontier. Key early explorers in the sub-basin were Esso Exploration and Production, Hematite Petroleum and Bridge Oil. Permits were held in the sub-basin as recently as 2012. In 2004, acreage was made available across most of the sub-basin and permits were subsequently awarded to 3D Oil (T/41P) and Bass Strait Oil (T/42P and T/43P). T/39P, awarded to Benaris Petroleum, was mostly located in the adjacent Cape Wickham Sub-basin. Despite leads and prospects being identified (3D Oil, 2008, 2012), none of the permits were renewed. Nearly three decades have elapsed since the last well, Chat 1, was drilled in the Durroon Sub-basin in 1986.

2.9.5 Data

Key data sets for the Durroon Sub-basin are listed in Table 2.31–Table 2.33. Only two wells have been drilled in the sub-basin (Durroon 1 and Chat 1; Figure 2.49); neither encountered significant hydrocarbons. 2D seismic data coverage across the Durroon Sub-basin is good given its frontier exploration status, although much of the data was acquired prior to 1992. Seismic line spacing varies from <1 km to >10 km (Figure 2.49). During the most recent phase of exploration (2005–2012), approximately 3400 km of 2D seismic data was acquired in the Durroon Sub-basin. 3D Oil's Dalrymple 3D survey was acquired to the west of Chat 1, however most of the survey area was located within the Cape Wickham Sub-basin.

2.9.5.1 Confidence rating

Medium

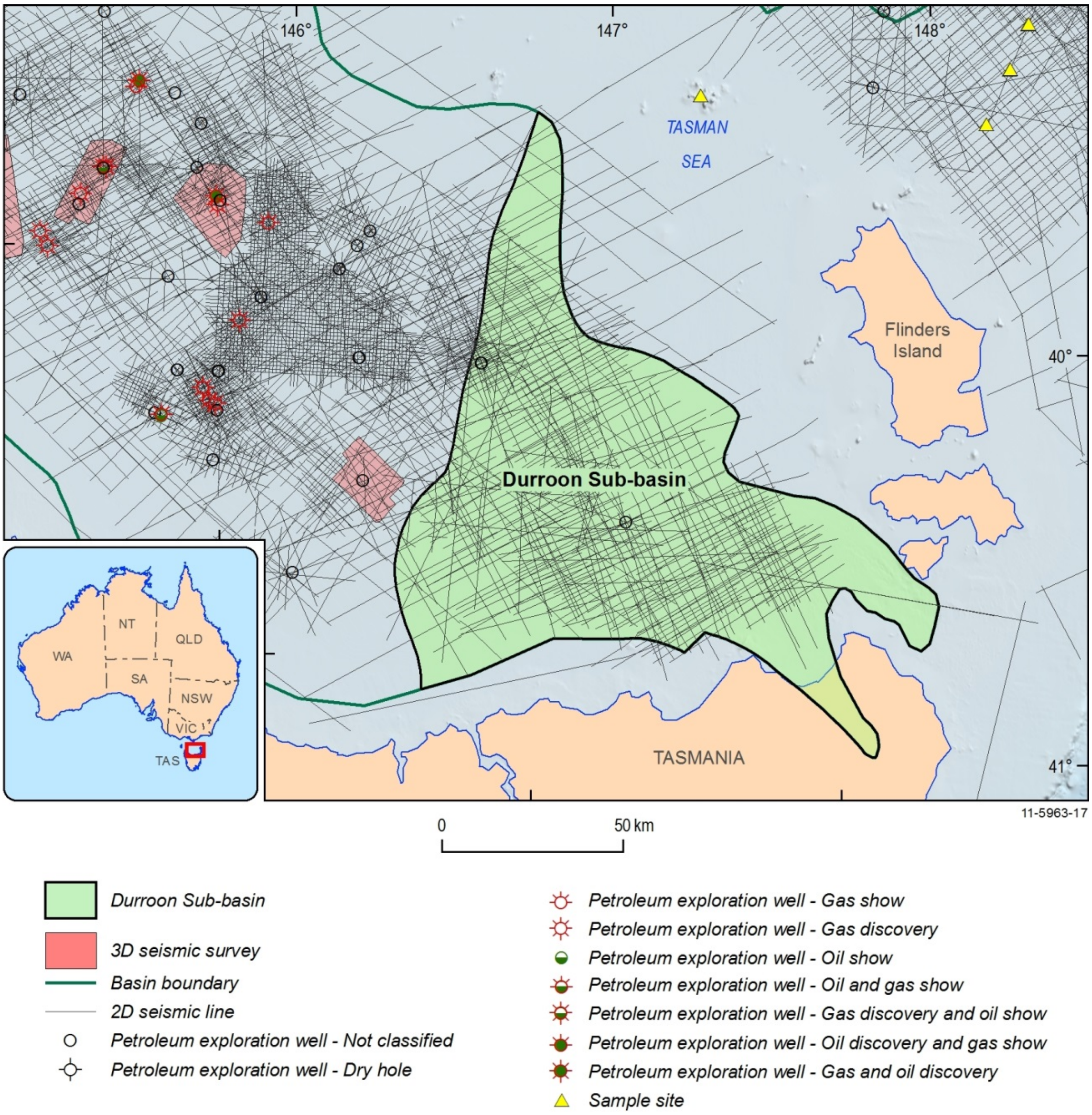

Figure 2.49: Seismic, well and sample distribution.

2.9.6 Issues and remaining questions

As only two wells, Durroon 1 and Chat 1, have been drilled in the Durroon Sub-basin, the lithology, facies and age of the basin fill away from those wells is unknown. As a result, questions persist about the prospectivity of the sub-basin. These relate largely to the distribution, quality and maturity of source rocks, the presence of good quality reservoirs and the relative timing of generation and migration versus uplift and erosion events.

2.9.6.1 Recommendations

- The sub-basin has a relatively good 2D seismic coverage, so these gaps in knowledge would be best addressed through further drilling together with acquisition of high quality, preferably 3D, seismic data. This additional data would enable better testing of existing play concepts, such as those based on Otway Megasequence/Eumeralla Formation equivalent Austral 2 source rocks.

- Following acquisition of new seismic/well data, detailed sequence stratigraphic and structural interpretation and modelling could be used to develop new play concepts and to better understand:
  - The extent, facies and source rock potential of the Turonian–Campanian “Durroon Lake” sediments (Durroon Megasequence);
  - The impact of uplift and erosion on the flanks of the depocentre, particularly the Bassian Rise to the east, and the potential for the development of localised reservoir sands.
- Using data from adjacent data-rich depocentres (Cape Wickham Sub-basin and Gippsland Basin), undertake basin–regional-scale palaeogeographic mapping to assist in understanding the distribution and nature of potential source, reservoir and seal units.

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2.9.8 Data Tables

Table 2.31: List of wells, Durroon Sub-basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1972	Durroon 1	Exploration	Esso	3024	Early Cretaceous	Oil indications	Esso, 1973
1986	Chat 1	Exploration	Bridge Oil	3104	Middle Jurassic (dolerite)		Bridge Oil, 1986; Blevin & Cathro, 2008

Table 2.32: Key seismic surveys, Durroon Sub-basin.

Year	Survey	Operator	Line-km	Reference
1988	Bass 1988 2D MSS (BB88)	Bridge Oil	551	
1990	Survey 90	BMR		
1996	Bass Basin 1990	Bridge Oil	1055	
1991	Durroon 1991 2D MSS	Bridge Oil	376	
2008	TDOB08	3D Oil	2200	3D Oil, 2008
2008	Targa 2D (BOBS08)	Bass Strait Oil	1192	

Table 2.33: Key geological sampling surveys, Durroon Sub-basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
1992	Rig Seismic Survey 104	BMR	Torquay Sub-basin, eastern Otway Basin, Gippsland Basin, Durroon Sub-basin	Geochemical sampling, vibrocores, seismic	Surficial sediments	Bishop et al., 1992
2001	Geoscience studies on the SE Australian continental slope and shelf (RV Franklin cruise FR3/01	AGSO/CSIRO	Eastern Tasmania, Bass Strait	Cores, grabs	Calcareous sand, shelly mud	Exon et al., 2002
	Carbonate mud sedimentation on a temperate shelf: Bass Basin	University of Sydney	Bass Basin	Cores, grabs	Carbonate mud	Blom & Alsop, 1988

3 Southwestern margin basins

The offshore southwestern margin region includes the Southern Carnarvon, Perth and Mentelle basins, and the Wallaby and Naturaliste plateaus (Figure 3.1). The basins of Australia's southwestern continental margin developed as a result of a complex, multi-phase history of extension and reactivation. Multiple phases of extension during the Permian were followed by a long period of subsidence from the late Permian to the Early Jurassic. Extensional phases in the Jurassic and Early Cretaceous culminated in continental breakup in the Valanginian. Periods of inversion in the Miocene–Holocene also affected the basins. Basin development was primarily controlled by tectonic processes on the western margin of Australia, although activity along southern margin has also influenced the Mentelle Basin and Naturaliste Plateau.

Key references that discuss the geology and tectonic evolution of the southwestern margin include: Mory & Iasky (1996), Norvick & Smith (2001), Borissova (2002), Bradshaw et al. (2003), Crostella & Backhouse (2000), Norvick (2004), Borissova et al. (2010), Jones et al. (2011), Jones et al. (2012), Pfahl (2011), Rollet et al. (2013a, b).

On the southwestern margin, hydrocarbons have only been discovered in the Vlaming and Abrolhos sub-basins of the Perth Basin, as well as in adjacent areas of the onshore northern Perth Basin. This inventory addresses the nine offshore frontier regions on the southwestern margin. The Houtman and Zeewyck sub-basins, and Turtle Dove Ridge of the Perth Basin lie outboard of the Abrolhos Sub-basin, which hosts numerous hydrocarbon discoveries. These areas are under-explored; however, the Houtman Sub-basin in particular has recently become the focus of renewed exploration interest. To the north and northwest of the Houtman Sub-basin are the vast frontier regions of the Southern Carnarvon Basin (Bernier Platform and Gascoyne Sub-basin) and Wallaby Plateau. At the southern end of the margin are the underexplored deep-water frontiers of the Eastern and Western Mentelle Sub-basins. Farther west, the geology of the extensive Naturaliste Plateau is poorly known, and its hydrocarbon potential untested (Figure 3.1).

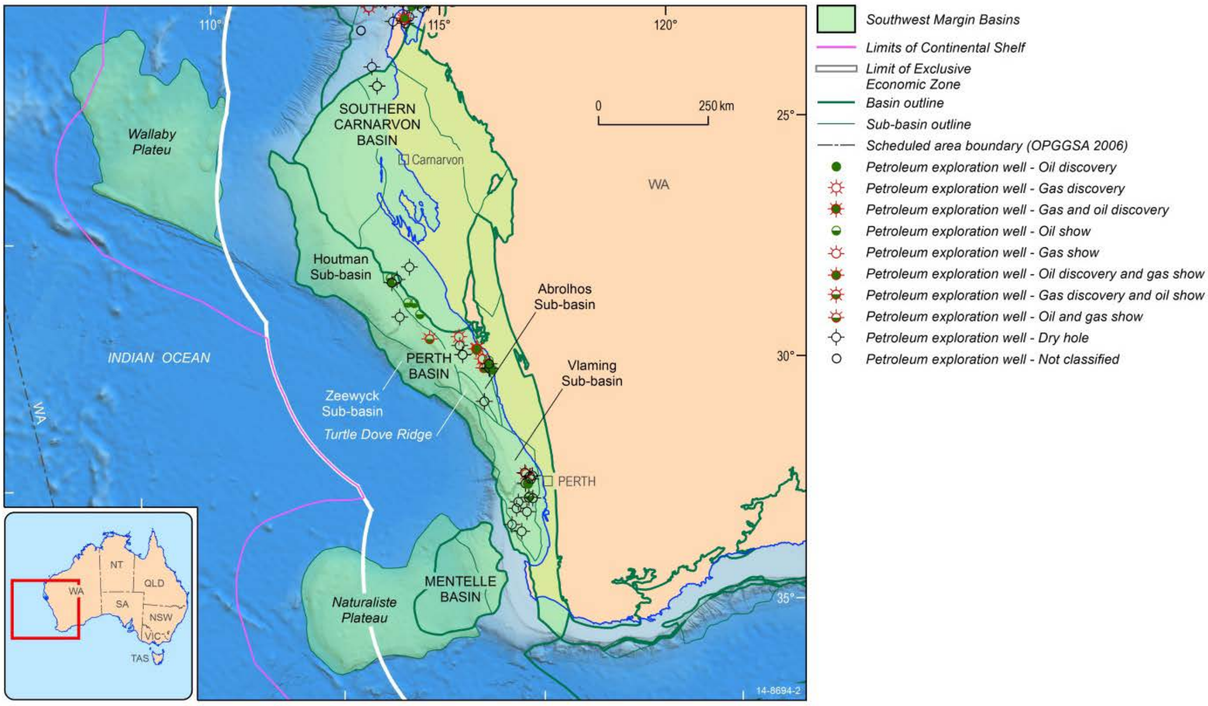

Figure 3.1: Basins and provinces of the southwestern Australian margin

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3.1 Naturaliste Plateau

3.1.1 Summary

State(s)		WA
Area (km^2)		90,000
Water Depth (m)		~2000–5000
Maximum sediment thickness (m)		2500
Age range		?Jurassic–Holocene
Basin	**Overlies**	Pinjarra Orogen?
	Adjacent basins	Mentelle Basin
Basin type		Extensional basins within continental(?) plateau
Depositional setting, rock types		unknown
Overall prospectivity		Low
Confidence		*Low*

3.1.2 Geology

The Naturaliste Plateau is a large submarine plateau that lies off the southwest tip of mainland Australia (Figure 3.2). Recovery of continental rocks on the southern margin of the plateau, and the presence of sedimentary sequences similar to those in the Perth Basin, show that the plateau is underlain mostly by continental crust (Royer & Beslier, 1998; Beslier et al., 2004; Borissova, 2002; Halpin et al., 2008).

During Gondwanan breakup, the Naturaliste Plateau was located at the junction of the Australia, Antarctica and India plates (Norvick & Smith, 2001; Borissova, 2002; Direen et al., 2007; Gibbons et al., 2012; Whittaker et al., 2013; Williams et al., 2013). The western and northern flanks of the Naturaliste Plateau formed during the rifting of India from Australia, while the southern flank formed during rifting between Australia and Antarctica (Borissova, 2002; Direen et al., 2007; Whittaker et al., 2013; Williams et al., 2013).

3.1.2.1 Structural geology

Across the plateau, a series of rift basins imaged on seismic profiles typically show half-graben geometries, and are bounded by steep east-northeast oriented normal faults dipping south or southeast (Figure 3.2 and Figure 3.3; Borissova, 2002). The basins are 10 to 30 km wide and up to 120 km long (Borissova, 2002). Overall, the basement of the southern Naturaliste Plateau is faulted and more eroded in comparison to its northern part (Borissova, 2002). The largest rift basin is located in the southeast part of the plateau and consists of several en echelon segments (Figure 3.2; Borissova, 2002). Two smaller rift basins have been mapped in the north western and south western parts of the Naturaliste Plateau (Figure 3.2; Borissova, 2002). A large circular-shaped bathymetric and gravity high on the north western flank of the Naturaliste Plateau has been mapped as a possible volcanic/intrusive complex (Borissova, 2002).

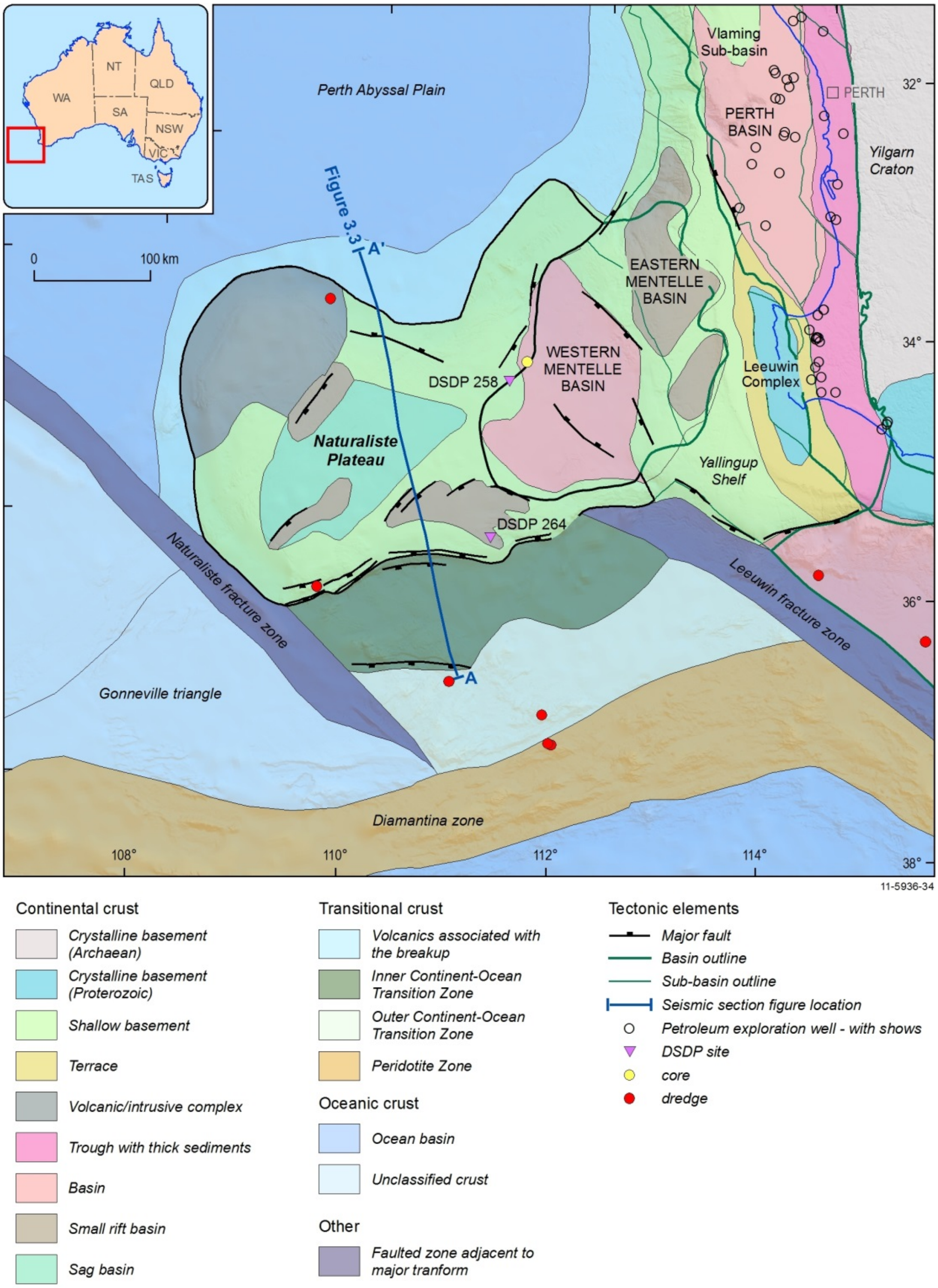

Figure 3.2: Structural elements of the Naturaliste Plateau from Borissova (2002).

A marked continent–ocean transition zone (COTZ) flanks the plateau. To the south, the COTZ consists of a mixture of modified continental lower crust, breakup-related volcanics and exhumed continental mantle (Borissova, 2002; Direen et al., 2007; Halpin et al., 2008). To the north, it has a more volcanic nature and is part of the southwestern Australian rifted margin (Borissova, 2002;

Gibbons et al., 2012; Hall et al., 2013; Whittaker et al., 2013). Plate reconstructions show that the Batavia and Gulden Draak Knolls, continental fragments now situated over a thousand kilometres to the northwest in the Indian Ocean (Williams, 2011; Kobler, 2012; Gardner, 2012), were juxtaposed to the north and south of the Naturaliste Plateau immediately prior to their final breakup from Australia/Antarctica (Gibbons et al., 2012: Whittaker et al., 2013).

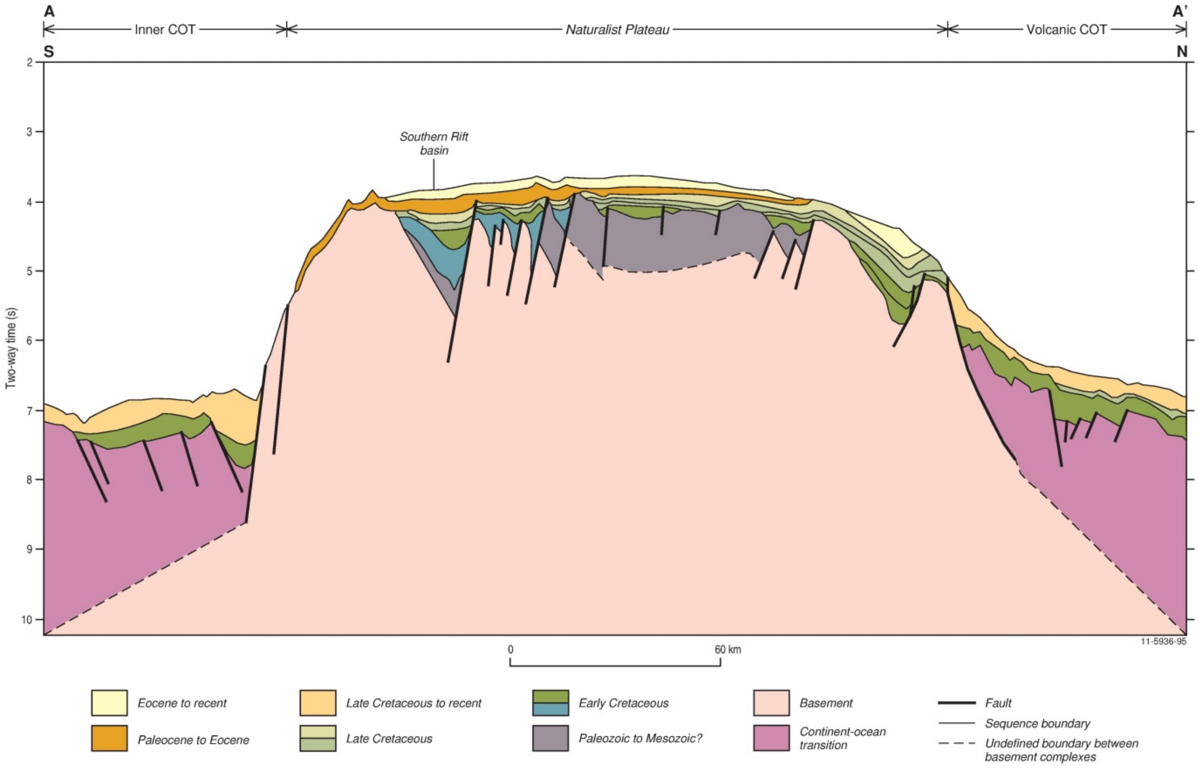

Figure 3.3: Geological cross-section of the Naturaliste Plateau showing structural and stratigraphic relationships (Borissova, 2002). See Figure 3.2 for cross-section location.

3.1.2.2 Tectonic evolution and depositional history

The Naturaliste Plateau has undergone multiple phases of extension and volcanism, controlled by the rifting and subsequent breakup of Australia, India and Antarctica (Figure 3.4; Norvick & Smith, 2001; Borissova, 2002; Bradshaw et al., 2003; Direen et al., 2007; Borissova et al., 2010a, b; Gibbons et al., 2012; Whittaker et al., 2013).

Rocks dredged from the southern margin of the Naturaliste Plateau show that it is floored by continental crust (Beslier et al., 2004; Halpin et al., 2008). The protoliths show greatest affinity to Mesoproterozoic rocks of the Albany–Fraser Orogen in Western Australia and the Wilkes Orogen in east Antarctica (Clark et al., 2000). High-grade metamorphic overprinting occurred in the early Cambrian, coeval with tectonic activity in the onshore Leeuwin Complex (Collins, 2003; Fitzsimons, 2003). This metamorphic event is interpreted to have been related to the early Paleozoic collision between India and Australia–Antarctica that formed East Gondwana (Meert, 2003; Collins & Pisarevsky, 2005).

In the Permian, the Naturaliste Plateau was part of Gondwana (Norvick, 2004; Gibbons et al., 2012) and was above sea level (Borissova, 2002). During that time, intra-cratonic rifting occurred across the Perth Basin, Greater India and Antarctica (e.g. Veevers & Tewari, 1995; Bradshaw et al., 2003;

Norvick, 2004). Although Permo-Triassic strata have not been identified on the Naturaliste Plateau, it is possible that Permian sedimentary successions are present beneath younger rifts in the central part of the plateau (Borissova, 2002).

Middle Jurassic–Early Cretaceous northwest–southeast extension between India and Australia resulted in the formation of several small rift basins across the plateau (Borissova, 2002). These are typically small graben or half graben containing up to 2.5 km of basin fill (Borissova, 2002). Movement along large strike-slip zones, representing the future Naturaliste and Batavia (or Leeuwin) Fracture Zones, resulted in reactivation of Jurassic faults, with strike-slip movement on some normal faults (Borissova, 2002; Norvick, 2004).

Breakup of India and Australia and the onset of sea-floor spreading in the Perth Abyssal Plain began in the Valanginian at around 136–137 Ma (Veevers et al., 1991; Norvick, 2004; Gibbons et al., 2012; Whittaker et al., 2013), although it is possible that outboard of the Mentelle Basin sea-floor spreading began slightly later in the Hauterivian, at around 132 Ma (Hall et al., 2013). Breakup was accompanied by significant uplift and erosion across the plateau and a Valanginian breakup unconformity has been mapped in all of the plateau's basins (Borissova, 2002).

An interpreted Valanginian to Barremian sequence has been mapped in the north western part of the Naturaliste Plateau (Figure 3.4; Borissova 2002). An angular unconformity of Barremian age at the top of this succession may correspond to breakup and the onset of sea-floor spreading between the northwestern edge of the Naturaliste Plateau and Greater India, which occurred at ~130–127 Ma (Gibbons et al., 2013; Whittaker et al., 2013; Williams et al., 2013).

Extension and breakup was accompanied by significant basaltic volcanism (Coffin et al., 2002; Borissova 2002; Crawford et al., 2006; Johnston et al., 2010; Borissova 2010a, b). The earliest known volcanism in the region, associated with the Bunbury Basaltic Province, began in the Valanginian (Colwell et al., 1994; Frey et al., 1996; Coffin et al., 2002). Several large volcanic provinces, which developed close to the locus of the breakup, affected the evolving southwestern margin, including the northern margin of the Naturaliste Plateau (Borissova, 2002; Crawford et al., 2006). Seismic data suggests the presence of lava flows and intrusions in the northern COTZ (Borissova, 2002). It is likely that the volcanic complex in the northwestern part of the plateau was emplaced at this time (Borissova, 2002).

The interpreted Barremian to Albian succession is faulted in the north eastern part of the plateau and is relatively undisturbed elsewhere on the plateau (Figure 3.3; Borissova, 2002). Over most of the plateau this sequence is absent from uplifted and eroded blocks, indicating that up to the mid-Albian large areas of the plateau were still subaerial (Borissova, 2002). Continued faulting along the northeast margin of the plateau during the Barremian–mid-Aptian could be explained by the final stages of transform margin activity along the Batavia Fracture Zone (Borissova, 2002; Gibbons et al., 2012; Hall et al., 2013; Whittaker et al., 2013).

Extensive volcanism commenced on the Southern Kerguelen Plateau during the Aptian (117 Ma), which is also likely to have affected the plateau (Borissova et al., 2002).

After the Valanginian breakup, the locus of extension moved to the south of the Naturaliste Plateau, with the onset of extensional faulting between the Naturaliste Plateau and its conjugate feature on the Antarctic margin, the Bruce Rise (Borissova, 2002). The middle Albian to Santonian sequence ranges from less than 100 m thick on the uplifted southern part of the plateau to about 800 m in its northern part and comprises chalk and limestone (Figure 3.3; Borissova, 2002).

In the late Santonian to early Campanian (~83 Ma), very slow seafloor spreading started on the southern margin in the central Bight Basin (Totterdell et al., 2000; Sayers et al., 2001). However, the Naturaliste Plateau/Diamantina Zone and the Bruce Rise (offshore Antarctica) may have remained connected at that time (Borissova, 2002). The Santonian to lower Paleocene sequence is thin (less than 100 m) or absent on basement highs and up to 500 m thick in the depocentres (Figure 3.3; Borissova, 2002).

Late Paleocene to Eocene uplift of the southern flank of the plateau preceded the separation of the Naturaliste Plateau/Diamantina Zone from the Bruce Rise (Royer & Coffin, 1992) and the onset of fast seafloor spreading in the Southern Ocean (Norvick & Smith, 2001). This resulted in fault reactivation in the Mentelle Basin to the east in settings varying from transtensional to transpressional (Borissova, 2002). The upper Paleocene to lower Eocene sequence is 300 to 500 m thick and is thickest in the northwestern part of the plateau (Figure 3.3; Borissova, 2002).

Separation of the Diamantina Zone and the Labuan Basin (now located thousands of kilometres to the southwest on the Kerguelen Plateau) occurred in the mid-Eocene, at about 43 Ma, which coincided with the start of fast seafloor spreading in the Southeast Indian Ocean (Royer & Coffin, 1992; Borissova et al., 2002). Breakup was preceded by uplift on the southern part of the Naturaliste Plateau, resulting in very steep faults along the southern margin of the plateau (Borissova, 2002).

Subsidence continued from the middle Eocene to Holocene (Figure 3.2 and Figure 3.3), although minor fault reactivation is observed in the eastern part of the plateau (Borissova, 2002). The middle Eocene to Holocene sequence is fairly thin (0.2–0.3 s TWT) over most of the plateau increasing to the northeast up to 0.4 s TWT (Borissova, 2002). These sediments have been deposited at depths similar to those of the present day and consist of nannofossil oozes (Borissova, 2002).

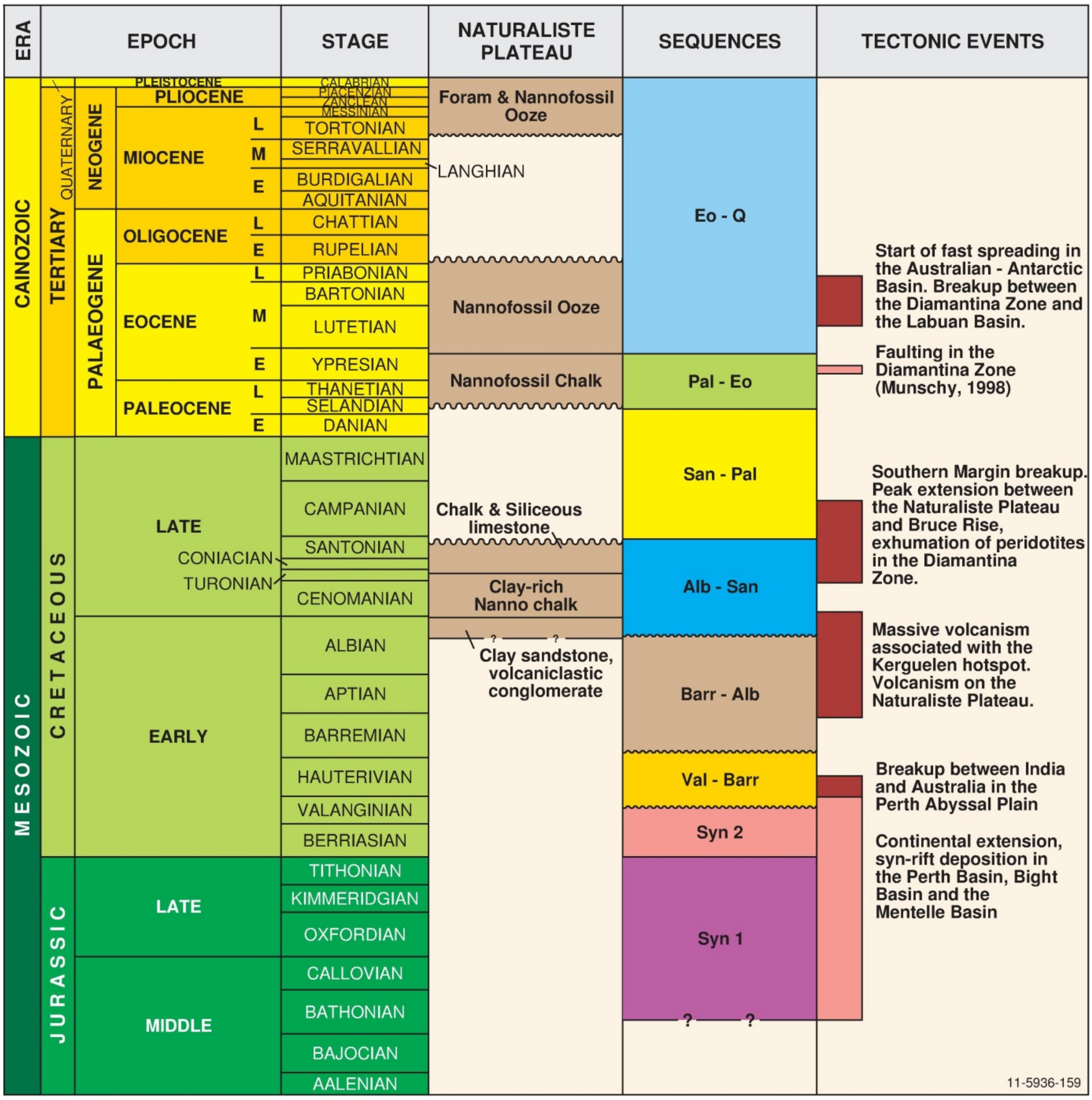

Figure 3.4: Correlation between seismic sequences, drilled stratigraphy and regional tectonic events in the Naturaliste Plateau (Borissova, 2002).

3.1.2.3 Level of knowledge

Data coverage across the Naturaliste Plateau is extremely sparse. The post-rift Cretaceous to Holocene stratigraphy is determined from seismic ties to DSDP 264 (Hayes et al., 1975). The age, lithology and potential petroleum systems for older strata are inferred through indirect correlation with the Vlaming Sub-basin (Crostella & Backhouse, 2000; Borissova, 2002; Borissova et al., 2010a, b). The presence or any older sedimentary strata beneath these sequences is still to be determined (Borissova, 2002).

3.1.3 Petroleum systems

There are no known petroleum systems in the Naturaliste Plateau and no hydrocarbon indicators (e.g. seeps) have been observed (Borissova, 2002). Within the small rift basins that have been imaged on seismic data, there is insufficient sediment thickness for hydrocarbon generation from Jurassic and younger rocks, indicating these basins have poor petroleum prospectivity. However, if the rocks underlying these basins on the Naturaliste Plateau include Permian–Triassic rocks, analogy with coeval proven source rocks in the onshore Perth Basin indicates the plateau, including the rift basins, may have some petroleum potential (Borissova, 2002).

3.1.3.1 Critical risks

The main risks for petroleum systems in the Naturaliste Plateau are:

- no direct evidence for the presence of Permo-Triassic source rocks (Borissova, 2002)
- insufficient thickness of Upper Jurassic to Lower Cretaceous sediments means any potential source rocks of this age are likely to be immature (Borissova, 2002)
- the presence of suitable seals within extensively deformed strata is untested (Borissova, 2002)
- the suitability of the volcanics to provide effective top seals and cross-fault seals remains uncertain (Borissova et al., 2010a, b)
- the risk of trap breaching is high, especially for any potential Permo-Triassic plays, due to multiple stages of fault reactivation
- the distribution and thickness of volcanics across the plateau is poorly constrained.

3.1.3.2 Overall prospectivity classification

Low

3.1.4 Exploration status

No petroleum exploration areas have been released in the Naturaliste Plateau and exploration has been limited to reconnaissance seismic acquisition and sampling programs. These include the Shell Development “*Petrel*” Survey and BMR’s Continental Margins Surveys in the 1970s (Borissova, 2002), as well as Deep Sea Drilling Project (DSDP) wells (sites 258 and 264; Figure 3.2). More recently, a series of Geoscience Australia sampling and seismic cruises from 2005 to 2008 collected additional data across parts of the region (details provided in Data section; Crawford et al., 2006; Heap et al., 2008).

3.1.5 Data

Key data sets for the Naturaliste Plateau are listed in Table 3.1–Table 3.4. Only one stratigraphic well has been drilled on the Naturaliste Plateau, DSDP264 (Figure 3.2 and Figure 3.5). This was located in a small half graben and intersected only post-rift Cretaceous to Holocene rocks (Table 3.1; Hayes et al., 1975). An additional stratigraphic well has been drilled on the western flank of the western Mentelle sub-basin, just to the east of the Naturaliste Plateau, DSDP258 (Figure 3.2 and Figure 3.5). This also intersected only post-rift Cretaceous to Holocene rocks (Davies et al., 1974).

Most of the seismic surveys and drilling on the Naturaliste Plateau took place in the 1960s to early 1970s (Table 3.2). Two seismic programs were designed to survey the Naturaliste Plateau in some detail: GA Continental Margins Surveys 18 and 19 (1972); and the Shell Development "Petrel" Survey (1973). Two recent Geoscience Australia surveys, GA 280 and GA 310, have greatly improved the seismic coverage and resolution in the Mentelle Basin and partly extend into the eastern Naturalise Plateau (Foster et al., 2009). Record length for these surveys is 12 s TWT. No 3D seismic data has been collected in this area.

Six surveys have collected either core or dredge samples from the Naturaliste Plateau and surrounds (Table 3.3). Swath bathymetry coverage of the Naturaliste Plateau is patchy; however six surveys cover part of the plateau area (Table 3.4).

Gravity and magnetic data was collected over the Naturaliste Plateau as part of Geoscience Australia surveys GA 280 and GA 310. These datasets have been levelled and gridded to provide continuous coverage across the whole southwestern margin (Hackney, 2012).

3.1.5.1 Confidence Rating

Low

3.1.6 Issues and remaining questions

The current interpretation of Lower Cretaceous and older rocks on the Naturaliste Plateau is based solely on analogy with the southern Perth Basin. As a result, there are no direct constraints on the following:

- age of the succession
- presence of source rocks and other key petroleum systems elements
- timing of generation and migration
- the impact of volcanism (including the distribution and thickness of volcanics).

3.1.6.1 Recommendations

Resolving the above questions to promote further exploration in the region would require significant additional data collection and interpretation, including:

- drilling of a stratigraphic well, followed by sequence stratigraphic, biostratigraphic, petrophysical and geochemical studies as appropriate
- collection and interpretation of closely spaced, industry standard seismic data, processed to capture the full section (12 s TWT)
- collection and modelling of aeromagnetic data to assess intrabasinal volcanic distribution and thickness
- collection of seismic refraction data to better constrain crustal thickness and composition.

Factors that affect future work in the Naturaliste Plateau include the deep to ultra-deep water depths, large distances from the coast and existing infrastructure, low overall prospectivity and high data-acquisition costs.

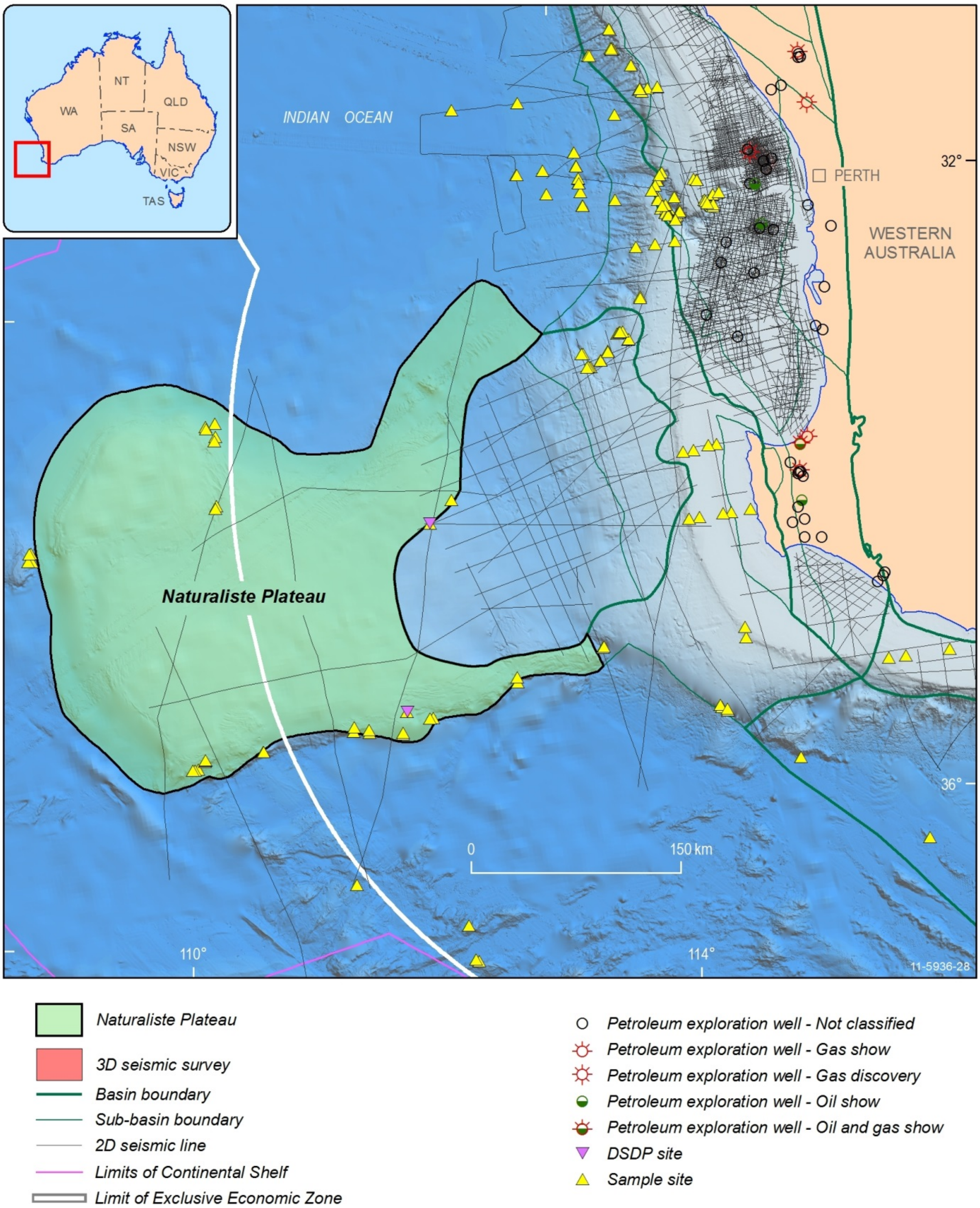

Figure 3.5: Seismic, well and sample distribution for the Naturaliste Plateau.

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3.1.8 Data Tables

Table 3.1: List of wells on or close to the Naturaliste Plateau.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1974	DSDP258	Stratigraphic	DSDP	525 bsf	Cretaceous	Not classified	Davies et al., 1974
1974	DSDP264	Stratigraphic	DSDP	215.5	Cretaceous	Not classified	Hayes et al., 1975

Table 3.2: Key 2D seismic surveys, Naturaliste Plateau.

Year	Survey	Operator	Line-km	Reference
1965	R/V *"Robert Conrad"*			Burkle et al., 1967
1971– 1972	R/V "*Eltanin"* (cruises 54 and 55A)			Frakes, 1973; Cassidy et al., 1977
1971	Shell Development "Petrel" Survey	Shell Development	1270	Borissova, 2002
1972	GA Continental Margins Survey 18	BMR (now Geoscience Australia)	17863	Borissova, 2002
1987	GA Survey 187	BMR (now Geoscience Australia)		Borissova, 2002
2004	GA 280 Southwest Frontier	Geoscience Australia	1060	
2008	GA 310	Geoscience Australia	2570	Foster et al., 2008

Table 3.3: Key geological sampling surveys, Naturaliste Plateau and adjacent areas.

Year	Survey	Operator	Region	Type	Rock types	Reference
1966	*Robert Conrad*			Core	Sediments	Borissova, 2002
1972	R/V "*Eltanin"* (cruises 54 and 55A)			Dredge	Basement, sediments	Frakes, 1973; Cassidy et al., 1977; Borissova, 2002
1994	*Marion Dufresne* 80		Diamantina Zone to the south of the Naturaliste Plateau	Dredge	Basement, volcanics	Borissova, 2002

Year	Survey	Operator	Region	Type	Rock types	Reference
1998	*Marion Dufresne* 110		Diamantina Zone to the south of the Naturaliste Plateau	Dredge	Basement, volcanics	Borissova, 2002
2005	GA SS2005/09	Geoscience Australia	Naturaliste Plateau	Dredge	Sediments, volcanics, basement	Crawford et al., 2006

Table 3.4: Key swath bathymetry surveys, Naturaliste Plateau.

Year	Survey	Operator	Area (km^2)	Reference
1995	WEST10MY (R/V Melville)		114,721	
1996	BMRG06MV (R/V Melville)	BMR (now Geoscience Australia)	189,343	
1998	Margau (R/V *Marion Dufresne;* Cruise 110)		168,882	Royer & Beslier, 1998; Borissova et al., 2002
2004	MR03K04L6 (R/V Melville)		109,000	
2005	SS09/2005 (Naturaliste Rocks; R/V Southern Surveyor)	Geoscience Australia	17,616	Crawford et al., 2006
2006	SS04/2006 (Leeuwin Currents; R/V Southern Surveyor)	Geoscience Australia	16,765	

3.2 Western Mentelle Sub-basin (Mentelle Basin)

3.2.1 Summary

State(s)		WA
Area (km^2)		24,800
Water Depth (m)		1300–4000
Maximum sediment thickness (m)		>11,000
Age range		Jurassic (and older?)–Holocene
Basin	**Overlies**	Pinjarra Orogen
	Subdivisions	Eagle, Rosa and Clairault depocentres
	Parent	Mentelle Basin
	Adjacent basins	Naturaliste Plateau, Eastern Mentelle Sub-basin
Basin type		Extensional basin
Depositional setting, rock types		unknown
Overall prospectivity		Medium–low
Confidence		*Medium*

3.2.2 Geology

The Mentelle Basin is a large (36,400 km^2), deep-water basin (500–4000 m) located just east of the Naturaliste Plateau, on the southwestern Australian continental margin (Figure 3.6; Borissova et al., 2010a, b). The basin is divided into the Western and Eastern Mentelle sub-basins. The Western Mentelle Sub-basin is the deeper of the two sub-basins and is located in water depths of 2000–4000 m (Figure 3.6; Borissova et al., 2010a, b). Seismic data indicates that the sub-basin contains up to 7–11 km of Paleozoic to Cenozoic sedimentary rocks (Figure 3.6 and Figure 3.7; Borissova et al., 2010a, b).

3.2.2.1 Structural geology

The Mentelle Basin forms part of an extensional rift system on Australia's southwestern margin that developed during the Paleozoic to Mesozoic breakup of eastern Gondwana (Borissova et al., 2010a, b). The basin formed close to the triple junction between the Indian, Australian and Antarctic plates (Norvick & Smith, 2001; Borissova, 2002; Direen et al., 2007; Whittaker et al., 2013; Williams et al., 2013) and therefore structurally represents a transition between the Perth Basin to the north and the southern margin basins to the south (Bradshaw et al., 2003; Borissova et al., 2010a, b).

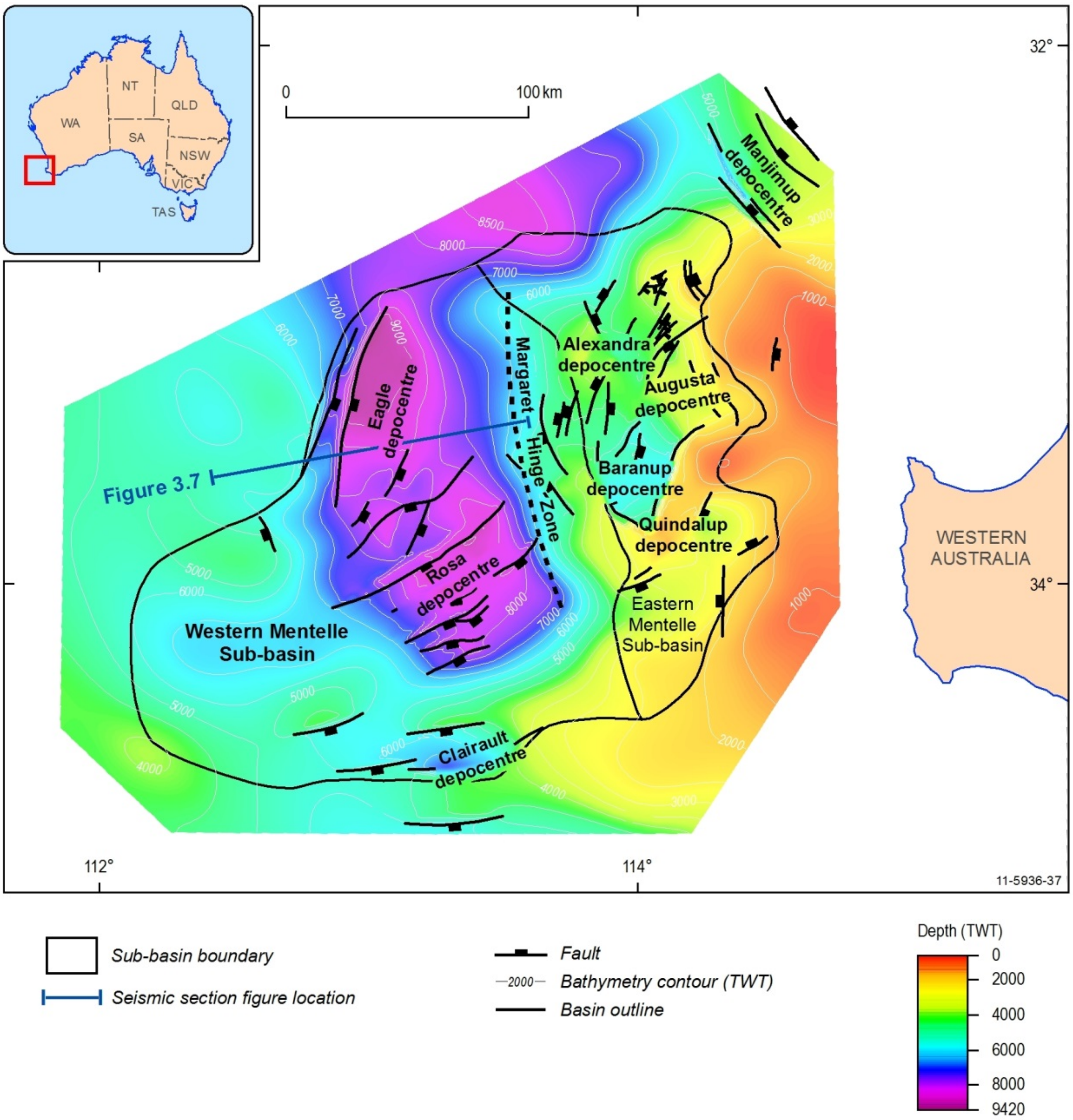

Figure 3.6: Structural elements of the Mentelle Basin, shown on depth to base of resolvable sedimentary section in ms TWT (from Borissova et al., 2010a).

Seismic data shows that there are three main depocentres in the Western Mentelle Sub-basin: the Eagle, Rosa and Clairault depocentres (Figure 3.6; Borissova et al., 2010a, b). The Eagle and Rosa depocentres, in the northern and central parts of the Western Mentelle Sub-basin, are north-northeast to northeast trending half graben that contain between 9 and 11 km of sediment (Figure 3.6 and Figure 3.7; Borissova et al., 2010a, b). These half graben are interpreted to have formed in the Jurassic–Early Cretaceous as a result of northwest–southeast extension during the separation of India and Australia (Borissova et al., 2010a, b). In the south, several smaller, en echelon half graben containing up to 3–5 km of sediment have been mapped as the Clairault depocentre (Borissova et al., 2010a). These half graben can be interpreted as an eastward continuation of the small rifted basins identified in the southern part of the Naturaliste Plateau, and their east-northeast orientation and structural style are consistent with early extension on the southern margin related to Australia–Antarctica breakup (Borissova, 2002; Borissova et al., 2010a). Gravity modelling suggests the presence of very thin continental crust in the central parts of the western Mentelle Basin (Johnston et al., 2010).

The Western Mentelle Sub-basin is separated from the Eastern Mentelle Sub-basin by the north–south oriented Margaret Hinge Zone (Figure 3.6 and Figure 3.7; Borissova et al., 2010a). This corresponds to a zone of continental margin collapse and is characterised by a series of down-stepping fault blocks that are onlapped by the Western Mentelle Sub-basin sedimentary succession (Figure 3.7; Borissova et al., 2010a).

The Western Mentelle Sub-basin is separated from the oceanic crust of the Perth Abyssal Plain by a wide continent–ocean transition zone (Norvick, 2004; Hall et al., 2013). Plate reconstructions show that prior to India–Australia breakup, the Batavia Knoll (a continental fragment now situated in the Indian Ocean; Williams, 2011; Williams et al., 2013; Kobler, 2012) formed the conjugate margin to the Mentelle Basin (Gibbons et al., 2012; Whittaker et al., 2013; Hall et al., 2013).

3.2.2.2 Basin evolution and depositional history

The Western Mentelle Sub-basin has undergone multiple phases of extension and volcanism, primarily controlled by the rifting and subsequent breakup of Australia, India and Antarctica (Figure 3.8; Norvick & Smith, 2001; Borissova, 2002; Bradshaw et al., 2003; Borissova et al., 2010a, b; Gibbons et al., 2012; Hall et al., 2013; Whittaker et al., 2013).

Plate reconstructions show that prior to India–Australia breakup, the Batavia Knoll, a continental fragment now situated in the Indian Ocean (Williams, 2011; Kobler, 2012), formed a conjugate margin to the Mentelle Basin (Whittaker et al., 2013; Hall et al., 2013). Basement rocks dredged from the Batavia Knoll (Kobler, 2012; Whittaker et al., 2013) show a similar tectonic evolution to rocks of the Pinjarra Orogen, which outcrop in the Leeuwin Complex (Collins, 2003; Fitzsimons, 2003). The pre-breakup location of the Mentelle Basin between the Leeuwin Complex and Batavia Knoll (Gibbons et al., 2012; Whittaker et al., 2013) strongly suggests that similar basement rocks underlie the Mentelle Basin.

Analogy with the Vlaming and Eastern Mentelle Sub-basins suggests that the Western Mentelle Sub-basin may be underlain by Permian to Triassic sediments (Figure 3.8). However, the lack of well data and poor seismic quality at depth makes it difficult to confirm any units of this age.

Middle Jurassic to Early Cretaceous northwest–southeast extension was driven by the separation of India and Australia (Norvick, 2004). Within the Mentelle Basin, extension was focused in the western sub-basin, producing a series of half graben and resulting in the accumulation of about 6–9 km (2500–3500 ms TWT) of syn-rift sediments (Figure 3.7; Borissova et al., 2010a, b).

Seismic interpretation indicates that three supersequences were deposited during this period (Figure 3.8; Borissova et al., 2010a), as follows:

- Mentelle 2 Supersequence, which is correlated to the mid-Bajocian–Kimmeridgian part of the Yarragadee Formation in the Vlaming Sub-basin
- Mentelle 3 Supersequence (Tithonian–Berriasian), which is correlated to the upper Yarragadee Formation and lower part of the Parmelia Group in the Vlaming Sub-basin
- Mentelle 4 Supersequence (Berriasian), which is correlated to the upper part of the Parmelia Group in the Vlaming Sub-basin.

The Valanginian to Hauterivian breakup of India and Australia (Veevers et al., 1991; Norvick, 2004; Gibbons et al., 2012; Hall et al., 2013; Whittaker et al., 2013; Williams et al., 2013) is represented by a syn-breakup supersequence (Mentelle 5) up to 1 km thick (Figure 3.7 and Figure 3.8; Borissova et al., 2010a, b). The sedimentary part of the Mentelle 5 supersequence is correlated to the marine to deltaic Gage Sandstone and South Perth Shale in the Vlaming Sub-basin. This sequence also shows evidence of extensive syn-depositional volcanism associated with Valanginian breakup (Borissova et al., 2010a, b; Johnston et al., 2010). Extrusive flows, cones and sills and dykes have been identified and a strong correlation exists between the distribution of the thickest volcanic material and regions of greatest crustal thinning (Johnston et al., 2010). This volcanism has been correlated with breakup-related volcanics in the Perth Basin associated with the Bunbury Basalt at around 132 Ma (Coffin et al., 2002; Crawford et al., 2006; Crostella & Backhouse, 2000; Johnston et al., 2010; Borissova et al., 2010a, b).

Hauterivian to Cenomanian post-breakup thermal subsidence was characterised by deposition of deltaic, deep marine and carbonate dominated sediments (Mentelle supersequences 6–9), interpreted to be equivalent to the Leederville Formation and Coolyena Group of the Vlaming Sub-basin (Figure 3.8; Borissova, 2010a, b).

Paleocene to Eocene margin collapse resulted in the development of the Margaret Hinge Zone between the east and west Mentelle sub-basins (Figure 3.8; Borissova et al., 2010a, b). This occurred at about the same time as the onset of fast seafloor spreading in the Southern Ocean in the late Paleocene (Norvick & Smith, 2001), and was accompanied by fault reactivation, some volcanism and partial inversion in the western Mentelle Sub-basin (Borissova et al., 2010a, b). Supersequences Mentelle 10 and 11 were deposited during this period (Figure 3.8; Borissova, 2010a, b).

Miocene to Holocene deep-water sequences (Mentelle 12) are thin. Compressional anticlinal structures that affect this succession could be related to the convergence between the Australian and Eurasian plates (Borissova et al., 2010a).

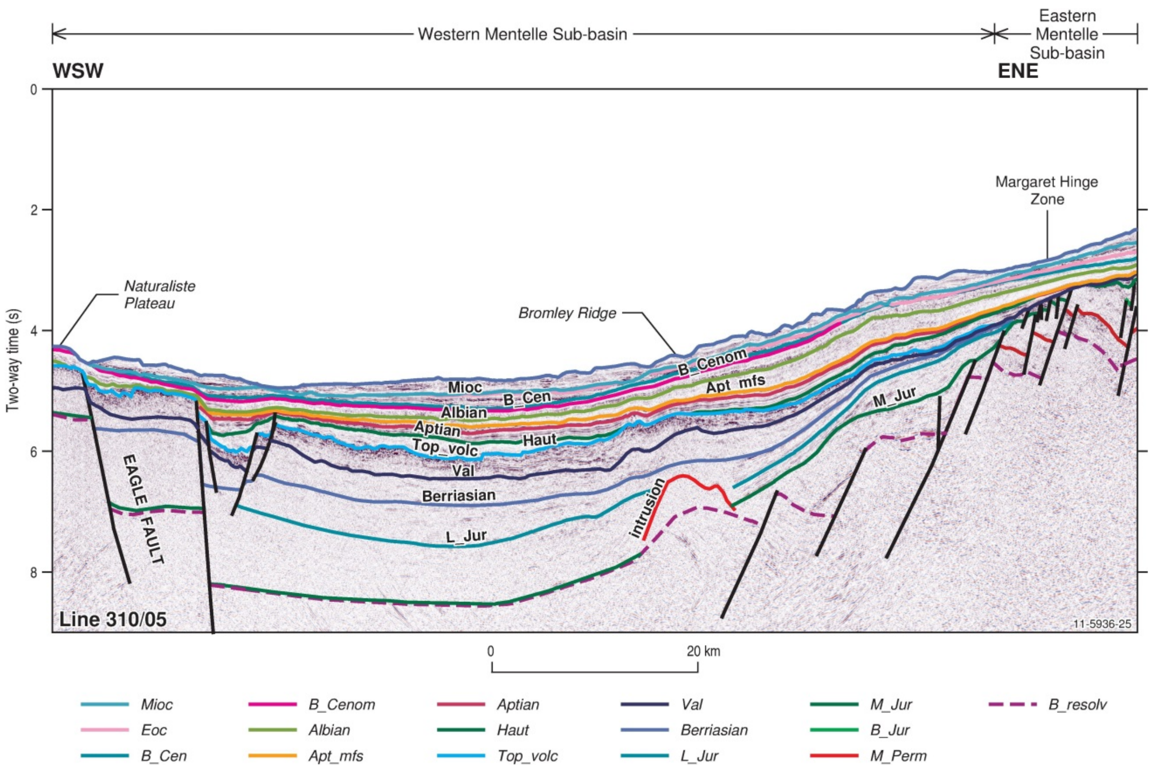

Figure 3.7: Seismic cross-section through the Western Mentelle Sub-basin showing structural and stratigraphic relationships (from Borissova et al., 2010a). See Figure 3.6 for line location.

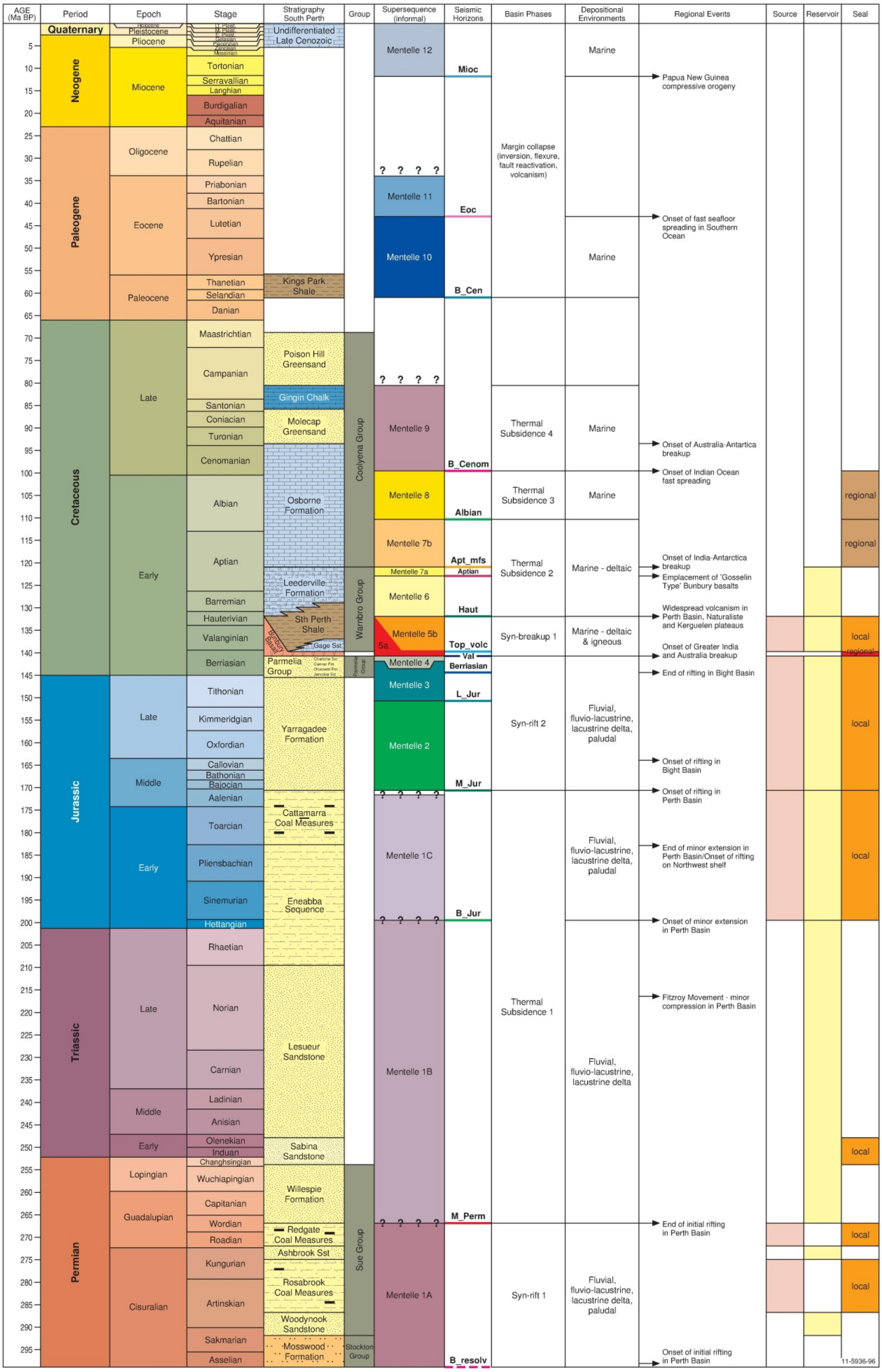

Figure 3.8: Stratigraphy of the Mentelle Basin, including sequence stratigraphy and tectonic events from Borissova et al. (2010a), using the 2012 geological timescale of Gradstein et al. (2012).

3.2.2.3 Level of knowledge

Data coverage in the Western Mentelle Sub-basin is extremely sparse. The stratigraphy is inferred from seismic ties to DSDP wells 258 (Davies et al., 1974), which provides high resolution data on the mid-Albian to Holocene part of the section, and comparisons to the adjacent Vlaming Sub-basin (Figure 3.8; Borissova et al., 2010a). The age, lithology and potential petroleum systems for older strata are interpreted through comparison with the Vlaming Sub-basin, based on stratal relationships and seismic characteristics (Borissova et al., 2010a).

Analogy with the Vlaming and Eastern Mentelle sub-basins indicates that the Western Mentelle Sub-basin may also be underlain by older Permo-Triassic sediments (Figure 3.8). However, the lack of well data and poor seismic quality at depth makes it difficult to identify units of this age.

3.2.3 Petroleum systems

There are no known petroleum systems in the Western Mentelle Sub-basin; however, hydrocarbon indicators have been interpreted on seismic data (some supported by AVO analysis) and potential slicks detected by SAR (synthetic aperture radar), suggest at least one petroleum system is present in the basin (Cook, 2005, 2006; Borissova et al., 2010a).

Given the absence of wells within the Western Mentelle Sub-basin, assessments of petroleum prospectivity are based on comparisons with data from the Vlaming Sub-basin to the east, where several active petroleum systems have been identified (Bradshaw et al., 1994; Crostella, 1995; Miyazaki et al., 1996; Crostella & Backhouse, 2000; Boreham et al., 2000; Kempton et al., 2002; Volk et al., 2004; Boreham, 2008; Borissova et al., 2010a).

3.2.3.1 Source rocks

Potential source rocks include Middle to Upper Jurassic fluvial to lacustrine coal and carbonaceous shales, equivalent to the Yarragadee Formation, and Lower Cretaceous lacustrine shales, equivalent to the Carnac and Otorowiri formations (Borissova et al., 2010a). In the Western Mentelle Sub-basin, petroleum systems modelling indicates that only the Jurassic source rocks have reached the oil window, and Cretaceous rocks are likely to be immature (Borissova et al., 2010a). Generation and expulsion from these source rocks probably occurred from the Early Cretaceous onwards (Borissova et al., 2010a).

3.2.3.2 Reservoirs and seals

Good quality reservoir rocks are likely to be present at multiple stratigraphic levels due to the interpretation of predominantly fluvial environments in both the pre and syn-rift sections (Borissova et al., 2010a).

Seals within the syn-rift succession are probably mostly intraformational, while potential regional seals are provided by Lower Cretaceous volcanic rocks and thick marine mudstones of Aptian to Albian age, such as those intersected in DSDP well 258 (Borissova, 2002; Borissova et al., 2010a).

3.2.3.3 Play types

Play types in the western Mentelle Basin include syn-rift high-side fault block traps developed in the Late Cretaceous–Early Jurassic, sub-basalt anticlines and fault blocks, post-rift anticlines and a range of stratigraphic traps (Figure 3.9; Borissova et al., 2010a).

3.2.3.4 Critical risks

The main risks for petroleum systems in the Western Mentelle Sub-basin are:

- the Jurassic–Lower Cretaceous stratigraphy is unconstrained and the current understanding is based on seismic interpretation and analogy with Perth Basin
- the presence of Permian rocks remains speculative, due to lack of well data and poor quality seismic data at depth
- the suitability of Lower Cretaceous volcanic rocks to provide effective top seals and cross-fault seals remains uncertain (Borissova et al., 2010a)
- hydrocarbon charge is the key uncertainty, as a number of potential structural and stratigraphic traps post-date the main phase of generation and expulsion in the Early Cretaceous (Borissova et al., 2010a).

3.2.3.5 Overall prospectivity classification

Moderate–low

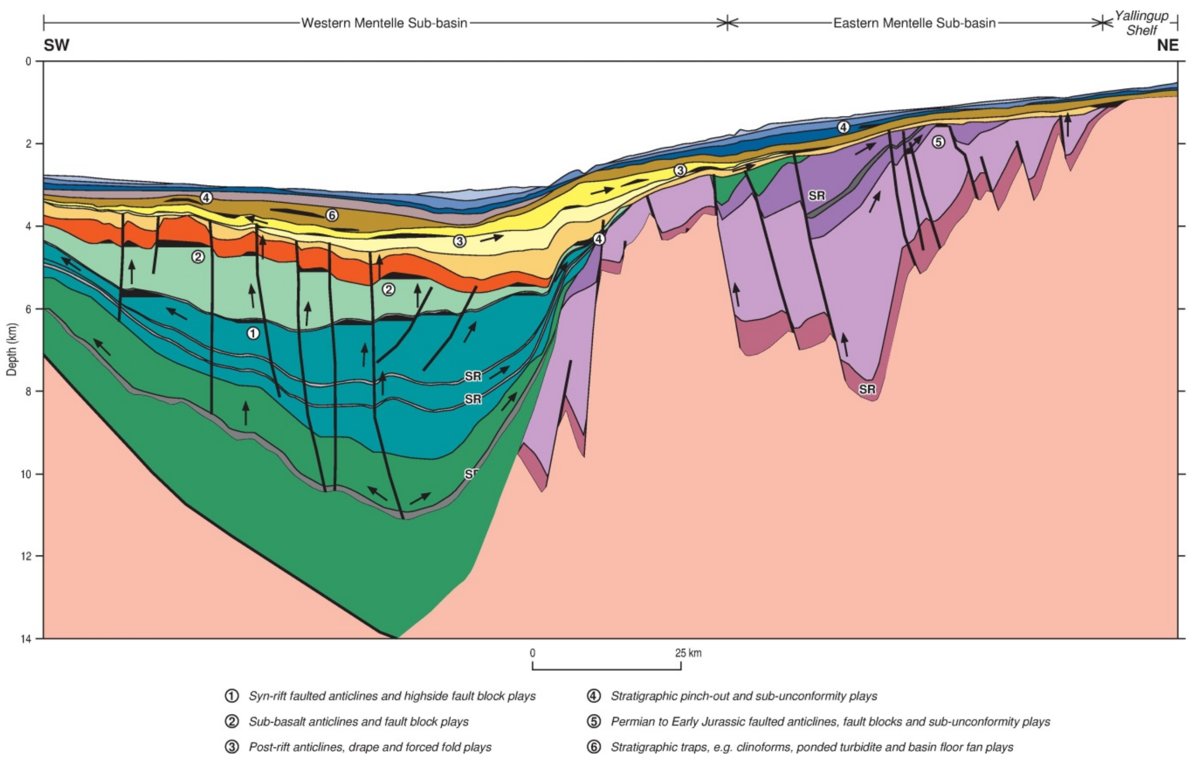

Figure 3.9: Conceptual play diagram for the Mentelle Basin (Borissova et al., 2010a). See Figure 3.8 for key to sequences.

3.2.4 Exploration status

To date, exploration in the Western Mentelle Sub-basin has been limited to reconnaissance seismic acquisition and sampling programs. These include the Shell Development "Petrel" Survey and BMR's Continental Margins Surveys in the 1970s (Borissova, 2002), and more recently, a series of Geoscience Australia sampling and seismic cruises from 2005 to 2008 (Crawford et al., 2006; Heap et al., 2008; Borissova et al., 2010a).

Exploration acreage was released across the Mentelle Basin for the first time in 2010, however no bids were received.

3.2.5 Data

Key data sets for the Western Mentelle Sub-basin are listed in Table 3.5–Table 3.8. Only one stratigraphic well has been drilled on the western flank of the Western Mentelle Sub-basin, DSDP 258, which intersected only post-rift Cretaceous to Holocene rocks (Table 3.5; Figure 3.10; Davies et al., 1974).

Reflection seismic data over the Mentelle Basin varies considerably in quality and coverage (Table 3.6; Figure 3.10). The 1972 BMR Continental Margins surveys and 1973 Shell Development surveys created coverage with a line spacing between 20 and 60 km. The two more recent Geoscience Australia surveys, GA 280 and GA 310, have greatly improved the seismic coverage and resolution in the Mentelle Basin, reducing line spacing to around 10–20 km (Foster et al., 2009). Record length for these surveys is 12 s TWT. No 3D seismic data has been collected in this area.

Dredge samples have not been collected from the central Western Mentelle Sub-basin. However, several surveys have collected samples in the surrounding region (Table 3.7; Figure 3.10). They include:

- BMR Survey 80 in the Perth Canyon (previously also known as Fremantle Canyon)
- *Southern Surveyor* sampling cruise SS 08/2005 on the Mentelle margin (Heap et al., 2008)
- *Southern Surveyor* sampling cruise SS 09/2005 on the Naturaliste Plateau (Crawford et al., 2006).

The Western Mentelle Sub-basin is completely covered by 16 ERS2 SAR images, collected between 1996 and 2006. In addition, Radarsat SAR images cover the northern part of the sub-basin. Processing, interpretation and mapping of the slicks is documented in Cook (2005, 2006).

Swath bathymetry coverage of the Western Mentelle Sub-basin is patchy. Seven surveys intersect the basin (Table 3.8).

All good quality potential field datasets have been compiled, levelled and gridded to provide continuous gravity and magnetic coverage across the entire southwestern margin (Hackney, 2012).

3.2.5.1 Confidence Rating

Medium

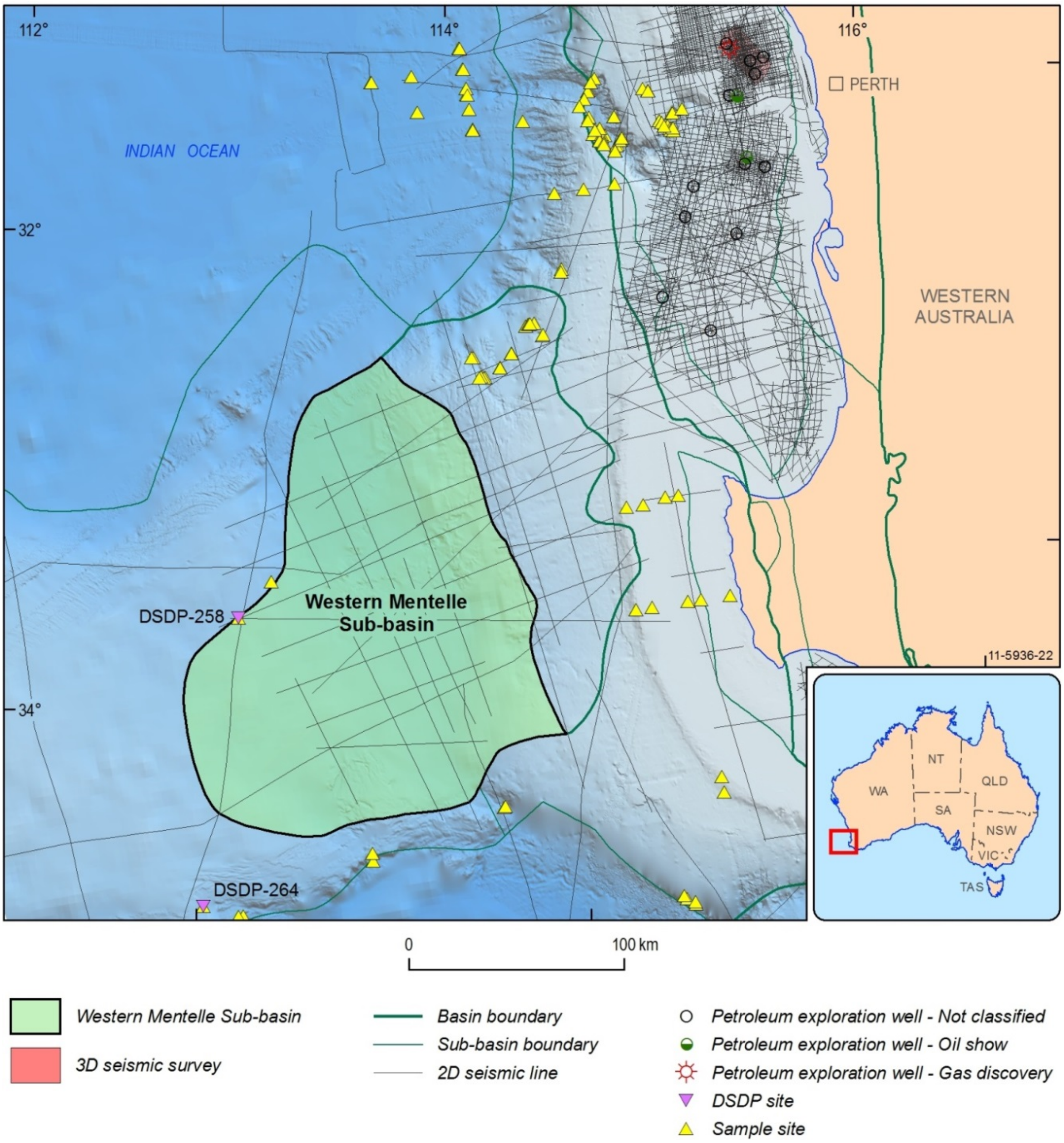

Figure 3.10: Seismic, well and sample distribution for the Western Mentelle Sub-basin.

3.2.6 Issues and remaining questions

The current interpretation for the presence of Lower Cretaceous and older rocks in the Western Mentelle Sub-basin is based solely on analogy with the Vlaming Sub-basin. As a result, there are no direct constraints on the following:

- age of the succession
- presence of source rocks and other key petroleum systems elements
- timing of generation and migration
- the impact of volcanism (including the distribution and thickness of volcanic rocks).

3.2.6.1 Recommendations

To resolve the above questions and promote further exploration in the region, significant additional data collection is required, such as:

- drilling of a stratigraphic well, followed by sequence stratigraphic, biostratigraphic, petrophysical and geochemical studies
- acquisition and interpretation of closely spaced (<5 km), industry standard seismic data
- acquisition and modelling of aeromagnetic data to assess intrabasinal volcanic distribution and thickness
- acquisition of seismic refraction data to determine crustal thickness and composition.

The petroleum potential of the Western Mentelle Sub-basin is enhanced by the presence of indirect hydrocarbon indicators such as interpreted seeps and seismic anomalies, as well as its thick sedimentary section. Deep to ultra-deep water depths, the large distance from the coast and infrastructure and high data acquisition costs are key concerns in this basin.

3.2.7 References

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3.2.8 Data Tables

Table 3.5: List of wells in or close to the Western Mentelle Sub-basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1974	DSDP258	Stratigraphic	DSDP	525	Cretaceous	Not classified	Davies et al., 1974

Table 3.6: Key 2D seismic surveys, Western Mentelle Sub-basin.

Year	Survey	Operator	Line-km	Reference
1972	GA Continental Margins Survey 18	BMR (now Geoscience Australia)	17,863	Borissova, 2002
1971	Shell Development “Petrel” Survey	Shell Development	1270	Borissova, 2002
2004	GA 280 Southwest Frontier	Geoscience Australia	1060	
2008	GA 310	Geoscience Australia	2570	Foster et al., 2008

Table 3.7: Key geological sampling surveys ,Western Mentelle Sub-basin and adjacent areas.

Year	Survey	Operator	Region	Type	Rock types	Reference
1988	BMR Survey 80	BMR	Perth Canyon	Dredge	Basement, volcanics	Marshall et al., 1989
2005	GA SS2005/08	Geoscience Australia	northern Mentelle Basin	Dredge	Sediments, basement	Heap et al., 2008
2005	GA SS2005/09	Geoscience Australia	Naturaliste Plateau	Dredge	Sediments, volcanics, basement	Crawford et al., 2006

Table 3.8: Key swath bathymetry surveys, Western Mentelle Sub-basin.

Year	Survey	Operator	Area (km^2)	Reference
1995	WEST10MY (R/V Melville)		114,721	
1996	BMRG06MV (R/V Melville)	BMR	189,343	
1998	Margau (MD110; R/V *Marion Dufresne*)		168,882	Royer & Beslier, 1998; Borissova et al., 2002
2004	MR03K04L6 (R/V Melville)		109,000	
2005	SS09/2005 (Naturaliste Rocks; R/V Southern Surveyor)		17,616	Crawford et al., 2006
2006	SS04/2006 (Leeuwin Currents; R/V Southern Surveyor)		12,436	
2006	SS05/2006 (Meso Eddies; R/V Southern Surveyor)	Geoscience Australia	16,765	

3.3 Eastern Mentelle Sub-basin (Mentelle Basin)

3.3.1 Summary

State(s)		WA
Area (km^2)		24,800
Water Depth (m)		500–3800 (85% is at 500–2500 m water depth)
Maximum sediment thickness (m)		~8000 (generally <6000 m thick)
Age range		Permian–Holocene
Basin	**Overlies**	Pinjarra Orogen
	Subdivisions	Baranup, Alexandra and Quindalup depocentres
	Parent	Mentelle Basin
	Adjacent basins	Western Mentelle Sub-basin; Yallingup Shelf
Basin type		Extensional basin
Depositional setting, rock types		unknown
Overall prospectivity		Moderate–low
Confidence		*Medium*

3.3.2 Geology

The Mentelle Basin is a large (36,400 km^2), deep water basin (500–4000 m) located just west of the Naturaliste Plateau, on the southwest Australian continental margin (Figure 3.11; Borissova et al., 2010a, b). The basin is divided into the Western and Eastern Mentelle sub-basins. The Eastern Mentelle Sub-basin is the shallower of the Mentelle sub-basins and is located in water depths of 500–2000 m (Borissova et al., 2010a). Seismic data indicates that the sub-basin contains up to 8 km of Paleozoic to Cenozoic sediments (Borissova et al., 2010a, b).

3.3.2.1 Structural geology

The Mentelle Basin forms part of an extensional rift system on Australia's southwestern margin that developed during the Paleozoic to Mesozoic breakup of eastern Gondwana (Borissova et al., 2010a, b). The basin formed close to the triple junction between the Indian, Australian and Antarctic plates (Norvick & Smith, 2001; Borissova, 2002; Direen et al., 2007; Whittaker et al., 2013; Williams et al., 2013) and therefore structurally represents a transition between the Perth Basin to the north and the southern margin basins to the south (Bradshaw et al., 2003; Borissova et al., 2010a, b).

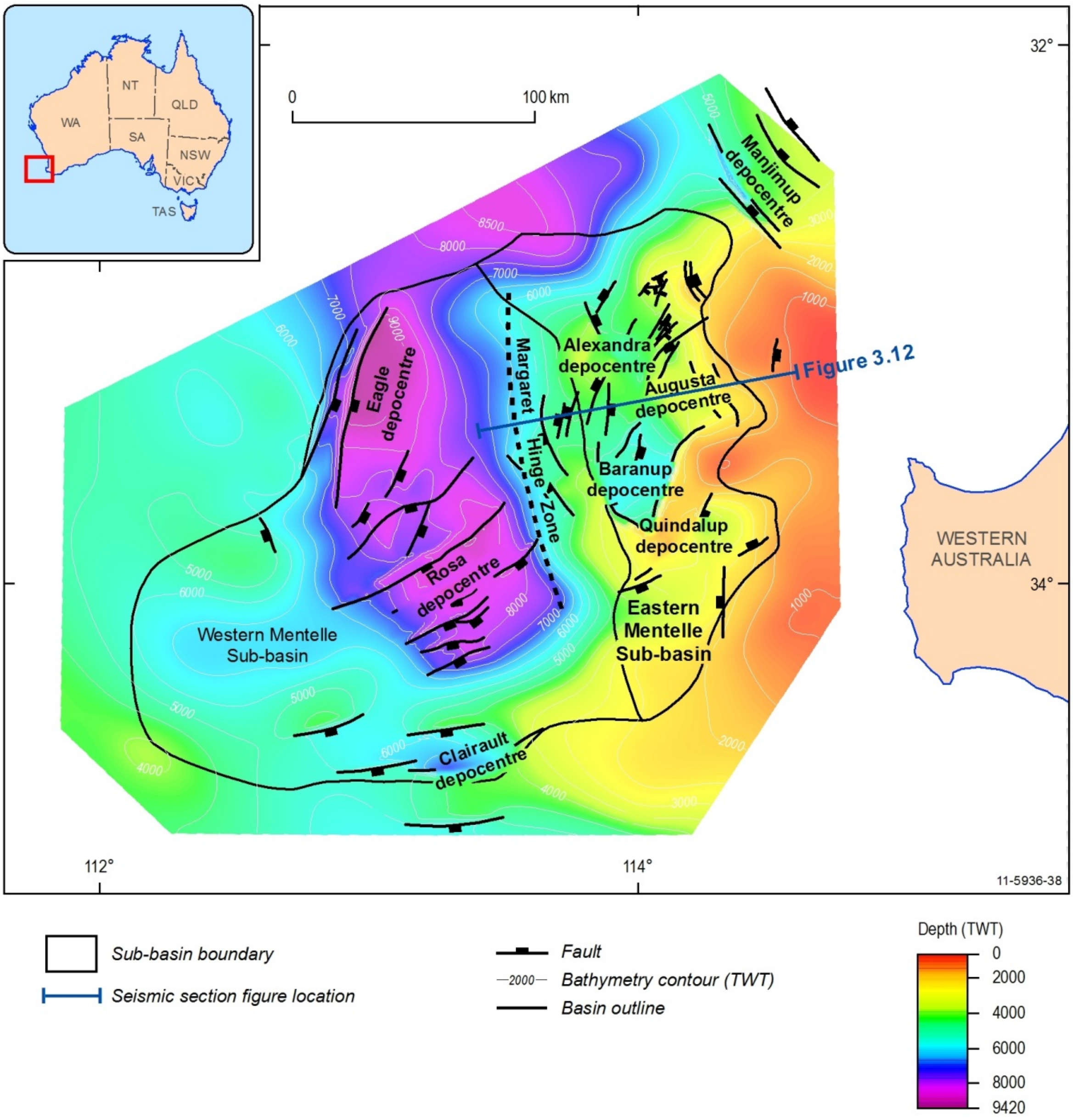

Figure 3.11: Structural elements of the Mentelle Basin, shown on depth to base of resolvable sedimentary section in ms TWT (from Borissova et al., 2010a).

The Eastern Mentelle Sub-basin contains three main depocentres: the Baranup, Alexandra and Quindalup depocentres (Figure 3.11; Borissova, 2002; Borissova et al., 2010a, b). These contain a series of tilted fault blocks bounded by east-dipping faults that predominantly strike north-northwest to north-northeast (Figure 3.11 and Figure 3.12; Borissova et al., 2010a, b).

To the west, the Eastern Mentelle Sub-basin is separated from the Western Mentelle Sub-basin by the north–south oriented Margaret Hinge Zone (Figure 3.11 and Figure 3.12; Borissova et al., 2010a). This feature is a zone of continental margin collapse and is defined by a series of down-stepping fault blocks that are onlapped by the Western Mentelle Sub-basin sedimentary succession (Borissova et al., 2010a). To the east is the Yallingup Shelf, a north–south trending basement high, beyond which sits the Leeuwin Complex, an area of outcropping Proterozoic–early Cambrian basement (Norvick, 2004; Collins, 2003).

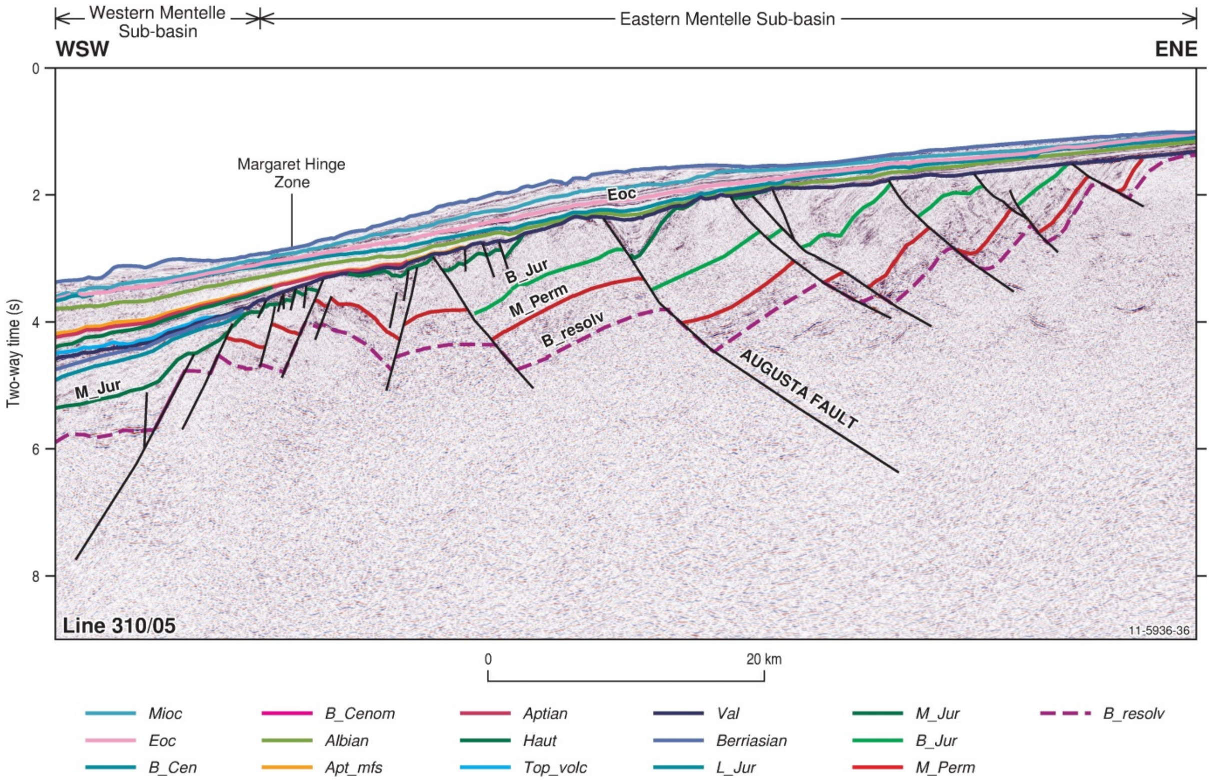

Figure 3.12: Seismic cross-section through the Eastern Mentelle Sub-basin showing structural and stratigraphic relationships (from Borissova et al., 2010a). See Figure 3.11 for line location.

3.3.2.2 Basin evolution and depositional history

The Eastern Mentelle Sub-basin has undergone multiple phases of extension and volcanism, primarily controlled by the rifting and subsequent breakup of Australia, India and Antarctica (Figure 3.13; Norvick and Smith, 2001; Borissova, 2002; Bradshaw et al., 2003; Borissova et al., 2010a, b; Hall et al., 2013; Whittaker et al., 2013; Williams et al., 2013).

Plate reconstructions show that prior to India–Australia breakup, the Batavia Knoll, a continental fragment now situated in the Indian Ocean (Williams, 2011; Kobler, 2012), formed a conjugate margin to the Mentelle Basin (Whittaker et al., 2013; Hall et al., 2013). Basement rocks dredged from the Batavia Knoll (Kobler, 2012; Whittaker et al., 2013) show a similar tectonic evolution to rocks of the Pinjarra Orogen, which outcrop in the Leeuwin Complex (Collins, 2003; Fitzsimons, 2003). The pre-breakup location of the Mentelle Basin between the Leeuwin Complex and Batavia Knoll (Gibbons et al., 2012; Whittaker et al., 2013) strongly suggests that similar basement rocks underlie the Mentelle Basin.

Late Carboniferous to early Permian rifting resulted in the development of north–south oriented graben in the both Eastern Mentelle Sub-basin and Perth Basin (Veevers, 1988; Harris, 1994; Song & Cawood, 2000). This phase of extension is correlated with supersequence Mentelle 1A, which is mapped on seismic across the sub-basin (Figure 3.12 and Figure 3.13; Borissova et al., 2010a). Sediments deposited during this time are likely to include glacio-marine, fluvial, lacustrine and deltaic strata equivalents of the Mosswood Formation, Woodynook Sandstone and Rosabrook and Redgate Coal Measures of the Vlaming Sub-basin and onshore southern Perth Basin (Crostella & Backhouse, 2000; Borissova et al., 2010a).

The initial phase of extension was followed by a period of mid-Permian to Early Jurassic thermal subsidence, during which time supersequences Mentelle 1B and C are interpreted to have been deposited (Figure 3.13; Borissova et al., 2010a). This succession was extensively deformed, faulted and eroded at the onset of second phase of rifting in the Middle Jurassic (Borissova et al., 2010a).

Middle Jurassic to Early Cretaceous northeast–southeast extension was driven by the separation of India and Australia (Norvick, 2004), but sediments of this age (supersequences Mentelle 2 to 4) are largely absent over the Eastern Mentelle Sub-basin (Borissova et al., 2010a, b).

The subsequent breakup of India and Australia in the Valanginian–Hauterivian (Veevers et al., 1991; Norvick, 2004; Gibbons et al., 2012; Hall et al., 2013; Williams et al., 2013) was accompanied by extensive volcanism, uplift and erosion across the Mentelle Basin (Borissova, 2002; Coffin et al., 2002; Crawford et al., 2006; Borissova, 2010a, b; Johnston et al., 2010). However, the syn-breakup sequence (Mentelle 5) identified in the Western Mentelle Sub-basin is not present in the east (Borissova et al., 2010a, b). Furthermore, volcanism is also generally restricted to the western part of the basin and few flows are observed in the Eastern Mentelle Sub-basin (Johnston et al., 2010).

Hauterivian to Cenomanian post-breakup thermal subsidence was characterised by deposition of Mentelle supersequences 6–9, which are interpreted to contain deltaic, deep marine and carbonate dominated sediments (Leederville Formation and Coolyena Group equivalents; Figure 3.12 and Figure 3.13; Borissova, 2010a, b).

Paleocene to Eocene margin collapse resulted in the development of the Margaret Hinge Zone between the two sub-basins (Figure 3.12). This coincided with the onset of fast spreading in the Southern Ocean in the late Paleocene (Figure 3.13; Norvick & Smith, 2001), and was accompanied by fault reactivation and some volcanism. Supersequences Mentelle 10 and 11 were deposited during this period (Figure 3.13; Borissova, 2010a, b).

Miocene to Holocene deep-water sequences (Mentelle 12) are thin and are often associated with compressional anticlinal structures possibly related to the convergence between the Australian and Eurasian plates (Figure 3.13; Borissova et al., 2010a).

3.3.2.3 Level of knowledge

Data coverage in the Eastern Mentelle Sub-basin is sparse. The stratigraphy is inferred from seismic ties to DSDP 258 in the Western Mentelle Sub-basin (Davies et al., 1975), which provides high resolution data on the mid-Albian to Holocene part of the section, and comparisons to wells and seismic in the adjacent Vlaming Sub-basin (Borissova et al., 2010a). Age, lithology and potential petroleum systems for older strata are inferred through comparison with the Vlaming Sub-basin, based on stratal relationships and seismic characteristics (Borissova et al., 2010a). The age control for the Permo-Triassic section is provided by a seismic tie to two dredges in the Perth Canyon (Heap et al., 2008; Borissova et al., 2010a).

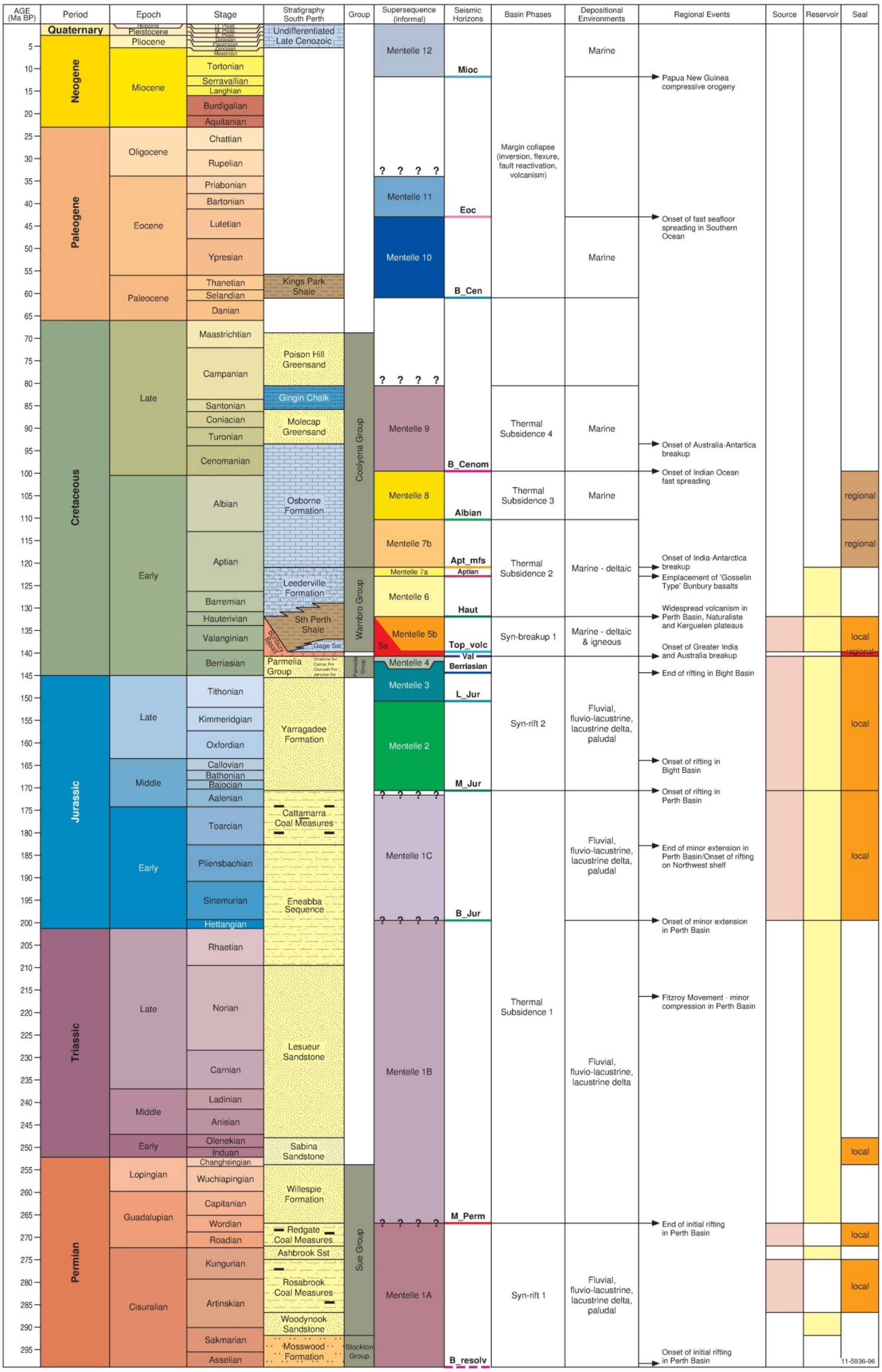

Figure 3.13: Stratigraphy of the Mentelle Basin, including sequence stratigraphy and tectonic events from Borissova et al. (2010). Geologic time scale after Gradstein et al. (2012).

3.3.3 Petroleum systems

There are no known petroleum systems in the Eastern Mentelle Sub-basin, however, hydrocarbon indicators visible on seismic data (some supported by AVO analysis) and potential slicks detected by SAR, suggest at least one petroleum system is present in the Western Mentelle Sub-basin (Cook, 2005, 2006; Borissova et al., 2010a).

Given the absence of wells within the Eastern Mentelle Sub-basin, assessments of petroleum prospectivity potential are based on comparisons with data from the Vlaming Sub-basin where several active petroleum systems have been identified (e.g. Bradshaw et al., 1994; Crostella, 1995; Miyazaki et al., 1996; Crostella & Backhouse, 2000; Boreham et al., 2000; Kempton et al., 2002; Volk et al., 2004; Boreham, 2008; Borissova et al., 2010a).

3.3.3.1 Source rocks

Potential source rocks include Permian fluvio-lacustrine coal and carbonaceous shale, equivalent to the Sue Group, and Lower to Middle Jurassic coal and carbonaceous shale, equivalent to the Cattamarra Coal Measures (Borissova et al., 2010a). Petroleum systems modelling indicates that only Permian source rocks are likely to be mature in the eastern part of the Mentelle Basin (Borissova et al., 2010a). In addition, the modelling suggests that generation and expulsion from Permian source rocks probably occurred from the Early to Middle Jurassic onwards (Borissova et al., 2010a).

3.3.3.2 Reservoir and seal

Good quality reservoir rocks are likely to be present at multiple stratigraphic levels given the interpretation of predominantly fluvial environments in both the pre- and syn-rift sections (Borissova et al., 2010a).

Seals within the syn-rift succession are probably mostly intraformational, while in the westernmost parts of the sub-basin, potential seals are provided by Aptian–Albian marine mudstones (Borissova et al., 2010a).

3.3.3.3 Play types

Potential play types are shown in Figure 3.14.

3.3.3.4 Critical risks

The main risks for petroleum systems in the Eastern Mentelle Sub-basin are:

- a thin Jurassic–Holocene succession implies that any Upper Jurassic to Lower Cretaceous source rocks are unlikely to have reached maturity (Borissova et al., 2010a).
- the presence of seals within extensively deformed strata remains a key uncertainty (Borissova et al., 2010a).
- the risk of breaching of Permian traps is high due possible fault reactivation in the Middle Jurassic–Early Cretaceous.

3.3.3.5 Overall prospectivity classification

Moderate–low

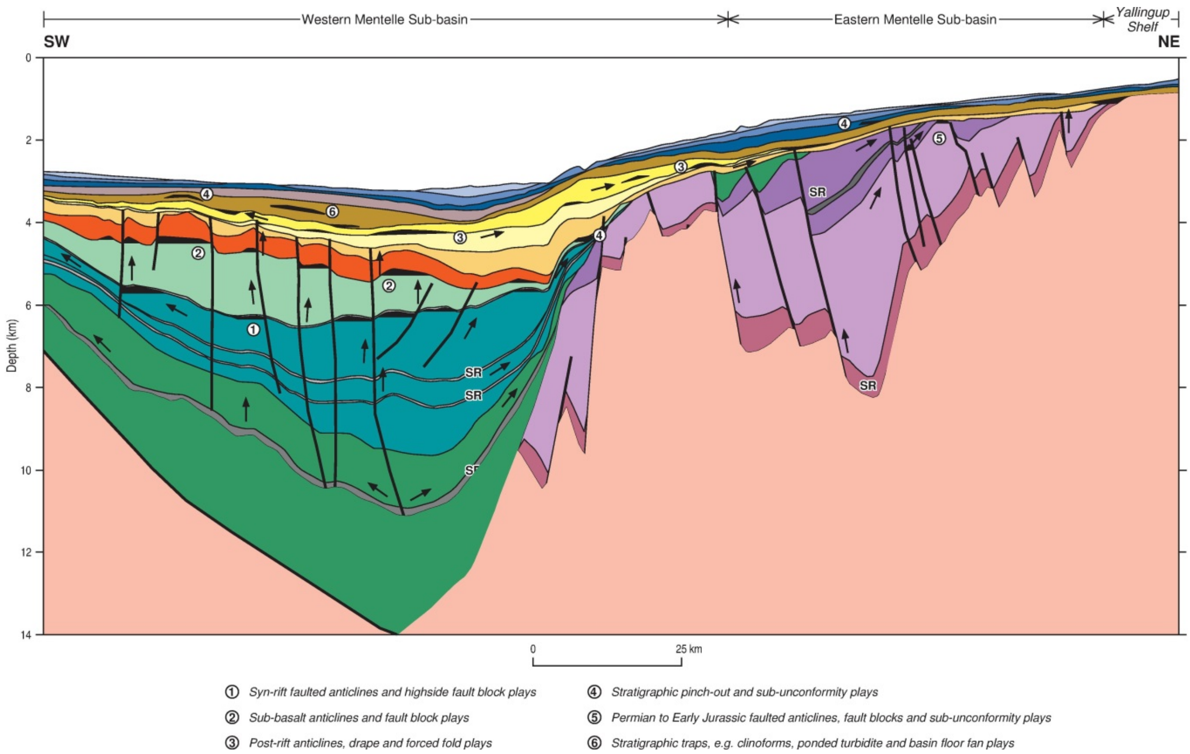

Figure 3.14: Conceptual play diagram for the Mentelle Basin (from Borissova et al., 2010a). See Figure 3.13 for key to sequences.

3.3.4 Exploration status

Exploration in the Eastern Mentelle Sub-basin has been limited to regional seismic acquisition and sampling programs. These include the Shell Development "*Petrel*" Survey and BMR's Continental Margins Surveys in the 1970s (Borissova, 2002), and more recently, a series of Geoscience Australia sampling and seismic cruises from 2005 to 2008 (Crawford et al., 2006; Heap et al., 2008; Borissova et al., 2010a).

Exploration acreage was released across the Mentelle Basin for the first time in 2010. No bids were received.

3.3.5 Data

Key data sets for the Eastern Mentelle Sub-basin are listed in Table 3.9–Table 3.12. No wells have been drilled in the Eastern Mentelle Sub-basin (Figure 3.15). The stratigraphy is inferred from seismic ties to DSDP 258 in the western Mentelle Sub-basin (Table 3.9; Davies et al., 1974) and to wells in the adjacent Vlaming Sub-basin (Borissova et al., 2010a, b).

Reflection seismic data over the Mentelle Basin varies considerably in quality and coverage (Table 3.10; Figure 3.15). The 1972 BMR Continental Margins surveys and 1973 Shell Development surveys created coverage with a line spacing between 20 and 60 km. The two more recent Geoscience Australia surveys, GA 280 and GA 310, have greatly improved the seismic coverage and resolution in the Mentelle Basin, reducing line spacing to around 10–20 km (Foster et al., 2009). Record length for these surveys is 12 s TWT. No 3D seismic data has been collected in this area.

Two surveys have collected dredge samples from the Mentelle Basin:

- GA (SS2005/08) northern Mentelle (sedimentary, basement)
- GA (SS2005/09) Naturaliste Plateau (sedimentary, volcanic and basement rocks).

The Eastern Mentelle Sub-basin is completely covered by 15 ERS2 Synthetic Aperture Radar (SAR) images, collected between 1996 and 2006. In addition, two Radarsat SAR images cover the northern and central parts of the sub-basin. Processing, interpretation and mapping of SAR slicks is documented in Cook (2005, 2006).

Swath bathymetry coverage of the Eastern Mentelle Sub-basin is variable. The coverage is nearly complete in the northern part of the sub-basin, but patchy in the south. Twelve surveys overlap parts of the basin, as shown in Table 3.12.

All good quality potential field datasets have been compiled, levelled and gridded to provide continuous gravity and magnetic coverage across the entire southwestern margin (Hackney, 2012).

3.3.5.1 Confidence Rating

Medium

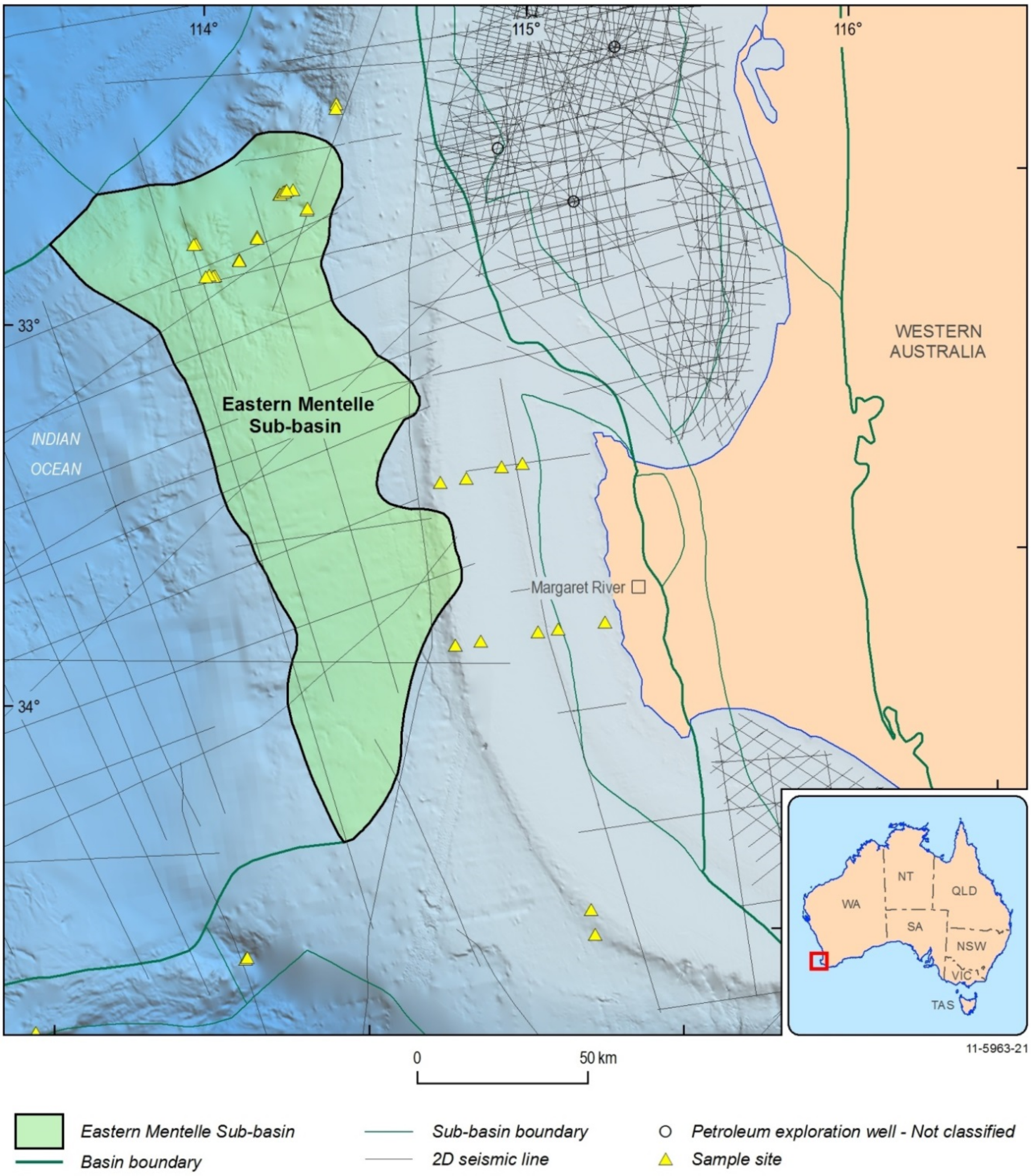

Figure 3.15: Seismic, well and sample distribution for the Eastern Mentelle Sub-basin.

3.3.6 Issues and remaining questions

The current interpretation for Lower Cretaceous and older rocks is based on analogy with the Vlaming Sub-basin. As a result, there are no direct constrains on the following:

- age of the succession
- presence of source rocks and other key petroleum systems elements
- timing of generation/ migration
- the impact of volcanism (including the distribution and thickness of volcanics)

3.3.6.1 Recommendations

To resolve the above questions and promote further exploration in the region, significant additional data collection is required, such as:

- drilling of a stratigraphic well, followed by sequence stratigraphic, biostratigraphic, petrophysical and geochemical studies
- acquisition and interpretation of closely spaced (<5 km), industry standard seismic data
- acquisition and modelling of aeromagnetic data to assess the distribution and thickness of igneous rocks
- acquisition of seismic refraction data to determine crustal thickness and composition.

Perceptions of prospectivity in the Eastern Mentelle Sub-basin are based on the presence of active petroleum systems in the adjacent basins and sub-basins. However, the depth of water, large distance from the coast line and infrastructure and high costs of data acquisition are key concerns in this region.

3.3.7 References

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3.3.8 Data Tables

Table 3.9: List of wells close to the Eastern Mentelle Sub-basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1974	DSDP258	Stratigraphic	DSDP	525	Cretaceous	Not classified	Davies et al., 1974

Table 3.10: Key 2D seismic surveys, Eastern Mentelle Sub-basin

Year	Survey	Operator	Line-km	Reference
1972	GA Continental Margins Survey 18	BMR (now Geoscience Australia)	17863 line-km	Borissova, 2002
1971	Shell Development "*Petrel*" Survey	Shell Development	1270 line-km	Borissova, 2002
2004	GA 280 Southwest Frontier	Geoscience Australia	1060 line-km	
2008	GA 310	Geoscience Australia	2570 line-km	Foster et al., 2008

Table 3.11: Key geological sampling surveys in the Eastern Mentelle Sub-basin and adjacent areas.

Year	Survey	Operator	Region	Type	Rock types	Reference
2005	GA SS2005/08	Geoscience Australia	northern Mentelle Basin	Dredge	Sediments, basement	Heap et al., 2008
2005	GA SS2005/09	Geoscience Australia	Naturaliste Plateau	Dredge	Sediments, volcanics, basement	Crawford et al., 2006

Table 3.12: Key swath bathymetry surveys Eastern Mentelle Sub-basin.

Year	Survey	Operator	Area (km^2)	Reference
1994	ADEDAV (N.O. *L'Atalante*)	Geoscience Australia/FREMER	41,778	
1994– 1995	SOJN05MV (R/V *Melville*)	SIO	61,001	
1995	WEST10MY (R/V *Melville*)	SIO	114,721	
1995	Rottnest (HMAS *Cook*)	RAN-JCU	2036	
1996	BMRG06MV (R/V *Melville*)	BMR (now Geoscience Australia)	18,9343	
2004	MR03K04L6 (R/V *Melville*)	SIO	109,000	
2005	SS08/2005 (Mentelle; R/V *Southern Surveyor*)	Geoscience Australia	7269	Heap et al., 2008
2005	SS07/2005 (Wabio; R/V *Southern Surveyor*)	CSIRO	12,240	
2005	SS09/2005 (Naturaliste Rocks; R/V *Southern Surveyor*)		17,616	Crawford et al., 2006
2005	SS10/2006 (Wabio_2; R/V *Southern Surveyor*)	CSIRO	10,373	
2006	SS04/2006 (Leeuwin Currents; R/V *Southern Surveyor*)		12,436	
2006	SS05/2006 (Meso_Eddies; R/V *Southern Surveyor*)	Geoscience Australia	16,765	

3.4 Houtman Sub-basin (Perth Basin)

3.4.1 Summary

State(s)		WA
Area (km^2)		52,900
Water Depth (m)		100–35000
Maximum sediment thickness (m)		~8000 (generally <6000 m thick)
Age range		Permian–Holocene
Basin	**Overlies**	Pinjarra Orogen; Southern Carnarvon Basin
	Parent	Perth Basin
	Adjacent basins	Abrolhos Sub-basin, Gascoyne Sub-basin, Southern Carnarvon Basin, Turtle Dove Ridge, Zeewyck Sub-basin
Basin type		Extensional
Depositional setting, rock types		Marine and non-marine siliciclastic rocks
Overall prospectivity		High
Confidence		*High–low*

3.4.2 Geology

The Houtman Sub-basin forms the largest structural element in the Perth Basin. It extends approximately 700 km along-strike, covers an area of 52,900 km^2 and is located on the continental shelf and slope in water depths ranging from 100–3500 m (Figure 3.16; Jones et al., 2011). It is an elongate, northwest–southeast trending depocentre that contains up to 14,000 m of sediment (Copp, 1994).

3.4.2.1 Structural geology

The thick Houtman Sub-basin succession is extensively faulted. Its location adjacent to the Wallaby–Zenith Transform Margin (Figure 3.16) suggests the basin developed in a strike-slip to transitional setting (Bradshaw et al., 2003; Jones et al., 2011; Bernardel & Nicholson, 2013; Hall et al., 2013; Rollet et al., 2013a, b).

Faulting is characterised by closely spaced, predominantly westerly-dipping, normal faults (Figure 3.17; Jones et al., 2011; Bernardel & Nicholson, 2013). Despite limited seismic resolution at depth, Permian half graben are visible in the northern part of the sub-basin (Iasky et al., 2003; Jones et al., 2011; Bernardel & Nicholson, 2013). Erosion during regional uplift associated with Valanginian–Aptian transform margin development removed most of the Middle Jurassic–Lower Cretaceous syn-rift section (Figure 3.17; Quaife et al., 1994; Hall et al., 2013). Post-breakup deposits form a westerly-thickening (up to ~1,500 m thick), carbonate-dominated, passive margin succession across the sub-basin (Figure 3.17; Jones et al., 2011).

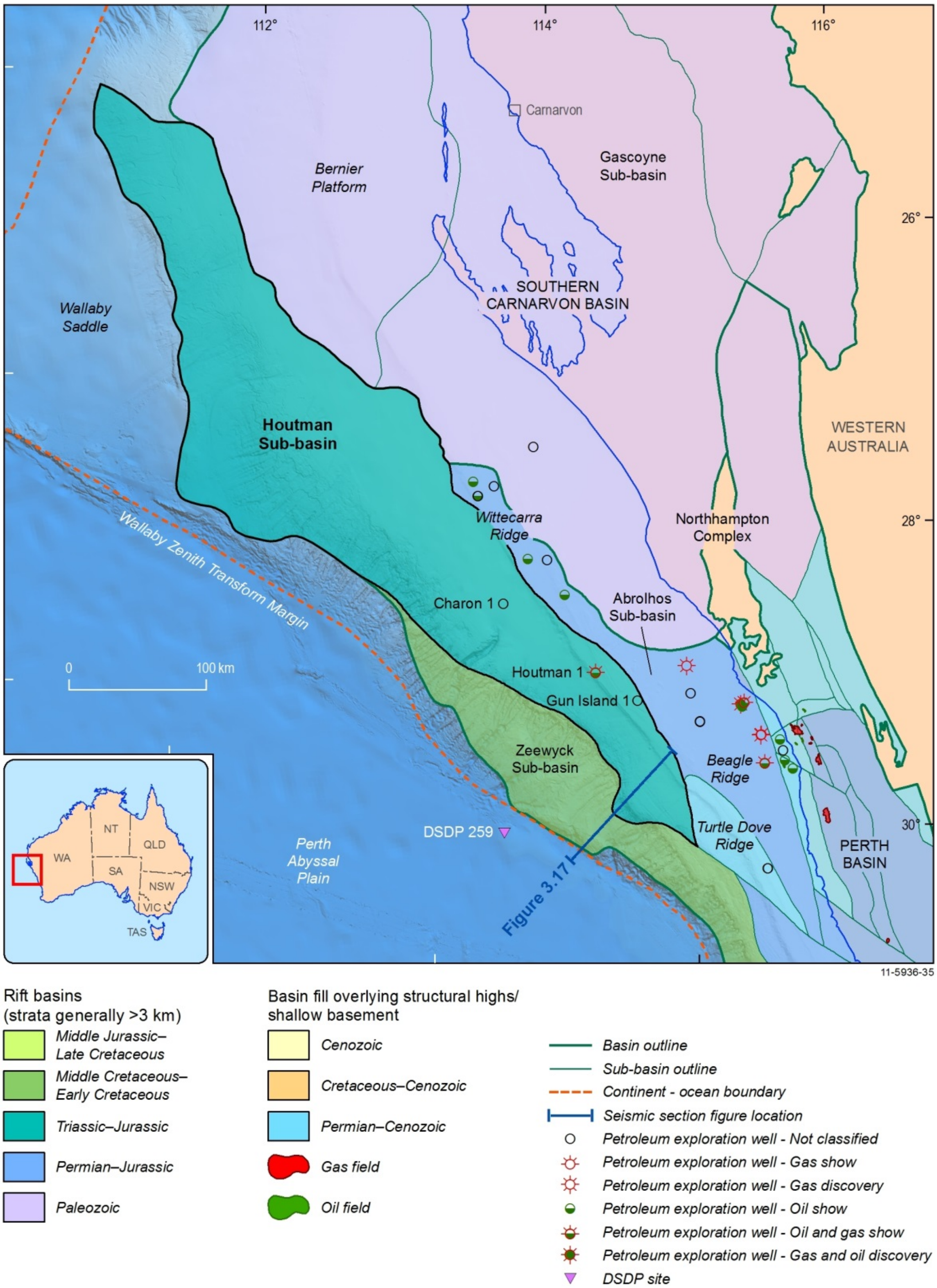

Figure 3.16: Regional setting of the Houtman Sub-basin.

The eastern boundary of the Houtman Sub-basin is defined by the Houtman Fault System, which separates it from the Abrolhos Sub-basin and Southern Carnarvon Basin (Figure 3.17; Jones et al., 2011). The southeastern boundary is characterised by strata that have been uplifted onto the Turtle

Dove Ridge (Figure 3.16; Jones et al., 2011). To the southwest, however, the Houtman Sub-basin is bordered by a north-northwest-striking, listric fault zone that steps down into the outboard deep-water Zeewyck Sub-basin (Figure 3.16 and Figure 3.17; Jones et al., 2011).

To the northwest, the Houtman Sub-basin is bordered by the Wallaby Saddle (Figure 3.16), represented in seismic data by a seaward-dipping reflector sequence. This succession has previously been interpreted as flood basalts emplaced during, or just after, Valanginian breakup (Colwell et al., 1994; Symonds et al., 1998).

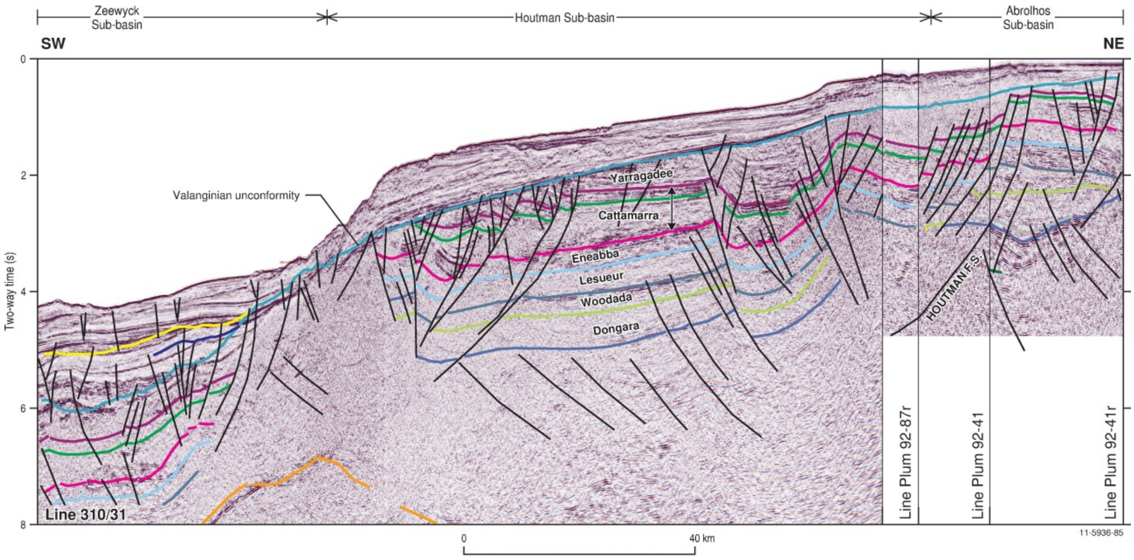

Figure 3.17: Cross-section through the Houtman Sub-basin (Jones et al., 2011; Rollet et al., 2013a). See Figure 3.16 for cross-section location.

3.4.2.2 Basin evolution and depositional history

The Houtman Sub-basin has had a complex, multi-phase history of extension and reactivation lasting from the Permian to Holocene (Figure 3.18; Bradshaw et al., 2003; Norvick, 2004; Pfahl, 2011; Jones et al., 2011, 2012; Bernardel & Nicholson, 2013; Hall et al., 2013; Rollet et al., 2013a, b).

The area is likely to be underlain by Mesoproterozoic–lower Cambrian metamorphic rocks of the Pinjarra Orogen (Fitzsimons, 2003; Hackney et al., 2012; Johnston & Petkovic, 2012; Hall et al., 2013). Pre-rift strata, comprising the upper Cambrian–Ordovician Tumblagooda Sandstone of (Iasky et al., 2003; Jones et al., 2011), was intersected on the Wittecarra Terrace in Livet 1 and Hadda 1 and may also underlie the Houtman Sub-basin (Jorgensen et al., 2011; Jones et al., 2011; Rollet et al., 2013a). This succession of fluvial sandstones may locally exceed 4 km in thickness in some locations (Playford et al., 1976).

Early- to mid-Permian east-northeast oriented intra-cratonic extension led to the formation of north-northwest oriented half graben separated by saddles and characterised by en echelon border faults in the offshore northern Perth Basin (Iasky et al., 2003; Norvick, 2004; Jones et al., 2011; Rollet et al., 2013a, b). Based on seismic data, Permian strata are interpreted to underlie the majority of the Houtman Sub-basin (Bernardel & Nicholson, 2013). Sediments of this age, equivalent to the Nangetty–lower Carynginia succession in the onshore northern Perth Basin, are inferred to have been deposited in a glacial to pro-glacial marine environment (Figure 3.18; Mory & Iasky, 1996; Jones et al., 2011).

The top of the lower- to mid-Permian syn-rift succession is marked by a major angular unconformity which is interpreted to be the result of a regional tectonic uplift (Figure 3.18; Rollet et al., 2013a, b). Tilted fault blocks were exposed to sub-aerial erosion at this time (Roc Oil, 2004). However, tectonic subsidence analysis indicates that the amount of uplift was minor, about 100–250 m (Pfahl, 2011). Widespread erosion may have been accentuated by a major eustatic sea level fall at the end of mid-Permian (Jones et al., 2011).

Middle Permian to Middle Jurassic thermal subsidence resulted in the formation of a westward-thickening sag basin (up to 1500m thick) across the Houtman Fault System (Figure 3.17 and Figure 3.18; Enterprise Oil Exploration & Nippon Oil Exploration, 1994; Bradshaw et al., 2003; Jones et al., 2011; Pfahl, 2011; Rollet et al., 2013a, b). Comparison with seismic sequences in the Abrolhos and onshore Perth Basin suggests this succession includes the Dongara Sandstone, Lower–Middle Triassic marine shales of the Kockatea Shale, the fluvio-deltaic Woodada Formation and the fluvial Lesueur Sandstone (Figure 3.18; Mory & Iasky, 1996; Bradshaw et al., 2003; Jones et al., 2011; Rollet et al., 2013a, b). The overlying Eneabba Sequence comprises fluvial sandstone interbedded with varicoloured siltstone and claystone (Figure 3.18; Jorgensen et. al., 2011; Jones et al., 2011; Rollet et al., 2013a, b)

Acceleration of syn-rift subsidence during initial deposition of the Cattamarra Sequence is recorded in all wells of the Houtman Sub-basin and reflected on seismic data (Pfahl, 2011; Jorgensen et al., 2011; Rollet et al., 2013a, b). The Houtman Fault System is likely to have been a major growth fault zone during this period of extension, accommodating the rift fill in the main depocentre of the Houtman Sub-basin (Rollet et al., 2013a, b). Rifting coincided with a slow relative sea level rise during the Early to Middle Jurassic, which led to the deposition of interbedded sandstones, siltstones and coals of the Cattamarra Sequence (Figure 3.18; Jones et al., 2011; Rollet et al., 2013a). The maximum flooding event was recorded in the Cadda Sequence (Figure 3.18; Jorgensen et al., 2011; Jones et al., 2011).

Subsidence models indicate that during the Middle to Late Jurassic the offshore Perth Basin entered a second phase of post-rift subsidence (Pfahl, 2011; Rollet et al., 2013). During this time, a relative sea level fall and waning post-rift subsidence led to the deposition of the Yarragadee Sequence (Figure 3.18; Jorgensen et. al., 2011; Robertson et al., 2011; Jones et al., 2011; Rollet et al., 2013a). Initial deposition of fluvio-deltaic sandstones and siltstones was followed by deposition of coarse-grained fluvial sediments by a northerly-flowing river system (Mory & Iasky, 1996; Norvick, 2004).

A Late Jurassic to Early Cretaceous northwest–southeast extensional phase preceded the final separation of the Australia and Greater India in the Valanginian (Larson et al., 1979; Veevers et al., 1985, 1991; Bradshaw et al., 2003; Norvick, 2004; Pfahl, 2011; Gibbons et al., 2012; Rollet et al., 2013a; Hall et al., 2013). Seismic interpretation shows that the main depocentre during the Late Jurassic was located outboard in the southern Houtman and Zeewyck sub-basins (Figure 3.17; Jones et al., 2011; Rollet et al., 2013a). This Early Cretaceous rift phase continued the development of a north-northwest-striking system of closely spaced, predominantly westerly-dipping rotated fault blocks (Figure 3.17; Jones et al., 2011; Rollet et al., 2013a). A series of small north to north-northwest-striking inversion anticlines and pop-up structures in the Houtman and Abrolhos sub-basins may have formed through localised transpressional stresses during the late stages of extension (Hall et al., 2013; Rollet et al., 2013a). The inversion structures are characterised by well-developed fault propagation folds that have been truncated by the Valanginian unconformity (Rollet et al., 2013a).

Continental breakup between India and Australia began in the Perth Abyssal Plain in the Valanginian, initiating the development of the Wallaby Zenith Transform Margin (Veevers et al., 1985, 1991; Norvick, 2004; Gibbons et al., 2012: Hall et al., 2013). Active transform motion lasted from approximately 137–124 Ma (Valanginian to early Aptian), outboard of the Zeewyck sub-basin, and may have continued until as late as 115 Ma (late Aptian) outboard of the northern Houtman sub-basin (Hall et al., 2013). Wells and seismic data indicate widespread uplift and erosion related to breakup (Figure 3.17 and Figure 3.18; Quaife et al., 1994; Bradshaw et al., 2003; Pfahl, 2011). This erosion produced an angular unconformity (Figure 3.17), and resulted in the total removal of Lower Cretaceous strata and extensive erosion of Upper Jurassic strata across large areas of the Houtman Sub-basin. Significant volcanic activity was associated with this tectonic event (Gorter & Deighton, 2002; Jones et al., 2011). A seaward dipping reflector sequence close to the western boundary is interpreted to represent flood basalts and shallow sills (Symonds et al. 1998). Abundant sills, cones and dykes can be seen within the sedimentary section (Gorter & Deighton, 2002).

Breakup was followed by rapid passive margin subsidence and widespread westward regional tilting in the Valanginian–Aptian during the development of the Wallaby Zenith Transform Margin (Hall et al., 2013; Rollet et al., 2013a). Post-breakup deposits form a westward thickening (up to ~1500 m thick) passive margin cover of predominantly carbonate rocks (Figure 3.17 and Figure 3.18; Enterprise Oil, 1994; Bradshaw et al., 2003; Jones et al., 2011).

Evidence of late-stage fault reactivation and inversion, with minor folding of Cretaceous and younger strata extending just below the seafloor, is evident along some of the major basin-bounding fault systems in the offshore northern Perth Basin (Gorter et al., 2004; Rollet et al., 2013a). This inversion event is interpreted to be the result of Miocene convergence between the Australian and Eurasian plates (Rollet et al., 2013a). Evidence from seismic data, swath bathymetry and seafloor dredging indicate that minor volcanic activity also occurred in the sub-basin during this time (Daniell et al., 2010; Rollet et al., 2013). During the Neogene to Quaternary, cool-water ramp carbonates were deposited in a reefal platform environment (e.g. Houtman and Abrolhos coral reefs) near the shelf edge (Collins et al., 1998).

3.4.2.3 Level of knowledge

The origin and structural characteristics of the sub-basin are only well documented in the south where most data has been acquired (Bradshaw et al., 2003; Jones et al., 2011; Rollet et al., 2013a, b).

Upper Triassic (Eneabba Sequence) and younger rocks have been intersected by wells within the inner part of the southern Houtman Sub-basin (Jorgensen et al., 2011). The age, lithology and depositional environments of the Middle Triassic and older units have been interpreted using seismic data through direct correlation with wells in the adjacent Wittecarra Terrace and Abrolhos Sub-basin (Bradshaw et al., 2003; Jones et al., 2011; Bernardel & Nicholson, 2013; Rollet et al., 2013a, b).

Despite the lack of well data in the northern Houtman sub-basin, regional seismic interpretation has enabled correlation of the sequences defined in the southern part of the sub-basin, with horizons in the north (Bernardel & Nicholson, 2013). However the large correlation distances involved and the highly structured nature of the margin leads to significant uncertainty in this interpretation (Bernardel & Nicholson, 2013).

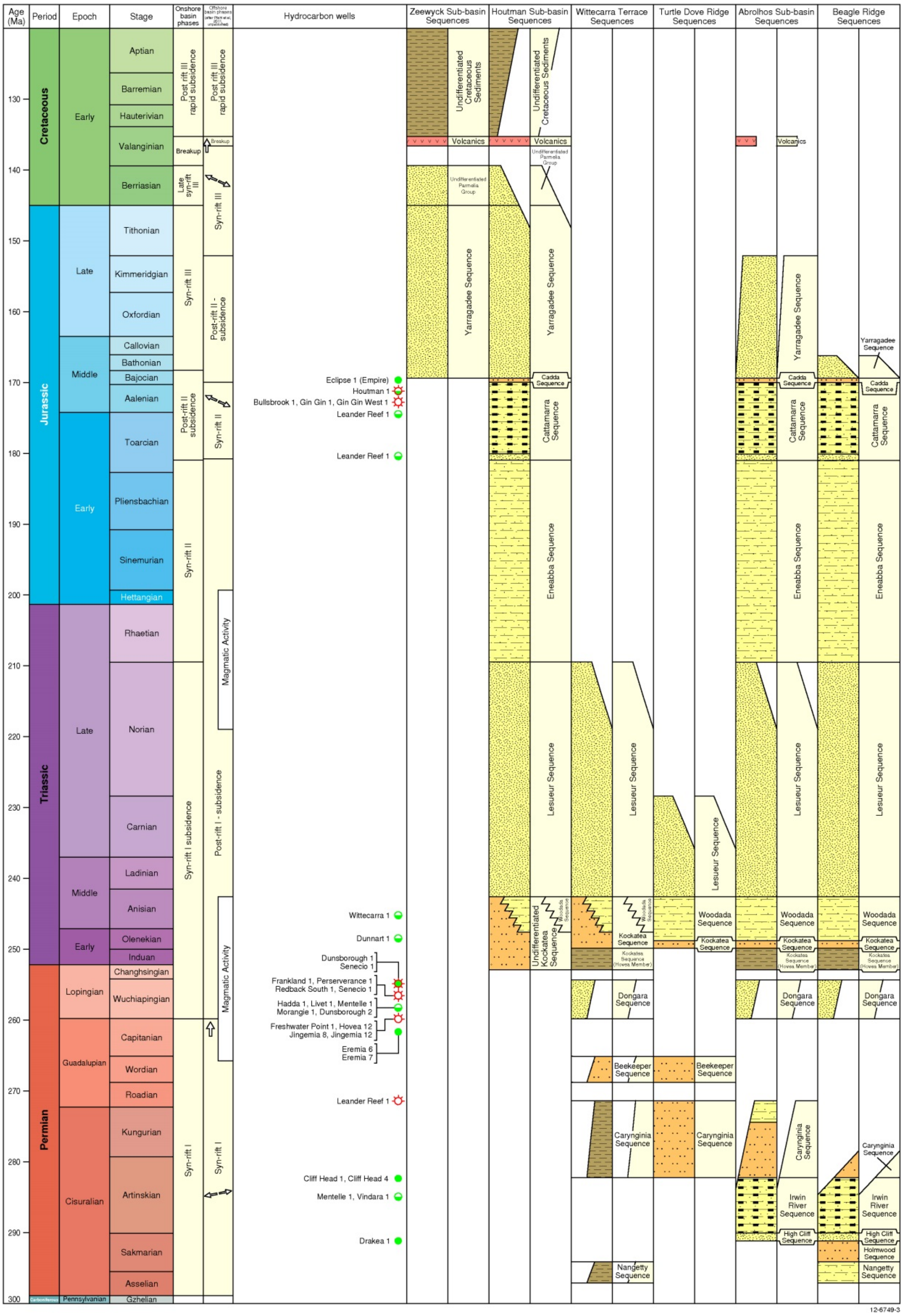

Figure 3.18: Stratigraphy and hydrocarbon discoveries of the offshore northern Perth Basin, based on the Offshore Northern Perth Basin Biozonation and Stratigraphy Chart (Jones et al., 2012). Geological Time Scale after Gradstein et al (2012).

3.4.3 Petroleum systems

Several hydrocarbon families and associated petroleum systems are recognised within the Houtman Sub-basin and in its immediate surrounds (Figure 3.19). The petroleum systems potential of the Houtman Sub-basin is summarised below as described by Jones et al. (2011), Grosjean et al. (2012, 2014) and Rollet et al. (2013a, b).

3.4.3.1 Source Rocks

The Permian Irwin River Sequence intersected in wells located on the Beagle Ridge and in the central Abrolhos Sub-basin adjacent to the Houtman Sub-basin shows good organic richness with TOC >1% for the majority of samples (up to 16.9%) and are predominantly gas-prone with HI below 200 mg HC/g TOC (Figure 3.19). Although this sequence has not been penetrated by drilling or confidently identified on seismic data in the Houtman Sub-basin (Figure 3.18), it is possible this source is present at depth (Bernardel & Nicholson, 2013). The thermal maturity of the Irwin River Sequence in the adjacent sub-basins ranges from immature to early mature with respect to oil generation, although it could have reached the main oil window in deeper depocentres.

The marine upper Permian–Lower Triassic Kockatea Sequence has long been known to be the source of onshore oil and condensate accumulations from the greater Dongara area fields in the onshore Perth Basin (Figure 3.19; Summons et al., 1995; Thomas & Barber, 2004). Within the Kockatea Sequence the basal Hovea Member was shown by Thomas & Barber (2004) to be the richest source interval. In addition, offshore, organic-rich intervals are identified with 2% mean TOC and a predominantly oil-prone character (HI >300 mg HC/g TOC). While the Kockatea Sequence has not been intersected within the Houtman Sub-basin, seismic interpretation suggests that it is likely to be present at depth across large parts of the sub-basin (Figure 3.17 and Figure 3.18; Bernardel & Nicholson, 2013).

The best Hovea Member source rocks for oil are found on the Beagle Ridge and in its vicinity; however, source potential gradually declines further north and outboard with only fair potential for mixed oil and gas observed in wells of the northern Wittecarra Terrace (to the north of the Houtman Sub-basin).

Extensive oil charge from the Hovea Member source in the offshore northern Perth Basin is also revealed from the geochemical composition of reservoired and migrated hydrocarbons, as well as from fluid inclusions. These oil shows may be, in part, remnants of palaeo-oil columns recognised in these wells on the basis of fluid inclusion data (Geotech, 2005; Kempton et al., 2011; Grosjean et al., 2012, 2014).

The thermal maturity of the Hovea Member ranges from immature to mature for oil generation in the adjacent Beagle Ridge and Abrolhos Sub-basin. The Hovea Member was shown to be of limited quality and only marginally mature in wells of the northern Wittecarra Terrace, suggesting a non-local charge from a fully mature source kitchen, potentially located to the west in the adjacent Houtman Sub-basin.

In contrast to the Hovea Member, the overlying Lower Triassic Kockatea Sequence is rather lean with TOC mainly <1% and, consequently, has only fair potential for both oil and gas generation. The middle and upper Kockatea Sequence lie within the main zone of oil generation in wells in the adjacent sub-basins.

In several Wittecarra Terrance and Abrolhos Sub-basin wells, units within the Lower to Middle Triassic Woodada Sequence have good source richness (TOC >1%) and potential for both oil and gas generation (HI values of 131–446 mg HC/g TOC; Figure 3.19). In those wells, the Woodada Sequence potential source rocks are immature to early mature. This suggests there may also be some source potential for this sequence in the Houtman Sub-basin.

The Houtman Sub-basin also contains potential source rocks within the Jurassic succession (Figure 3.19; Jones et al., 2011, Rollet et al., 2013). Organic-rich sediments are present throughout the Eneabba Sequence in Gun Island 1; these rocks have the potential to generate both oil and gas. The Cattamarra and Cadda sequences exhibit good organic richness with a TOC average of 3.2% and 3.7%, respectively, with the potential for generating mostly gas (HI<200 mg HC/g TOC) and in a few samples, minor liquids (Rollet et al., 2013a). Both sequences are within the oil window in the Houtman Sub-basin.

The Yarragadee Sequence is characterised by highly carbonaceous sediments, with an average TOC of 12%, and the potential for both oil and gas generation. Carbonaceous shales and coals (TOC >5% to 64%) are highly oil-prone and a fault-bounded depocentre is interpreted on the cross-section shown in Figure 3.18.The Yarragadee Sequence is immature to early mature in the Abrolhos and Houtman sub-basins.

The presence of a working Jurassic petroleum system in the offshore northern Perth Basin is supported by fluid inclusion data, which shows that a palaeo-oil column in the Cadda Sequence in Houtman 1 was most likely sourced from Jurassic strata (Volk et al., 2004).

3.4.3.2 Generation and expulsion

Thomas & Barber (2004) suggest that in the onshore Perth Basin, oil generation from the Hovea Member was virtually coincident with gas generation from the underlying Permian Irwin River Coal Measures. Their model showed that the main pulse of hydrocarbon generation occurred in the Late Jurassic–Early Cretaceous, at the same time as the deposition of the Yarragadee Sequence. Thus, in most onshore areas, oil charge from the Hovea Member was in direct competition with gas generated from the Permian section.

Petroleum systems modelling by Gorter et al. (2004) indicates that basal Kockatea Shale could have expelled oil in the Early to Middle Jurassic. Modelled oil and gas expulsion from the Cattamarra Coal Measures occurred in the latest Jurassic to earliest Cretaceous (135–150 Ma), immediately preceding uplift and erosion. Minor oil and gas were also expelled during the latest Cretaceous and Cenozoic.

More recent burial history modelling of the Hovea Member in the offshore northern Perth Basin (Figure 3.19; Pfahl, 2011; Rollet et al., 2013a) has shown that the Hovea Member entered the main oil window in the Late Triassic in most of the Houtman Sub-basin. The Houtman Sub-basin underwent a rapid increase of maturity during the Middle Jurassic following the Early Jurassic rifting phase, resulting in the Hovea Member entering the wet gas and subsequently dry gas windows in the central and western areas. All the pseudo-wells of the Houtman Sub-basin had entered the wet gas and dry gas window by the Early Cretaceous. Hydrocarbon generation rates were fairly low throughout the Late Triassic and Early Jurassic in all areas of the Houtman Sub-basin except the central region (Charon 1), where generation peaks in the Late Triassic. Maximum generation rates in the northern and western Houtman Sub-basin occurred later, between 180 and 170 Ma (Early–Middle Jurassic).

3.4.3.3 Reservoirs

The primary reservoir units in the offshore Perth Basin are the upper Permian Dongara Sequence and Irwin River Sequence, which are hosts to several oil and gas accumulations. Potentially good reservoirs are present within the Triassic (Woodada Sequence, Lesueur Sequence) and Jurassic to Lower Cretaceous successions (Eneabba Sequence, Cattamarra Sequence, Yarragadee Sequence; Figure 3.19; Jones et al., 2011; Rollet et al., 2013a, b).

3.4.3.4 Seals

The Lower Triassic Kockatea Sequence is proven to be an effective regional seal across the northern Perth Basin (Figure 3.19; Jones et al., 2011). This regional seal is 50–443 m thick on structural highs and is over 1000 m thick in depocentres above the Permian half graben. The thickness is generally sufficient to provide robust vertical and cross-fault seal, unless breached by subsequent reactivation.

The best potential seal above the Kockatea regional seal is the Middle Jurassic Cadda Sequence (Figure 3.19). These marine shales are demonstrated to be an effective local seal at Houtman 1, where they overly the 15 m palaeo-oil column detected in the sandy basal Cadda Sequence (Kempton et al., 2011; Jones et al., 2011). The Cadda Sequence is 400 m thick in well intersections in the Houtman Sub-basin, but only 40–123 m thick in the other offshore wells (Jones et al., 2011). Thin sandstone intervals in the Cadda Sequence were also intersected by Houtman 1 and Gun Island 1, which may compromise fault juxtaposition seals (Gorter et al., 2004).

Intraformational seals are potentially present within Eneabba, Cattamarra and Yarragadee sequences (Figure 3.19; Jones et al., 2011; Robertson et al., 2011). Fluid inclusion data indicate that they locally provide impedance barriers to oil migration, such as in Leander Reef 1 (Kempton et al., 2011), but their potential to seal hydrocarbon accumulations remains speculative.

3.4.3.5 Play types

The dominant play type tested in the offshore northern Perth Basin is upper Permian/basal Triassic sandstones (previously variously referred to as Dongara, Wagina or Wittecarra sequences), sourced and sealed by the Kockatea Sequence within tilted fault and horsts blocks (Jones et al., 2011; Rollet et al., 2013a, b).

In the Houtman Sub-basin, leads have been identified within the Jurassic section (Rollet et al., 2013). A faulted horst at the top of Cattamarra Sequence located west of Houtman 1 is ideally placed to trap hydrocarbons migrating from the main Houtman depocentre (Callisto lead; Gorter et al., 2004). To the northwest, a complex faulted anticlinal horst block with growth from the Eneabba Sequence and thickening of the Cadda Sequence also shows some evidence of closure (Gorter et al., 2004).

A potential, large upper Permian stratigraphic play occurs within two large depocentres approximately 20 km and 50 km, respectively, to the west of Leander Reef 1 (Jones et al., 2011; Rollet et al., 2013). These depocentres contain a thick basinal succession of the Dongara Sequence, that onlaps the upper Permian unconformity and is overlain by a thick section, which in part includes the Kockatea Sequence.

3.4.3.6 Critical risks

A major exploration risk in the offshore northern Perth Basin is the potential loss of accumulations and the effect on maturation history of the Early Cretaceous uplift and erosion event. At a prospect level, trap breach and ineffective seals are also key risks. This is particularly important for the main

Permian–Triassic oil/gas play, and the frequent palaeo-oil accumulations in the numerous dry wells indicate hydrocarbon loss (Jones et al., 2011; Rollet et al., 2013a, b). The trap breach has been attributed to either fault reactivation and structuring associated with Late Jurassic extension and Valanginian breakup, or tilting of the margin following the breakup or inversion of faults during the Miocene (Kempton et al., 2011).

An additional risk is the unknown distribution of source intervals away from well control, particularly in the northern Houtman Sub-basin.

3.4.3.7 Overall prospectivity classification

High

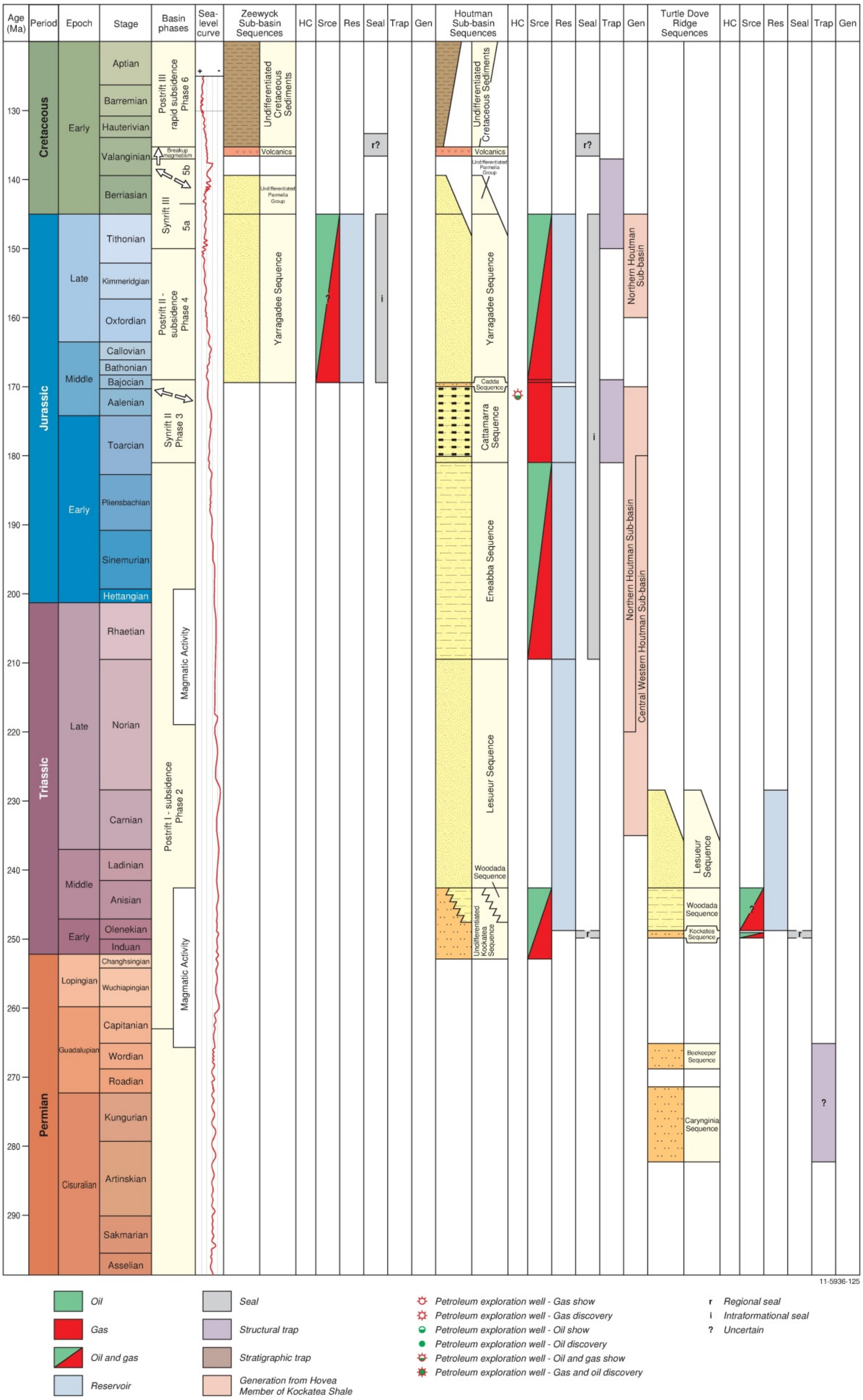

Figure 3.19: Petroleum systems elements for the Houtman Sub-basin (based on Rollet et al., 2013a).

3.4.4 Exploration status

Exploration commenced in 1965 with the acquisition of the Abrolhos Marine Seismic Survey. The first wildcat well to be drilled in the Houtman Sub-basin was Gun Island 1, drilled by BP Petroleum Development Australia Pty Ltd in 1968 as a stratigraphic test on the edge of the Houtman Sub-basin (Figure 3.20; BP, 1969; Jorgensen et al. 2011). In 1978, Houtman 1 was drilled by Esso Australia Ltd, approximately 100 km west of Geraldton; this well was the first petroleum exploration test of the Houtman Sub-basin (Esso Australia Ltd, 1978; Jorgensen et al. 2011). A general lack of drilling success in the offshore northern Perth Basin led to a period of decreased exploration activity and an 18-year hiatus between the drilling of Leander Reef 1 in 1983 and Cliff Head 1 in 2001 in the adjacent Abrolhos Sub-basin. The most recent activity in the Houtman Sub-basin was in 2008 by Eni Australia, with the drilling of Charon 1. This well was supported by the Apollo 3D seismic survey, acquired in 2004 (Figure 3.20; Eni Australia, 2010; Jorgensen et al. 2011).

The only current permit within the sub-basin is WA-481-P, which covers the southern end of the Houtman Sub-basin and significant sections of the Abrolhos Sub-basin and Turtle Dove Ridge (Jones et al., 2011b). The permit was awarded to a joint venture led by Murphy Australia in 2012; the guaranteed work program includes the drilling of three wells. Two areas to the north of this permit, covering a large area of the Houtman Sub-basin, were released for exploration in 2013.

3.4.5 Data

Key data sets for the Houtman Sub-basin are listed in Table 3.13–Table 3.17. Three petroleum wells have been drilled in the Houtman Sub-basin—Gun Island 1, Houtman 1 and Charon 1 (Figure 3.20; Table 3.13). Further details of wells drilled in adjacent sub-basins are provided in Jorgensen et al. (2011).

Seismic coverage in the sub-basin varies from excellent to poor, comprising a mixture of vintages ranging from the 1970s to 2009 (Table 3.14 and Table 3.15; Figure 3.20). Seismic surveys that have reasonable, good or excellent penetration and resolution in the region include GA s310 (Foster et al., 2009), and the Abrolhos and Abrolhos West surveys. All 2D seismic surveys intersecting the Houtman sub-basin are listed in the appendix (Table 3.14). One 3D seismic survey was collected in the Houtman Sub-basin in 2008—the Apollo 3D is located in the central Houtman in the region surrounding the Charon 1 well (Table 3.15).

Geoscience Australia's 2008–2009 marine reconnaissance survey acquired a range of dredge samples from the walls of deeply incised canyons across the Houtman Sub-basin (Table 3.16; Figure 3.20). The oldest samples that could be age dated were of Berriasian age (Daniell et al., 2010).

SAR coverage over the Houtman Sub-basin is limited to the southern tip of the sub-basin.

Swath bathymetry coverage of the Houtman Sub-basin is variable, with the majority of data located in the central and deeper water regions of the sub-basin. Seven surveys intersect the basin, the most recent of which is the 2008–2009 marine reconnaissance survey conducted by Geoscience Australia (Table 3.17).

All good quality potential field datasets have been compiled, levelled and gridded to provide continuous gravity and magnetic coverage across the entire southwestern margin (Hackney, 2012).

3.4.5.1 Confidence rating

High–low

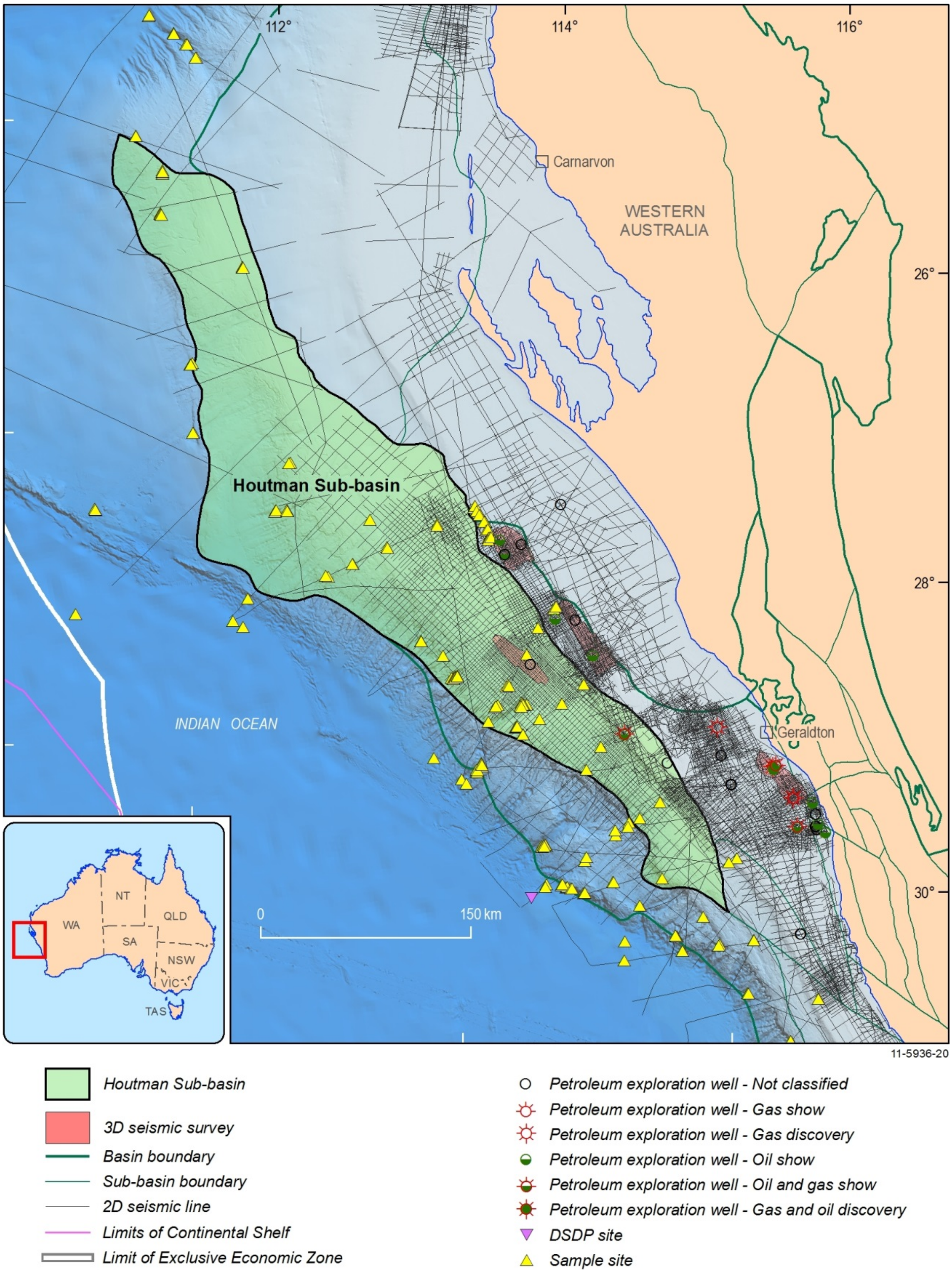

Figure 3.20: Seismic, well and dredge samples in the Houtman Sub-basin and surrounds.

3.4.6 Issues and remaining questions

Well and seismic distribution is primarily limited to the southern Houtman Sub-basin; as a result, there are only limited constraints on the following in the central and northern Houtman:

- age of the succession
- presence of source rocks and other key petroleum systems elements
- timing of generation and migration

3.4.6.1 Recommendations

Resolving these questions would require significant data collection, including drilling of a stratigraphic well within the northern Houtman Sub-basin followed by additional sequence stratigraphic, biostratigraphic, petrophysical and geochemical studies.

In addition the following studies could be undertaken on existing data to better understand the petroleum prospectivity and exploration risk:

- detailed seismic interpretation of the central and northern Houtman sub-basin, tying seismic data to the southern Houtman Sub-basin, as well as the Southern Carnarvon Basin. Identification of possible play types
- petroleum systems modelling to better constrain maturity of, and generation from, key source rock intervals across the sub-basin
- trap integrity modelling to better constrain risk of trap breaching.

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3.4.8 Data Tables

Table 3.13: List of wells in the Houtman Sub-basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1968	Gun Island 1	Stratigraphic	Petroleum Development Australia Pty Ltd	3725	Jurassic	Dry	BP, 1969; Jorgensen et al., 2011
1978	Houtman 1	Exploration	Esso Australia Ltd	3860	Cretaceous	Minor oil and minor gas	Esso Australia, 1978; Jorgensen et al., 2011
2008	Charon 1	Exploration	Eni Australia Ltd	3940	Jurassic	Gas shows	Eni Australia (2010); Jorgensen et al., 2011

Table 3.14: Key 2D seismic surveys, Houtman Sub-basin

Year	Survey	Operator	Line-km	Reference
1971	Shell Development “Petrel” Survey	Shell Development	27326	
1972	BRM 18	BMR (now Geoscience Australia)	17863	
1973	Zuytdorp	Continental Oil	628	
1976	A76A Abrolhos	Esso Australia	1632	
1977	A77A Abrolhos	Esso Australia	340	
1977	Arranoo (423)	Wapet	205	
1978	A78A Abrolhos	Esso Australia	634	
1978	A80A Abrolhos	Western Mining	836	
1978	Hartog	Continental Oil	1967	
1979	WA-81-P II (81P79)	Continental Oil	1375	
1980	Murchison 81P	Concoc	1249	
1985	WA-162 Experimental 1985 (DS85)	Diamond Shamrock	1651	
1986	AGSO 57R, North Perth Basin	AGSO (now Geoscience Australia)	1056	

Year	Survey	Operator	Line-km	Reference
1989	Abrolhos Spec 1989 (S89)	Halliburton Geophysics	1599	
1990	Narwhale (C90)	Command Petroleum	104	
1990	Peacock (E93AU22)	Enterprise Oil	498	
1992	Abrolhos West (WA91)	Conoco	2863	
1992	Fiddich (S92)	Seafield Resources	204	
1992	Plum (EA92AU09)	Enterprise Oil	4369	
1992	Scarlet (E92AU08)	Enterprise Oil	2334	
1993	Livet	Seafield Resources	467	
1994	AGSO 135, Law of the Sea	AGSO (now Geoscience Australia)	4212	
1994	HP94 (aka HP93)	BHP	1268	
2001	Houtman Basin 2001 Non Exclusive (HB01)	Western Geco	2710	
2008	GA 310	Geoscience Australia		See discussion in Daniell et al., 2010

Table 3.15: 3D Seismic surveys, Houtman Sub-basin.

Year	Survey	Operator	Area (km^2)	Reference
2004	Apollo 3D	Eni Australia Ltd	420	

Table 3.16: Key geological sampling surveys in or close to the Houtman Sub-basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
2008–09	GA2476	Geoscience Australia	Houtman Sub-basin, Cuvier margin	Dredge, box core, grab	Siliciclastic and carbonate rocks, volcanic rocks	Daniell et al., 2010

Table 3.17: Key swath bathymetry surveys Houtman Sub-basin

Year	Survey	Operator	Area (km^2)	Reference
1994	ADEDAV (N.O. *L'Atalante*)	GA/FREMER	41,778	Survey lead: PJ Davies
2000	MD119 (TIP2000; R/V *Marion Dufresne*)	LOCEAN	12,892	
2001	EW0113 (R/V *Ewing*)	LDEO	33,242	
2004	MR04-01 (R/V *Mirai*)	JAMSTEC	25,309	
2005	SS07/2005 (Wabio; R/V *Southern Surveyor*)	CSIRO	12,240	Survey lead: Allan Williams/ Ruby Kloser
2005	SS10/2006 (Wabio_2; R/V *Southern Surveyor*)	CSIRO	10,373	
2008–2009	GA-2476 (WA Margins reconnaissance; R/V *Sonne*)	Geoscience Australia	229,000 km^2	Daniell et al., 2010

3.5 Zeewyck Sub-basin (Perth Basin)

3.5.1 Summary

State(s)		WA
Area (km^2)		17,700
Water Depth (m)		1000–5000
Maximum sediment thickness (m)		>7200
Age range		Early Cretaceous–Recent
Basin	**Overlies**	Pinjarra Orogen?
	Parent	Perth Basin
	Adjacent basins	Houtman Sub-basin, Turtle Dove Ridge, Vlaming Sub-basin, Yallingup Shelf
Basin type		Extensional
Depositional setting, rock types		unknown
Overall prospectivity		Moderate–low
Confidence		*Medium–low*

3.5.2 Geology

The Zeewyck Sub-basin of the Perth Basin extends across the western part of the continental margin under the continental slope, in water depths ranging from 1000–5000 m (Figure 3.21; Jones et al., 2011). It covers an area of 17,700 km^2 in a narrow zone that borders the oceanic crust of the Perth Abyssal Plain to the west (Figure 3.21; Jones et al., 2011). To the east, the sub-basin is bound by the Houtman Sub-basin, Turtle Dove Ridge and Vlaming Sub-basin.

3.5.2.1 Structural geology

The Zeewyck Sub-basin is a north–south to northwest–southeast trending depocentre and its location adjacent to the Wallaby–Zenith Transform Margin suggests the basin developed as a pull-apart basin in a strike-slip to transtensional setting (Figure 3.21 and Figure 3.22; Bradshaw et al., 2003; Jones et al., 2011; Rollet et al., 2013a, b; Hall et al., 2013; Bernardel & Nicholson, 2013).

Although the plate reconstructions and overall basin geometry strongly suggest that a northwest-trending strike-slip fault underlies the Houtman–Zeewyck boundary zone, this is not clearly resolved in the seismic data. Seismic data shows that the geometry of the hinge between the two sub-basins is dominated by a west dipping fault zone, across which Jurassic strata from the Houtman Sub-basin are downthrown to the southwest (Jones et al., 2011). This has been interpreted to indicate a transtensional setting rather than one dominated by pure strike-slip motion (Jones et al., 2011); however, comparison with sand box models and other global analogues indicate that such geometries are also consistent with localised transtension within the setting of a pull-apart basin (e.g. McClay & Dooley, 1995).

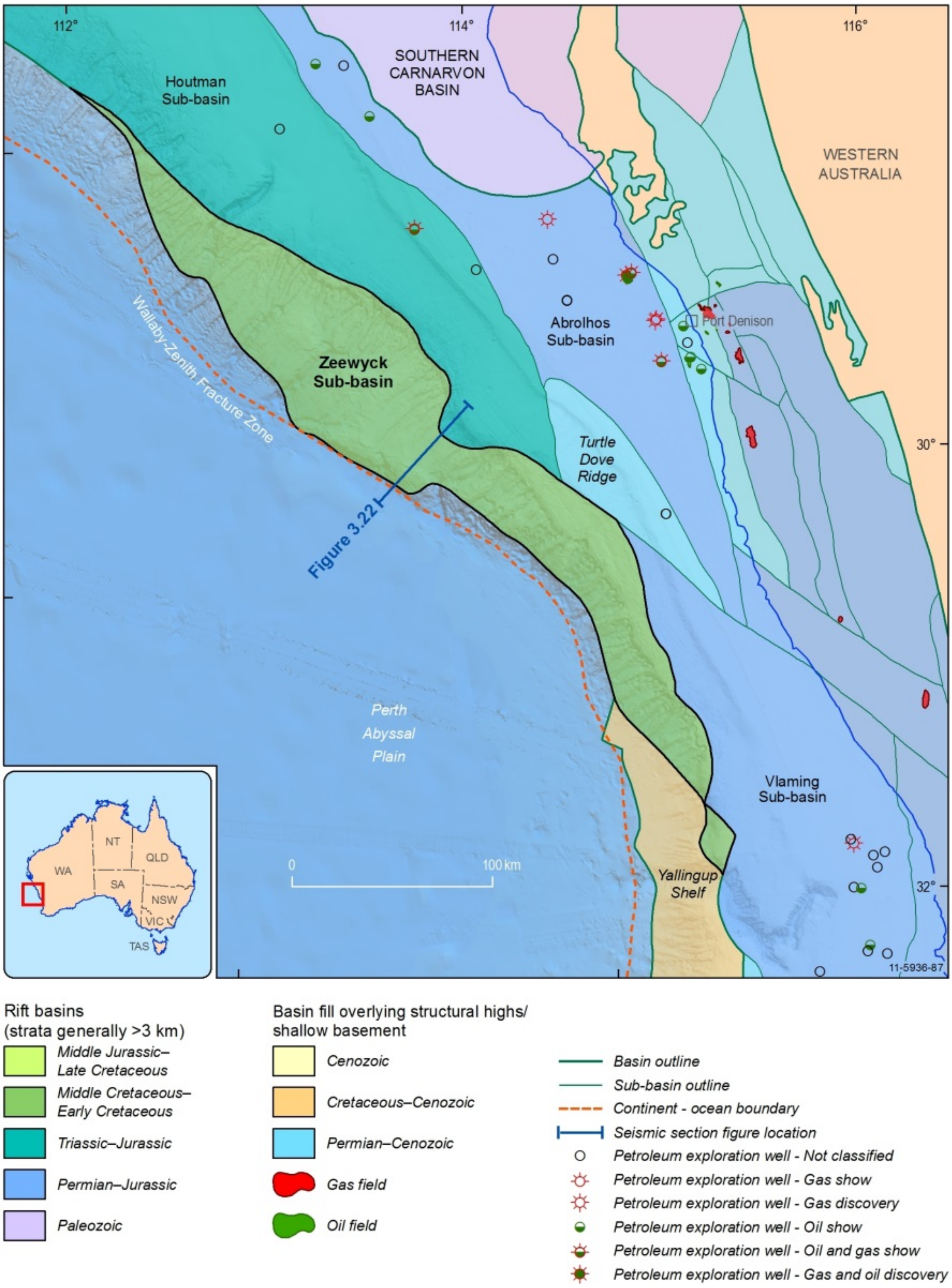

Figure 3.21: Regional setting of the Zeewyck Sub-basin

The main depocentre is characterised by a symmetrical, un-faulted sag succession that overlies and onlaps an extensively faulted sedimentary section, and underlies a basinward-thinning passive margin cover (Figure 3.22; Bradshaw et al., 2003; Jones et al., 2011).

3.5.2.2 Basin evolution and depositional history

The sub-basin has had a complex, multi-phase history of extension and reactivation lasting from the Permian to the Early Cretaceous (Figure 3.23).

Middle Jurassic–Early Cretaceous northwest–southeast rifting of Indian and Australia resulted in strike-slip faulting along the future Wallaby–Zenith transform. Dextral transform margin activity along the Wallaby-Zenith Fracture Zone commenced at about 136–137 Ma (Hall et al., 2013). As seafloor spreading continued, the mid-ocean ridge moved from east to west along the transform and tectonic activity along the margin only ceased once the ridge passed. Plate reconstructions indicate that active transform motion lasted from about 137 to 123 Ma (Valanginian to early Aptian) outboard of the Zeewyck Sub-basin. The Zeewyck Sub-basin formed at the eastern end of this structure as a pull-apart basin and its faulted section is believed to contain at least 4 km of Jurassic continental to marine siliciclastic rocks (Figure 3.22; Bradshaw et al., 2003; Hall et al., 2013; Bernardel & Nicholson, 2013).

India–Australia continental breakup in the Valanginian resulted in the development of a regional unconformity (Figure 3.22; Veevers et al., 1991; Bradshaw et al., 2003; Norvick, 2004; Jones et al., 2011; Hall et al., 2013). In addition, significant magmatism was likely to have occurred across the basin during this time (Bradshaw et al., 2003; Gorter & Deighton, 2004). The entire depocentre has been downthrown from the Houtman Sub-basin through highly-rotational upper crustal faulting, as a result of lower crustal extension and margin collapse (Bradshaw et al., 2003; Jones et al., 2011).

Early Cretaceous post-rift sag resulted in the deposition of approximately 2 km of strata. The deep-water Zeewyck Sub-basin was the primary depocentre in the northern Perth Basin during this time, with the accumulation of possibly marine equivalents of the Warnbro Group in the Vlaming Sub-basin (Norvick, 2004; Jones et al., 2011).

Overlying passive margin strata are about 1.2 km thick, and are correlated with Aptian to Holocene deep water calcareous and argillaceous rocks intersected in DSDP 259 (Veevers & Johnstone, 1974), drilled a short distance west of the Zeewyck Sub-basin (Bradshaw et al., 2003; Jones et al., 2011).

3.5.2.3 Level of knowledge

Data coverage in the Zeewyck Sub-basin is sparse. Ages, lithology and petroleum systems for Lower Cretaceous and older strata are interpreted through indirect correlation with other areas of the northern Perth Basin, based on stratal relationships and seismic characteristics.

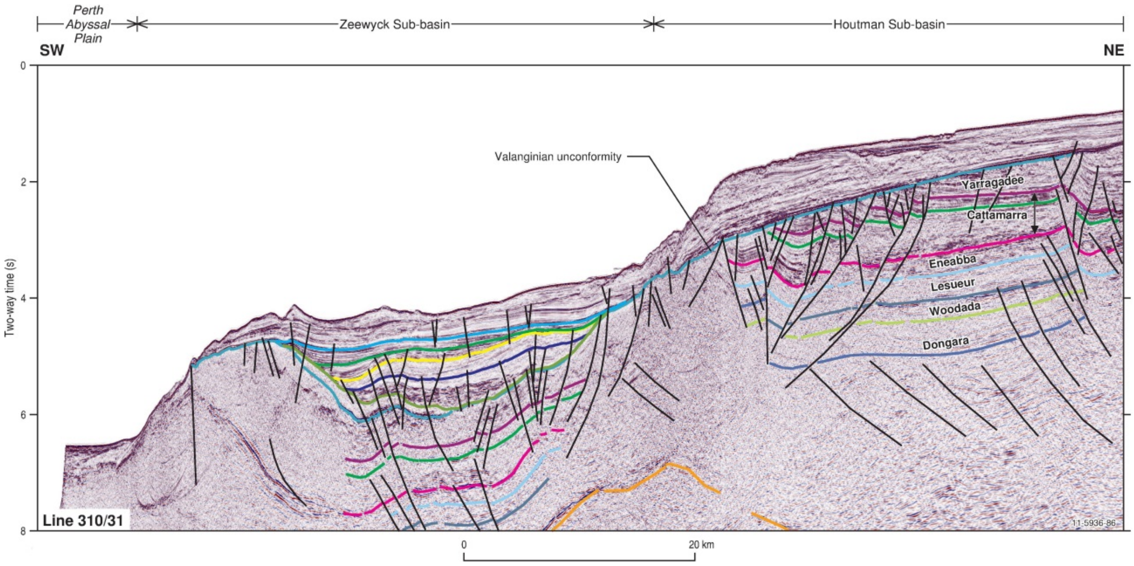

Figure 3.22: Interpreted seismic section through the Zeewyck Sub-Basin (Rollet et al., 2013a; Hall et al., 2013). See Figure 3.21 for cross-section location.

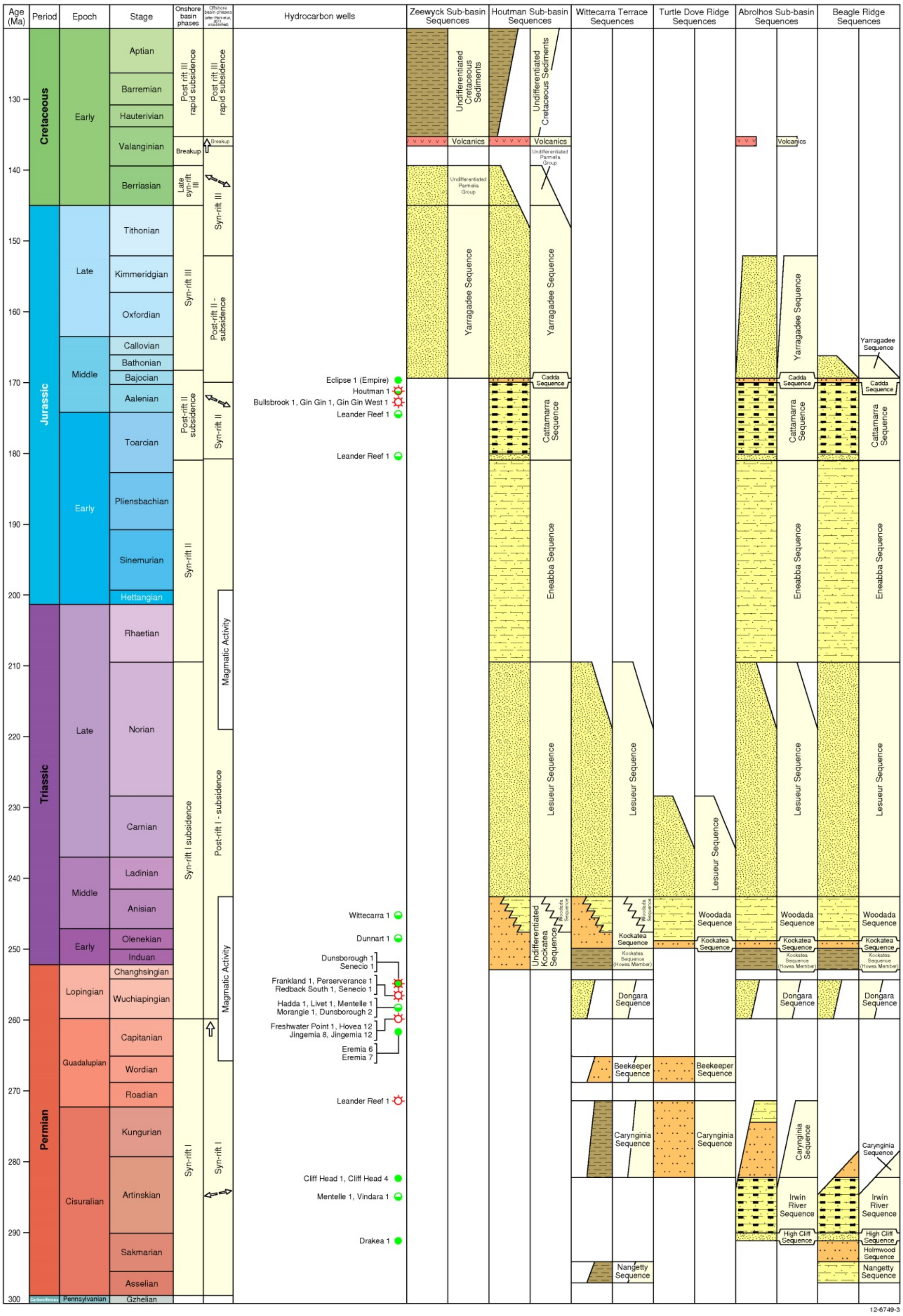

Figure 3.23: Stratigraphy and hydrocarbon discoveries of the offshore northern Perth Basin based on the Offshore Northern Perth Basin Biozonation and Stratigraphy Chart (Jones et al., 2012). Geological time scale after Gradstein et al (2012).

3.5.3 Petroleum systems

The petroleum potential of the Zeewyck Sub-basin is difficult to evaluate due to the absence of well data to constrain the presence of source rocks (Bradshaw et al., 2003).

Petroleum systems potential for the northern Perth Basin, recently reviewed by Jones et al. (2011), can be summarised as follows:

- In the Zeewyck Sub-basin, hydrocarbons may have generated from Jurassic and Lower Cretaceous source rocks later (i.e. post-Valanginian) rather than from other source kitchens in the Perth Basin (Figure 3.24; Bradshaw et al., 2003; Jones et al. 2011; Bernardel & Nicholson, 2013).
- Potentially good reservoirs may exist within Jurassic sediments equivalent to the upper Yarragadee Formation.
- The Middle Jurassic to Lower Cretaceous succession may contain intraformational seals, especially in the upper part of the section as deposition at that level transitions to a marine environment. Elsewhere in the northern Perth Basin, coeval intraformational seals in the Yarragadee Formation are proven to provide impedance barriers to oil migration (Kempton et al., 2011), but potential to seal accumulations in this area remains speculative. It is possible that a post-breakup regional seal exists within the thick Lower Cretaceous succession, but there is no direct evidence for this (Bradshaw et al., 2003).
- Petroleum systems modelling suggests that generation and expulsion probably occurred from the Early to Middle Jurassic onwards.

Play types include structural and stratigraphic traps developed in the late syn-rift and post-breakup phases, with possible charge from adjoining depocentres in the Houtman Sub-basin (Bradshaw et al., 2003).

Key risks for petroleum systems in the Zeewyck Sub-basin include the lack of a proven regional seal, fault reactivation and the impact of the passing spreading ridge on the thermal evolution of the region.

3.5.3.1 Overall prospectivity classification

Moderate–low

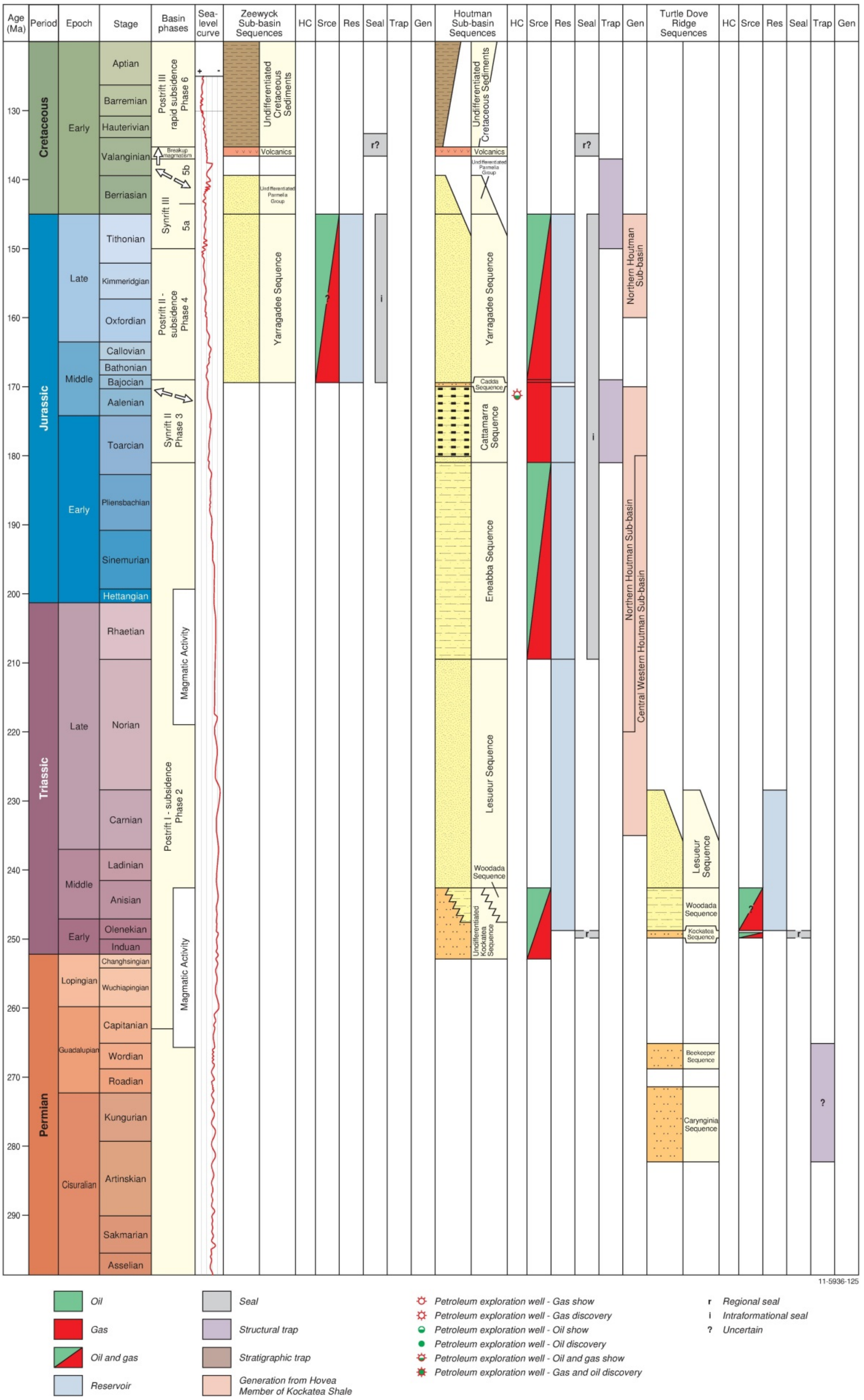

Figure 3.24: Potential petroleum systems elements for the Zeewyck Sub-basin (after Rollet et al., 2013a).

3.5.4 Exploration status

Exploration in the Zeewyck Sub-basin has been limited to reconnaissance seismic acquisition and sampling programs. These primarily include a series of Geoscience Australia sampling and seismic cruises from 2005 to 2008.

No exploration permits are currently held in the Zeewyck Sub-basin.

3.5.5 Data

Key data sets for the Zeewyck Sub-basin are listed in Table 3.18–Table 3.21. No wells have been drilled in the Zeewyck Sub-basin (Figure 3.25). Cretaceous and younger strata were tied to stratigraphic well DSDP 259, drilled 20 km west of the Zeewyck Sub-basin (Veevers & Johnstone, 1974). Further details of wells in the adjacent Houtman and Abrolhos Sub-basin are summarised in Jorgensen et al. (2011).

Seismic coverage in the sub-basin varies from good adjacent to the southern Houtman Sub-basin to poor (Figure 3.25), comprising a mixture of vintages ranging from the 1970s to 2009. Seismic surveys of note that have fair, good or excellent penetration and resolution in the region include Geoscience Australia surveys GA 310 and GA 280 (Foster et al., 2009), and the Abrolhos and Abrolhos West surveys. All 2D seismic surveys in the Zeewyck sub-basin are listed in Table 3.19. No 3D seismic data has been collected in this area.

Geoscience Australia’s 2008–2009 marine reconnaissance survey (GA 2476) acquired a number of dredge samples of Berriasian–Valanginian age from the walls of deeply incised canyons (Daniell et al., 2010).

SAR coverage is restricted to the central and southern parts of the Zeewyck Sub-basin. Swath bathymetry coverage of the Zeewyck Sub-basin is nearly complete. Eleven surveys intersect the basin, the most recent of which is the 2008–2009 marine reconnaissance survey conducted by Geoscience Australia.

All good quality potential field datasets have been compiled, levelled and gridded to provide continuous gravity and magnetic coverages across the entire southwestern margin (Hackney, 2012).

3.5.5.1 Confidence Rating

Medium–Low

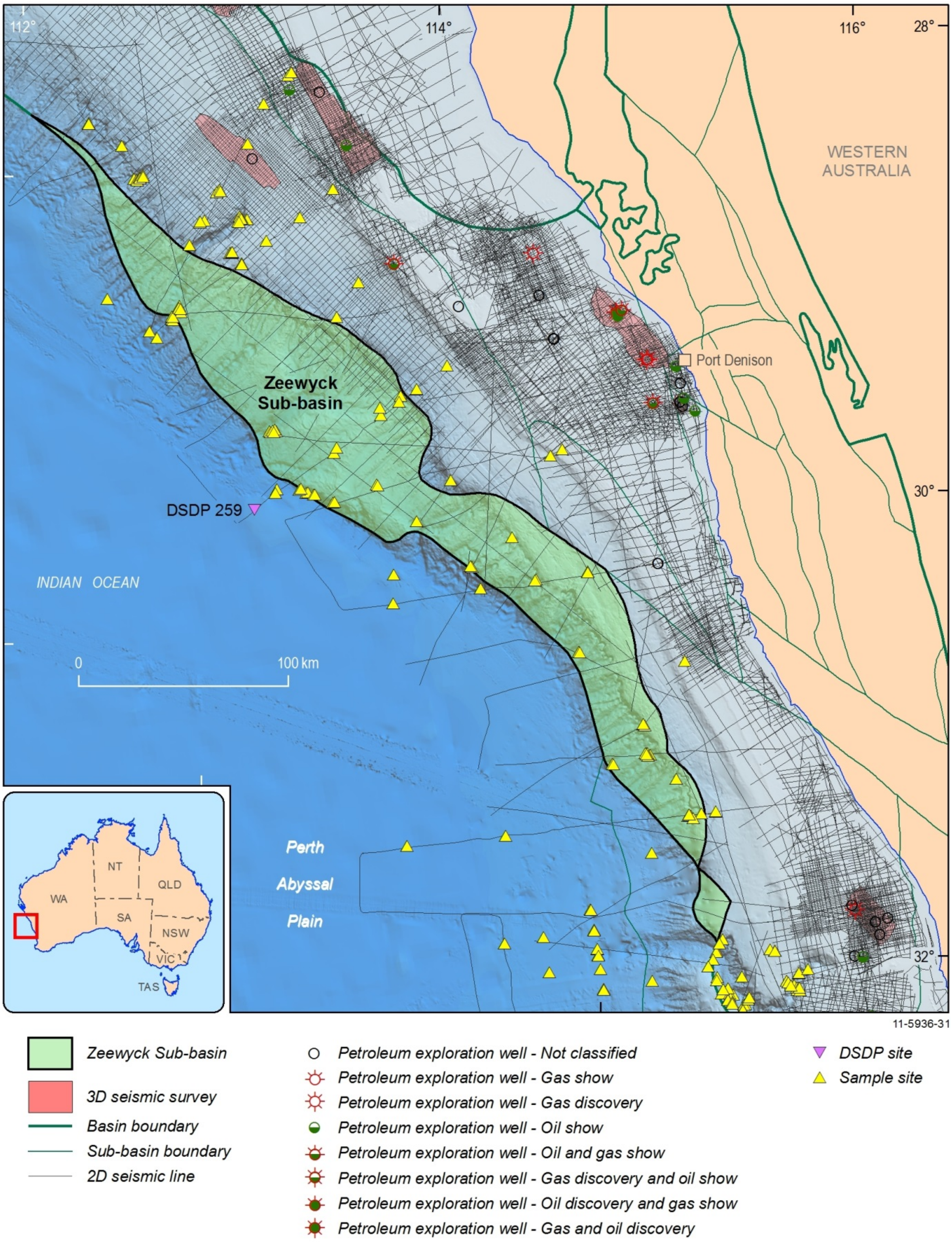

Figure 3.25: Seismic, wells and dredge samples in the Zeewyck Sub-basin and surrounds.

3.5.6 Issues and remaining questions

The current interpretation for Lower Cretaceous and older rocks is based on solely on links to a single DSDP well, the results of dredge sampling (Daniell et al., 2010) and analogy with the adjacent Houtman and Abrolhos Sub-basins. As a result, there are few direct constraints on the age of the succession or the presence of source rocks and other key petroleum systems elements for units Early Cretaceous and older. A stratigraphic well would be required to resolve this uncertainty; however, opportunities remain for further dredge sampling as the outer margin of the sub-basin is incised by numerous canyons. Acquisition of closely-spaced 2D seismic data in this currently data-poor area would also be valuable.

The structural architecture of the Zeewyck Sub-basin is similar to basins formed on sheared margins elsewhere in the world (Bernardel & Nicholson, 2013). The increasing global exploration interest in sheared margins basins may focus attention on the hydrocarbon potential of outboard areas of the Perth Basin that developed along the Wallaby–Zenith Fracture Zone, such as the Zeewyck Sub-basin. Bernardel & Nicholson (2013) noted that the complex structural geology and fault reactivation history of the basin could provide some exploration challenges. In addition, the deep to ultra-deep water depths of the sub-basin could be an impediment to exploration.

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3.5.8 Data Tables

Table 3.18: List of wells adjacent to the Zeewyck Sub-basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1974	DSDP 259	Stratigraphic	DSDP	346	Cretaceous	Not classified	Veevers & Johnstone, 1975

Table 3.19: Key 2D seismic surveys, Zeewyck Sub-basin.

Year	Survey	Operator	Line-km	Reference
	Abrolhos West			
	AGSO 57R, North Perth Basin	AGSO (now Geoscience Australia)		
	BRM 18	BMR (now Geoscience Australia)		
1973	Shell Development “Petrel” Survey	Shell Development	Shell Development “Petrel” Survey	
2004	GA 280 Southwest Frontier	Geoscience Australia	1060	
2008	GA 310	Geoscience Australia	2570	Foster et al., 2009

Table 3.20: Key geological sampling surveys in or close to the Houtman Sub-basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
2008–09	GA 2476	Geoscience Australia	Houtman Sub-basin, Cuvier margin	Dredge, box core, grab	Siliciclastic and carbonate rocks, volcanic rocks	Daniell et al., 2010

Table 3.21: Key swath bathymetry surveys, Zeewyck Sub-basin.

Year	Survey	Operator	Area (km²)	Reference
1994	ADEDAV (N.O. *L'Atalante*)	GA/FREMER	41,778	Survey lead: PJ Davies
1994	KN145L4 (Perth Canyon; R/V *Knorr*)	WHOI	1592	
1994– 1995	SOJN05MV (R/V *Melville*)	SIO	61,001	
1995	Rottnest (HMAS *Cook*)	RAN-JCU	2036	
2000	MD119 (TIP2000; R/V *Marion Dufresne*)	LOCEAN	12,892	
2001	EW0113 (R/V *Ewing*)	LDEO	33,242	
2001	EW0112 (R/V *Ewing*)	LDEO	52,873	
2006	SS04/2006 (Leeuwin Currents; R/V *Southern Surveyor*)		12,436	Survey lead: Charitha Pattiaratchi
2006	SS05/2006 (Meso_Eddies; R/V *Southern Surveyor*)	Geoscience Australia	16,765	Survey lead: Anya Waite
2007	KNOX03RR (Dunedin-Antarctica-Freemantle; R/V *Roger Revelle*)	SIO/NSF	163,904	
2008–2009	GA-2476 (WA Margins reconnaissance; R/V *Sonne*)	Geoscience Australia	229,000	Daniell et al., 2010

3.6 Turtle Dove Ridge

3.6.1 Summary

State(s)		WA
Area (km^2)		3190
Water Depth (m)		50–1000
Maximum sediment thickness (m)		5000
Age range		Permian–Triassic
Basin	**Overlies**	Pinjarra Orogen
	Parent	Perth Basin
	Adjacent basins	Abrolhos Sub-basin, Houtman Sub-basin, Vlaming Sub-basin, Zeewyck Sub-basin
Basin type		Extensional
Depositional setting, rock types		Marine and non-marine siliciclastic rocks
Overall prospectivity		Moderate–low
Confidence		*Medium*

3.6.2 Geology

The Turtle Dove Ridge is a north-northwest trending structural high within the northern Perth Basin that separates the southern part of the Abrolhos Sub-basin in the east from the southern Houtman, Zeewyck and northern Vlaming sub-basins to the west (Figure 3.26; Jones et al., 2011). The sub-basin covers an area of 3190 km^2 beneath the continental shelf and slope, in water depths of 50–1000 m (Jones et al., 2011).

3.6.2.1 Structural geology

The structural nature of the Turtle Dove Ridge is poorly understood and it is best described as a broad area of shallow basement (Bradshaw et al., 2003; Jones et al., 2011). It correlates with a strong gravity high, but has no distinctive magnetic signature. Modelling of both gravity and magnetic data indicate a basement high overlain by around 3 km of sediment (Petkovic, 2012; Johnston & Petkovic, 2012).

The eastern boundary of the ridge is defined by a major easterly dipping fault that originated during Permian rifting and was reactivated during latest Jurassic–Early Cretaceous extension and breakup (Figure 3.27; Jones et al., 2011). The southwestern boundary is difficult to resolve using the limited seismic data available, and is mapped based on the extent of the inferred Turtle Dove Transfer (Tyler & Hocking, 2001). To the northeast, the boundary with the Abrolhos Sub-basin is mapped, where possible, using seismic data to identify the first evidence of significant inversion (Jones et al., 2011). The western boundary is more ambiguous but is defined by a prominent uplifted hanging-wall block (Jones et al., 2011).

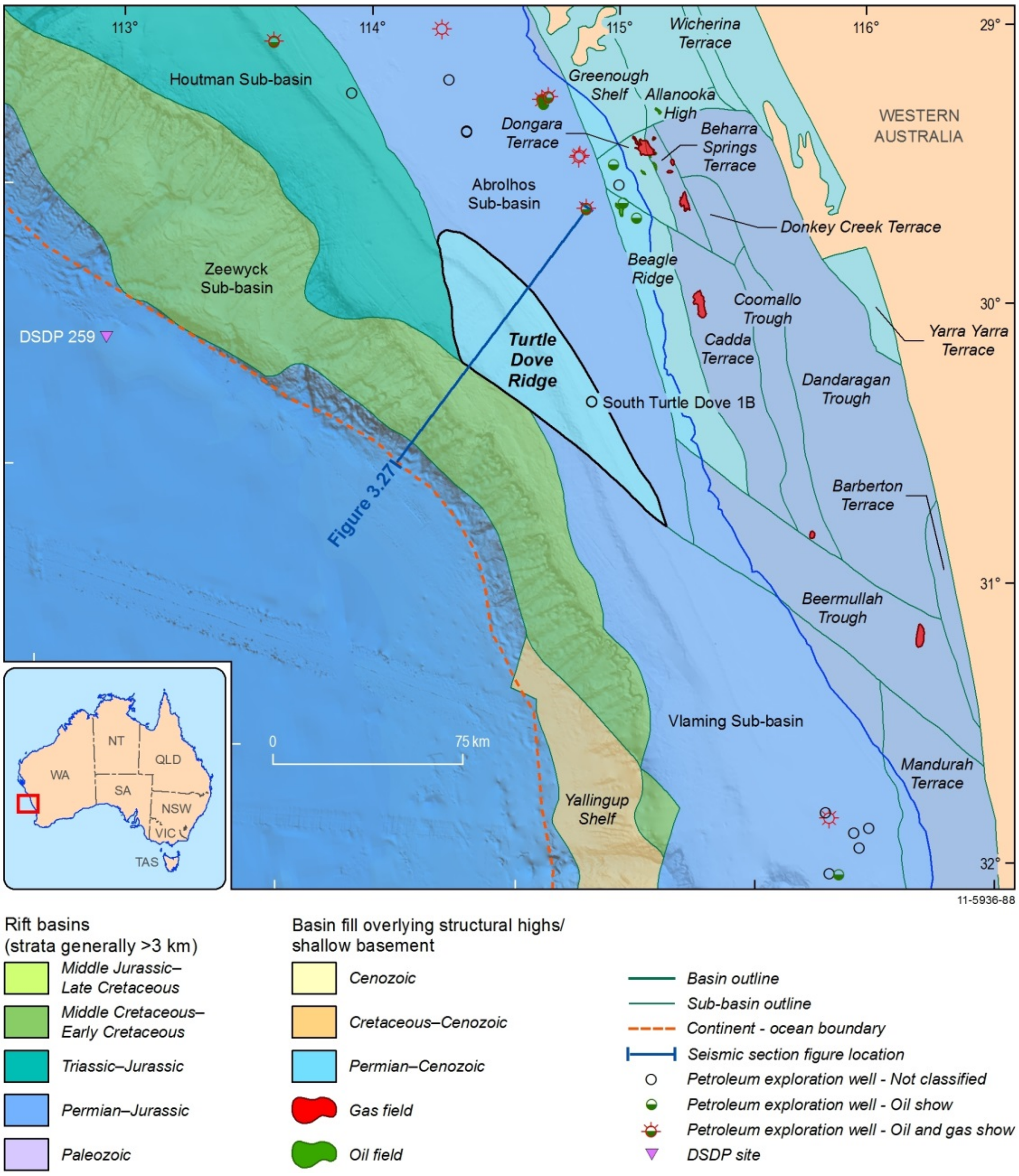

Figure 3.26: Regional setting of the Turtle Dove Ridge.

Up to 3400 m of Permian–Lower Triassic strata are interpreted to underlie the Valanginian unconformity in a series of small westerly-dipping half graben (Figure 3.27; Jones et al., 2011). These half graben appear to be uplifted Permian rift structures that continue north into the Abrolhos Sub-basin and south into the northern Vlaming Sub-basin (Jones et al., 2011; Rollet et al., 2013a, b).

3.6.2.2 Basin evolution and depositional history

The region has had a complex, multi-phase history of extension and reactivation lasting from the Permian to the Early Cretaceous (Figure 3.28; Bradshaw et al., 2003; Pfahl, 2011; Jones et al., 2011, 2012). The Permian and younger stratigraphy is determined from the South Turtle Dove 1B well (Jorgensen et al. 2011).

Early Permian east-northeast-directed rifting resulted in the development of a series of half graben beneath the Turtle Dove Ridge and adjacent Abrolhos Sub-basin (Jones et al., 2011; Rollet et al., 2013a). Sediments deposited include the marine Caryngina and Beekeeper Sequences (Figure 3.28; Jorgensen et al. 2011; Jones et al., 2011, 2012). Rifting was followed immediately by a regional uplift, which is marked by a major angular unconformity. Widespread erosion may have been accentuated by a major eustatic sea level fall (Jones et al., 2011).

Middle Permian to Middle Jurassic thermal subsidence resulted in the deposition of marine shales of the Kockatea Shale, the fluvio-deltaic Woodada Formation and the fluvial Lesueur Formation (Figure 3.28; Jorgensen et al. 2011; Jones et al., 2011, 2012).

Middle Jurassic to Early Cretaceous northwest–southeast extension culminated in the breakup of India and Australia in the Valanginian (Veevers et al., 1991; Bradshaw et al., 2003; Norvick, 2004: Gibbons et al., 2012; Hall et al., 2013). Significant uplift and inversion occurred along the Turtle Dove Ridge immediately prior to and/or during breakup, resulting in the erosion of up to 3000 m of Permian, Triassic and Jurassic strata (Figure 3.27 and Figure 3.28; Bradshaw et al., 2003; Jones et al., 2011, 2012). Uplift was probably driven by transpressional movement on strike-slip faults at a restraining bend associated with the transition between oblique extension along the southern Perth Basin margin and the Wallaby Zenith Transform Margin (Quaife et al., 1994; Enterprise Oil Exploration & Nippon Oil Exploration, 1994a; Song & Cawood, 2000; Bradshaw et al., 2003; Hall et al., 2013).

3.6.2.3 Level of knowledge

The structural geology and stratigraphy of the Turtle Dove Ridge is poorly constrained due to poor seismic imaging and the lack of well coverage.

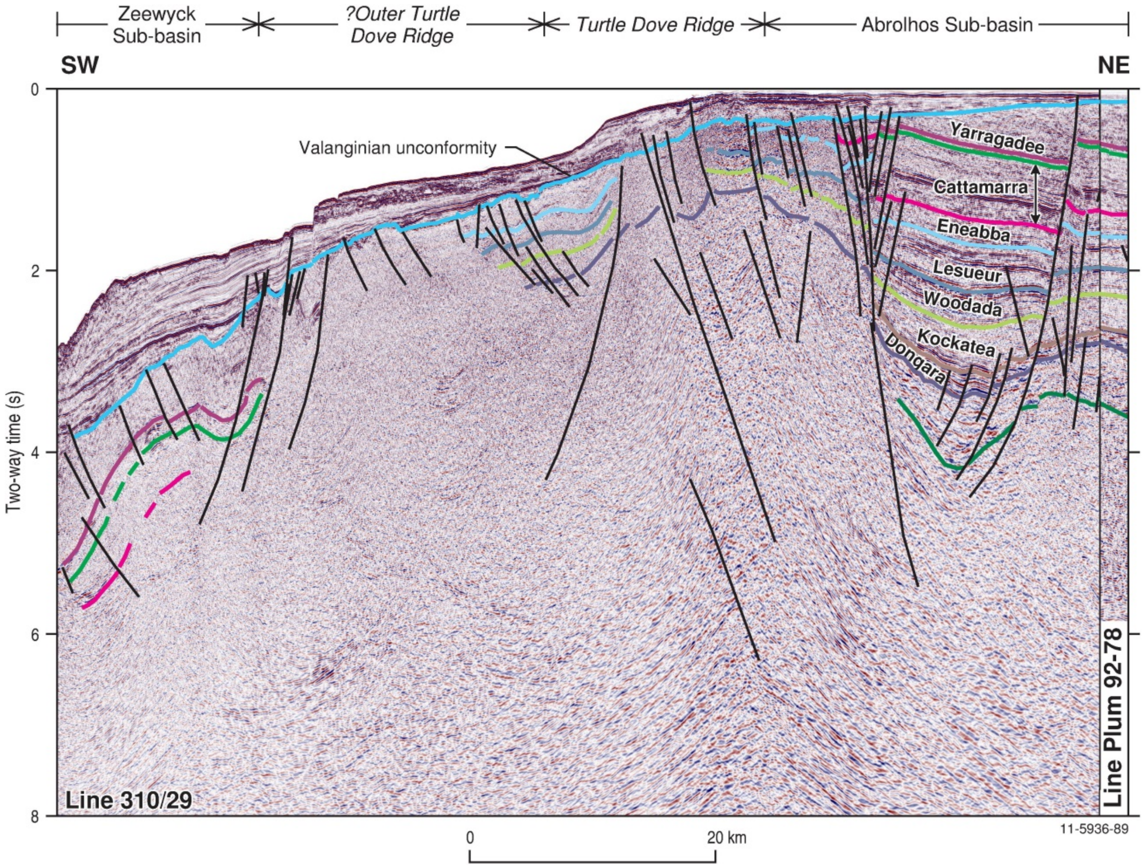

Figure 3.27: Seismic section across the Turtle Dove Ridge (from Jones et al., 2011). See Figure 3.26 for location of this line.

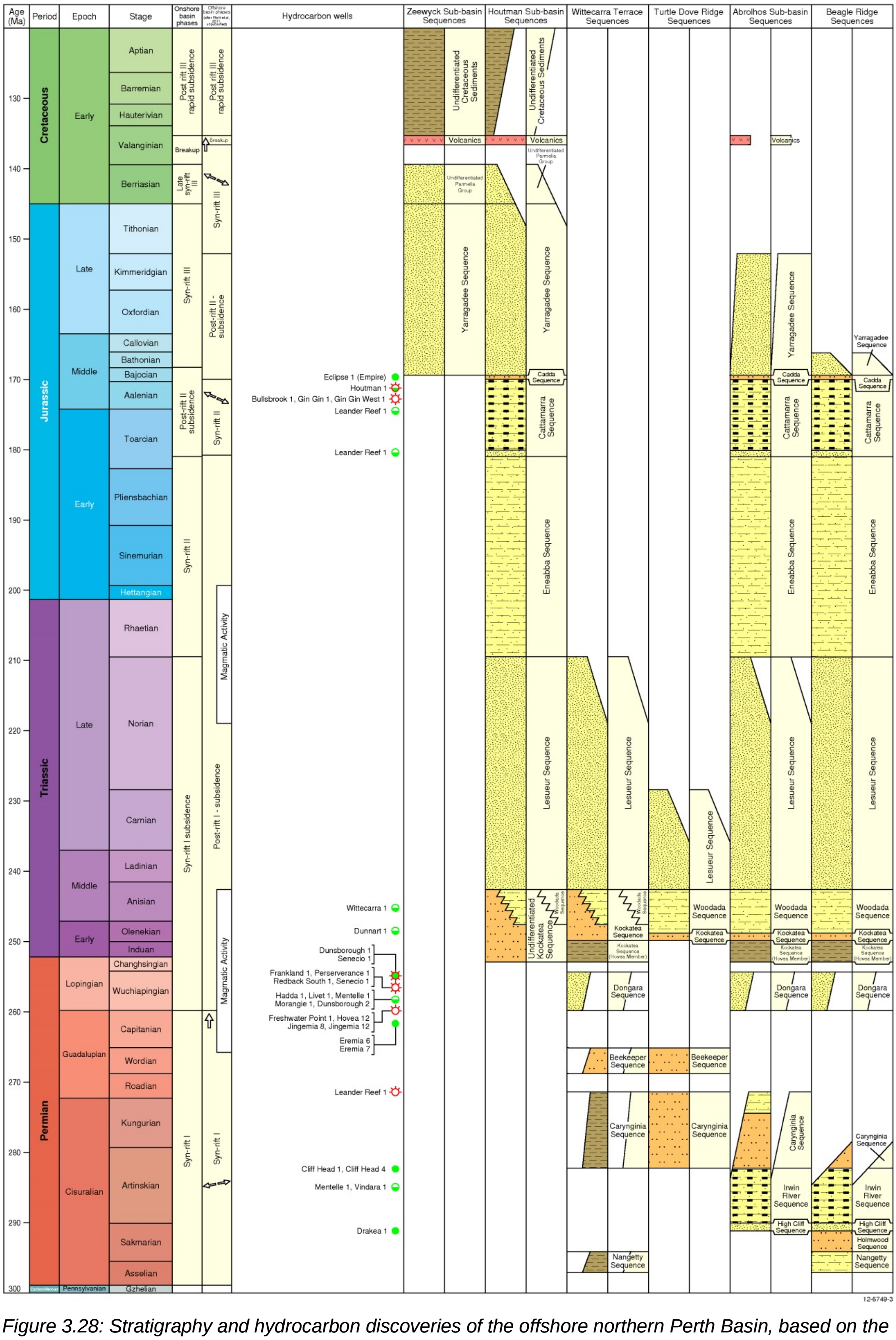

Figure 3.28: Stratigraphy and hydrocarbon discoveries of the offshore northern Perth Basin, based on the Offshore Northern Perth Basin Biozonation and Stratigraphy Chart (Jones et al., 2012). Geological Time Scale after Gradstein et al (2012).

3.6.3 Petroleum systems

There are no known petroleum systems within the Turtle Dove Ridge. Nonetheless, multiple active hydrocarbon systems have been identified in the surrounding Houtman, Abrolhos and Vlaming Sub-basins (e.g. Thomas & Barber, 2004; Gorter et al., 2004; Jones et al., 2011; Kempton et al., 2011).

3.6.3.1 Source rocks

Probable source rocks include Permian and Lower Jurassic coals and carbonaceous shales (Figure 3.29). The Triassic Hovea Member is not recognised in the base of the Kockatea Sequence in South Turtle Dove 1B (Jorgensen et al., 2011), but may be present elsewhere. Plays on the Turtle Dove Ridge would probably rely on charge from source kitchens in the adjacent Abrolhos Sub-basin.

3.6.3.2 Reservoirs and seals

Potential reservoirs may be present in the Permian Irwin River Coal Measures, Carynginia Formation and Dongara Sandstone. There is also the potential for secondary porosity to have developed in carbonate facies within the Carynginia Formation during uplift and erosion in the Early Cretaceous. In South Turtle Dove 1B, the Permian section beneath the Kockatea Sequence proved to be more shaly than expected and the targeted upper Permian Dongara Sandstone, which is an important reservoir elsewhere in the northern Perth Basin, was not encountered. However, reservoir units within the upper Permian section may be better developed elsewhere on the Turtle Dove Ridge (Crostella, 2001; Jorgensen et al., 2011). South Turtle Dove 1B also penetrated good quality reservoirs sands within the Triassic Woodada and Leseur sequences, but these overlie the regional seal (Kockatea Sequence).

The Lower Triassic Kockatea Shale is proven to be an effective regional seal across the northern Perth Basin (Jones et al., 2011).

3.6.3.3 Play types

Traps include several large (~100 km^2) Valanginian and possible Permian structures with fault-dependent closure (Bradshaw et al., 2003).

3.6.3.4 Critical risks

Key risks include:

- absence of source rocks; no source units were recognised within South Turtle Dove 1B (Jorgensen et al., 2011)
- the failure of South Turtle Dove 1B to intersect good quality reservoirs beneath the Kockatea Sequence suggests that reservoir distribution may also be a risk for the rest of the area (West Australian Petroleum, 1975; Jorgensen et al., 2011)
- the significant risk associated with the timing of hydrocarbon migration versus trap formation.

3.6.3.5 Overall prospectivity classification

Moderate–low

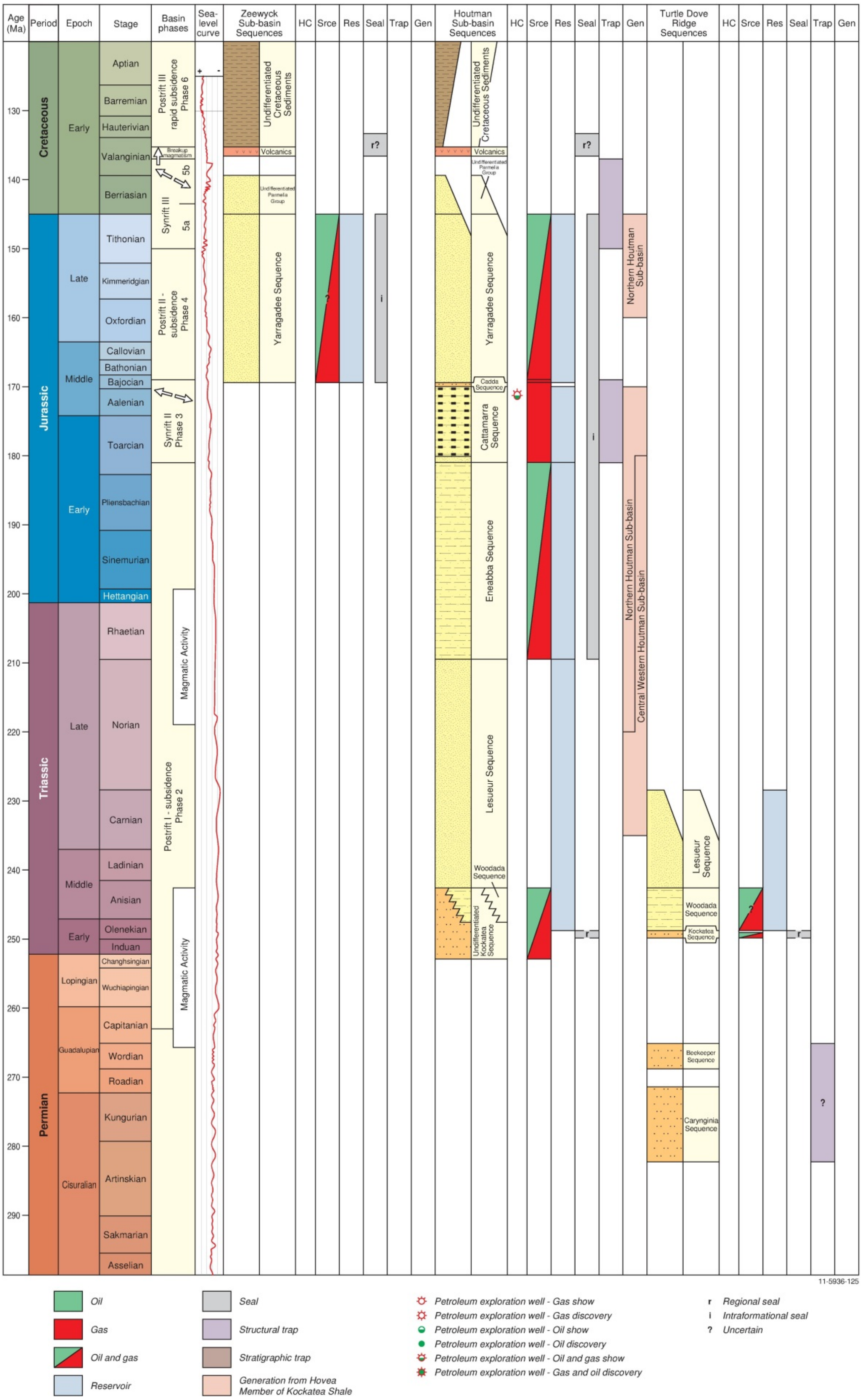

Figure 3.29: Petroleum systems elements for the Turtle Dove Ridge (Rollet et al., 2013).

3.6.4 Exploration status

The Turtle Dove Ridge is a poorly explored part of the Perth Basin. The only well, South Turtle Dove 1B, was drilled in 1975 (Figure 3.30). A new phase of exploration commenced in 2012 with the award of exploration permit WA-481-P to a joint venture led by Murphy Australia. The permit covers much of the Abrolhos Sub-basin, the Turtle Dove Ridge and the southern tip of the Houtman Sub-basin; the guaranteed work program for this permit includes the drilling of three wells. Prior to this current phase, no significant petroleum exploration had occurred in the Turtle Dove Ridge since acquisition of the Beagle (Woodside) and Plum (Enterprise Oil) seismic surveys in 1992. The most recent seismic acquisition in the region was a series of regional 2D lines acquired as part of Geoscience Australia's s310 seismic survey in 2008–2009.

3.6.5 Data

Key data sets for the Turtle Dove Ridge are listed in Table 3.22–Table 3.24. South Turtle Dove 1B was drilled by West Australian Petroleum Pty Ltd in 1975 on the Turtle Dove Ridge and remains the only well to be drilled in that part of the Perth Basin (West Australian Petroleum, 1975; Crostella, 2001: Jorgensen et al., 2011).

Seismic coverage over the Turtle Dove Ridge varies from excellent to poor, and seismic data quality tends to deteriorate over shallow basement. The seismic datasets comprise a mixture of vintages ranging from the 1960s to 2008. Seismic surveys that have fair, good or excellent penetration and resolution in the region include Geoscience Australia's survey GA 310 (Foster et al., 2009), and the Abrolhos and Abrolhos West surveys. All 2D seismic surveys crossing the Turtle Dove Ridge are listed in the Table 3.23. No 3D seismic data has been collected in this area, although the guaranteed work program in permit WA-481-P, which covers the Turtle Dove Ridge, includes the acquisition of both 2D and 3D seismic data.

No dredge samples have been collected from the Turtle Dove Ridge, but Geoscience Australia's 2008–2009 marine reconnaissance survey acquired a number of dredge samples from the Houtman and Zeewyck sub-basins to the west (Daniell et al., 2010).

Swath bathymetry coverage of the Turtle Dove Ridge is limited. Three surveys cover part of the ridge, the most recent of which is the 2008–2009 marine reconnaissance survey conducted by Geoscience Australia.

All good quality potential field datasets have been compiled, levelled and gridded to provide continuous gravity and magnetic coverage across the entire southwestern margin (Hackney, 2012).

3.6.5.1 Confidence Rating

Medium

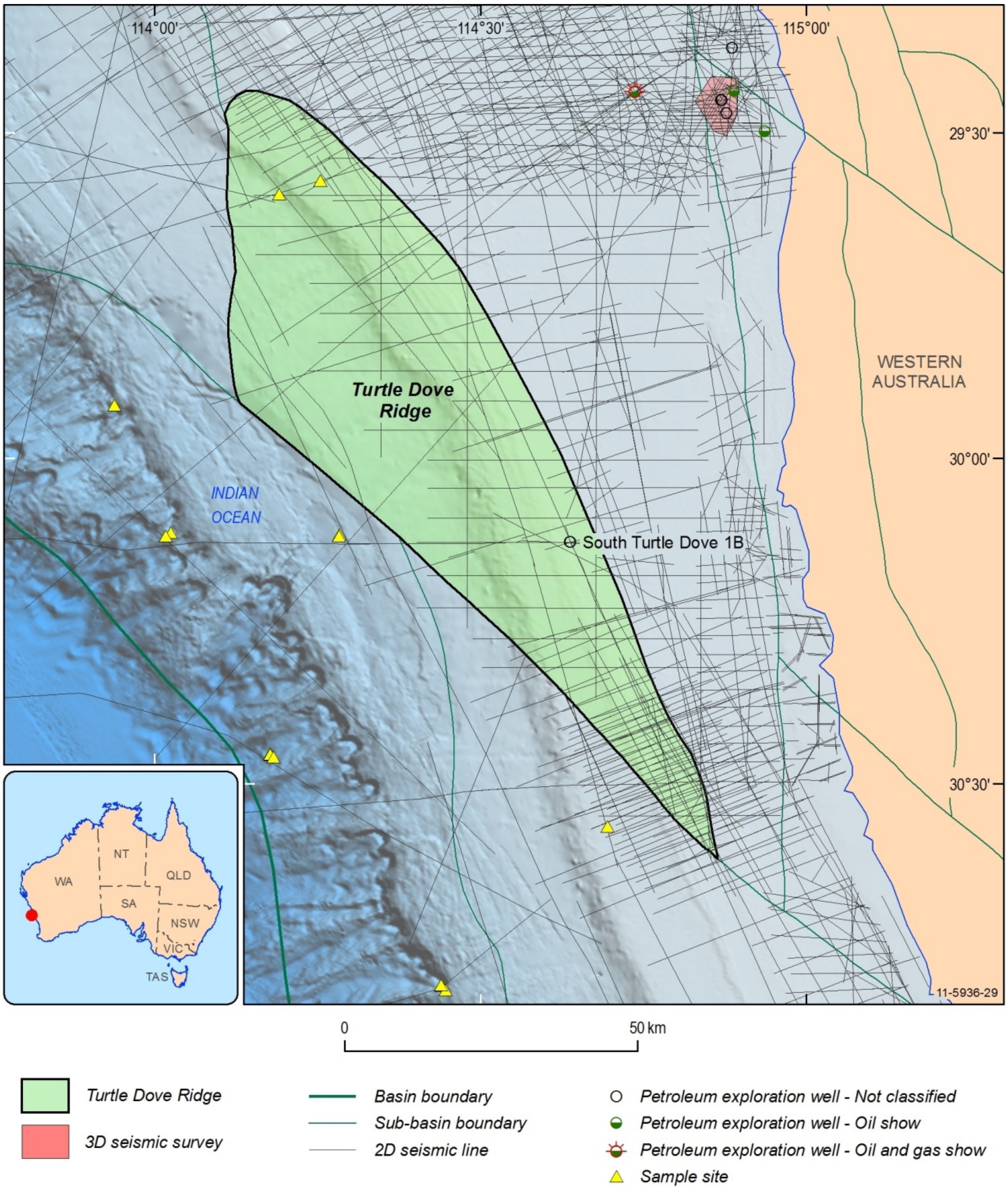

Figure 3.30: Seismic, wells and dredge samples in the Turtle Dove Ridge and surrounds.

3.6.6 Issues and remaining questions

Despite regional scale seismic data coverage with well ties, the Turtle Dove Ridge remains poorly understood. Seismic imaging is poor and only one well has been drilled on the ridge. An important issue is the distribution of Permian to Jurassic units given the extent of Late Jurassic–Early Cretaceous uplift and erosion. Additional well data and higher resolution seismic would help resolve this issue, as well as constrain the extent of key source, reservoir and seal units.

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3.6.8 Data Tables

Table 3.22: List of wells on the Turtle Dove Ridge.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1975	South Turtle Dove 1B	Petroleum exploration	West Australian Petroleum	1830	Permian	Dry	West Australian Petroleum, 1975; Crostella, 2001; Jorgensen et al., 2011

Table 3.23: Key 2D seismic surveys, Turtle Dove Ridge.

Year	Survey	Operator	Line-km	Reference
1971	Shell Development "*Petrel*" Survey	Shell Development	27,326	
1985	WA-162 Experimental 1985 (DS85)	Diamond Shamrock	1651	
1986	AGSO 57R, North Perth Basin	AGSO (now Geoscience Australia)	1056	
1989	Abrolhos Spec 1989 (S89)	Halliburton Geophysics	1599	
1992	Abrolhos West (WA91)	Conoco	2863	
1992	Plum (EA92AU09)	Enterprise Oil	4369	
1992	Beagle 2D	Woodside	1427	
1993	Blackpoint 1993	Woodside	97	
2008	GA 310	Geoscience Australia	7317	See discussion in Daniell et al., 2010

Table 3.24: Key swath bathymetry surveys, Turtle Dove Ridge

Year	Survey	Operator	Area (km^2)	Reference
2005	SS07/2005 (Wabio; R/V *Southern Surveyor*)	CSIRO	12,240	Survey lead: Allan Williams/ Ruby Kloser
2005	SS10/2006 (Wabio_2; R/V *Southern Surveyor*)	CSIRO	10,373	
2008–2009	GA-2476 (WA Margins reconnaissance; R/V *Sonne*)	Geoscience Australia	229,000	Daniell et al., 2010

3.7 Offshore Southern Carnarvon Basin

3.7.1 Summary

State(s)		WA
Area (km^2)		95,000
Water Depth (m)		0–2000
Maximum sediment thickness (m)		>5000
Age range		Ordovician–Mesozoic
Basin	**Subdivisions**	Bernier Platform, Gascoyne Sub-basin
	Overlies	Pinjarra Orogen?
	Parent	Southern Carnarvon Basin
	Adjacent basins	Perth Basin, Abrolhos Sub-basin, Houtman Sub-basin, Northern Carnarvon Basin, Exmouth Sub-basin, Gascoyne Platform
Basin type		Extensional
Depositional setting, rock types		Marine, non-marine and glacial siliciclastic rocks; marine carbonate rocks
Overall prospectivity		Moderate
Confidence		*Low–medium*

3.7.2 Geology

The Ordovician–Permian Southern Carnarvon Basin is a large basin (192,000 km^2) located on the central Western Australian margin. The Southern Carnarvon Basin comprises the Gascoyne, Merlinleigh and Byro sub-basins and the Bernier Platform. Of these, the Bernier Platform and western Gascoyne Sub-basin are located offshore (Figure 3.31). The offshore part of the Gascoyne Sub-basin (Iasky et al., 2003; Mory et al., 2003) lies mostly in shallow water (50–200 m), whereas the Bernier Platform is in much deeper water (200–2000 m). The offshore Southern Carnarvon Basin is bordered by the Exmouth Sub-basin (Northern Carnarvon Basin) in the northwest, and the Houtman Sub-basin (Perth Basin) in the southwest (Figure 3.31). The offshore part of the Southern Carnarvon Basin covers approximately 95,000 km^2.

3.7.2.1 Structural geology

The Gascoyne Sub-basin is a structurally elevated platform adjacent to the eastern Permian and Mesozoic depocentres of the Southern Carnarvon Basin (Figure 3.31). It comprises two distinct depocentres containing up to 5 km of ?Cambrian to Devonian strata overlain by a thin Cretaceous to Cainozoic cover. The sub-basin covers an area of approximately 103,000 km^2, about half of which is offshore.

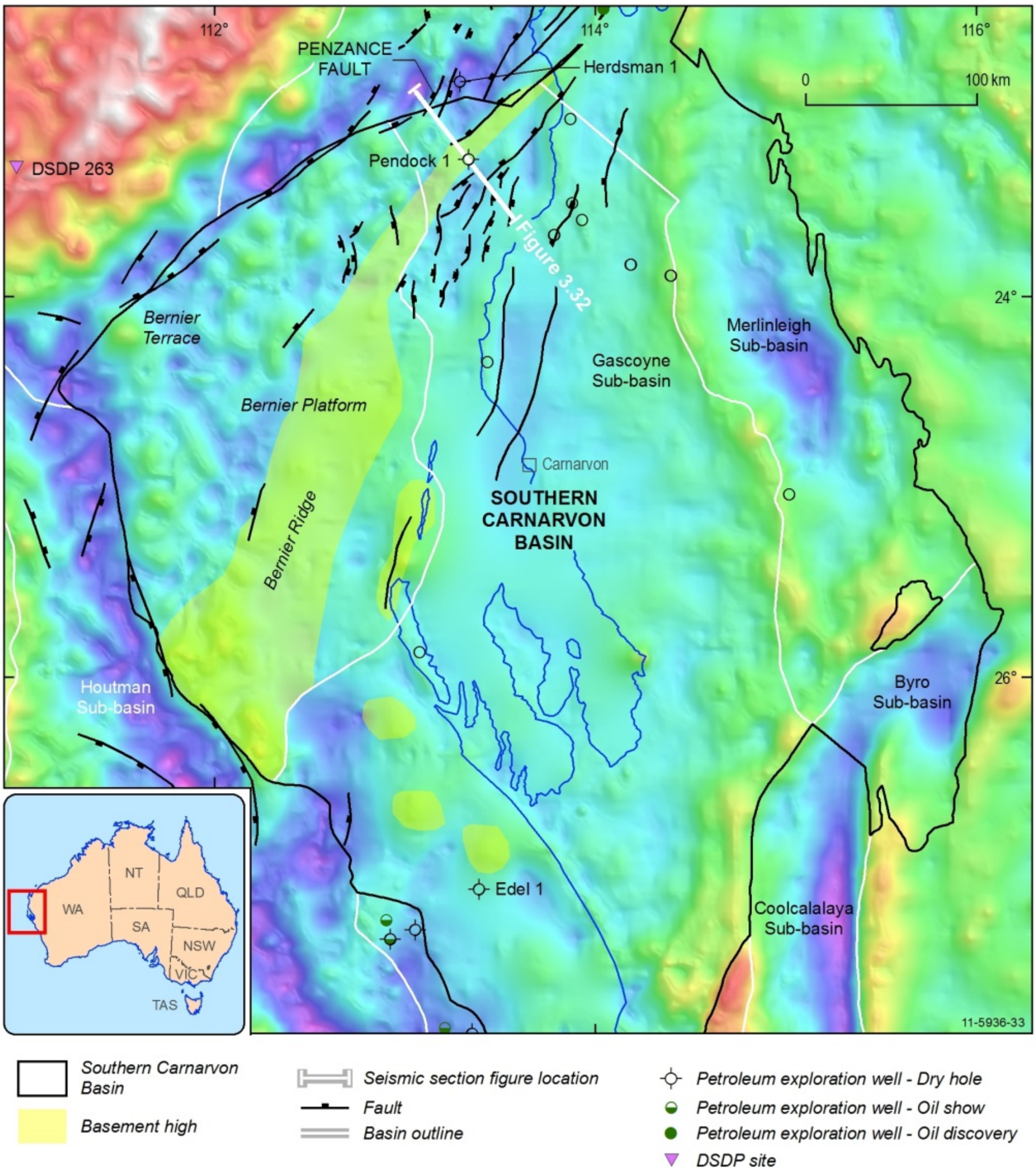

Figure 3.31: Regional setting of Gascoyne Sub-basin and Bernier Platform shown on Bouguer gravity image (Borissova & Nelson, 2011).

The Bernier Platform is an uplifted northerly trending part of the Southern Carnarvon Basin (Figure 3.31 and Figure 3.32), which is separated from the Gascoyne Platform by a series of en echelon faults (Lockwood & D'Ercole, 2004). Gravity modelling by Lockwood & D'Ercole (2004) suggests that the ridge corresponds to a faulted crystalline basement high. The Bernier Platform has an area of approximately 47,000 km^2.

The area lying between the Bernier Platform and Mesozoic depocentres of the southern Exmouth and northern Houtman sub-basins is known as the Bernier Terrace (Figure 3.31 and Figure 3.32). Based on the limited seismic data available and regional geological knowledge (Iasky et al. 2003; Mory et al., 2003; Lockwood & D'Ercole, 2004), it appears to have a similar structure and depositional history to that of the Gascoyne Sub-basin.

The Bernier Terrace is separated from the Mesozoic depocentres by a series of large basement-involved faults (Figure 3.32), which strike northwest–southeast along the boundary with the southern Exmouth Sub-basin and north-northwest–south-southeast along the boundary with northern Houtman Sub-basin.

3.7.2.2 Basin Evolution and Stratigraphy

The geological evolution of the Southern Carnarvon Basin has been influenced by multiple extensional episodes related to the breakup of Gondwana, accompanied by reactivation of Achaean and Proterozoic structures (Figure 3.33; Mory et al., 2003).

Basement beneath the offshore Southern Carnarvon Basin is poorly understood but is likely to be the northernmost extension of the Pinjarra Orogen (Lockwood & D'Ercole, 2004).

Sedimentation in the Gascoyne Sub-basin commenced in the late Cambrian (?)–Ordovician, in a northwards opening intracratonic basin (Figure 3.33; Mory et al., 2003; Lockwood & D'Ercole, 2004). A period of faulting occurred during the Ordovician (Lockwood & D'Ercole, 2004). At this time deposition was characterised by the widespread fluvial Tumblagooda Sandstone. In the latest Ordovician–Silurian, a broad, north-plunging syncline formed on the Southern Carnarvon margin (Figure 3.33; Iasky et al., 2003). Deposition of the Dirk Hartog Group (Ajana and Coburn formations) occurred during this time in a restricted marine environment with short periods of open marine conditions (Figure 3.33; Lockwood & D'Ercole, 2004; Borissova & Nelson 2011).

Early Devonian tectonism resulted in a northwards shift of the major depocentres and deposition of the shallow marine, mixed siliciclastics and dolomites of the Kopke Sandstone and Sweeney Mia Formation. After a depositional hiatus lasting until the late Middle Devonian, sedimentation re-commenced with the deposition of shallow marine to coastal siliciclastics and shelf carbonates (Nannyarra Sandstone, Gneudna Formation; Figure 3.33; Iasky et al., 2003; Borissova & Nelson, 2011). In the mid-Carboniferous the Devonian–Mississippian sequences were folded and faulted along north-trending axes (Geary, 1994), possibly as a result of the convergence of Gondwana with Laurasia.

The first major rifting event in the latest Carboniferous to Cisuralian (early Permian) resulted in the formation of a north-northeast–south-southwest trending graben across the Southern Carnarvon Basin and the development of the Merlinleigh, Byro and Coolcalalaya sub-basins onshore in the eastern Southern Carnarvon Basin (Figure 3.33). At the same time, the Bernier Platform was uplifted and partially eroded (Iasky et al., 2003). From the Pennsylvanian (late Carboniferous) to Cisuralian, shales and sandstones of the Lyons Group, were deposited in a glaciomarine environment (Hocking et al., 1987). Although this group is primarily restricted to the northernmost part of the Gascoyne Sub-basin, recent seismic data indicate that some Carboniferous–Permian strata may also be present in the northern part of the Bernier Platform (Partington et al., 2003).

Evidence for sedimentation during the Permian to Triassic is limited, which indicates that the basin was a topographically high feature at this time. Permian Lyons Group sediments are present in the onshore northern part of the Gascoyne Sub-basin (Figure 3.33; Iasky et al., 2003), and have been interpreted to extend offshore across the northern part of the Bernier Platform. Over large areas of the Gascoyne Sub-Basin and Bernier Platform Pennsylvanian–Permian tectonism caused uplift and erosion (Hocking et al., 1987; Ghori et al., 2005).

The Early Jurassic to Early Cretaceous was characterised by two extensional phases: the first was associated with breakup of Argoland (Norvick, 2002) and the second, starting in the Middle Jurassic, preceded the breakup of Australia and Greater India (Muller et al., 2002). The focus of extension lay northwest and southwest of the Bernier Platform and it is inferred that, following the Permian glaciation, most of the Bernier Platform and Gascoyne Sub-basin were emergent until the earliest Cretaceous (Mory et al., 2003). As a result, the thick accumulation of Triassic, Jurassic and Lower Cretaceous syn-rift sediments present in the Exmouth Sub-basin to the north is largely absent. The exception is in the southernmost part of the Gascoyne Sub-basin, where a thin succession (about 300 m) of the Triassic Kockatea Shale has been interpreted above the mid to late Permian unconformity (Iasky et al., 2003). Uplift of the Bernier Platform may have resulted in up to 6 km of erosion between the late Permian and Early Cretaceous (Iasky et al., 2003). The only confirmed Jurassic unit in the Gascoyne Sub-basin is located onshore within the Woodleigh impact structure (Figure 3.33; Iasky & Mory, 1999; Mory et al., 2003).

The last significant rifting episode in the region occurred during Middle Jurassic to Early Cretaceous northwest–southeast extension preceding the breakup with Greater India. The early extensional phase was characterised by significant uplift and faulting which was accompanied by extensive erosion (Iasky et al., 2003; Lockwood & D'Ercole, 2004). Along the western margin of the Southern Carnarvon Basin, breakup was associated with extensive volcanism (Direen et al, 2008.; Symonds et al., 1998)

Rapid subsidence following the breakup resulted in a widespread transgression and deposition of a fining-upward marine sequence over the Valanginian unconformity surface. This resulted in deposition of the Winning Group across the western part of the Southern Carnarvon Basin (Figure 3.33). The Winning Group consists of a basal transgressive sandstone (Birdrong Sandstone) overlain by low-energy marine shale (Muderong Shale). In the Aptian, shallow marine conditions spread to current onshore areas of the Gascoyne Sub-basin, resulting in deposition of the Windalia Radiolarite, a uniform white radiolarian siltstone, which is overlain by the argillaceous Gearle Siltstone. The onset of full ocean circulation in the Turonian resulted in deposition of the Toolonga Calcilutite which is widespread in the Gascoyne Sub-basin. Santonian inversion structures are widespread in the Southern Carnarvon Basin. This inversion is coincident with and may have been caused by the major plate re-organisation in the Indian Ocean, when Greater India changed its path from northwest to north (Gibbons et al., 2010).

The Cenozoic succession in the Southern Carnarvon Basin is predominantly flat lying and consists of shallow-marine carbonate rocks (Cardabia and Giralia calcarenites and Trealla Limestone; Figure 3.33). During most of the Cenozoic, thick prograding carbonates were deposited offshore, whereas onshore, the Gascoyne Sub-basin remained largely subaerial, with only minor deposition in the Eocene and Miocene (Hocking et al., 1987).

Miocene inversion also affected the whole region, driven by the convergence of Australia and Eurasia in the middle Miocene (Partington et al., 2003). This led to the formation of widespread compressional fault reactivation and inversion anticlines (Iasky et al., 2003).

3.7.2.3 Level of knowledge

Geological knowledge of the offshore Southern Carnarvon Basin is based on limited drilling, a variable seismic coverage and correlation to the onshore succession. Particularly poor data coverage over the Bernier Platform limits our understanding of the geology of this region.

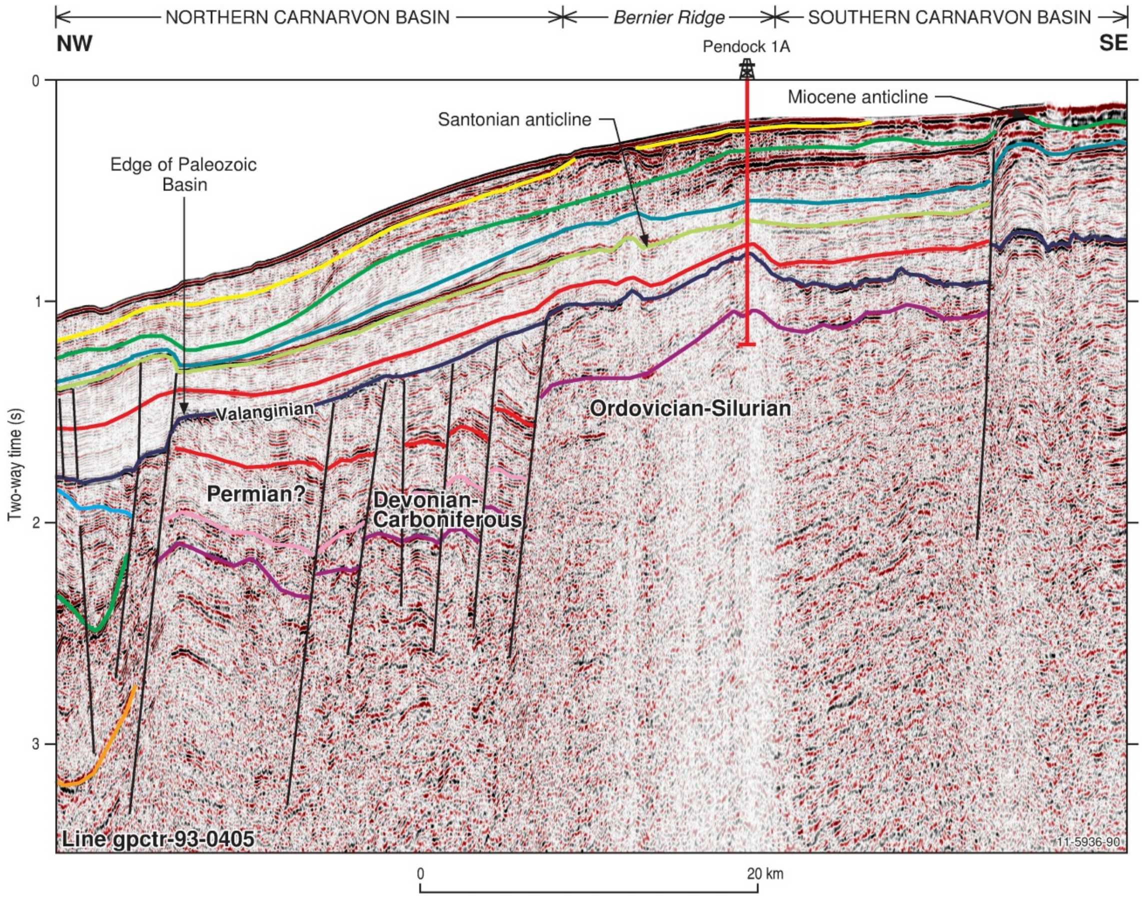

Figure 3.32: Interpreted composite seismic line across the western Bernier Platform (from Borissova & Nelson, 2011). See Figure 3.31 for location of this line.

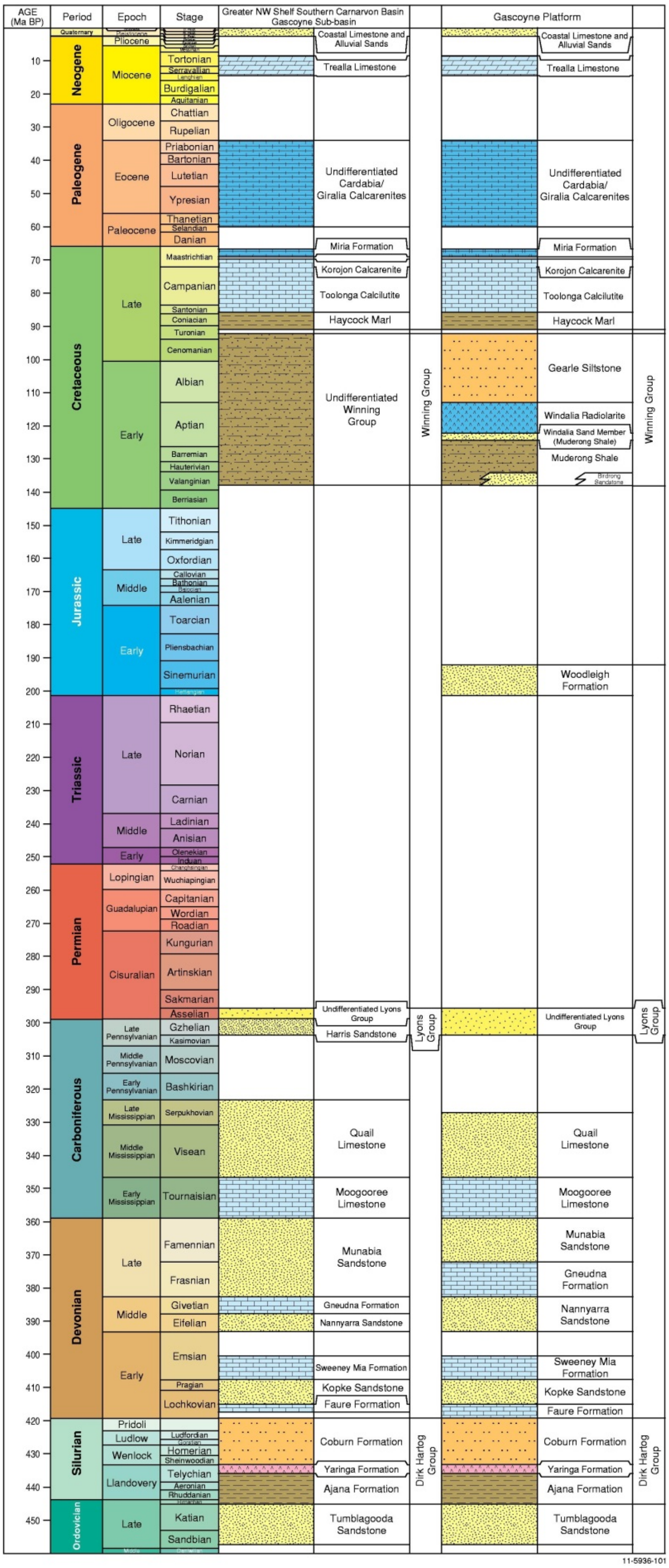

Figure 3.33: Stratigraphy of the Gascoyne sub-basin. Geologic time scale from Gradstein et al. (2012).

3.7.3 Petroleum systems

Evidence for active Paleozoic hydrocarbon systems in the Gascoyne Sub-basin is found in Pendock 1A, where minor shows of oil were found in the Devonian and Silurian succession (Genoa Oil N.L., 1970: Canadian Superior Oil (Aust.), 1970). Oil stains were detected in the Nannyarra and Gneudna Formations and both oil staining and fluorescence were detected within the Coburn Formation of the Dirk Hartog Group. No direct evidence for active hydrocarbon systems has been found within the Bernier Platform.

3.7.3.1 Source Rocks

The most important potential source rocks in the Gascoyne Sub-basin are Silurian and Devonian organic rich and oil-prone laminated mudstones within carbonate-dominated facies (Silurian Coburn Formation, and Devonian Gneudna Formation; Ghori, 1998; Ghori et al., 2005). These also form the main potential source rocks within the Bernier Platform. However, all of these source rocks are thin and probably of limited extent. Maturity and petroleum generation modelling of the Paleozoic succession (Ghori et al., 2005) showed that the maturity of these units progressively increases from immature in the south-southeast to mature in the north-northwest, commensurate with increasing depth of burial.

3.7.3.2 Generation and Migration

Burial, thermal and erosional histories are complex and poorly constrained (Iasky et al., 2003). Geohistory modelling in the Gascoyne Sub-basin by Ghori et al. (2005) indicated that petroleum generation and migration from Silurian and Devonian source rocks peaked during the Permian. For this reason, mid-Carboniferous to early Permian structures are the most prospective.

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

3.7.3.3 Reservoirs and seals

The Paleozoic succession contains a number of potential reservoir units. Ordovician red beds (Tumblagooda Sandstone) have variable porosity and permeability, but even at depths greater than 1000 m porosity is typically good, with an average of 13%. The Gneudna Formation provides the prime reservoir potential. The reefal Point Maud Formation also exhibits favourable reservoir properties.

Potential seal is inferred to be provided by thick marine shales and marls of the upper Gneudna Formation overlying the Point Maud Member.

3.7.3.4 Play types

The Paleozoic Gascoyne Sub-basin hosts a number of structural and stratigraphic plays (Figure 3.34). Structural plays include fault block and Miocene reactivation anticline plays. Paleozoic traps include

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

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

3.7.3.5 Critical Risks

- the possibly limited distribution and extent of Silurian–Devonian source rocks. In addition, depth of burial may have been insufficient in the southeast for source rocks to reach maturity (Ghori et al., 2005)
- risk of breaching of mid-Carboniferous to early Permian structural traps during later structural reactivation (Ghori et al., 2005).
- other risks include artesian flow (Birdrong Sandstone) and the biodegradation of shallow accumulations.

3.7.3.6 Overall prospectivity classification

Moderate

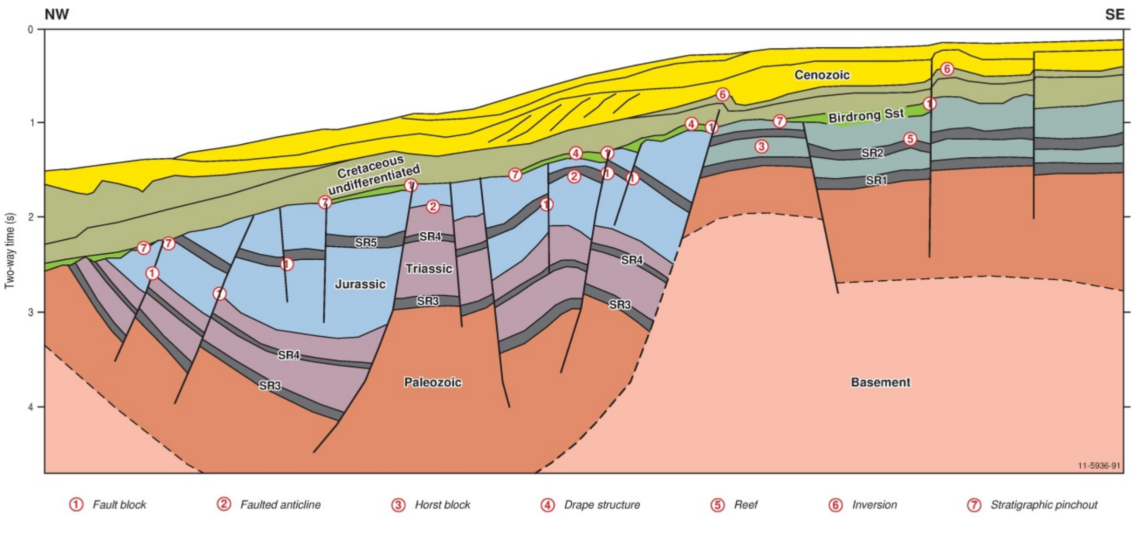

Figure 3.34: Conceptual play diagram for the Southern Carnarvon Basin.

3.7.4 Exploration status

Petroleum exploration of the Southern Carnarvon Basin (Figure 3.35) began with the discovery of Rough Range oil field in 1953. It was followed by two decades of regional mapping and unsuccessful drilling. By the mid-1970s, petroleum discoveries in the adjacent Northern Carnarvon Basin attracted exploration focus and exploration in the Southern Carnarvon Basin almost ceased. Only two offshore wells (Pendock 1A and Edel 1) have been drilled in the Gascoyne Sub-basin and none have been drilled in the Bernier Platform. The last well was drilled in 1972, although Herdsman 1 was drilled in 2003 in the southern Exmouth Sub-basin close to the boundary with the Southern Carnarvon Basin. No offshore accumulations have been discovered.

In 2013, Total Exploration and Production Australia (Total) was granted two large exploration permits covering much of the Bernier Platform. The guaranteed work program includes acquisition or licensing of 2,500 km of new 2D seismic data.

3.7.5 Data

Key data sets for the Offshore Southern Carnarvon Basin are listed in Table 3.25–Table 3.28. Two wells have been drilled in the offshore Gascoyne Sub-basin:

- Pendock 1A was drilled in 1969 by Canadian Superior Oil (Aust.) Pty Ltd in the Gascoyne Sub-basin. The well reached a total depth of 2501 m and penetrated the Upper Ordovician to Silurian Dirk Hartog Formation. (Genoa Oil N.L., 1970: Canadian Superior Oil (Aust.), 1970).
- Edel 1 was drilled in 1972 by Ocean Ventures Pty Ltd. It reached a total depth of 2750 m in Triassic strata (Ocean Ventures, 1972).

In addition, seismic interpretation in the Jurassic–Cenozoic section can be tied to Herdsman 1 in the Exmouth Sub-basin (Woodside Energy Ltd, 2003a).

Seismic coverage in the sub-basin varies in quality and consists of a mixture of vintages ranging from the 1960s to 2009. Key seismic datasets of note in the offshore Southern Carnarvon Basin include the Western Geco Carnarvon Terrace 2D Speculative Survey and 2D and 3D Coverack surveys (Woodside Energy Ltd, 2003b, c). In 2008–09 under the Offshore Energy Security Program, Geoscience Australia acquired regional seismic data in frontier areas of the western Australian margin (survey GA 310), including parts of the Southern Carnarvon Basin (Foster et al., 2009; Geoscience Australia, 2011). In November 2009, Searcher Seismic shot the non-exclusive 2D Acheron seismic survey with line spacing of 25 km across the region (Searcher Seismic, 2010).

Satellite hydrocarbon slick detection in the region was undertaken by Shell in 2000. Datasets collected included ALF, SAR, Landsat 1, Spot, IRS, IKONOS and Earth Resources satellite scenes. Analysis of these data resulted in the identification of two medium confidence slicks (Partington et al., 2003).

All good quality potential field datasets have been compiled, levelled and gridded to provide continuous gravity and magnetic coverage across the entire southwestern margin (Hackney, 2012).

3.7.5.1 Confidence rating

Low–medium

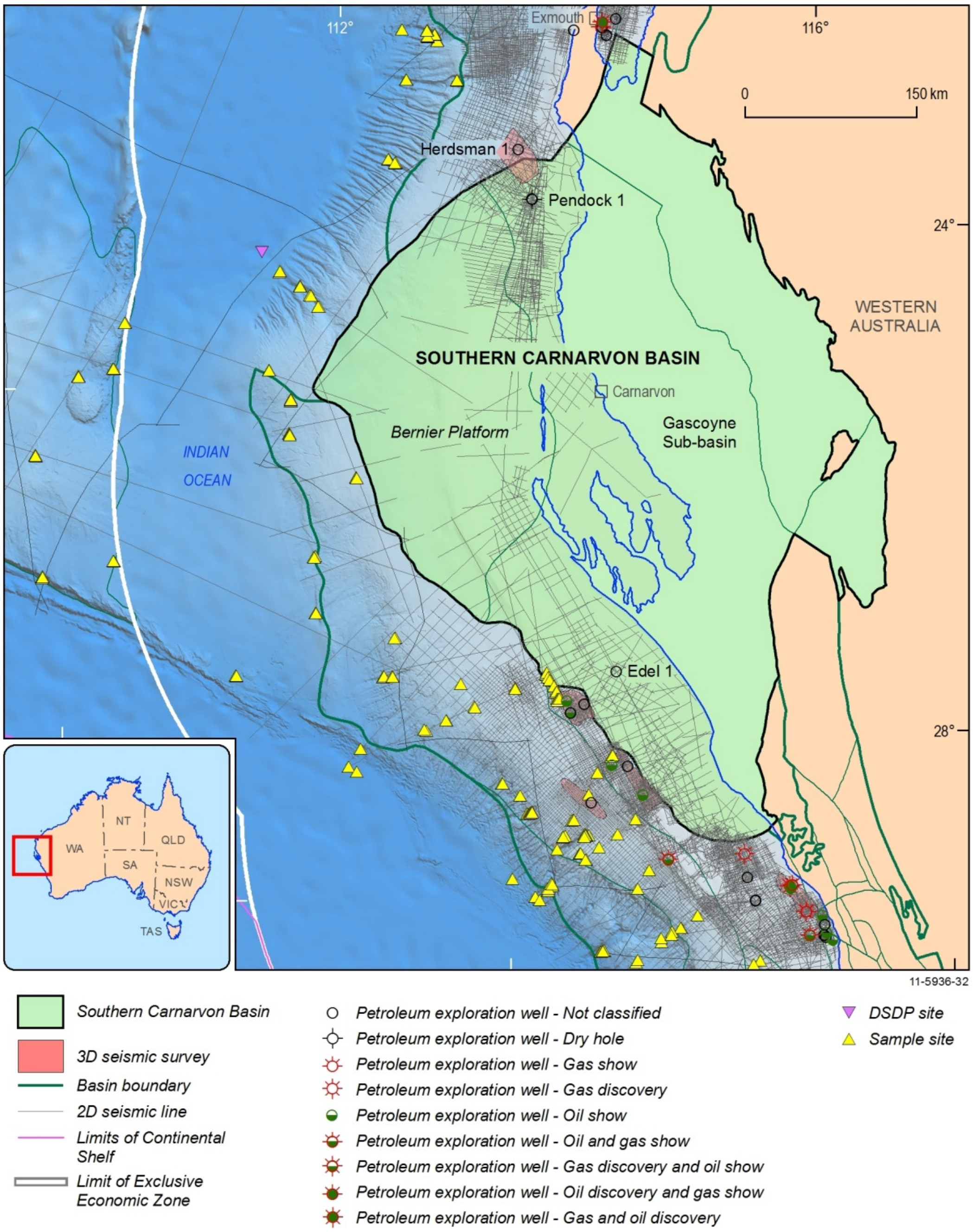

Figure 3.35: Seismic, wells and dredge samples in the Turtle Dove Ridge and surrounds.

3.7.6 Issues and remaining questions

The offshore Southern Carnarvon Basin remains under-explored. Until recently, seismic coverage was restricted to its northern and southern parts with virtually no seismic over the central part of the Bernier Platform. In addition, well coverage is extremely sparse. Consequently, geological knowledge of the area is poorly constrained. Knowledge gaps include:

- age of the succession
- presence of source rocks and other key petroleum systems elements

- timing of generation and migration
- subsidence and uplift history, including the amount of eroded section.

3.7.6.1 Recommendations

These questions can only be addressed by additional data collection, including drilling of wells and acquisition of new seismic data sets, followed by structural, sequence stratigraphic, biostratigraphic, petrophysical and geochemical studies. Total's current exploration program includes acquisition of new 2D seismic data that will provide valuable insights into the geology of the region.

In addition the following studies could be undertaken on existing data to better understand the petroleum prospectivity and exploration risk:

- detailed seismic interpretation of the offshore Southern Carnarvon Basin, tying seismic data to both the Perth Basin in the south, and the adjacent Northern Carnarvon Basin, and identification of possible play types
- detailed petroleum systems modelling to better constrain maturity and generation of key source rock intervals across the sub-basin.

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3.7.8 Data Tables

Table 3.25: List of wells in the offshore Southern Carnarvon Basin and surrounds.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1969	Pendock 1A		Canadian Superior Oil (Aust.) Pty Ltd	2501	Silurian		Genoa Oil N.L., 1970: Canadian Superior Oil (Aust.), 1970
1972	Edel 1		Ocean Ventures Pty Ltd	2750	Triassic		Ocean Ventures, 1972
2003	Herdsman 1		Woodside Energy Ltd.	2010	Jurassic		Woodside Energy, 2003a

Table 3.26: Key 2D seismic surveys, offshore Southern Carnarvon Basin.

Year	Survey	Operator	Line-km	Reference
1998	Carnarvon Terrace 2D Speculative Survey	Western Geco		
2002	2D and 3D Coverack surveys	Woodside		Woodside Energy, 2003b, c
2008–09	GA 310	Geoscience Australia		Geoscience Australia, 2011
2009	Acheron 2D	Searcher Seismic		Searcher Seismic, 2010

Table 3.27: Key geological sampling surveys, adjacent to the offshore Southern Carnarvon Basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
2008–09	GA 2476	Geoscience Australia	Houtman Sub-basin, Cuvier margin	Dredge, box core, grab	Siliciclastic and carbonate rocks, volcanic rocks	Daniell et al., 2010

Table 3.28: Key swath bathymetry surveys, offshore Southern Carnarvon Basin.

Year	Survey	Operator	Area (km^2)	Reference
2001	Exmouth/Cuvier margins	LDEO		
2008	CERF Carnarvon Shelf	GA		
2009	South Ningaloo Reef	GA/AIMS		

3.8 Wallaby Plateau

3.8.1 Summary

State(s)		WA
Area (km^2)		~100,000
Water Depth (m)		2100 to >4500
Maximum sediment thickness (m)		unknown
Age range		Early Cretaceous (?and older) to Holocene
Basin	**Overlies**	?Continental crust
	Adjacent basins	Wallaby Saddle
Basin type		?Extensional; volcanic
Depositional setting, rock types		Marine, non-marine and glacial siliciclastic rocks; marine carbonate rocks
Overall prospectivity		Low
Confidence		*Low*

3.8.2 Geology

The Wallaby Plateau is an extensive bathymetric high located approximately 450 km west of Carnarvon, Western Australia. The plateau covers about 100,000 km^2 in water depths of 2200 m to greater than 4500 m (Figure 3.36; Symonds & Cameron, 1977; Colwell et al., 1994; Symonds et al., 1998; Sayers et al., 2002; Nelson et al., 2009; Daniell et al., 2010; Goodwin et al., 2014). The Wallaby Plateau lies largely within the Australia's extended continental shelf, ratified under the United Nations Convention on the Law of the Sea in 2008 by the Commission on the Limits of the Continental Shelf (Symonds et al., 2009).

The geology of the Wallaby Plateau is poorly understood and its origin remains unresolved. Early studies based on dredge samples suggested the plateau was of oceanic origin (von Stackelberg et al., 1980; Colwell et al., 1990, 1994). However more recent studies based on new dredge samples, seismic and potential field data, suggest a continental origin is more likely (Symonds et al., 1998; Sayers et al., 2002; Planke et al., 2002; Nelson et al., 2009; Daniell et al., 2010; Stillwell et al., 2012; Goodwin et al., 2014).

3.8.2.1 Structural geology

The Wallaby Plateau comprises two bathymetric highs: the Quokka Rise, in the northwest, and a more extensive feature, the Cuvier Plateau, in the southeast (Figure 3.36; Veevers et al., 1985; Sayers et al., 2002; Daniell et al., 2010). 3D gravity modelling indicates that the crustal densities of both the Cuvier Plateau and Quokka Rise are consistent with continental crust (Goodwin et al., 2014).

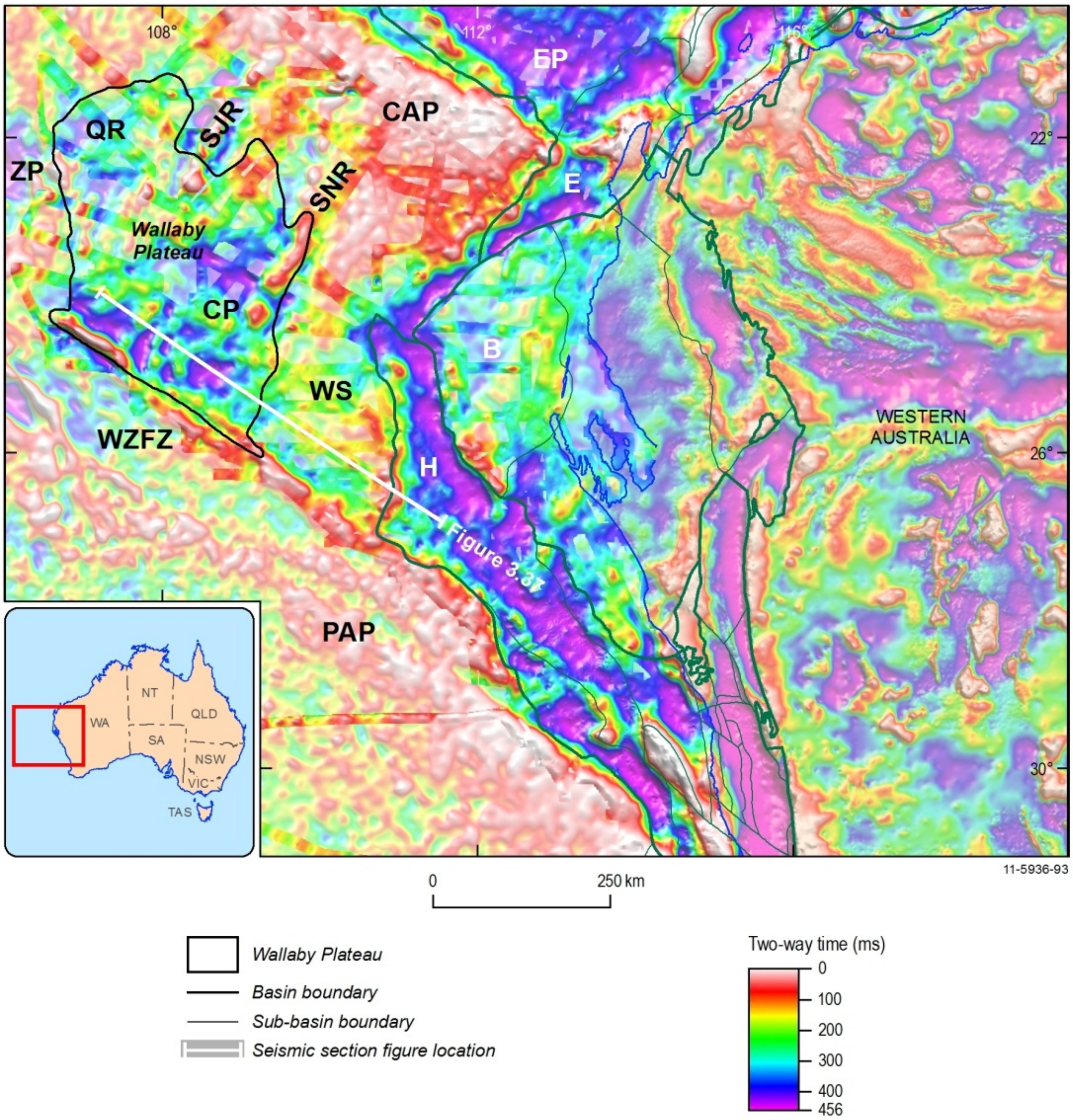

Figure 3.36: Wallaby Plateau structural elements shown on residual gravity image. B: Bernier Platform; CAP: Cuvier Abyssal Plain; CP Curvier Plateau; E: Exmouth Sub-basin; EP: Exmouth Plateau; H: Houtman Sub-basin; PAP: Perth Abyssal Plain; QR: Quokka Rise; SJN: Sonja Ridge; SNR: Sonne Ridge; WS: Wallaby Saddle; WZFZ: Wallaby Zenith Fracture Zone; ZP: Zenith Plateau.

Thick and laterally extensive divergent dipping reflector sequences (DDRS) are mapped from seismic data on the flanks of the Cuvier Plateau and Quokka Rise (Figure 3.37). The DDRS have geometric affinities with Seaward Dipping Reflector Sequences (SDRS) described by Symonds et al. (1998). SDRS drilled on the Norwegian Vøring margin are represented by alternating layers of lava flows and volcaniclastic sediments (Planke et al., 2000; Symonds et al., 1998). Based on seismic character, SDRS have been interpreted in the Wallaby Saddle region to the east of the Wallaby Plateau.

DDRS are similar to SDRS in seismic character which may indicate similarity in origin and composition. However, the velocity structure of the DDRS is faster than that of the SDRS on the Wallaby Saddle (Goncharov & Nelson, 2010, 2012). Moreover, samples of sedimentary rocks collected in localities where DDRS are imaged on the seismic, contain foraminifera older than the onset of spreading on this part of the margin (Quilty, 2011; Daniell et al., 2010). The Wallaby Plateau DDRS are therefore interpreted to be composed of clastic sedimentary and volcanic rocks. Thermal uplift of the inboard region preceding breakup may have resulted in erosion of the basement and pre-existing sedimentary successions.

The southeastern Cuvier Plateau is partially intersected by a large rift valley which extends from the plateau's southern margin about 100 km to the northeast (Figure 3.37). This large valley likely originated as a failed rift during the initial stages of opening of the Perth Abyssal Plain. The rift valley is 5 to 23 km wide and clearly imaged on several seismic lines (Figure 3.37). The valley is bounded by steep basement faults and underlain by half graben with syn-rift growth sections. The rift valley has an overall symmetrical structure with the central horst block separating eastern and western half graben (Figure 3.37). The age of the syn-rift succession post-dates the formation of DDRS sequences. The prominent topographic expression of the failed rift may indicate slow erosion rates or recent reactivation of the structure.

To the south, the Wallaby Plateau is separated from the oceanic crust of the Perth Abyssal Plain by the Wallaby–Zenith Fracture Zone (Figure 3.36; Sayers et al., 2002; Nelson et al., 2009). This is a major oceanic fracture zone at least 2000 km in length, which extends from the northern Perth Basin northwest into the Indian Ocean (Nelson et al., 2009; Gibbons et al., 2012). The fracture zone is unusually wide (~200 km) and is composed of several smaller offset ridges oriented at acute angles to its southern edge which are interpreted to have formed gradually under a transtensional regime (Nelson et al., 2009; Gibbons et al., 2012).

Immediately to the north of the plateau is the Cuvier Abyssal Plain (Figure 3.36; Symonds et al., 1998; Robb et al., 2005; Direen et al., 2008). The Sonne and Sonja ridges trend north-northeast across the Cuvier Abyssal Plain from the northern margin of the Wallaby Plateau (Figure 3.36; Veevers et al., 1985; Müller et al., 1998; Daniell et al., 2010). The Sonne Ridge is interpreted to be an abandoned spreading ridge formed between about 132 and 127 Ma (Mihut & Müller, 1998a; Müller et al., 1998; Gibbons et al., 2012). The Sonja Ridge has been interpreted either as a pseudo-fault that developed from a westwards ridge jump (Mihut & Müller, 1998a; Müller et al., 1998) or more recently, as a second abandoned spreading centre (Robb et al., 2005; Gibbons et al., 2012). Both ridges are composed of basalt, volcanic breccia and tuff as identified from dredge samples (von Stackelberg et al., 1980).

The Wallaby and Cuvier seamounts form part of the southern end of the Sonne Ridge and were identified from swath bathymetry collected during Geoscience Australia's marine reconnaissance survey (GA 2476) in 2008–2009 (Daniell et al., 2010). The Wallaby Seamount is a circular feature with a 40 km diameter that lies at depths of 2500–3600 m (Daniell et al., 2010). The Cuvier Seamount is an irregular northeast-trending feature that extends over 50 km and lies at depths of 2800–3600 m (Daniell et al., 2010).

To the east of the plateau lies the Wallaby Saddle, a bathymetrically lower region between the Wallaby Plateau and the northern Houtman Sub-basin (Figure 3.36; Symonds et al., 1998; Norvick, 2004).

The Zenith Plateau is located to the west (Figure 3.36). The lack of available data means that the nature of this feature remains undetermined, however a continental origin for this has also been suggested (Planke et al., 2002; Gibbons et al., 2012). The Wallaby and Zenith plateaus are separated by a bathymetric trough, which is sometimes referred to as the Wallaby–Zenith Basin (Mihut & Müller, 1998a; Sayers et al., 2002).

3.8.2.2 Tectonic Evolution and Stratigraphy

Despite the ambiguity of the nature of the Wallaby Plateau, most evidence points to a continental origin. The oldest sedimentary rocks dredged from the plateau are determined from foraminifera to be Middle to Late Jurassic in age (Daniell et al., 2010; Quilty, 2011; Stilwell et al., 2012). Furthermore, these results show that the Wallaby Plateau existed as a shallow marine platform for 10–15 Ma, prior to Valanginian breakup and rifting (Quilty, 2011; Stilwell et al., 2012).

Seafloor spreading began along the Cuvier Margin (on the Sonne Ridge) and in the Perth Abyssal Plain in the Valanginian, at around 136–137 Ma (Gibbons et al., 2012). The Wallaby–Zenith Fracture Zone formed at this time as a right-lateral transform fault connecting the newly formed spreading centres and separated the northern Perth Basin from the Greater India tectonic plate (Gibbons et al., 2012; Hall et al., 2013).

Following the initiation of seafloor spreading along the Cuvier Margin, large areas of the Western Australian margin, including the Wallaby Plateau, were affected by significant magmatic activity (Mihut & Müller, 1998b; Symonds et al., 1998; Planke et al., 2000; Sayers et al., 2002). The large amount of emplaced volcanic material makes it difficult to determine whether or not spreading occurred within the Wallaby Saddle.

Gibbons et al. (2012) present the most recently published plate reconstructions of the area and suggest as many as three ridge jumps occurred in the Wallaby Plateau region within a 12 myr period after the initial onset of sea-floor spreading. At around 128 Ma (Barremian), seafloor spreading ceased along the Sonne Ridge and jumped further west to the Sonja Ridge, transferring the Wallaby Plateau from Greater India to the Australian Plate (Gibbons et al., 2012). A second ridge jump occurred around 127 Ma, at which point the Sonja Ridge was abandoned (Gibbons et al., 2012). A third westward ridge jump, at around 124 Ma, transferred the Zenith Plateau from Greater India to the Australian plate (Gibbons et al., 2012).

The syn-rift package mapped below the breakup unconformity within the failed rift valley in the central part of the plateau (Figure 3.37) is characterised by low amplitude continuous reflections with clear growth geometries against the basement-involved faults. The unit is up to 0.75 s TWT thick and could have accumulated as early as the onset of breakup in the Valanginian or later during extension along the Sonne and Sonja ridges. Alternatively it could have developed when the ridge crest in the Perth Abyssal Plain was close to the current location of the rift valley.

The post-breakup succession on the Wallaby Plateau is laterally extensive and has a maximum thickness of about 0.650 s TWT. It has been correlated with Lower to Upper Cretaceous successions of the Southern Carnarvon Basin and likely includes shallow-marine clastic units at the base overlain by a largely carbonate deep-water succession (Symonds & Cameron, 1977; Colwell et al., 1994).

Plate reconstructions indicate that the en echelon fracture zones within the Wallaby–Zenith Fracture Zone to have formed from around 110 Ma (Albian), as Greater India underwent a slight counter-clockwise rotation, bifurcating the original fracture zone (Gibbons et al., 2012; Williams et al., 2013).

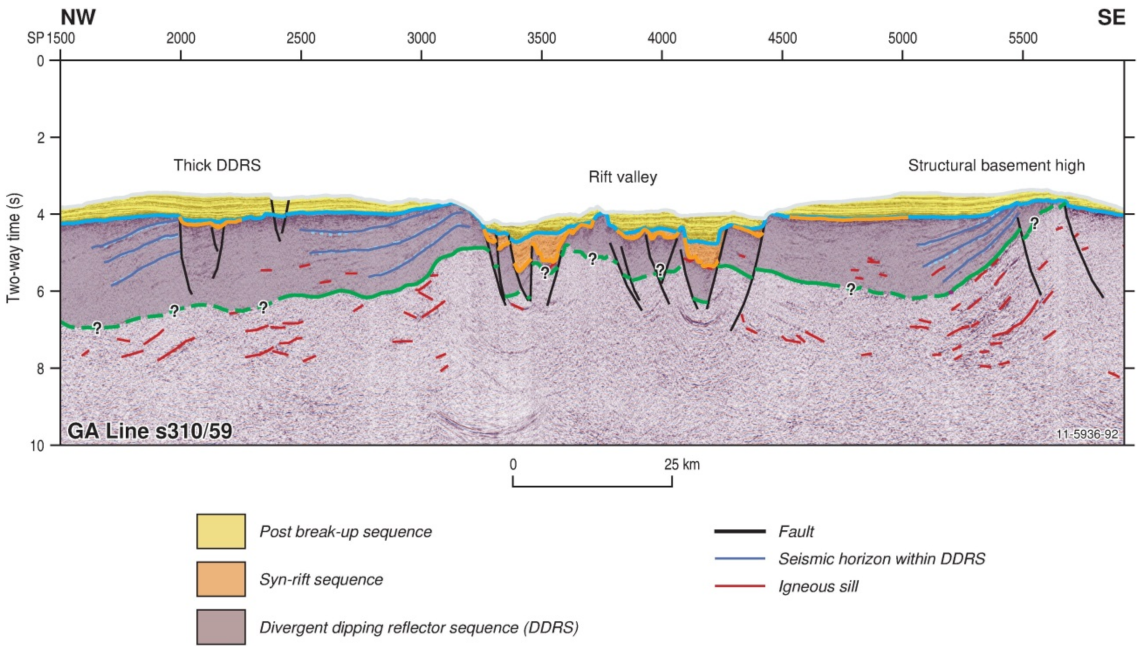

Figure 3.37: Wallaby Plateau cross-section. DDSR: divergent dipping seismic reflectors. See Figure 3.36 for cross-section location.

3.8.2.3 Level of knowledge

Gravity modelling indicates that the plateau is largely composed of continental crust, but it remains unclear whether any substantial sedimentary basins are present (Goodwin et al., 2014). The evidence for the sedimentary versus volcanic origin of the DDRS remains inconclusive.

3.8.3 Petroleum systems

The Wallaby Plateau is a vast, geologically complex and poorly understood province. However, based on assessment of seismic, potential field and sampling data, the petroleum prospectivity of the Wallaby Plateau is considered to be low. Even if the DDSRs prove to be predominantly of sedimentary origin, the remote location, deep water and the extensive breakup-related volcanics present high risks for exploration. Any upgrade of the perceptions of prospectivity would require more and stronger evidence of thick sedimentary basins, and sampling of those successions to provide age and lithological constraints.

3.8.3.1 Overall prospectivity classification

Low

3.8.4 Exploration status

Exploration in the Wallaby Plateau has been limited to reconnaissance seismic acquisition and sampling programs.

3.8.5 Data

Key data sets for the Wallaby Plateau are listed in Table 3.29–Table 3.31. Prior to recent investigations by Geoscience Australia, knowledge of the geology and tectonic evolution of the Wallaby Plateau was limited lack of data. New, high quality data over the plateau was acquired as part of Geoscience Australia's South West Australia margin 2D seismic survey (s310) and Marine Reconnaissance Survey (GA 2476) in 2008 to 2009 (Foster et al., 2009; Daniell et al., 2010). The former collected 1,100 line-km of seismic, gravity and magnetic data over the plateau, while the latter collected 65,000 km^2 of multibeam sonar, magnetic and gravity data and 31 rock samples. A list of all seismic surveys intersecting the plateau is given in Table 3.29 (see also Figure 3.38). All sample surveys are listed in Table 3.30 and swath bathymetry surveys are listed in Table 3.31.

All good quality potential field datasets have been compiled, levelled and gridded to provide continuous gravity and magnetic coverage across the entire southwestern margin (Hackney, 2012).

3.8.5.1 Confidence rating

Low

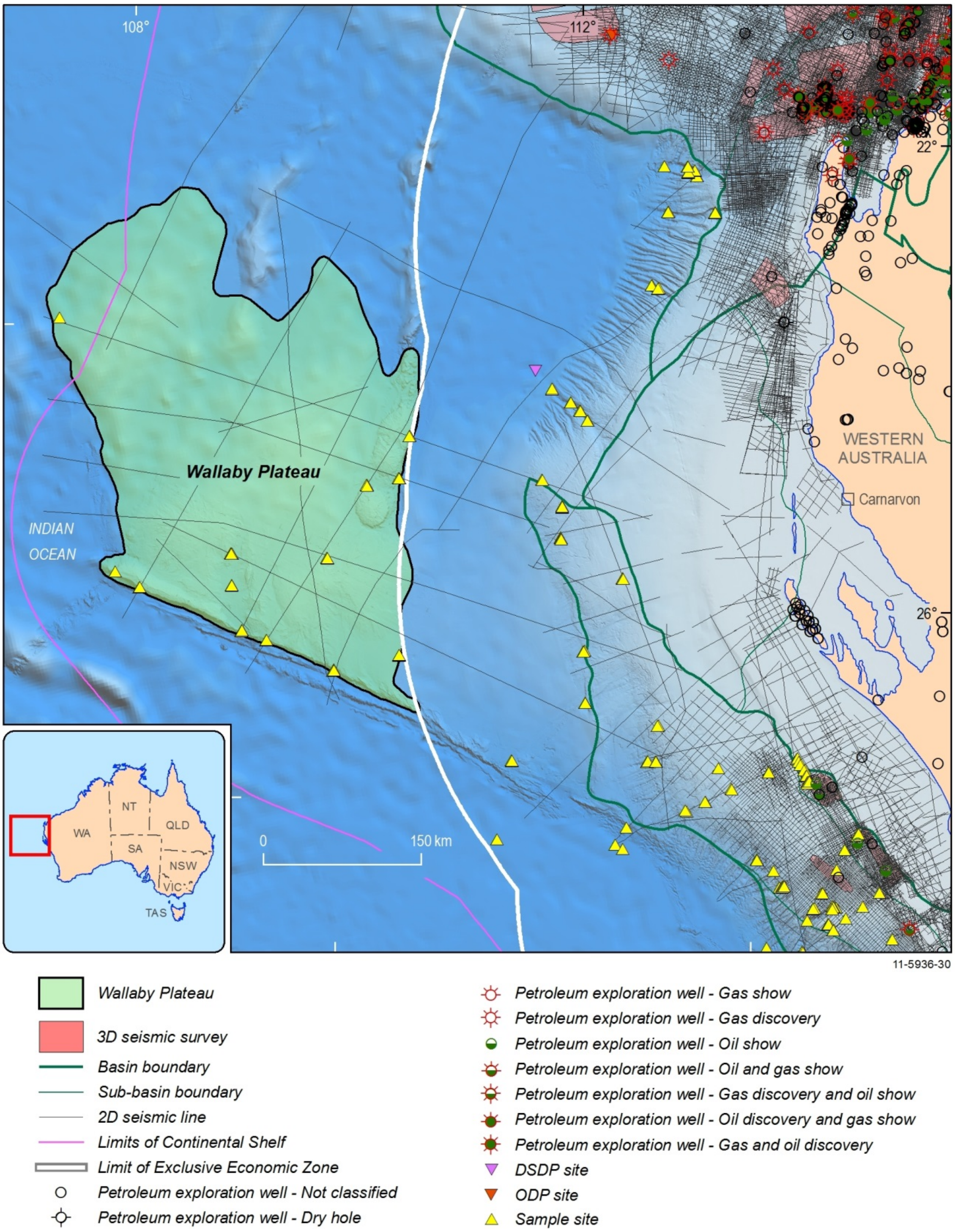

Figure 3.38: Seismic, wells and dredge sample coverage over the Wallaby Plateau and surrounds.

3.8.6 Issues and remaining questions

The key questions for the Wallaby Plateau concern whether or not the stratified successions observed on seismic are sedimentary or volcanic in nature (or a combination of both). If they are sedimentary, the size, thickness and distribution of those depocentres, the age and lithology of the basin fill, and the nature of any potential source, reservoir and seal facies need to be determined. Furthermore, the fundamental question of whether the Wallaby Plateau is continental or volcanic in origin is key to understanding the heat-flow and tectonic history of the area.

Impediments to future exploration in the Wallaby Plateau include its location in deep to ultra-deep water, large distance from the coast line and existing infrastructure, and the existing poor perceptions regarding prospectivity.

3.8.6.1 Recommendations

Resolving the above questions to promote further exploration in the region would require significant additional data collection and interpretation, including:

- further dredge sampling across the plateau
- drilling of a stratigraphic well, followed by sequence stratigraphic, biostratigraphic, petrophysical and geochemical studies
- acquisition and interpretation of closely spaced, industry standard seismic data, processed to capture the full section (to 12 s TWT)
- acquisition and modelling of aeromagnetic data to assess intrabasinal volcanic distribution and thickness
- acquisition of seismic refraction data to better constrain crustal thickness and composition.

3.8.7 References

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3.8.8 Data Tables

Table 3.29: 2D seismic surveys, Wallaby Plateau.

Year	Survey	Operator	Line-km	Reference
1971	Petrel Survey	Shell		Sayers et al., 2002
1972	BMR Surveys 17 and 18	BMR (now Geoscience Australia)		Sayers et al., 2002
1994	AGSO Survey 135	AGSO (now Geoscience Australia)	4243	Sayers et al., 2002
2008–9	GA 310	Geoscience Australia	2570	Foster et al., 2009

Table 3.30: Key geological sampling surveys, on or close to the Wallaby Plateau.

Year	Survey	Operator	Region	Type	Rock types	Reference
1979	BGR8	BMR (now Geoscience Australia)				Exon, 1979
1987	AGSO53	AGSO (now Geoscience Australia)				Choi, Stagg, et al., 1987
1989	RS A57					Marshall et al., 1989
1990	RS A96					Colwell, Graham, et al., 1990
2008–2009	GA2476	Geoscience Australia	Zeewyck and Houtman Sub-basins, Cuvier margin and Wallaby Plateau	Dredge, grabs, boxcores, benthic slabs.	Sedimentary, igneous	Daniell et al., 2010

Table 3.31: Key swath bathymetry surveys, Wallaby Plateau.

Year	Survey	Operator	Area (km^2)	Reference
2008–2009	GA-2476 (WA Margins reconnaissance; R/V *Sonne*)	Geoscience Australia	229,000	Daniell et al., 2010

4 Northern and northwestern margin basins

The basins of Australia's northwestern margin—the Northern Carnarvon, Roebuck, Browse and Bonaparte basins—form the Westralian Superbasin (Figure 4.1; Yeates et al., 1987). Towards the coast, the Westralian Superbasin overlies two northwest to north-northwest trending Paleozoic depocentres, the Canning Basin and Petrel Sub-basin. Initiation of the Westralian Superbasin in the Pennsylvanian (late Carboniferous) was characterised by a change to northwest–southeast extension related to the separation of the Sibumasu terrane from Gondwana (Metcalfe, 1988). The Westralian Superbasin subsequently developed in response to a series of extensional events that resulted in the rifting away of continental fragments and seafloor spreading in the Late Jurassic and Early Cretaceous (Longley et al., 2002). The post-breakup succession forms an eastward thinning wedge of sediment that extends beyond the main Paleozoic–Mesozoic depocentres to overlie the Arafura Basin, a Proterozoic–Paleozoic basin that developed within the Northern Australian Craton, and merges with the Carpentaria Basin in the east.

Key references that discuss the geology and tectonic evolution of the northern and northwestern margins are: Yeates et al. (1987), Bradshaw et al. (1988, 1994), Veevers (1988), AGSO North West Shelf Study Group (1994), Colwell & Kennard (1996), Blevin et al. (1998); Longley et al. (2002), Barber et al. (2004), Jablonski & Saitta (2004), Struckmeyer (2006), Marshall & Lang (2013).

The northwestern continental margin is Australia's primary hydrocarbon province. The margin is host to the prolific Northern Carnarvon Basin, and the rich gas and oil fields of the Bonaparte and Browse basins. Nonetheless, significant portions of the margin remain exploration frontiers, and the lack of success in these regions raises a number of questions about their potential petroleum systems.

The Rowley (Roebuck Basin) and Barcoo (Browse Basin) sub-basins are situated between the giant reserves of the Northern Carnarvon Basin and the Caswell Sub-basin of the Browse Basin. Both are under-explored and their geology and petroleum potential poorly understood, however they are currently the focus of renewed exploration interest. Further outboard, the Scott Plateau and Seringapatam Sub-basin are rank frontier regions of untested potential.

A feature of the northern and northwestern margins is the presence of prospective shallow water Paleozoic basins. The hydrocarbon potential of the relatively unstructured northern part of the Arafura Basin (Figure 4.1) is enhanced by the likely presence of rich Middle Cambrian source rocks, while the recent exploration success in the onshore Canning Basin highlights the potential of its offshore extension, the Oobagooma Sub-basin.

The easternmost basin on the northern margin is the Carpentaria Basin, which is underlain by the Paleozoic or older Bamaga Basin (Figure 4.1). Only one well has been drilled in this region, and the geology of prospective depocentres beneath the Mesozoic basin is completely untested.

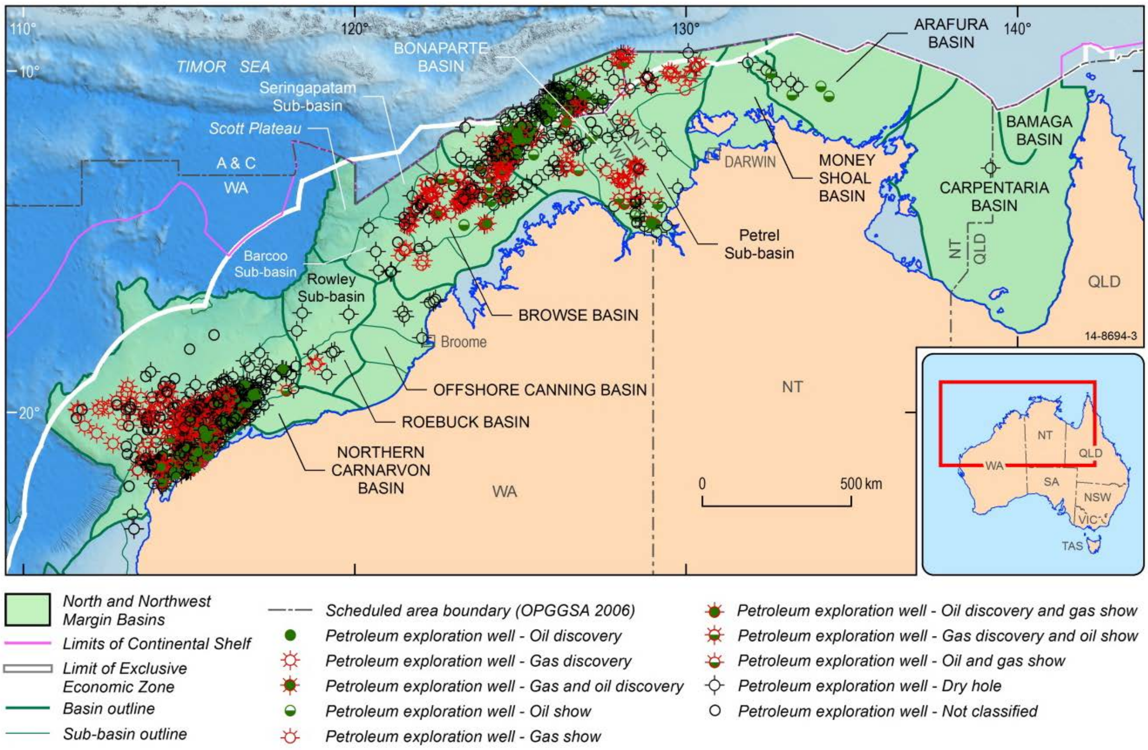

Figure 4.1: Basins of the northern and northwestern Australian margin

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4.1 Offshore Carpentaria and Bamaga basins

4.1.1 Summary

State(s)		Queensland and Northern Territory
Area (km^2)	**Offshore**	~380,000 (Carpentaria); ~26,000 (Bamaga)
	Onshore	~300,000
Water Depth (m)		<80
Maximum sediment thickness (m)		~1800 (Carpentaria); ~3000 (Bamaga)
Age range		Jurassic–Cretaceous; ?Proterozoic–?Permian
Basin	**Overlies**	Continental basement; McArthur Basin; Arafura Basin
	Underlies	Karumba Basin
	Adjacent basins	Money Shoal Basin
Basin type		Sag
Depositional setting, rock types		Marine and non-marine clastic sedimentary rocks
Petroleum prospectivity		Low
Confidence		*Low*

4.1.2 Geology

The offshore portion of the Jurassic to Cretaceous intracratonic Carpentaria Basin lies beneath the Gulf of Carpentaria in northern Australia (Figure 4.2). Unlike the coeval Money Shoal, Eromanga and Surat basins, which overlie large and thick older sedimentary basins, the Carpentaria Basin mainly overlies an erosional surface of deformed Proterozoic rocks (Figure 4.3). Pre-Jurassic rocks of possible Permo-Triassic and older age have been interpreted beneath the basal unconformity of the Carpentaria Basin (McConachie et al., 1994). In the northern part of the offshore basin, a large pre-Jurassic depocentre has been named the Bamaga Basin (Passmore et al., 1993). Although the offshore Carpentaria Basin covers a wide area (~380,000 km^2), it is typically thin (<1200 km) with a maximum thickness of about 1800 m in the Carpentaria Depression of the Weipa Sub-basin (McConachie et al., 1994). The Carpentaria Basin is overlain by a thin Cenozoic succession (Karumba Basin).

There has been only a minor amount of hydrocarbon exploration in the offshore part of the basin and only one well has been drilled—the unsuccessful Duyken 1 in 1984 (Blake et al., 1984). An exploration permit covering the Bamaga Basin has been held by Gulf Energy Limited since 2005; the permit is scheduled to expire in December 2014.

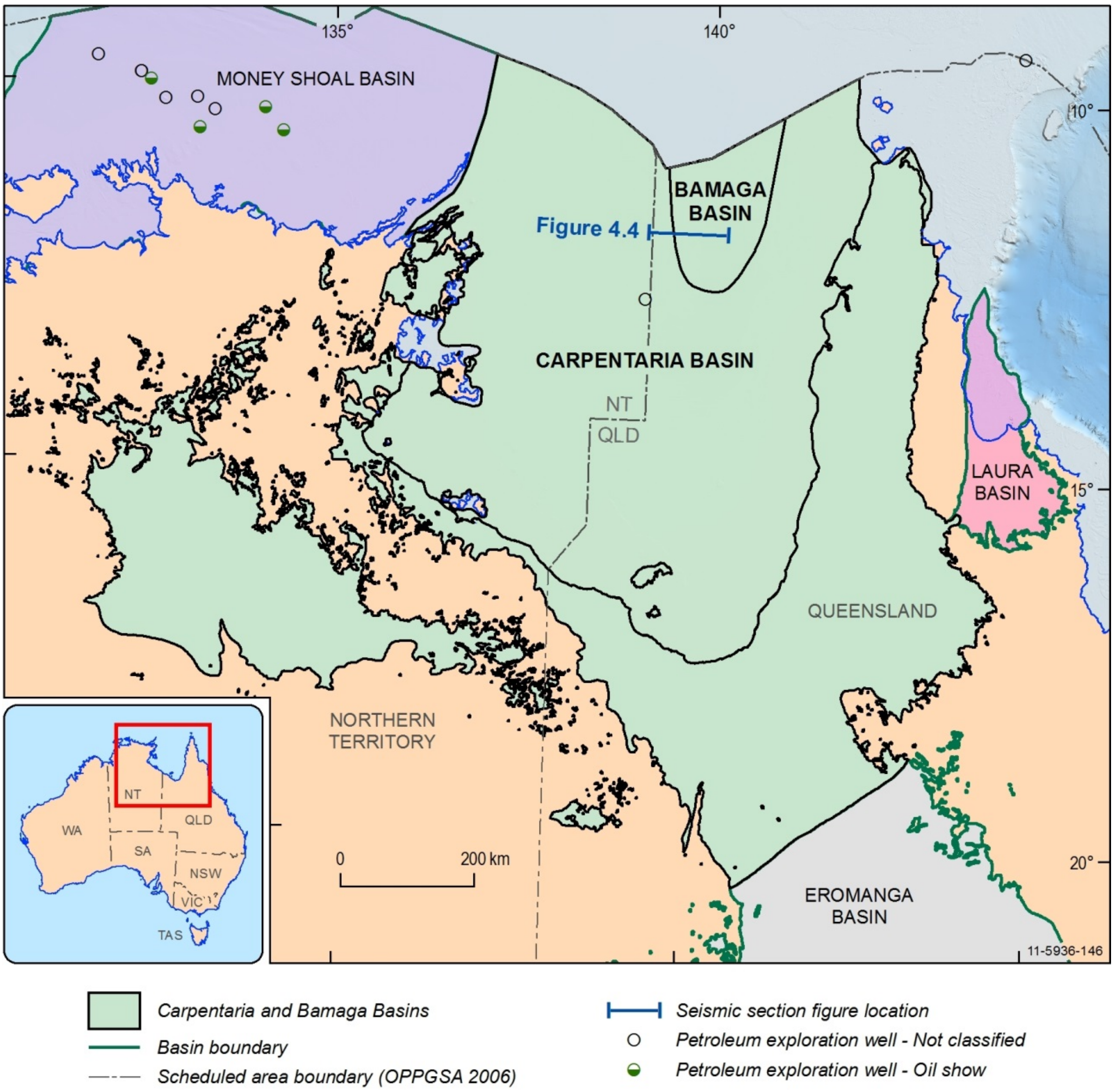

Figure 4.2: Structural elements map, Carpentaria and Bamaga basins.

4.1.2.1 Structural geology

The Carpentaria Basin forms the northern part of the Great Australian Superbasin, which also includes the Eromanga and Laura basins (Passmore et al., 1993), and is contiguous with the Money Shoal Basin to the northwest (Figure 4.2). The Carpentaria Basin is a broad, intracratonic sag basin with little structuring apart from minor folds and small displacement extensional faults. Small fault-related, drape-enhanced structures in the lower part of the section have been the main exploration targets. During the Late Cretaceous, the margins of the basin were locally faulted, uplifted and eroded prior to the commencement of sedimentation in the overlying Karumba Basin (Passmore et al., 1992).

The Bamaga Basin was described by Passmore et al. (1993) as a north-trending asymmetrical basin unconformably underlying the Mesozoic succession and containing up to 1.8 s TWT of strata of unknown age. The basin is imaged on 1980–1990s seismic data as a generally flat-lying succession; however, towards the western margins of the basin, the older succession underlies the Carpentaria Basin with a pronounced angular unconformity (Figure 4.4). There is no significant thinning of the basins to the north where it continues across the international border (Passmore et al., 1993). Overall the Bamaga Basin succession is only mildly deformed by small displacement extensional faults and related low amplitude folds. Faults generally strike to the north or northeast (Passmore et al., 1993).

4.1.2.2 Basin evolution and depositional history

Knowledge of the onshore stratigraphy of the Carpentaria Basin is derived from petroleum and stratigraphic wells and water bores, as well as scattered outcrop. The basal unit is the Middle–Upper Jurassic Garraway Sandstone, a fluvio-lacustrine succession (Figure 4.3). Thin coal seams and widespread reservoir quality sandstones within the basal section have been the focus for coal and petroleum exploration. The overlying Upper Jurassic–Upper Cretaceous succession becomes increasingly marine and fine-grained towards the top. Glauconitic sandstones are common towards the top of the Gilbert River Formation and at the bases of the Wallumbilla Formation, Allaru Mudstone and Normanton Formation, suggesting deposition in transgressive marine conditions. The upper Albian Toolebuc Formation equivalent is markedly less carbonaceous and contains less carbonate in the Carpentaria Basin than in the Eromanga Basin to the south (McConachie et al., 1997).

Results from Duyken 1, the only offshore well, indicate that the Cretaceous succession is more mudstone dominated and more marine further basinward (Blake et al., 1984). The well intersected a thin limestone at the base of the Wallumbilla Formation directly overlying Precambrian igneous basement (Blake et al., 1984).

The Bamaga Basin has not been drilled, and therefore the age and nature of the succession is unknown. McConachie et al. (1994) reported that the basin sequences have high seismic velocities, which may indicate that the basin fill comprises indurated lower Paleozoic or older rocks. Passmore et al. (1993) suggested a Devonian or late Paleozoic–Triassic age, based on analogy with undeformed basins to the south.

4.1.2.3 Level of knowledge

Geological knowledge of the offshore Carpentaria and Bamaga basins is limited, derived solely from sparse 2D seismic data (Figure 4.5), the Duyken 1 well, and correlation to wells and stratigraphic holes in the onshore portion of the basin.

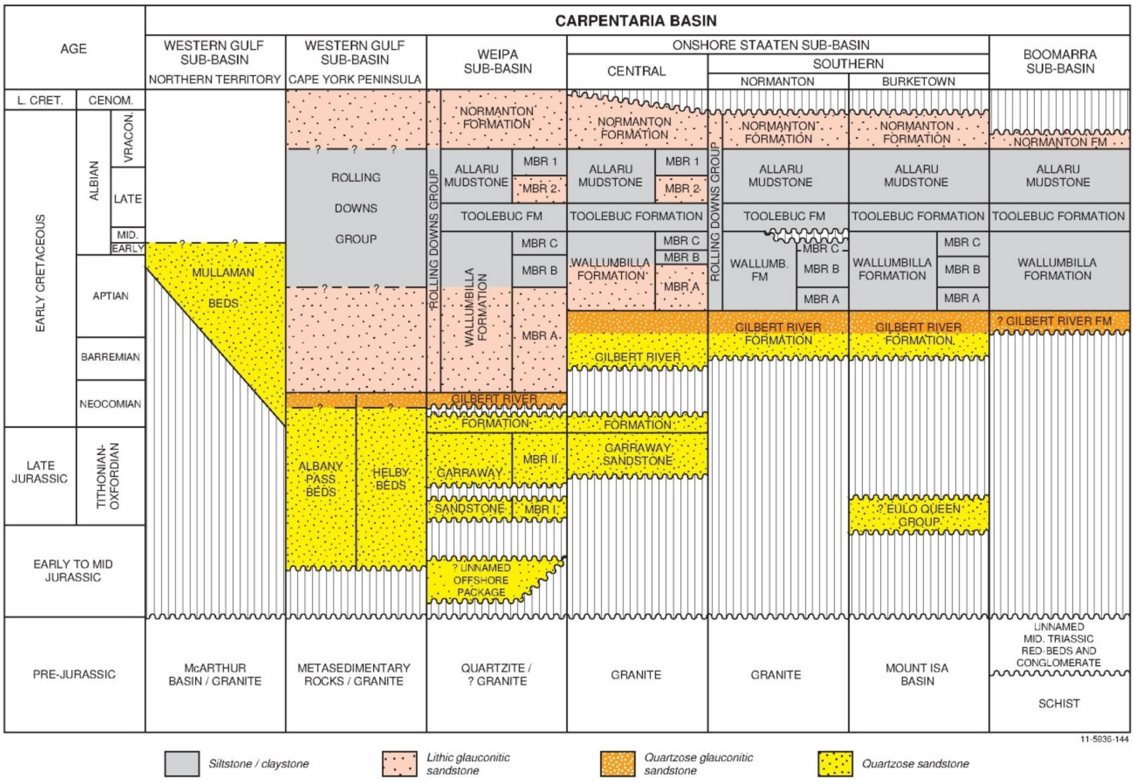

Figure 4.3: Stratigraphy of the Carpentaria Basin (from McConachie et al., 1997).

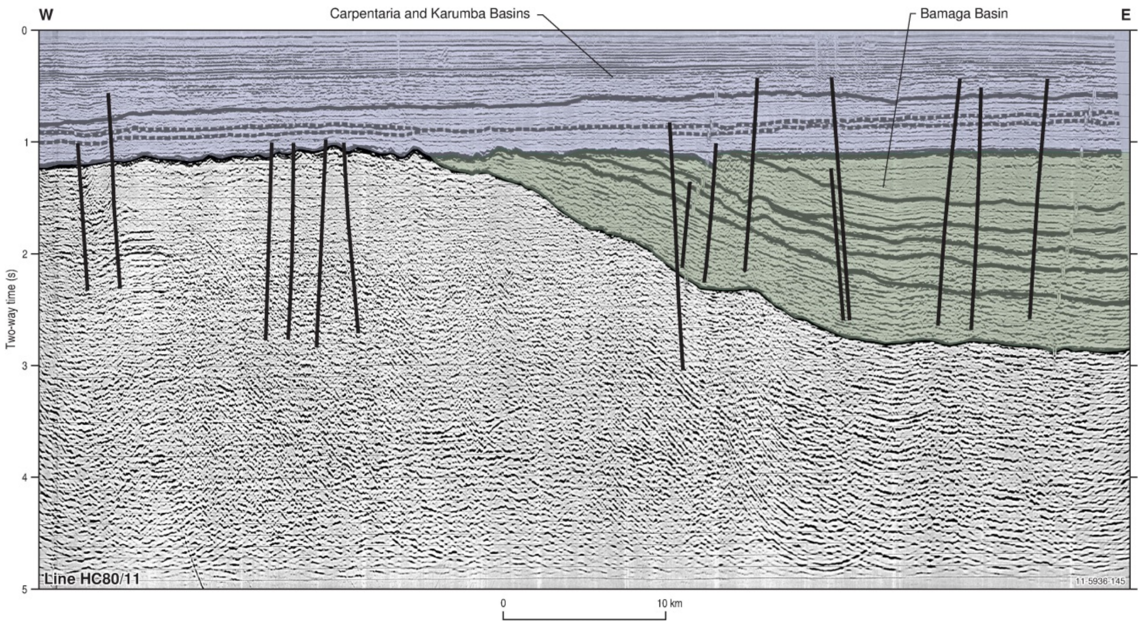

Figure 4.4: Seismic section across the Carpentaria Basin and western Bamaga Basin.

4.1.3 Petroleum systems

Only one well, Duyken 1, has been drilled in the offshore Carpentaria Basin (Figure 4.2 and Figure 4.5). The well was dry, and no hydrocarbon shows or indications reported. The Bamaga Basin has not been drilled. Based on existing data, the prospectivity of these basins is considered to be low; most of the Carpentaria Basin is likely to be too thin to be thermally immature, and the geology of the Bamaga Basin is unknown.

4.1.3.1 Source Rocks

Regionally, the best potential Mesozoic source rocks are carbonaceous mudstones of the Albian Toolebuc Formation (Figure 4.3). The Toolebuc Formation in the Carpentaria Basin is considered to be less organic-rich than in the Eromanga Basin (McConachie et al., 1997). Nevertheless, the Toolebuc section intersected in Duyken 1 was reported to have good–very good organic richness (2.72–3.5% TOC). Despite being largely composed of exinite, the organic material appears to be gas/condensate prone; possibly due to poor preservation (Blake et al., 1984). Gas/condensate-prone organic facies were also reported in the underlying Wallumbilla Formation, while the overlying section (?Allaru Mudstone) was determined to be gas-prone. Passmore et al. (1992) reported that the source richness of the Wallumbilla Formation reached values of up to 6.0% TOC in onshore wells to the south. Coaly units within the Jurassic succession may also have source potential (Passmore et al., 1993).

It is worth noting that the Albian succession also hosts the rich manganese deposits of Groote Eylandt in the western Gulf of Carpentaria. Frakes & Bolton (1984) suggested that the manganese was concentrated in oxygen-deficient conditions during marine transgression and maximum flooding. The presence of both rich manganese ores in the west, and organic-rich mudstones in Duyken 1, indicates that conditions conducive to the preservation of organic matter may have been present across large areas of the basin in the Albian

4.1.3.2 Generation and expulsion

Blake et al. (1984) reported that rocks near the base of Duyken 1 (992–1112 m) were of marginal or slightly better maturity, just reaching the early oil generation window. It follows that in the thickest part of the basin to the east of the well, potential source rocks near the base of the succession may be mature for hydrocarbon generation (McConachie et al., 1994).

4.1.3.3 Reservoirs and seals

The best potential reservoirs in the Carpentaria Basin are quartz sandstone units in the Garraway Formation, which has good measured porosity and permeability in onshore wells, and the laterally extensive Gilbert River Formation, which typically consists of up to 70% sandstone (Figure 4.3; Passmore et al., 1993; McConachie et al., 1994). Potential reservoirs may be present in Lower Cretaceous shallow marine glauconitic sandstones overlain by potential seal facies within the fine-grained Aptian to Albian marine succession. Potential seal facies are also present in the Albian Allaru Mudstone; Duyken 1 intersected an approximately 450 m thick siltstone and claystone dominated succession of this unit.

4.1.3.4 Play types

Potential structural and stratigraphic plays in the Carpentaria Basin include Jurassic sandstone units in basin floor depressions or onlapping basement highs, and fault-related drape-enhanced structures at several levels, including Jurassic and Lower Cretaceous sandstones, sealed by Lower Cretaceous mudstones (Passmore et al., 1993; McConachie et al., 1994).

In the Bamaga Basin, potential plays relate to structures formed by mild deformation and include anticlinal closures and fault-dependent traps. The potential source of hydrocarbons for these traps is unknown.

4.1.3.5 Critical risks

The main exploration risks for Carpentaria Basin plays are lack of mature source rocks and sufficient charge due to the marginal thermal maturity of much of the basin. The basin is only mildly structured, so the presence of large traps is also a risk. The absence of high quality seismic and sparse coverage (Figure 4.5) is a constraint on the assessment of basin prospectivity.

The absence of any control on the age or lithology of the Bamaga Basin succession precludes any real understanding of its prospectivity. The basin cannot be correlated with any confidence to any nearby basins, but analogies based on similar seismic character and deformation style can be drawn with the Arafura Basin to the northwest and the Georgina Basin to the south. If the basin is Proterozoic or early Paleozoic, preservation of any accumulations would be a key risk. However, without drilling, any further speculations regarding prospectivity are premature.

4.1.3.6 Overall prospectivity classification

Low

4.1.4 Exploration status

Early exploration in the Carpentaria Basin, from the 1950 to early 1970s, was limited to the acquisition of regional gravity, magnetic and seismic surveys (Passmore et al., 1993). In 1978, a Shell Company review of hydrocarbon potential suggested that source rocks in underlying Paleozoic or older basins could charge traps in the Mesozoic section (Thomas et al., 1990). This study sparked a new phase (1980–1985) of exploration interest in the basin, which resulted in the acquisition of seismic data by Shell, Hematite, Weeks, Cluff and Canada Northwest (McConachie et al., 1994). Duyken 1 was drilled by Canada Northwest in 1984 (Blake et al., 1984), but the well was dry; all permits in the basin were subsequently relinquished. Exploration recommenced in 1989, with the acquisition of new seismic data by Phoenix Resources Company of Australia and Comalco Aluminium Limited (McConachie et al., 1994).

Following relinquishment by Comalco of their permits in the mid-1990s, there was no further exploration until a permit was awarded in 2003 to Gulf Energy in the northern part of the basin. That permit is scheduled to expire in December 2014.

4.1.5 Data

Key data sets for the Carpentaria and Bamaga basins are listed in Table 4.1–Table 4.4.

Less than half the Carpentaria Basin is covered by seismic data (Figure 4.5). Seismic line spacing ranges from 50 km in the southern part of the basin to 3 km offshore from Weipa. All open-file seismic data was acquired prior to 1993.

The basin has only a patchy aeromagnetic and gravity data coverage.

Numerous scientific marine surveys have been undertaken in the basin, resulting in the collection of a broad suite of sea-bottom data and samples.

4.1.5.1 Confidence rating

Low

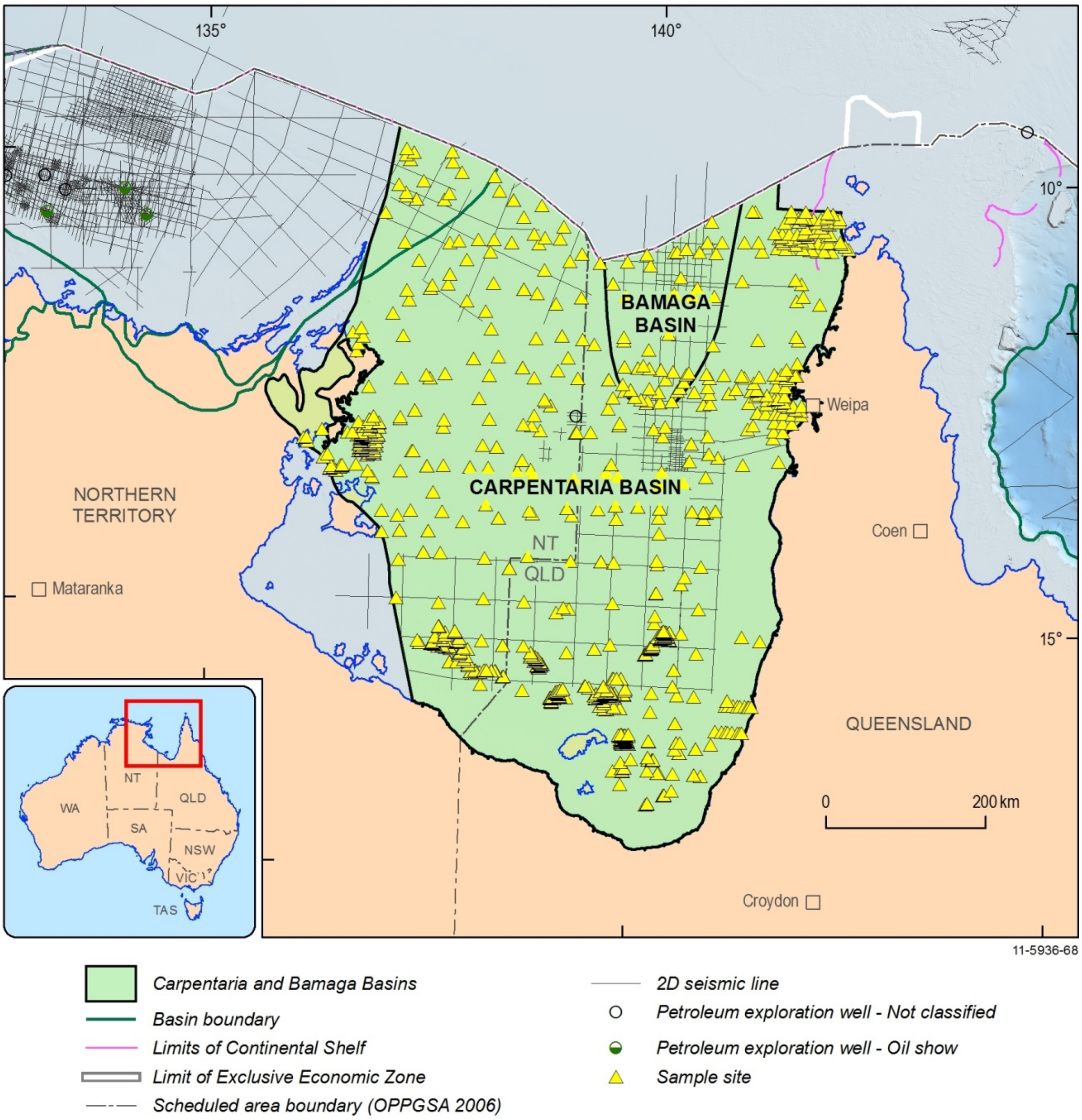

Figure 4.5: Seismic, well and sample distribution, offshore Carpentaria and Bamaga basins.

4.1.6 Issues and remaining questions

The key exploration issues concerning the Carpentaria and Bamaga basins are:

- Are potential source rocks in the Mesozoic section mature and have they generated any significant amount of hydrocarbons?
- What is the age, lithology and hydrocarbon prospectivity of the Bamaga Basin?

4.1.6.1 Recommendations

- In the long term, further drilling of the Carpentaria and Bamaga succession is required to determine the age of the Bamaga Basin, test the prospectivity of the region and provide constraints for petroleum systems modelling.
- An immediate improvement in the understanding of the stratigraphy, structural architecture and prospectivity of the basins would be achieved through the acquisition of new 2D seismic data, both regional-scale and closely-spaced data.
- Knowledge of the nature of basement underlying the basin and its controls on heat flow could be improved through acquisition and analysis of high resolution aeromagnetic data.

4.1.7 References

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4.1.8 Data Tables

Table 4.1: List of wells, Carpentaria and Bamaga basins.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1984	Duyken 1	Exploration	Canada Northwest Australia Oil N.L.	1117	Precambrian	Dry	Blake et al., 1984

Table 4.2: Key seismic surveys, Carpentaria and Bamaga basins.

Year	Survey	Operator	Line-km	Reference
1980	HC80	BHP Petroleum	1983	
1980	Q20P 1980 (W80)	WEP	1018	
1980	NTP32_Q17P_Q18P_1980 MSS	Shell Development Australia	3872	
1981	Gulf of Carpentaria 1981 MSS	Cluff Oil Australia	603	
1982	Duyken 1982 MSS	Canada Northwest Australia Oil N.L.	482	
1989	Q21P 1989 (P89)	PHR	868	
1991	Carpentaria 1991	Comalco	1650	
1992	Carpentaria 1992	Comalco	1071	

Table 4.3: List of key surveys involving geological sampling, Carpentaria and Bamaga basins.

Year	Survey	Operator	Region	Type	Rock types	Reference
2005	Submerged coral reefs and benthic habitats of the southern Gulf of Carpentaria: GA Survey 276, RV Southern Surveyor	Geoscience Australia	Gulf of Carpentaria	Benthic sled, grabs, rotary drill core	Carbonate rocks	Harris et al., 2007

Table 4.4: Swath bathymetry surveys, Carpentaria and Bamaga basins.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
2003	GA Survey 238; RV Southern Surveyor survey SS03/2004	Geoscience Australia		Harris et al., 2004

4.2 Arafura and Money Shoal basins

4.2.1 Summary

State(s)		Northern Territory
Area (km^2)	**Offshore**	~152,000 (Arafura); ~230,000 (Money Shoal)
	Onshore	~14,500 (Arafura)
Water Depth (m)		<290
Maximum sediment thickness (m)		~15,000 (Arafura); 4000 (Money Shoal)
Age range		Proterozoic–Permian; Jurassic–Holocene
Basin	**Overlies**	Continental basement; McArthur Basin
	Adjacent basins	Bonaparte Basin, Carpentaria Basin
Basin type		Extensional, sag
Depositional setting, rock types		Marine and non-marine clastic sedimentary rocks and carbonates
Petroleum prospectivity		Moderate–high
Confidence		*Medium–low*

4.2.2 Geology

The Arafura and Money Shoal basins are located on the northern margin of Australia in the Arafura Sea and extend from onshore Northern Territory to beyond the Australian–Indonesian border (Figure 4.6). The basins are located mostly in shallow water, with a maximum water depth of about 290 m. The Arafura Basin contains up to 15 km of upper Neoproterozoic to lower Permian sediments (Figure 4.7 and Figure 4.8; Totterdell, 2006). It unconformably overlies Archean to Mesoproterozoic basement terranes (the Pine Creek Inlier in the west and the northern McArthur Basin in the east) that appear to have exerted a considerable influence on the style and orientation of deformation in the basin. During the Paleozoic, the Arafura Basin was situated on the northern margin of eastern Gondwana, and the evolution of the basin was influenced by the episodic rifting of continental fragments from this margin. The Arafura Basin is unconformably overlain by the Middle Jurassic to Cenozoic Money Shoal Basin, which is up to 4 km thick (Figure 4.7; Struckmeyer, 2006c). The Money Shoal Basin comprises a westward thickening wedge of sediments (Figure 4.9a). It is bounded in the west by the Lynedoch Fault System, which separates it from the Calder Graben and Darwin Shelf of the Bonaparte Basin; in the east, a Mesozoic hinge separates the Money Shoal Basin from the Carpentaria Basin.

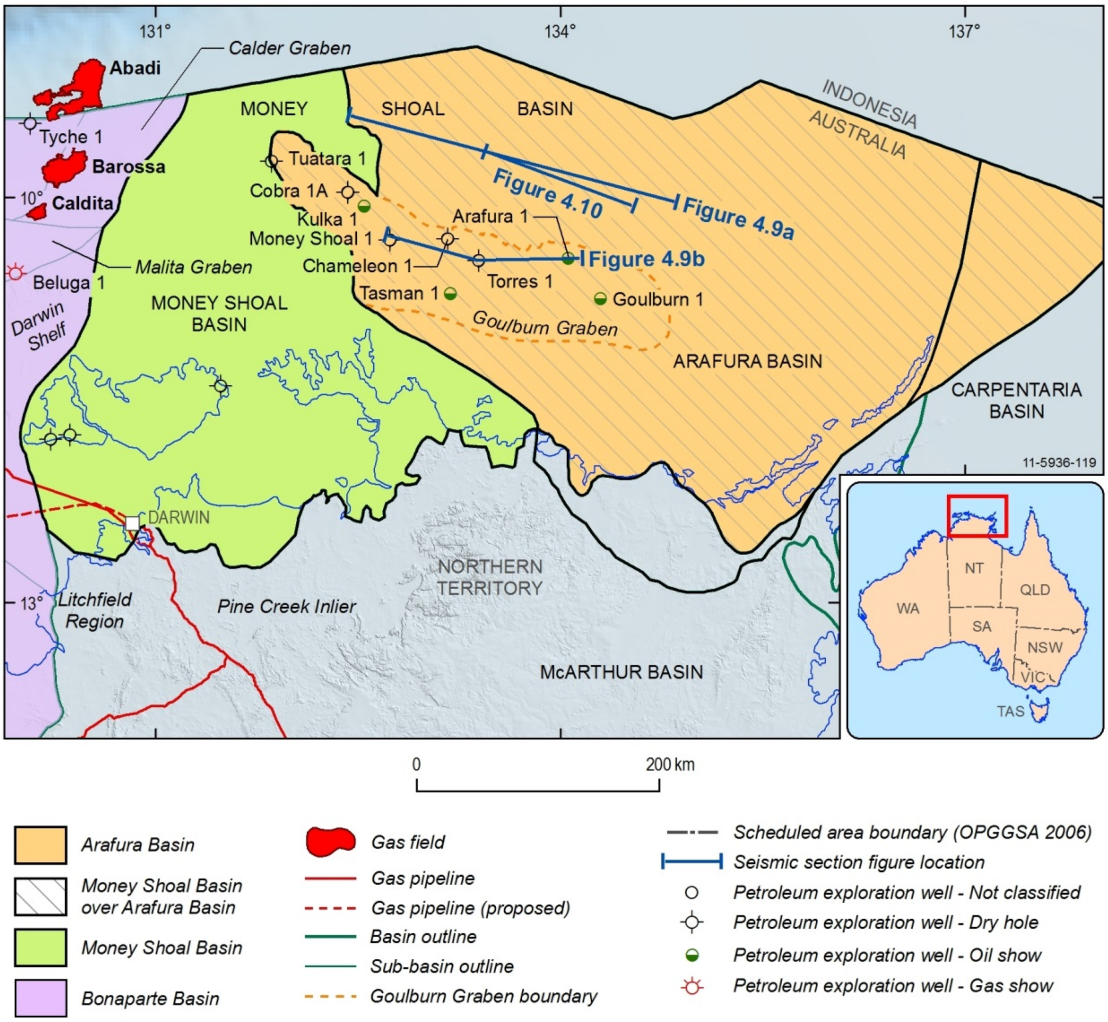

Figure 4.6: Structural elements map, Arafura and Money Shoal basins.

Both the Arafura and Money Shoal basins are under-explored with no commercial discoveries. Nine petroleum exploration wells have been drilled in the region (Figure 4.6); all penetrated the Money Shoal Basin succession and seven penetrated the underlying Arafura Basin succession in the Goulburn Graben. The main Paleozoic depocentre in the northern Arafura Basin has not been tested, and the main Money Shoal Basin depocentre, where it thickens toward the Calder Graben of the Bonaparte Basin, is also under-explored.

4.2.2.1 Structural geology

The structural architecture of the Arafura Basin is dominated by the roughly northwest-trending and highly deformed Goulburn Graben (Figure 4.6 and Figure 4.9b; Bradshaw et al., 1990). This feature is over 350 km long and 70 km wide, and contains a sedimentary section in excess of 10 km thick. It is flanked to the north and east by the Northern Platform, which is characterised by large Neoproterozoic half graben that have undergone some later contractional and extensional deformation (Figure 4.8; Totterdell, 2006). The maximum thickness of the Northern Platform succession is approximately 15 km. To the south of the Goulburn Graben is a north-dipping relatively undeformed ramp. Most of the basin is overlain by an eastward-thinning Money Shoal Basin succession.

The subsidence history of the Arafura Basin has been episodic, with periods of basin-wide subsidence in the Neoproterozoic, mid-Cambrian–Early Ordovician, Late Devonian and late Carboniferous–early Permian, separated by long, relatively tectonically quiescent periods of non-deposition and erosion (Figure 4.7). Deposition in the Arafura Basin commenced in the Neoproterozoic during a period of upper crustal extension (Totterdell, 2006). Northwest–southeast-oriented extension resulted in the formation of northeast–southwest-trending half graben across much of the basin (Figure 4.8 and Figure 4.9). Subsequent periods of subsidence in the Cambro-Ordovician and Late Devonian do not appear to be fault-controlled, and are interpreted to have been driven by more regional-scale stresses, generated by plate-margin events or thermal processes. Subsidence in the late Carboniferous–early Permian was driven by northeast–southwest-directed extension, which was localised in the Goulburn Graben (Figure 4.9b; Totterdell, 2006). Seismic data suggest that this extensional deformation was focused along a northeast–southwest-oriented highly deformed zone within the Pine Creek Province. Prior to the Triassic, the basin underwent little deformation, and the entire Neoproterozoic to Permian succession appears to be structurally conformable.

During the Triassic, the Goulburn Graben underwent contractional, probably transpressional, deformation characterised by inversion on pre-existing faults, folding, and the formation of thin-skinned thrust faults; the resulting uplift led to the erosion of up to 2.0 km of Paleozoic section (Totterdell, 2006). This oblique inversion event is considered to be equivalent to the Middle–Late Triassic Fitzroy Movement (Forman & Wales, 1981), which affected the Canning Basin and adjacent regions, including the Bonaparte Basin (Colwell et al., 1996). The style of contractional deformation seen in the Arafura Basin is consistent with a north-northwest–south-southeast regional compression direction postulated in the Petrel Sub-basin of the Bonaparte Basin (O'Brien & Higgins, 1996). Deformation was largely focused on the Goulburn Graben, but the rest of the basin was affected to a lesser extent. Limited inversion took place on some Neoproterozoic extensional faults, and the eastern part of the Northern Platform was affected by folding (Figure 4.9a). In addition, the margins of the basin were uplifted, resulting in a basinward tilt. Subsequent erosion resulted in the formation of a peneplain across the basin and adjacent basement areas. Recent drilling in the Indonesian part of the basin has revealed that the northern margin of the basin experienced a large amount of uplift and erosion during the Triassic deformation, resulting in the Upper Ordovician section immediately underlying the Mesozoic unconformity east of Aru Island (Suklis et al., 2013).

The basal, Lower Jurassic, sediments of the Money Shoal Basin onlap the regional Mesozoic unconformity. The Money Shoal Basin represents the proximal edge of the thicker and more complete Mesozoic–Cenozoic succession present in the Bonaparte Basin and elsewhere on the North West Shelf. A period of Late Jurassic extension that resulted in the formation of the Malita and Calder graben to the west is reflected in the Money Shoal basin by minor reactivation of Goulburn Graben bounding faults. This faulting had a local influence on Late Jurassic–Early Cretaceous deposition. The small Jurassic faults underwent some compressional reactivation in the Neogene, resulting in the development of anticlinal features of varying scale (Struckmeyer, 2006c).

4.2.2.2 Basin evolution and depositional history

The oldest succession in the Arafura Basin is the Neoproterozoic Wessel Group (Figure 4.7), which outcrops onshore (Plumb & Roberts, 1992; Rawlings et al., 1997), and is present throughout the offshore part of the basin. Offshore, the fill of the basal half graben and the overlying post-rift succession are interpreted as belonging to the Wessel Group. Onshore, the group consists mainly of shallow marine sandstone and mudstone, with lesser conglomerate and carbonate rocks (Plumb & Roberts, 1992; Rawlings et al., 1997). The age of the Wessel Group is poorly constrained, but limited radiometric data and stratigraphic constraints suggest that it is Neoproterozoic (Rawlings et al., 1997).

The group reaches a maximum thickness of approximately 10 km in the central, offshore, part of the basin.

The Wessel Group is overlain disconformably by the mid-Cambrian–Lower Ordovician Goulburn Group (Figure 4.7; Bradshaw et al., 1990; Nicoll et al., 1996; Zhen et al., 2011). The Goulburn Group has a sag- to sheet-like geometry and reaches a maximum thickness of about 2500 m in the central Northern Platform. The Goulburn Group represents prolonged deposition on a shallow marine shelf. The basal unit is the early to middle Cambrian Jigaimara Formation (Nicoll et al., 1996; Zhen et al., 2011), a shallow marine limestone, shale and dolomite succession. It is overlain by the largely dolomitic ?mid-Cambrian–Lower Ordovician Naningbura Dolomite (Nicoll et al., 1996; Zhen et al., 2011). The Lower Ordovician marine shelf mixed carbonate and clastic rocks of the Milingimbi and Mooroongga formations form the uppermost units of the Goulburn Group.

The Upper Devonian Arafura Group (Petroconsultants, 1989; Bradshaw et al., 1990; McLennan et al., 1990) overlies the Goulburn Group (Figure 4.7). Although the Goulburn and Arafura groups are in general structurally conformable, some localised uplift and erosion is evident, for example, at the Torres 1 and Tasman 1 wells. The Arafura Group has a sheet-like geometry and reaches a maximum thickness of approximately 1500 m. It consists of shallow marine to non-marine interbedded mudstone, siltstone, sandstone and minor carbonate. The basal unit is the Frasnian Djabura Formation, a dominantly shallow marine succession of interbedded clastics and minor limestone. It is overlain unconformably by the interbedded clastics of the ?Frasnian–Famennian Yabooma Formation (Bradshaw et al., 1990), which is also interpreted to represent dominantly shallow marine deposition. The overlying Famennian Darbilla Formation is a mudstone and siltstone dominated succession interpreted to have been deposited in a largely non-marine environment (Petroconsultants, 1989; Bradshaw et al., 1990).

The Arafura Group is overlain unconformably by an upper Carboniferous–lower Permian succession that is approximately equivalent in age to the Kulshill Group of the Bonaparte Basin (Figure 4.7). The hiatus of about 45 m.y. between the Arafura Group and the Permo-Carboniferous succession correlates with the final phase of the Alice Springs Orogeny, but there is no evidence of any significant contractional deformation of the Arafura Basin at that time (Totterdell, 2006). Well intersections of the Kulshill Group consist of non-marine to marginal marine interbedded sandstone, siltstone and claystone, with minor coal and dolomitic rocks. On the Northern Platform, the Kulshill Group is up to 1500 m thick and is structurally conformable with the underlying rocks. The Group is thicker in the Goulburn Graben (up to 5000 m), where the lower part of the section comprises an extensional growth wedge (Totterdell, 2006). The upper part of the succession represents post-rift deposition.

The Money Shoal Basin unconformably overlies the Arafura Basin succession and comprises Jurassic to Cretaceous siliciclastic sediments and Cenozoic carbonates (Figure 4.7) that thin rapidly towards the east (Figure 4.9; Struckmeyer, 2006c). Deposition commenced in the Early to Middle Jurassic in fluvial channels aligned with the axis of the western Goulburn Graben. Coarse, mature sandstones of the Plover Formation are unconformably overlain by mostly fine-grained, quartzose, partly glauconitic sandstones, interbedded mudstones and minor coals of the Flamingo Group. Deposition was more widespread and occurred in fluvio-deltaic environments grading into near-shore marine environments by the Early Cretaceous. The Aptian to Maastrichtian Bathurst Island Group comprises marine and deltaic mudstones and marls with interbedded sandstones and was deposited across a progradational shallow marine shelf. This is unconformably overlain by mostly upper Neogene, shallow marine carbonates of the Woodbine Group.

4.2.2.3 Level of knowledge

The focus of exploration in the Arafura and Money Shoal basins has been the Goulburn Graben, where nine wells have been drilled (Figure 4.6). These wells provide good stratigraphic control for the Goulburn Graben and overlying Money Shoal section. However, the nature of deformation in the Goulburn Graben means that confident correlation across the northern bounding fault of the graben to the thick northern Arafura section is difficult. The correlation proposed by Struckmeyer (2006c) and Totterdell (2006) and used here is based on the comparison of seismic stratigraphy, seismic facies, structure and basin phases in the two regions.

Seismic coverage (2D data only) is variable, but is concentrated in the Goulburn Graben, particularly the western part of the graben. A complicating issue in the basin is the marked degradation of seismic quality in the northern Arafura Basin east of about 134°E (Figure 4.10), which prevents any confident or detailed interpretation of the geology of this area.

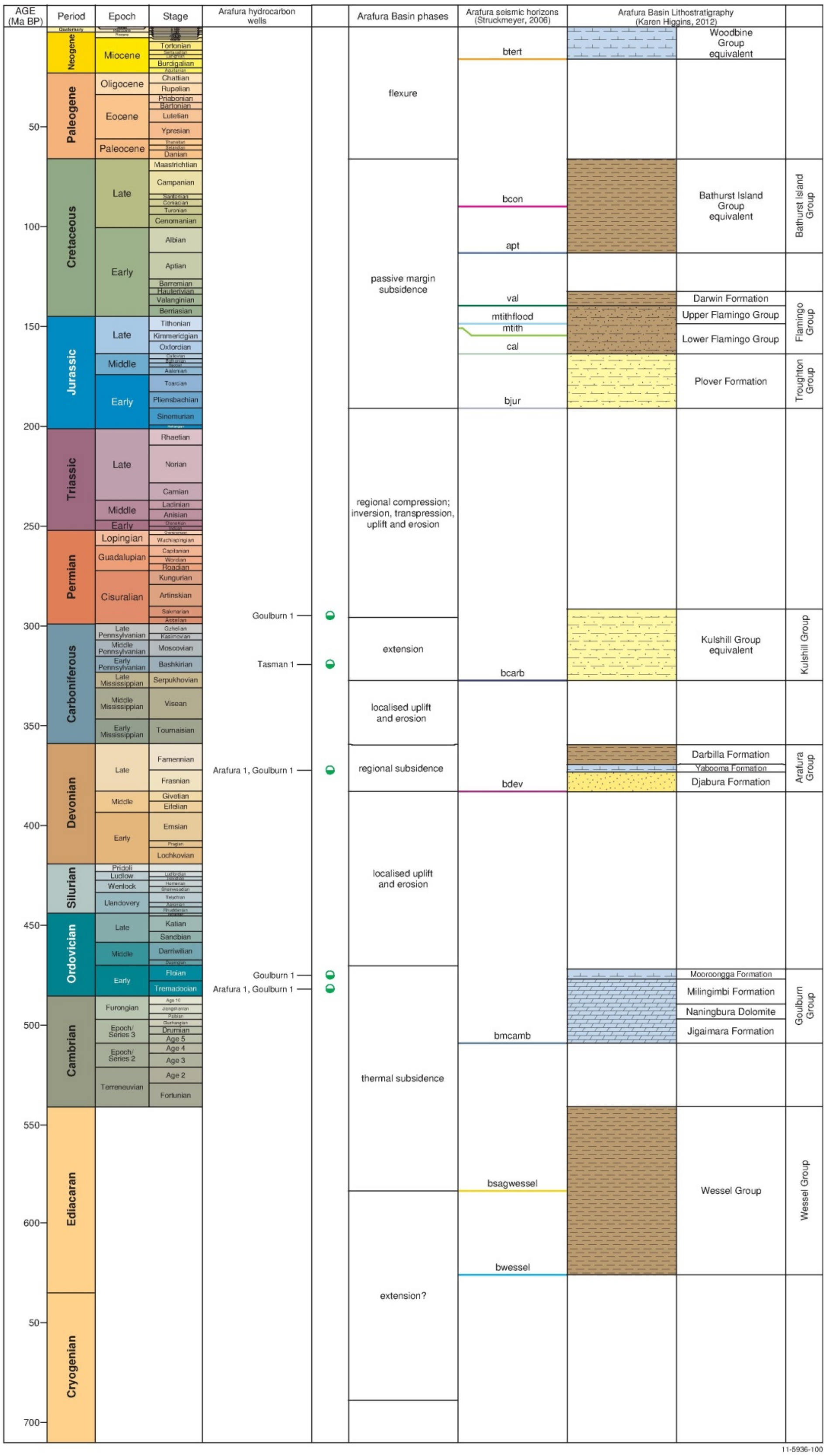

Figure 4.7: Stratigraphy of the Arafura and Money Shoal basins. Geologic time scale after Gradstein et al. (2012).

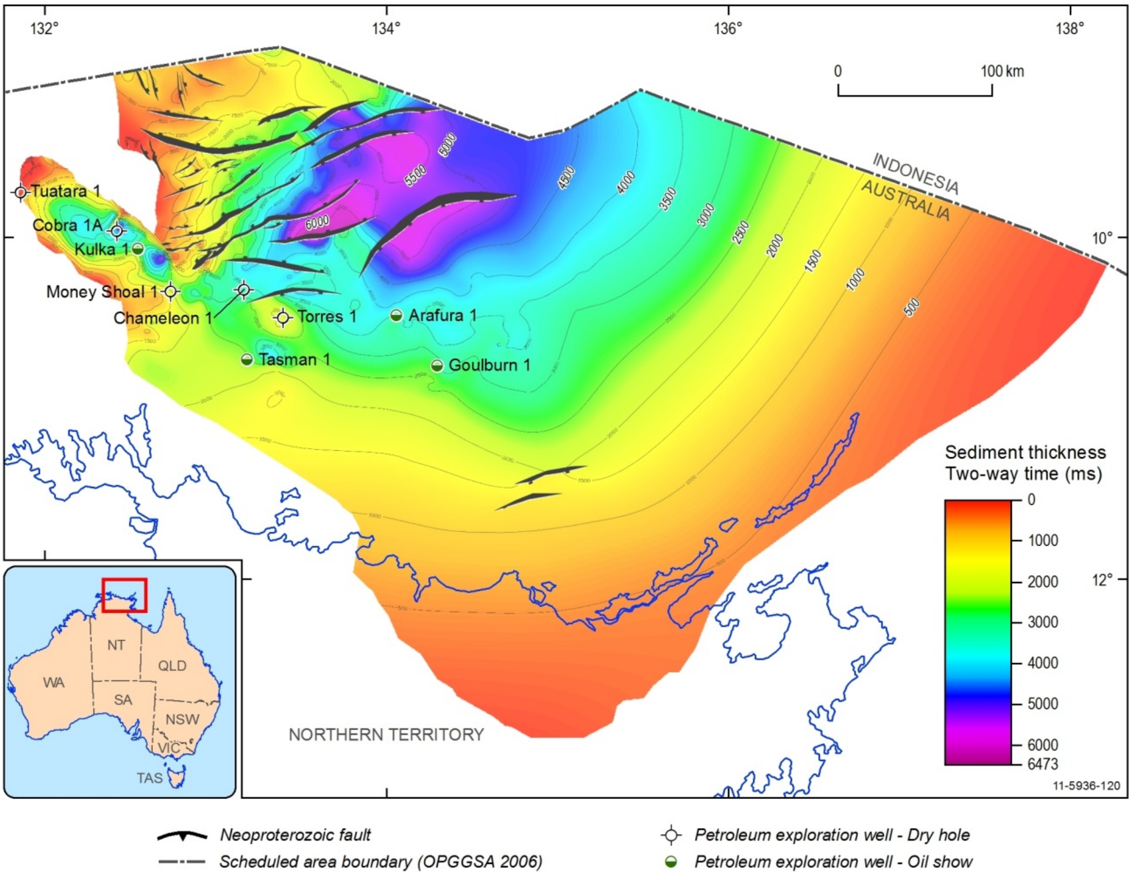

Figure 4.8: Total sediment thickness (s TWT), Arafura Basin (from Totterdell, 2006).

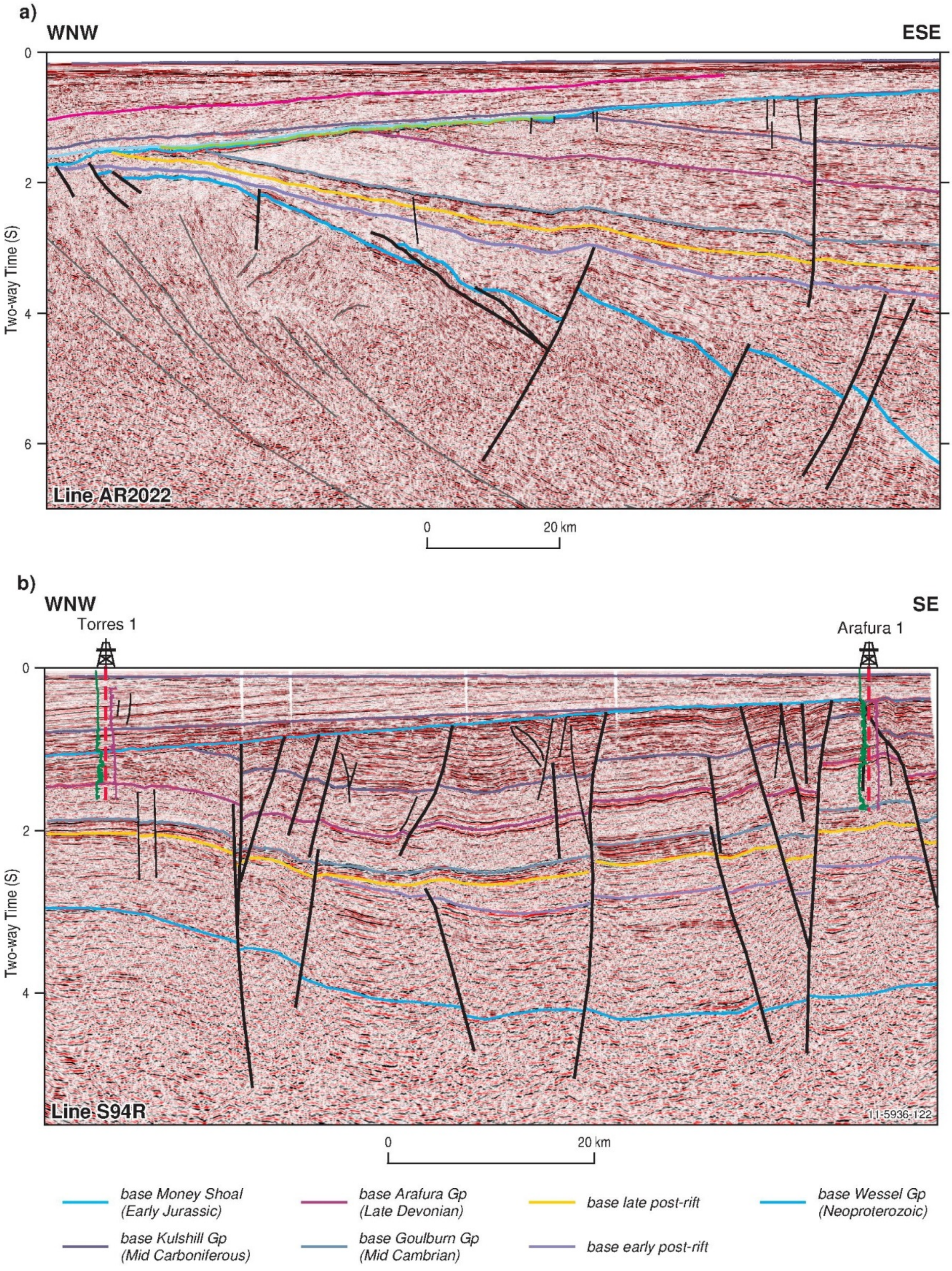

Figure 4.9: Seismic section across a) the western margin of the northern Arafura Basin and b) the Goulburn Graben (from Totterdell, 2006).

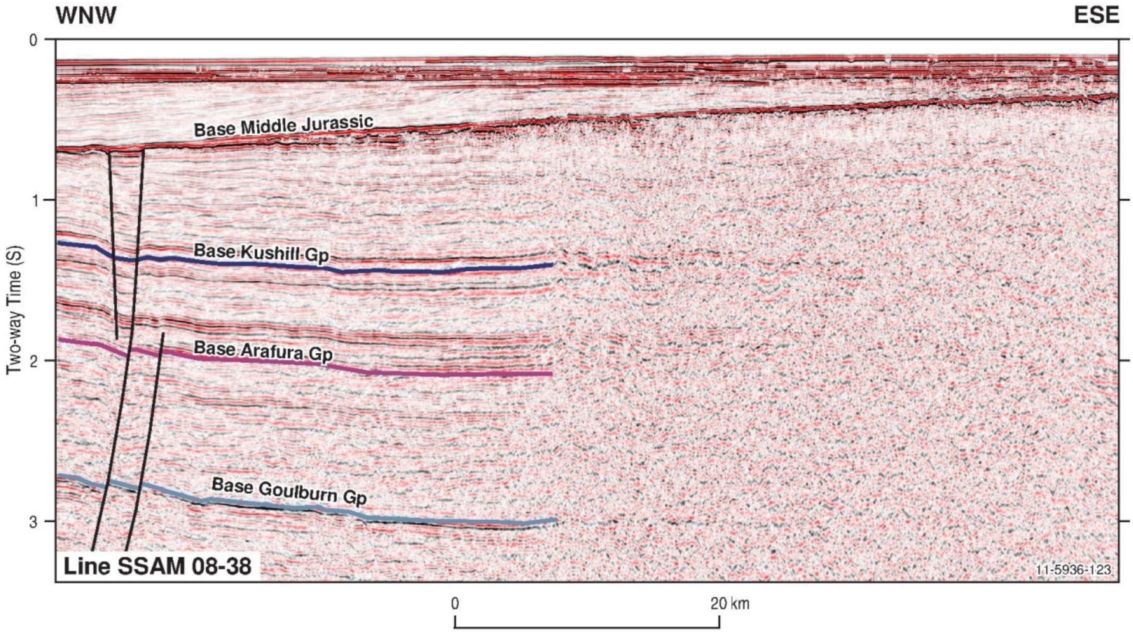

Figure 4.10: Seismic section illustrating the “bad data zone”, northern Arafura Basin.

4.2.3 Petroleum systems

No commercial discoveries have been made in the Arafura Basin, but there are numerous hydrocarbon indications in wells drilled in the Goulburn Graben (Figure 4.6). Oil and gas shows were encountered in Arafura 1 and an oil show in Goulburn 1. Chameleon 1, Cobra 1A, Kulka 1, Money Shoal 1, Tasman 1 and Tuatara 1 all contain oil indications in Mesozoic and Paleozoic reservoirs (Miyazaki & McNeil, 1998). These results, analysis of well and seismic data (Earl, 2006; Struckmeyer, 2006a, b), and indications of possible hydrocarbon seepage (Logan et al., 2006) all suggest that the Arafura and Money Shoal basins contain the necessary petroleum systems elements to generate, expel and trap hydrocarbons, and that generation and expulsion has occurred at least in the Goulburn Graben.

4.2.3.1 Source Rocks

In the Arafura Basin, potential source rocks occur within the Goulburn Group (Cambrian–Ordovician), the Arafura Group (Devonian) and the Kulshill Group equivalent (Carboniferous–Permian; Figure 4.7). Potential source rocks may be present within the Proterozoic Wessel Group, but no data are available for this section (Struckmeyer & Earl, 2006).

Samples from the Cambro-Ordovician succession, intersected in four wells, contain up to 8.6% TOC (Struckmeyer & Earl, 2006). The higher values represent migrated oil and solid bitumen (Keiraville Konsultants, 1984; Sherwood et al., 2006) rather than dispersed organic matter as reported in previous publications (Bradshaw et al., 1990, Edwards et al., 1997). Oil stains in lower Paleozoic rocks at Arafura 1 and Goulburn 1 have similar geochemical and isotopic characteristics to oils of algal/bacterial origin from lower mid-Cambrian Thorntonia Petroleum System in the Georgina Basin (Boreham & Ambrose, 2005; Boreham, 2006), which forms part of the Larapintine 1 Supersystem (Bradshaw, 1993). This suggests that the effective source rock in the Arafura Basin is likely to occur in the Jigaimara Formation, an approximate age equivalent of the Thorntonia Limestone. The presence of abundant interstitial bitumen in association with oil stains in lower Paleozoic samples is indicative of a multi-charge history from a prolific source nearby (Sherwood et al., 2006). Based on well data, the lower Paleozoic succession is typically mature to overmature for hydrocarbon generation.

Source potential for the Devonian fluvio-deltaic Arafura Group sediments is typically poor, however potentially fair source rocks are present within marine calcareous mudstones (Sherwood et al., 2006). Good to very good potential source rocks are also present in the Permo-Carboniferous Kulshill Group equivalent. The typical TOC range is <0.4 to 3%; however, several samples contain up to 9% TOC, comprising land plant-derived organic matter (Sherwood et al., 2006). The Kulshill Group is modelled to be immature to mature for oil generation, with maturity dependent on the thickness of the Money Shoal Basin overburden (Struckmeyer, 2006d; Struckmeyer & Earl, 2006).

The Jurassic section contains good to excellent potential source rocks and has a typical TOC range of 0.5–8% and HI values of up to 454 mg HC/g TOC. Several coaly intervals with TOC values up to 60% are also present, particularly in the Lower–Middle Jurassic Troughton Group equivalent. Sediments of this age (Plover Formation) provide the source rocks for gas/condensate accumulations in the nearby Malita Graben of the Bonaparte Basin (Preston & Edwards, 2000). Cretaceous potential source rocks contain up to 5% TOC, but are immature for hydrocarbon generation.

4.2.3.2 Generation and expulsion

Modelling by Struckmeyer (2006d) indicates that the major phase of hydrocarbon (light oil and gas) expulsion from the Cambrian source rock within the Goulburn Graben occurred in response to Devonian and Permo-Carboniferous subsidence. However, this expulsion pre-dates the Triassic structural event and potential trap formation, which probably resulted in the loss and/or degradation of the majority of these hydrocarbons. The mapped expulsion and preservation limit of hydrocarbons from the Cambrian source rock is shown in Figure 4.11.

Petroleum systems modelling by Struckmeyer (2006d) indicates that Arafura Group potential source rocks are mature in the Goulburn Graben and northern Arafura Basin, but that expulsion only occurred where these units were buried to about 4 km depth. In the western Goulburn Graben, Money Shoal Basin subsidence could have been sufficient to drive expulsion.

Based on vitrinite reflectance data from Kulka 1 (0.9–2.4% Ro), the Kulshill Group in the western Goulburn Graben is mature to overmature for oil generation and mature for gas generation due to loading by the Money Shoal Basin. Elsewhere in the Arafura Basin, the Kulshill Group is immature for hydrocarbon generation (Struckmeyer, 2006d). In the Arafura Basin region, the Jurassic section is mostly immature for oil generation; however, it reaches oil maturity in the westernmost Goulburn Graben.

4.2.3.3 Reservoirs and seals

Potential reservoir rocks in the Arafura Basin include shallow marine limestones and dolomites of the Cambro-Ordovician Goulburn Group, and terrestrial to fluvio-deltaic interbedded sandstones and mudstones of the Devonian Arafura Group and Permo-Carboniferous Kulshill Group equivalent (Struckmeyer & Earl, 2006). The Goulburn Group dolomite is an important potential reservoir in the region, hosting an oil and gas show in Arafura 1 and oil indications in Goulburn 1. The unit has a maximum porosity of 7.7%, but averages about 2% in intervals lacking significant secondary porosity; permeability values are also generally low. Reservoir quality in this unit relies on the development of secondary porosity through features such as vugs and fractures. A risk associated with this unit is reduction of secondary porosity by cementation. The cementation is probably at least partly related to Triassic contraction and uplift. The reduced impact of this event in the northern Arafura suggests that this may be a less important risk in this area compared with the Goulburn Graben (Struckmeyer & Earl, 2006).

Siltstones and sandstones of the Arafura Group form another important reservoir in the basin, hosting oil shows at both Arafura 1 and Goulburn 1. The unit has a maximum porosity of 19% and permeability of 7.83 mD in Goulburn 1, but averages 9.6% porosity with a large standard deviation (Struckmeyer & Earl, 2006). A significant proportion of the primary porosity has been destroyed by diagenetic effects, including silica overgrowths and carbonate cementation. As in the Goulburn Group, this is likely to be of less importance in the northern Arafura Basin.

The Kulshill Group equivalent has variable reservoir quality. Porosity averages 5.5%, although the upper parts of this unit generally have better porosity with a maximum of 17.7% at Tasman 1. Carbonate cements are sporadic throughout the unit but there is evidence of multiple fracture sets (such as at Chameleon 1), which could enhance the overall permeability and porosity (Struckmeyer & Earl, 2006).

There is little information about potential Paleozoic seals; however, oil shows/indications below thick Devonian fine-grained sediments at Arafura 1 and Goulburn 1 attest to the sealing capacity of this unit (Petroconsultants, 1989). It is likely that this section is a regional seal, at least in the central and eastern Arafura Basin. Oil indications above this seal in Arafura 1 are considered to be the result of migration along faults (Labutis et al., 1992; Earl, 2006). Mudstones at the top and base of the Cambro-Ordovician Goulburn Group may also provide a seal for adjacent carbonate reservoirs, and Permo-Carboniferous dolerite sills such as that intersected in Kulka 1, may provide local seals.

Mesozoic reservoirs are important in the adjoining Bonaparte Basin, where they host a number of commercial hydrocarbon accumulations (Barrett et al., 2004; Cadman & Temple, 2004). The Money Shoal Basin also contains high quality reservoirs within the Troughton Group equivalent (Jurassic), the Flamingo Group (Jurassic to Lower Cretaceous) and the Darwin Formation equivalent (Cretaceous). Money Shoal Basin reservoirs are well positioned to receive any late hydrocarbon charge from underlying potential Paleozoic source rocks. Sandstones of the Jurassic Troughton Group equivalent have average porosities of 8.5% with a maximum of 27% in Tasman 1. Blocky fluvio-deltaic sands of the Flamingo Group have an average porosity of 18.5%, with a maximum of 32% in Tasman 1. There is some dolomite cementation in these rocks, but the unit also contains fractures that may help facilitate fluid movement. Where it is sandstone-rich, the Darwin Formation equivalent (e.g. at Kulka 1) has excellent porosity, with an average of 25%.

Mudstones of the Bathurst Island Formation, which provide a regional seal in the Malita Graben of the Bonaparte Basin, are also present in the release areas. The unit is thick and laterally extensive, and typically overlies high quality Mesozoic reservoirs. In the eastern part of the Money Shoal Basin, the unit directly overlies Paleozoic sediments (Struckmeyer & Earl, 2006). Fault breach is unlikely due to the thickness of the unit. Potential intraformational seals are also present within the Jurassic to Lower Cretaceous section.

4.2.3.4 Play types

Interpretation of seismic data indicates that a large variety of potential play types are present in the Arafura and Money Shoal basins (Struckmeyer, 2006e). Exploration in the Goulburn Graben has focused on a range of fault-related traps within the deformed Paleozoic section and the overlying Money Shoal succession. Paleozoic plays in the northern Arafura region include large faulted anticlines and fault blocks that could provide traps at several stratigraphic levels. Sub-unconformity plays below the Triassic regional unconformity are present within Neoproterozoic, Cambrian–Ordovician, Devonian and Carboniferous–Permian strata. These plays occur at increasingly shallow depths towards the northeast, thus reducing the risk of reservoir destruction by cementation. Diagenetic traps and other stratigraphic traps within the Cambrian–Ordovician and Devonian carbonate successions are a strong possibility in this region, but are untested and insufficient stratigraphic information is available to allow a detailed assessment.

The overlying Mesozoic Money Shoal Basin section offers a variety of stratigraphic and combined structural/stratigraphic plays for hydrocarbons sourced from underlying Paleozoic sediments and from mature late Paleozoic and Mesozoic source kitchens in the westernmost part of the basin (Struckmeyer, 2006e). Onlap plays associated with the Triassic unconformity occur within increasingly younger strata to the east. Potential targets include Middle Jurassic fluvial sandstones and/or Upper Jurassic to Lower Cretaceous fluvio-deltaic clastics in lowstand, transgressive and highstand settings. Plays associated with these deposits also include drape closure over Triassic topography, fluvial channel plays, lowstand wedge plays and fault block plays. Stratigraphic/structural traps within channel fills and associated erosional features associated with a Tithonian channel system that runs along the major bounding faults of the Goulburn Graben. Although explored by BHP in the 1990s (BHP Petroleum, 1993; Miyazaki & McNeil, 1998; Barber et al., 2004), the feature still provides numerous untested plays. The mid- to Upper Cretaceous prograding shelf and contiguous slope and basin deposits provide numerous potential plays, particularly within lowstand wedge deposits such as slope fans, channel–levee systems and basin floor fans (Struckmeyer, 2006e).

4.2.3.5 Critical risks

Timing of hydrocarbon charge, breach of structure and reservoir quality have been identified as the major reasons for the failure of wells in the Goulburn Graben (Earl, 2006). Thus, reservoir quality of Paleozoic rocks and the timing of generation, expulsion and trap formation in relation to the major structuring event in the Triassic are regarded as the key exploration risks in the Arafura Basin. The Triassic contraction, uplift and erosion would have been a major cause for trap breach and loss of hydrocarbons that were generated prior to this event, as well as reservoir destruction associated with hydrothermal alteration. Deformation was focused on the Goulburn Graben, the location of all exploration wells in the basin. The event was much less significant in the northern Arafura Basin (Totterdell, 2006), so loss of reservoir quality due to hydrothermal alteration is likely to be less of a risk in this area. Away from the main northern Arafura depocentre and the Goulburn Graben, reduced depth of burial of potential Paleozoic reservoirs and comparatively low levels of erosion during the Triassic, may reduce the risk of cementation and loss of porosity.

The timing of generation and expulsion probably poses less of an exploration risk in the northern Arafura than in the Goulburn Graben. A geohistory study by Geoscience Australia of all exploration wells in the Goulburn Graben and six sites in the northern Arafura Basin (Struckmeyer, 2006a, d) shows that expulsion from a potential Cambro-Ordovician source rock occurred largely prior to the Triassic event. It is likely that in the northern Arafura region, a significant proportion of these early expelled light hydrocarbons are preserved and have thus preserved the primary porosity, particularly in areas where the Triassic event had negligible effects (Figure 4.11). The modelling suggests that, in places, significant expulsion from the Goulburn Group source rock also occurred in the Late Cretaceous to Cenozoic, in both the Goulburn Graben and Northern Platform regions. Permian source rocks are mature in the westernmost basin and geohistory modelling suggests expulsion from the Permian to have occurred from the Late Cretaceous to Holocene.

Direct evidence that hydrocarbon generation and expulsion has occurred in the Arafura Basin is provided by oil shows/indications and gas indications in the majority of wells drilled, and the presence of interstitial solid bitumen in many samples (Sherwood et al., 2006). More indirect evidence is provided by Synthetic Aperture Radar (SAR) data which revealed a number of anomalies across the northeastern part of the Northern Platform (Infoterra 2003). Seismic data show bright amplitudes at various stratigraphic levels and these may indicate hydrocarbons in the section. In addition, sub-bottom profiles, side-scan sonar and echosounder data collected by Geoscience Australia in the northern Arafura Basin have revealed features consistent with the presence of shallow gas (Logan et al., 2006; Rollet et al., 2009)

4.2.3.6 Overall prospectivity classification

Medium–high

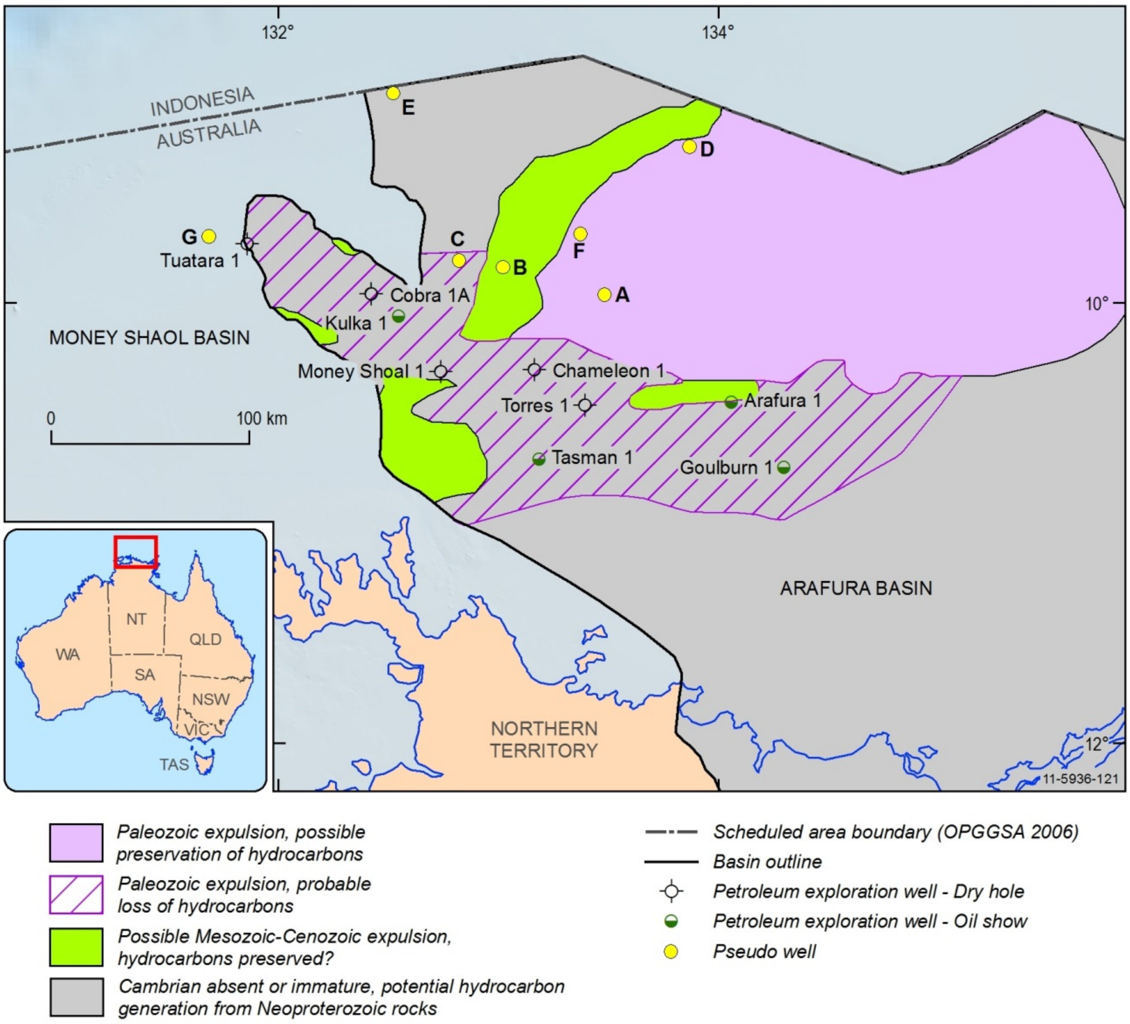

Figure 4.11: Interpreted hydrocarbon expulsion and preservation from postulated Cambrian source rock, Arafura Basin (from Struckmeyer, 2006d)

4.2.4 Exploration status

Petroleum exploration in the Arafura region (Figure 4.12) began in the 1920s when several boreholes were drilled on Elcho Island in response to reported bitumen strandings. In the 1960s and early 1970s, Shell Development (Australia) and Aquitaine commenced exploration programs in the offshore basin, carrying out extensive seismic acquisition and mapping and defining the Goulburn Graben as an important structural feature. During this period, Shell drilled the Money Shoal 1 well.

The next phase of exploration occurred in the early 1980s, with several companies operating in the region, including Diamond Shamrock, Esso, Petrofina and Sion Resources. A number of wells were drilled at this time, all of which tested the Paleozoic Arafura Basin sequence. Petrofina drilled Arafura 1 (1983) and Goulburn 1 (1985), both of which recorded hydrocarbon shows. Esso drilled two wells, Tasman 1 (1983) and Torres 1 (1983), and Diamond Shamrock drilled Kulka 1 (1984).

A third phase of petroleum exploration by BHP Petroleum in the late 1980s and early 1990s targeted mostly Mesozoic plays in the Goulburn Graben. The exploration program included an extensive 17,000 km seismic survey, a regional aeromagnetic survey, and the drilling of three exploration wells, Tuatara 1 (1990), Chameleon 1 (1991) and Cobra 1A (1993). During the early 1990s the Bureau of Mineral Resources (now Geoscience Australia) acquired a total of 5342 km of regional deep seismic data across the Arafura Basin.

In the most recent phase of exploration, Samson International acquired 3600 km of 2D seismic data across their northern Arafura permits prior to relinquishing them in 2010.

Exploration areas in the Arafura and Money Shoal basins were released in 2011 and 2012. One area in the Money Shoal Basin was granted as permit NT/P83 to Tangiers Petroleum Ltd in September 2012 with a guaranteed work program including 2D and 3D seismic acquisition. However this permit was cancelled in late 2013 for failure to meet work program commitments (ComLaw, 2013).

During the last decade, there has also been considerable exploration in the Indonesian part of the Arafura Basin. ConocoPhillips has held permits in the region since 2004, and in 2011, with partners Total and OPIC, drilled two wells (Suklis et al., 2013). The wells reached total depth within a thick Upper Ordovician section. In the northern well, the Ordovician section was intersected immediately underlying the Mesozoic (Money Shoal) succession. The southern of the two wells intersected a thin Kulshill Group beneath the unconformity; Devonian strata were missing in both wells. These drilling results indicate that the northern margin of the basins experienced significant uplift and erosion prior to the Jurassic. Despite this, Wendebourg et al. (2013) reported that the intersected Ordovician succession was overpressured.

4.2.5 Data

Key data sets for the Arafura and Money Shoal basins are listed in Table 4.5–Table 4.8. During the various exploration phases in the basins, seismic data acquisition has focused on the Goulburn Graben and adjacent areas. Exploration in the area has been supported by the acquisition of non-exclusive regional 2D seismic data sets by TGS Nopec in 1998 and Veritas DGC (Arafura 2002 2D MSS) in 2002, and Synthetic Aperture Radar acquisition and interpretation across the region by Infoterra (2003). More recently PGS acquired the GeoStreamer Northern Margin Australia–Arafura Multiclient 2D (NMAA-10) survey, and ION-GXT acquired the ArafuraSPAN deep seismic data set (Granath et al., 2011).

Seismic data quality varies markedly across the region. In particular, data quality deteriorates dramatically east of 134°E (Figure 4.10). This quality issue manifests as a reduction, and in some cases almost complete lack, of seismic penetration. This appears to be related largely to the nature of the Triassic unconformity, but may also be influenced by sea bottom conditions. Seismic data shows a correlation between an increase in the roughness of the unconformity/reflector and deterioration in data quality. Tests undertaken by Fugro for Samson showed that data quality could be improved to a small degree by changes in acquisition parameters such as streamer and gun depth (L. Jones, Geoscience Australia, pers. comm., March 2013).

Aeromagnetic data coverage is poor and is concentrated on the western Goulburn Graben region.

4.2.5.1 Confidence rating

Medium–low

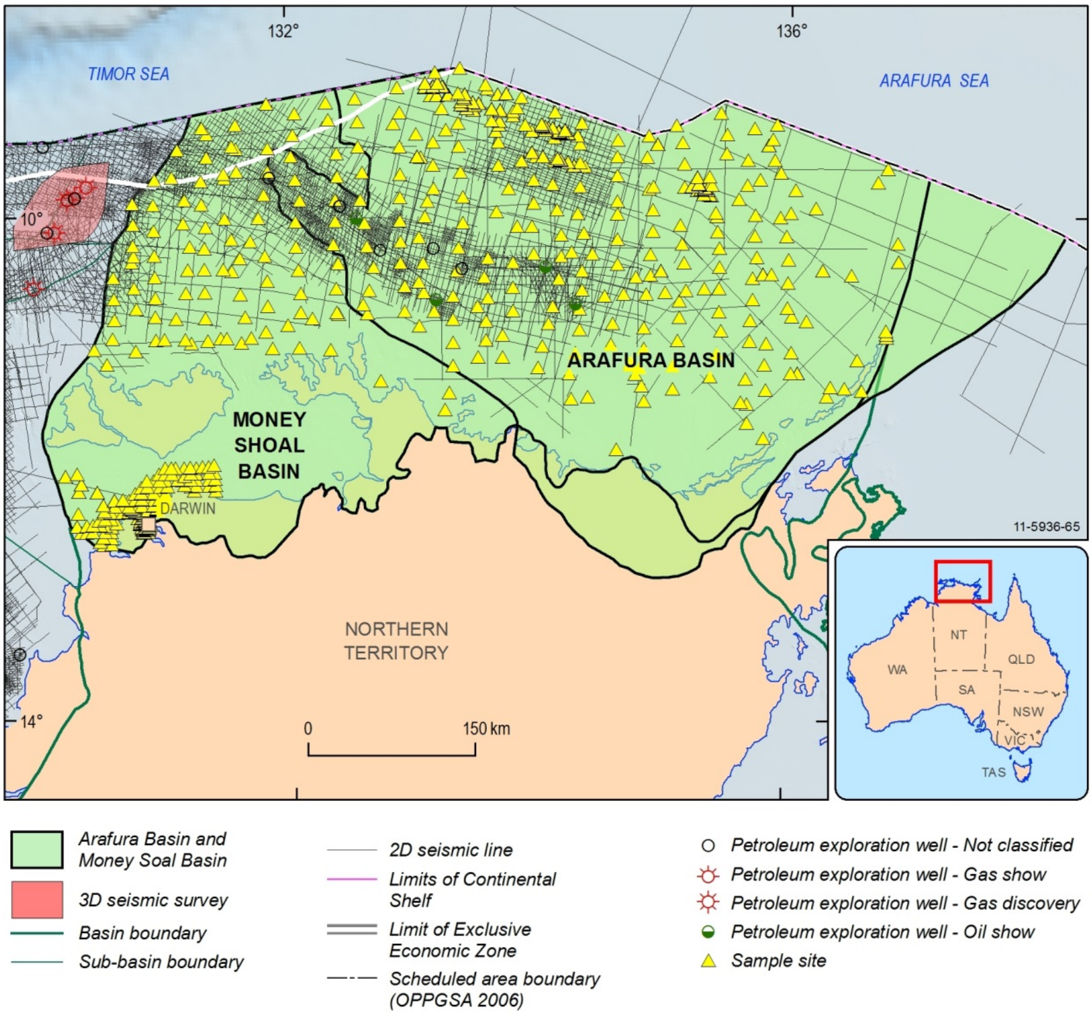

Figure 4.12: Seismic, well and sample distribution.

4.2.6 Issues and remaining questions

The key exploration issues concerning the Arafura and Money Shoal basins can be placed in two categories—prospectivity and data.

The prospectivity issues mainly concern those factors identified above as exploration risks—reservoir quality of Paleozoic rocks and the timing of generation, expulsion and trap formation in relation to the major structuring event in the Triassic. There is some understanding of these issues in the Goulburn Graben, where despite the encouragement of hydrocarbon shows or indications in most wells, exploration there has been unsuccessful. Successful exploration in the Goulburn Graben may depend on identifying plays based on late charge into Permian or Mesozoic reservoirs.

In the undrilled northern Arafura Basin, our understanding of these issues is limited and depends on seismic interpretations based on unproven correlations to wells in the Goulburn Graben. While the diminished impact of Triassic deformation in this area suggests that both reservoir degradation and timing issues may be less critical in the northern Arafura Basin, preservation of Cambro-Ordovician sourced accumulations since the Permian is still a concern. Another issue related to source is that the source potential of younger sequences in the northern Arafura is not well understood. Data from the Goulburn Graben wells suggests the source potential of the Devonian section is limited, and modelling indicates that, even if good potential source rocks are present in the Kulshill Group, much of this section is either immature or only marginally mature. In addition, the Arafura Basin lacks the Carboniferous section that hosts rich source rocks in the neighbouring Bonaparte Basin. Until this part of the basin is drilled, uncertainties about the prospectivity of the area will remain.

The likelihood of attracting exploration into this area is hampered by the severe seismic data quality issues (Figure 4.10) mentioned previously. Until the basin fill can be properly imaged, any assessment of its prospectivity is severely limited.

4.2.6.1 Recommendations

- In the long term, drilling of the northern Arafura Basin succession is required to test the prospectivity of the region.
- In the short term, the issue of poor seismic data in the northern Arafura Basin (and the likelihood of exploration drilling) could be addressed by studies that focus on the geological causes of the data problem, followed by the trialling of a range of seismic acquisition techniques and parameters to determine if seismic data acquisition can be improved.
- Acquisition of aeromagnetic data across the basin, with a line spacing not exceeding 800 m, would also assist in improving our understanding of the structure of the basin and depth to basement.
- Insights into the source rock potential of the Carboniferous–Permian Kulshill Group could be gained from a regional palaeogeographic study using data from the adjacent Bonaparte Basin and incorporating the results of uplift and exhumation, and provenance studies.
- Understanding of the stratigraphy and subsidence history could be assisted by improving age control (isotopic and biostratigraphic) of the onshore Wessel Group.

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4.2.8 Data Tables

Table 4.5: List of wells, Arafura and Money Shoal basins.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1983	Arafura 1	Exploration	Petrofina Exploration	3635	Neoproterozoic	Gas flowed on test, oil shows	Petrofina Exploration Australia S.A., 1983
1991	Chameleon 1	Exploration	BHP Petroleum	2179	Permian	Oil indication	BHP Petroleum, 1992
1993	Cobra 1	Exploration	BHP Petroleum	409	Cenozoic		BHP Petroleum, 1993
1993	Cobra 1A	Exploration	BHP Petroleum	2542	Jurassic	Oil indication	BHP Petroleum, 1993
1986	Goulburn 1	Exploration	Petrofina Exploration	1300	Cambrian	Oil recovered	Petrofina Exploration Australia S.A., 1986
1984	Kulka 1	Exploration	Diamond Shamrock Oil Co (Aust)	3998	Carboniferous	Oil indication	Diamond Shamrock Oil Company (Australia) Pty Ltd, 1985
1971	Money Shoal 1	Exploration	Shell Dev (Aust) P/L	2590	Permian	Oil indication	Shell, 1971
1983	Tasman 1	Exploration	Esso Exploration and Prod Aust Ltd	2720	Cambrian	Oil indication	Esso Australia Ltd, 1983a
1983	Torres 1	Exploration	Esso Exploration and Prod Aust Ltd	2758	Cambrian	No shows	Esso Australia Limited, 1983b
1990	Tuatara 1	Exploration	BHP Petroleum	3875	Jurassic	Oil indication	BHP Petroleum, 1991

Table 4.6: Key seismic surveys, Arafura and Money Shoal basins.

Year	Survey	Operator	Line-km	Reference
1988	HA88A	BHP Petroleum	3759	
1989	HA89A	BHP Petroleum	1495	
1990	HA90A	BHP Petroleum	1154	
1990	Survey 94, Arafura Sea 1	AGSO	2250	
1991	HA91A	BHP Petroleum	1743	
1991	Survey 106, East Arafura	AGSO	3240	

Year	Survey	Operator	Line-km	Reference
1993	Survey 118, Malita Graben	AGSO	4602	
2001	Money Shoals - NT/P58 NT/P59 NT/P60 Seismic Survey	Nexen Petroleum Australia Pty Ltd	3709	
2002	Arafura 2002 2D MSS	Veritas DGC Australia Pty Ltd	3218	
2007	ArafuraSPAN	Ion-GX Technology Corporation		
2008	Samson (Arafura 2D) Marine Seismic Survey	Samson International (Australia) Pty Ltd	3939	
2009	Northern Margin Australia Arafura Multiclient 2D (NMAA 9 MC2D)	Petroleum Geo-Services Asia Pacific Pty Ltd		
	Deep Water Northwest Shelf MC2D (New Dawn) PhII	Petroleum Geo-Services Asia Pacific Pty Ltd		

Table 4.7: Key geological sampling surveys, Arafura and Money Shoal basins.

Year	Survey	Operator	Region	Type	Rock types	Reference
1969	BMR Arafura Sea survey	BMR	Arafura Sea	Gravity cores, dredges	Seabed samples	Jongsma, 1974
2005	GA Marine Survey 282	Geoscience Australia	Arafura Sea	Swath bathymetry, sub-bottom profiler, side-scan sonar, gravity cores, grabs, dredges, water samples	Seabed samples	Logan et al., 2006

Table 4.8: Swath bathymetry surveys, Arafura and Money Shoal basins

Year	Survey	Operator	Line-km/Area (km^2)	Reference
2005	GA Marine Survey 282	Geoscience Australia		Logan et al., 2006

4.3 Barcoo Sub-basin (Browse Basin)

4.3.1 Summary

State(s)		Western Australia
Area (km^2)		~31,600
Water Depth (m)		~50–1800
Maximum sediment thickness (m)		~12,000
Age range		Carboniferous–Holocene
Basin	**Overlies**	Continental basement
	Parent	Browse Basin
	Adjacent basins	Scott Plateau, Seringapatam Sub-basin, Caswell Sub-basin, Leveque Shelf, Roebuck Basin (Rowley Sub-basin), offshore Canning Basin (Oobagooma Sub-basin)
Basin type		Extensional, passive margin
Depositional setting, rock types		Marine and non-marine clastic sedimentary rocks and marine carbonates.
Petroleum prospectivity		Moderate–high
Confidence		*High*

4.3.2 Geology

The Browse Basin is located in the southern Timor Sea region of Australia's North West Shelf (Figure 4.13). The two main depocentres of the Browse Basin are the Caswell and Barcoo sub-basins (Hocking et al., 1994). The Caswell Sub-basin contains a Paleozoic to Cenozoic succession in excess of 15,000 m thick, whereas the maximum sediment thickness in the Barcoo Sub-basin probably does not exceed 12,000 m (Struckmeyer et al., 1998). The Barcoo Sub-basin is separated from the Caswell Sub-basin by a major north to north-northeast trending structural zone, the Buffon–Scott Reef–Brecknock Anticlinal Trend (Figure 4.13; Struckmeyer et al., 1998). The sub-basin adjoins the Leveque Shelf to the southeast across a hinge zone that separates basinward dipping strata from a relatively flat-lying succession. The Seringapatam Sub-basin adjoins the Barcoo Sub-basin to the north and the deepwater Scott Plateau to the northwest (Hocking et al., 1994; Struckmeyer et al., 1998). To the south, the Barcoo Sub-basin adjoins the Rowley Sub-basin (Roebuck Basin) and the Oobagooma Sub-basin (offshore Canning Sub-basin).

The sub-basin comprises a structured upper Paleozoic to Jurassic section, overlain by a progradational post-breakup succession of Jurassic–Cenozoic clastic and carbonate rocks (Figure 4.14 and Figure 4.15). The Barcoo Sub-basin contains a thicker Triassic to Middle Jurassic succession and a thinner overlying wedge of Lower Jurassic to Cenozoic sediment than the Caswell Sub-basin (Blevin et al., 1998a; Struckmeyer et al., 1998). Breakup in the Callovian was accompanied by volcanism and the intrusion of sills and dykes. Igneous rocks become more widespread and conspicuous further basinward.

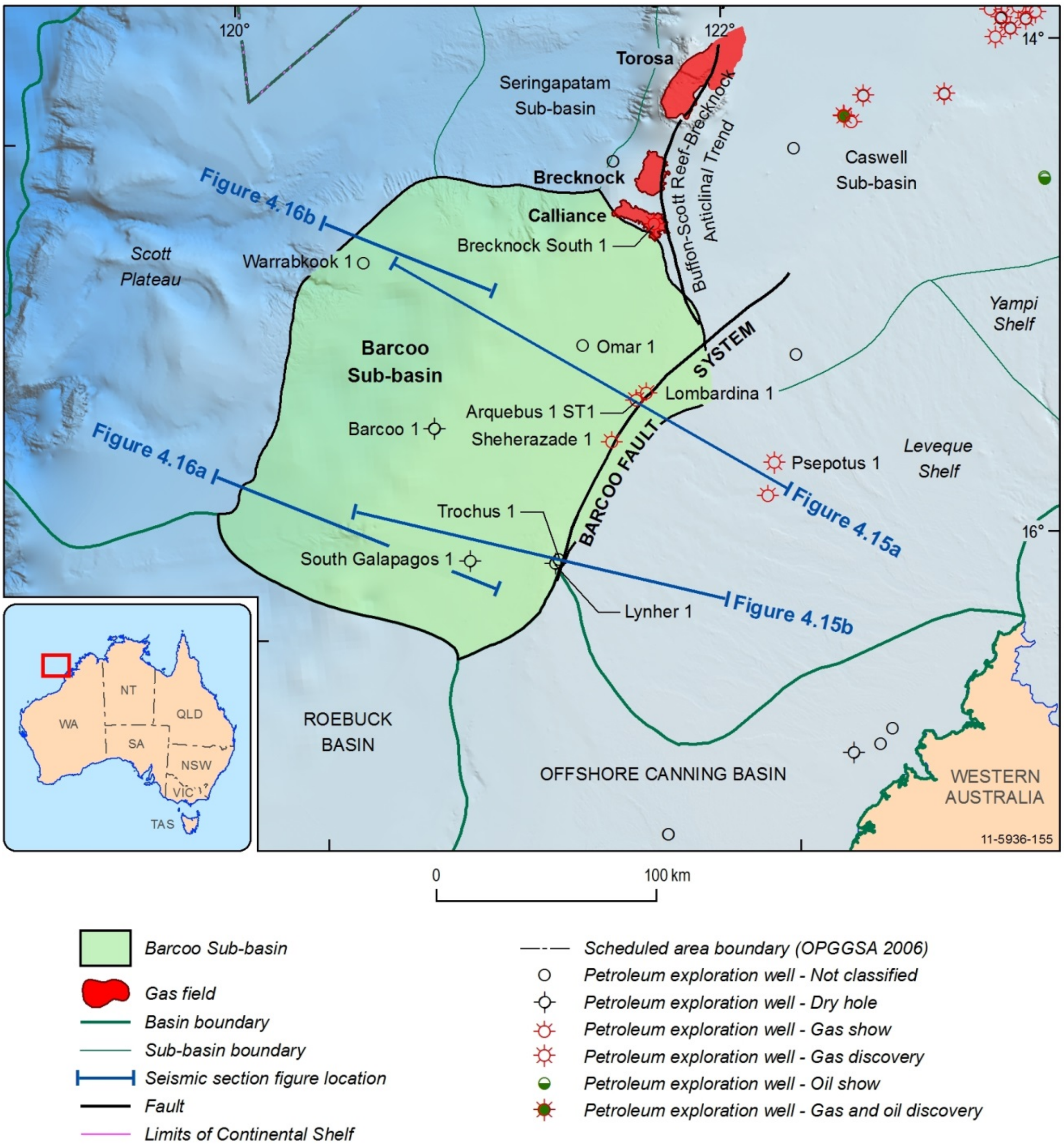

Figure 4.13: Structural elements map, Barcoo Sub-basin.

The adjacent Caswell Sub-basin is a proven hydrocarbon province. Several giant gas and condensate discoveries/fields, including the Calliance, Brecknock and Torosa fields, are located along the anticlinal trend that separates the Barcoo and Caswell sub-basins (Figure 4.13). Hydrocarbons are yet to be discovered in the Barcoo Sub-basin, but several wells have had gas shows (Figure 4.13). Although the Barcoo Sub-basin remains an exploration frontier, those hydrocarbon shows, nearby discoveries and the presence of a thick Mesozoic section beneath a prograding Jurassic–Cenozoic wedge provide encouragement for the moderate–high prospectivity assessment of the sub-basin.

4.3.2.1 Structural geology

The Browse Basin was initiated in the Carboniferous–early Permian in response to north-northwest-oriented extension, and forms part of the Westralian Superbasin (Struckmeyer et al., 1998; Symonds et al., 1994). Extension was accommodated along large-scale, northeast-striking normal faults.

Struckmeyer et al. (1998) suggested that the compartmentalisation of the basin into the Caswell and Barcoo depocentres is a consequence of the architecture established during this phase of basin development. A second, or continued, phase of extension in the late Permian–Early Triassic affected the southern and eastern parts of the Barcoo Sub-basin. This part of the sub-basin is characterised by a series of northeast-striking extensional faults that dip to the southeast (Figure 4.16a; Keep & Moss, 2000). Lower–Middle Triassic and older strata thicken into the bounding faults, providing a constraint on the timing of extension.

The late Paleozoic–Triassic extensional faults controlled the location of subsequent structuring. Contractional reactivation of some faults in the Late Triassic–Early Jurassic led to partial inversion of half graben, the formation of large anticlinal and synclinal structures. Anticline crests were subsequently eroded. The northeast-oriented Barcoo Trend was initiated at this time. Further east, the Obi High comprises the highly rotated and uplifted hanging wall block of a Permo-Triassic half graben (Keep & Moss, 2000). The Triassic inversion event has been correlated with the Fitzroy Movement observed in the Canning Basin (Forman & Wales, 1978; AGSO Browse Basin Project Team, 1997; Struckmeyer et al., 1998).

Extension in the Early–Middle Jurassic was accompanied by reactivation of Paleozoic–Triassic faults and widespread, but small-scale faulting, which in places led to the collapse of Triassic anticlines (Struckmeyer et al., 1998; Jason et al., 2006). In the Barcoo Sub-basin, faulting was focused along the eastern margin of the sub-basin (Keep & Moss, 2000).

In the outer Barcoo Sub-basin, large southeast-dipping extensional faults bound a thick growth section. The upper part of this growth section comprises a set of divergent, high amplitude reflections caused by volcanic rocks that thins to the east (Figure 4.16b); this volcanic section was penetrated at Warrabkook 1 (Figure 4.13; Ellis, 2008). Symonds et al. (1998) interpret the wedge of strata as a set of subaerial landward flows. Breakup and the initiation of seafloor spreading in the Argo Abyssal Plain occurred in the Callovian and were accompanied by volcanism and igneous intrusions, widespread erosion and the formation of a peneplain.

During the Late Jurassic–Paleogene period of passive margin subsidence, the basin underwent only minor structural reactivation. In the Miocene, however, convergence of the Australian and Eurasian plates led to inversion on major Paleozoic faults (Struckmeyer et al., 1998; Keep & Moss, 2000). In the Barcoo Sub-basin, inversion on the Barcoo Fault System along the Leveque Shelf margin (Keep et al., 2000) caused the formation of tight, northeast-trending anticlines (Figure 4.15a and Figure 4.15b). Deformation appears to have continued almost to the present-day in the southern part of the sub-basin (Figure 4.15b; Struckmeyer et al., 1998).

4.3.2.2 Basin evolution and depositional history

Limited well data suggests that deposition in the Browse Basin during the initial late Carboniferous–early Permian rift phase was generally fluvio-deltaic in nature. During the early Permian–Triassic, deposition took place under dominantly marine conditions and the succession includes transgressive sandstones, limestones and finer grained, deeper water shales and siltstone (Blevin et al., 1998a). The onset of Late Triassic inversion was marked by the formation of a northeast-trending, folded topography across the basin. Syn-inversion deposition occurred in the synclines and erosion affected the crests of the anticlines (Blevin et al., 1998a; Struckmeyer et al., 1998). An upper Norian transgressive sequence overlying the inversion-related unconformity in the outer Browse Basin is the oldest succession intersected by drilling in the Barcoo Sub-basin (in Barcoo 1; Figure 4.13). Inundation of the basin resulted in the deposition of onlapping shallow marine limestone, shelfal sandstone and siltstone. The latest Triassic highstand, penetrated at Barcoo 1, thickens toward the east in the central Barcoo Sub-basin and is predicted to contain seal and source facies (AGSO Browse Basin Project Team, 1997).

Deposition during the Early to Middle Jurassic extensional phase was dominated by fluvio-deltaic systems which extended across most of the basin. Stacked sequences of channel sands and/or coarsening upward prograding deltaic sands, interbedded with finer-grained beds of prodelta to delta plain siltstone and shale (Plover Formation; Figure 4.14) were deposited. The Barcoo Sub-basin contains a westward thickening Plover Formation succession (Jason et al., 2006); accommodation appears to have been controlled by large extensional faults. Barcoo 1 intersected a relatively complete Upper Triassic to Callovian section, which suggests that the outer Barcoo Sub-basin was a locus of subsidence during this time (Blevin et al., 1998a). Reorientation of drainage divides along tectonic boundaries in the Late Jurassic, redirected most sand-prone fluvial sediments away from the Barcoo Sub-basin (Blevin et al., 1998a).

During this Early to Middle Jurassic extensional phase, which culminated in breakup and the commencement of seafloor spreading in the late Callovian, the Browse Basin was situated on the margin of a major volcanic province, and extrusive and intrusive rocks have been intersected in many wells across the basin (Blevin et al., 1998a). Jason et al. (2006) proposed that magmatism occurred in two distinct phases and that Late Jurassic breakup-related magmatism, which resulted in the eruption of basaltic volcanics and the intrusion of sills and dykes, was preceded in the Early Jurassic by a phase of plume-related magmatism that led to the extrusion and intrusion of more felsic material. This proposed history is consistent with the distinct compositional change reported by Tovaglieri et al. (2013) in their recent detailed study of the Calliance and Brecknock fields. Seismic data suggests that in the outer parts of the sub-basin, the syn-breakup succession is dominated by volcanic rocks. This is supported by the 450 m of interbedded tuffs and volcanic rocks of inferred Callovian–Oxfordian age intersected in Warrabkook 1 (Ellis, 2008; Figure 4.13).

Following breakup in the Late Jurassic, sedimentation occurred under a regime of passive margin thermal subsidence. A thin Upper Jurassic fluvio-deltaic succession (Montara Formation) is present across most of the basin and is overlain by prograding, deltaic facies including highstand shales (lower Vulcan Formation; Figure 4.14; Blevin et al., 1998a). Berriasian to Aptian strata comprise a lowstand package (upper Vulcan Formation), including slope fans (Brewster Member), overlain by transgressive and highstand depositional packages (Echuca Shoals Formation; Blevin et al., 1998a). The Aptian to Turonian was characterised by marine flooding and prolonged highstand, during which thick successions of siltstone and shale were deposited (Jamieson and lower Woolaston Formations). Jason et al. (2006) proposed that lowstand deltas formed in the Barcoo Sub-basin during a regression in the latest Aptian–earliest Albian. Possible distal turbidite facies are interpreted on well logs in Barcoo 1 (Blevin et al., 1998a). The Turonian to lower Campanian succession is characterised by fine-grained pelagic sediments, primarily calcareous claystone, calcareous shale, marl and calcilutite. Deltaic progradation during the late Campanian to Maastrichtian was accompanied by the deposition of lowstand fans basinward of the palaeo-shelf margin (Blevin et al., 1998a).

The Cretaceous section is overlain by a thick, progradational Cenozoic succession, which thins to the south in the Barcoo Sub-basin. The Paleocene–middle Miocene succession is dominated by marginal marine to shallow marine shelf clastic sediments. After a major marine flooding of the basin in the middle Miocene, there was a shift from clastic-dominated sedimentation in the eastern basin to the widespread deposition of carbonates, including reefal facies (AGSO Browse Basin Project Team, 1997).

4.3.2.3 Level of knowledge

Exploration drilling has largely focused on the northeast-trending inversion anticlines along the eastern margin of the Barcoo Sub-basin; five of the nine wells drilled in the sub-basin are located on this feature (Figure 4.13 and Figure 4.17). The stratigraphic succession in the deeper water parts of the sub-basin is not well understood, despite good seismic coverage across the sub-basin (Figure 4.17).

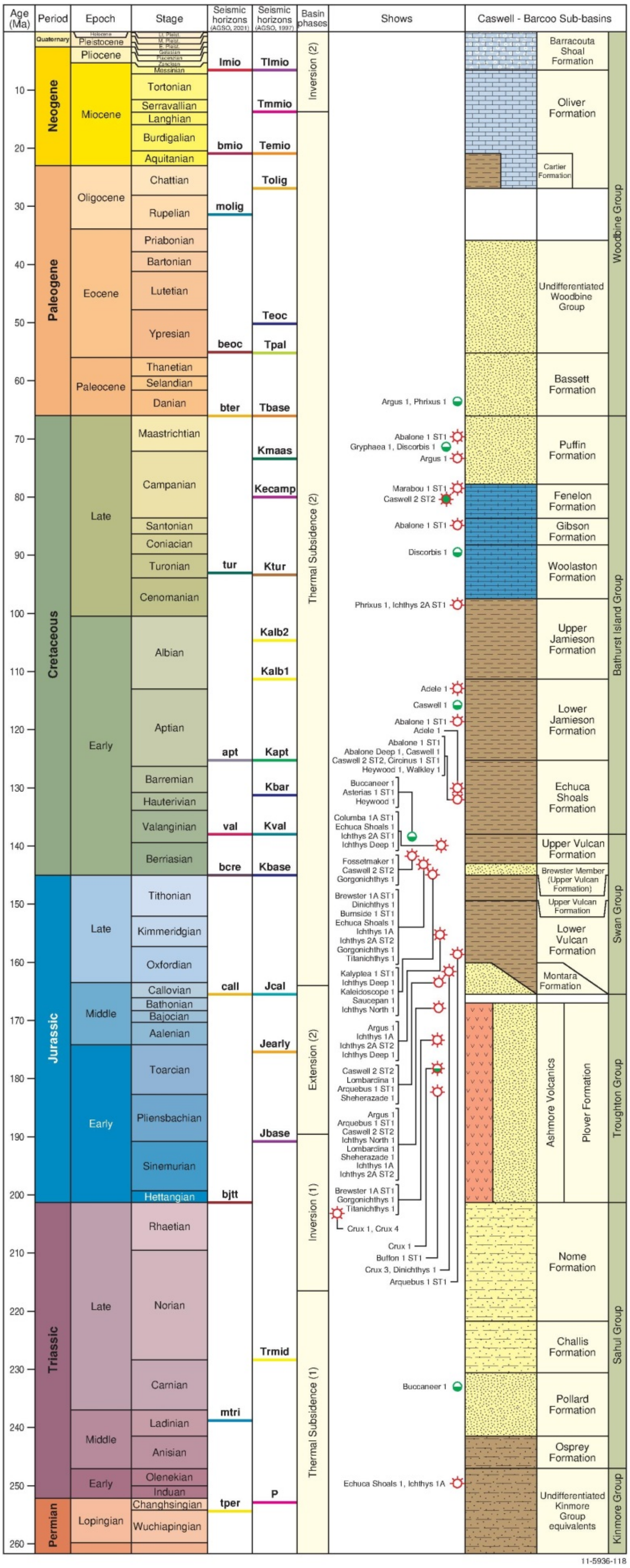

Figure 4.14: Stratigraphy of the Browse Basin. Geologic time scale after Gradstein et al. (2012).

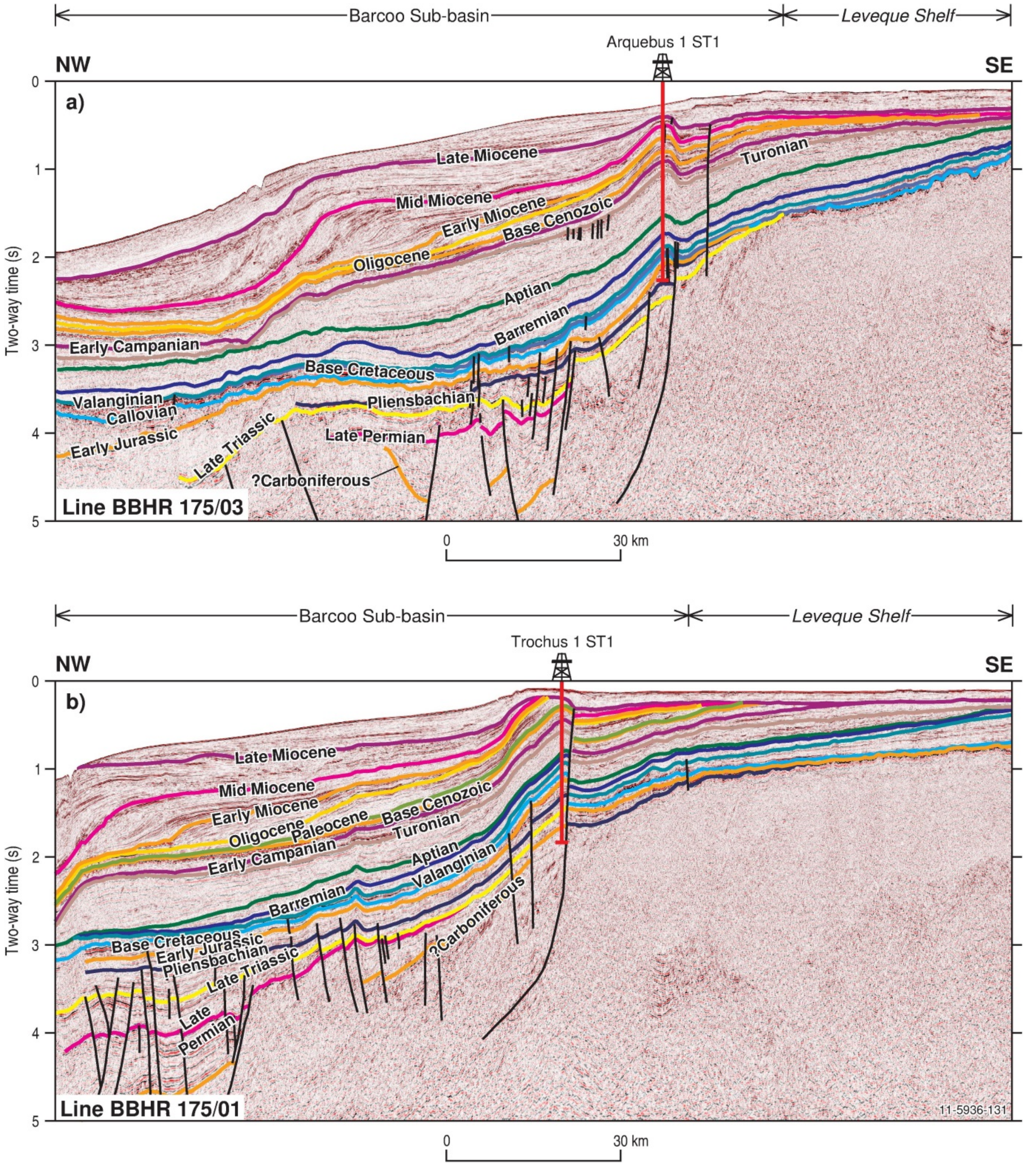

Figure 4.15: Seismic sections across a) the northern and b) southern Barcoo Sub-basin.

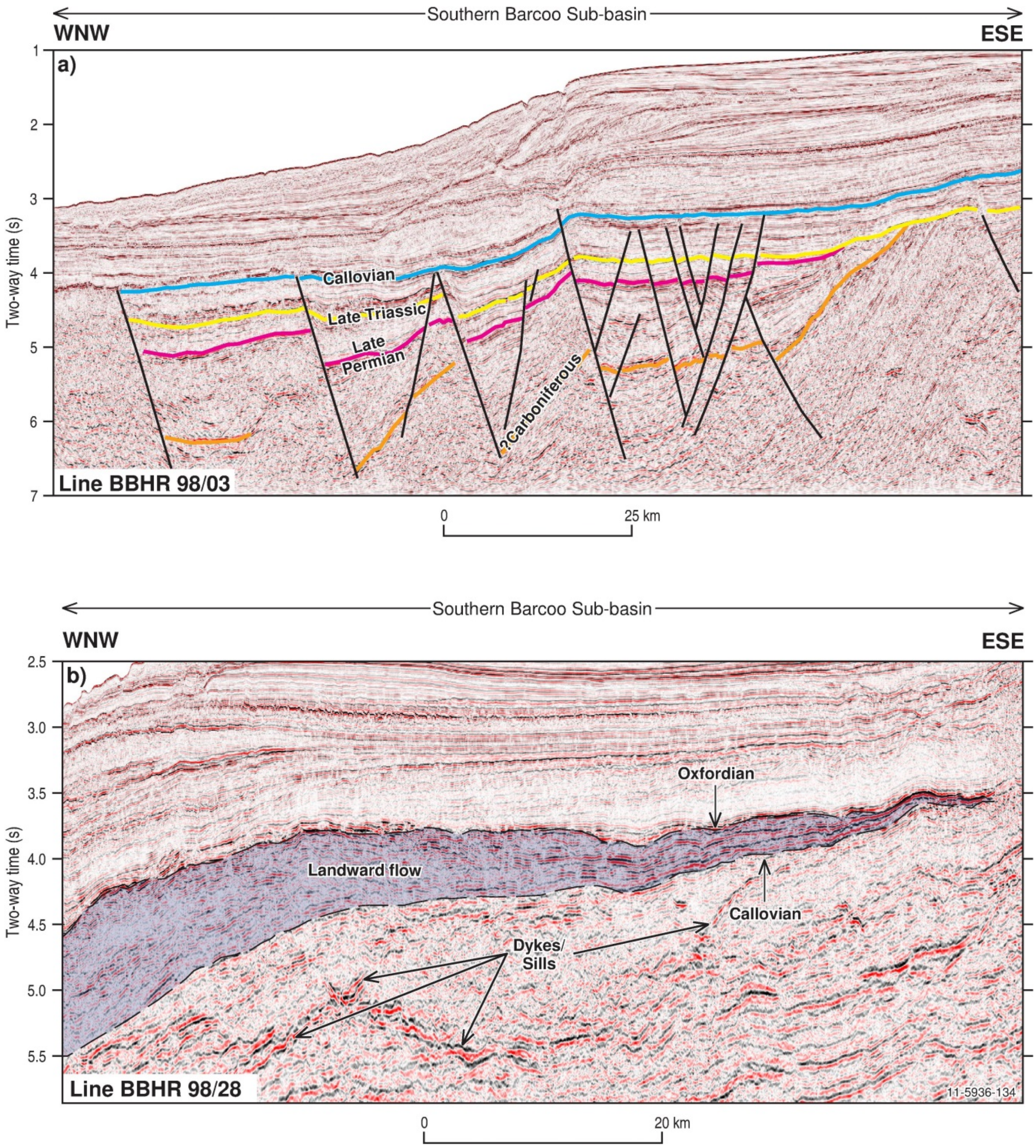

Figure 4.16: Seismic sections across a) the southern Barcoo Sub-basin and b) western volcanic margin of the Barcoo Sub-basin.

4.3.3 Petroleum systems

No commercial hydrocarbon discoveries have been made in the Barcoo Sub-basin, but gas shows were reported or inferred from geophysical logs in Lombardina 1, Arquebus 1 ST 1, and Sheherazade 1. These wells were all drilled along the inversion anticlinal trend on the eastern margin of the sub-basin (Figure 4.13 and Figure 4.15a). The large Calliance gas field straddles the boundary between the Caswell and Barcoo sub-basins (Figure 4.13), and a gas accumulation was intersected in Lower Cretaceous sediments draped over a basement high on the Leveque Shelf at Psepotus 1, east of the Barcoo Sub-basin. The most likely source of the hydrocarbons in the Barcoo Sub-basin is considered to be the Lower to Middle Jurassic Plover Formation (Figure 4.14; Blevin et al., 1998a). In the southernmost parts of the sub-basin, there may be some potential for long-range migration of hydrocarbons generated from mature Permo-Carboniferous or Upper Triassic source rocks in the adjacent Oobagooma and Rowley sub-basins. Triassic and Miocene fault-reactivation inversion anticlines provide potential structural traps, with an inferred hydrocarbon column present at Arquebus 1 ST1.

4.3.3.1 Source Rocks

Potential source rocks in the Barcoo Sub-basin include fluvio-deltaic and prodelta facies of the Lower–Middle Jurassic Plover Formation (potentially oil- and gas-prone) and Upper Triassic highstand shales. In addition, Upper Jurassic–Lower Cretaceous shales of the Vulcan and Echuca Shoals formations (Figure 4.14) are potentially oil-prone, but are immature to marginally mature (Blevin et al., 1998b; Kennard et al., 2004). Potential source rocks may also be present in the undrilled Permo-Carboniferous succession (Blevin et al., 1998a).

Thick accumulations of Lower to Middle Jurassic (pre-Callovian) organic-rich sediments are preserved in the western and northeastern Barcoo Sub-basin (AGSO Browse Basin Project Team, 1997). Blevin et al. (1998a) suggested that the best source potential in the Barcoo Sub-basin would be found in Lower Jurassic marine facies, particularly at third and fourth order sequence boundaries where reconnaissance exceed 2% TOC.

The Upper Jurassic–Lower Cretaceous succession contains mixed marine and terrestrial organic matter with moderate to good source potential (Blevin et al., 1998b). However, in the Barcoo Sub-basin, the Upper Jurassic succession is relatively thin and marginally mature, and the Lower Cretaceous succession is immature to marginally mature (Blevin et al., 1998b; Kennard et al., 2004). A significant thickness of mostly Barremian age shale was deposited in a topographic low between Barcoo 1 and Brecknock South 1; however, the effectiveness of this ‘pod’ to source structures in the Barcoo Sub-basin is dependent on maturity. In Barcoo 1, the oil window lies at a depth of 3800 m and the Lower Cretaceous succession is immature for oil (Blevin et al., 1998b).

Permo-Carboniferous to Late Triassic source intervals are not well documented, as this succession is poorly constrained by well data. Initial source rock richness shows that most of the intervals sampled from this succession have only poor to fair source potential, although these samples do not reflect the source potential of facies within the deeper half graben (Blevin et al., 1998a). For example, Upper Triassic highstand shales preserved at Barcoo 1 thicken toward the east into the central Barcoo Sub-basin, and are expected to contain viable source facies (Blevin et al., 1998a).

4.3.3.2 Generation and expulsion

Source rocks in the Lower to Middle Jurassic Plover Formation in the Barcoo Sub-basin (Figure 4.14) are mature for oil and wet gas generation. Petroleum systems modelling suggests that these source intervals expelled gas in the northern and eastern parts of the sub-basin in the Cenozoic (Kennard et al., 2004).

Kennard et al. (2004) reported that the Upper Jurassic to Cretaceous succession in the Barcoo Sub-basin is immature to marginally mature, with only minor gas expulsion from the central part of the sub-basin in the Neogene. Maturity modelling presented by Jason et al. (2006) suggests that the Upper Jurassic section is oil mature in the eastern part of the sub-basin only.

The Carboniferous to Triassic succession is considered to be overmature across much of the Browse Basin (AGSO Browse Basin Project Team, 1997). However, hydrocarbon generation could be occurring where source facies of this age are not as deeply buried. For example, petroleum systems modelling suggests the Upper Triassic succession intersected in Lombardina 1 (Figure 4.13) is currently in the oil window (AGSO Browse Basin Project Team, 1997). In addition, Jason et al. (2006) presented modelling results indicating that the top Triassic is mature for oil and gas in the Barcoo Sub-basin.

Post-Eocene migration of hydrocarbons was primarily towards the Late Triassic anticlinal highs and fault blocks in the western Barcoo Sub-basin, and fault traps, late stage anticlines and onlap plays in the eastern part of the sub-basin and on the Leveque Shelf (AGSO Browse Basin Project Team, 1997).

Kennard et al. (2004) highlighted the importance of the thick Neogene carbonate clinoforms in controlling the generation and expulsion history of source rocks in the Browse Basin, with the rapid progradation of the carbonate sequences providing significant burial, thereby driving maturation of source units. They also proposed that Neogene progradation may have resulted in an outward-migrating compaction wave that forced expelled fluids and hydrocarbons to outboard areas, resulting in local oil accumulations in these areas.

4.3.3.3 Reservoirs and seals

The Lower–Middle Jurassic fluvio-deltaic Plover Formation and Upper Jurassic marine Vulcan and Montara formations (Figure 4.14) provide the main potential reservoirs for outboard structural and stratigraphic traps in the Barcoo Sub-basin (AGSO Browse Basin Project Team, 1997). Jurassic sandstones intersected in wells have generally good–excellent reservoir qualities with porosities ranging from 14–24%; the poor reservoir qualities of Jurassic sandstones in Lombardina 1 and Arquebus 1 ST 1 have been attributed to diagenesis within a structurally complex zone (Department of Resources, Energy & Tourism, 2009). Reservoir quality sandstones may also be present in the Upper Triassic succession, and in mid-Cretaceous lowstand sands and distal turbidite facies.

Lower Cretaceous (Echuca Shoals Formation) and Upper Jurassic (Vulcan Formation; Figure 4.14) highstand shales provide regional seals within the Barcoo Sub-basin. Upper Triassic highstand shales in the central Barcoo Sub-basin are expected to contain seal facies for potential Permo-Carboniferous petroleum systems (Blevin et al., 1998a). Potential intraformational shale seals occur within the Lower–Middle Jurassic Plover Formation, but are poorly documented (Blevin et al., 1998a).

4.3.3.4 Play types

A key play type for exploration in the Barcoo Sub-basin has been Upper Jurassic–earliest Cretaceous sandstones in Miocene fault reactivation anticlinal traps. Such Miocene inversion plays include the prominent anticlinal trend along the eastern margin of the sub-basin (e.g. Lynher 1, Lombardina 1, Arquebus 1 ST 1, Sheherazarde 1), as well as smaller structures farther outboard (e.g. South Galapagos 1; Figure 4.13). To date, this play has proved unsuccessful, with the possible exception of an inferred hydrocarbon column at Arquebus 1 ST1 (Figure 4.15a; Haston & Farrelly, 1993). The timing of generation and expulsion (generally Neogene) relative to the timing of deformation (mid-Miocene and younger) is the critical issue for this play type, which is only suitable for very late generated (post-Miocene) hydrocarbons.

Potential play types in the Barcoo Sub-basin relying on charge from upper Paleozoic or Triassic source rocks include fault-related structural traps within the Carboniferous–Permian succession and Late Triassic tilted fault blocks and associated inversion anticlines. The latter may also provide traps for hydrocarbons sourced from the Lower–Middle Jurassic succession. The Late Triassic faulted anticline play, which hosts the giant gas fields along the outer margin of the Caswell Sub-basin, was tested unsuccessfully at Barcoo 1 (Figure 4.13), where the tested structure lacked closure.

There is also the potential for stratigraphic traps formed by mid-Cretaceous lowstand sandstones and distal turbidite facies sealed by deepwater shales (Blevin et al., 1998a; Jason et al., 2006; Laitrakull, 2012).

4.3.3.5 Critical risks

4.3.3.5.1 Presence of mature and generating source rocks

Gas shows in wells along the eastern margin of the sub-basin and the gas accumulation at Psepotus 1, on the Leveque Shelf to the east, are encouraging signs of active petroleum systems in the area. However, the failure of the outboard wells (Barcoo 1, South Galapagos 1, Warrabkook 1 and Omar 1; Figure 4.13), and petroleum system modelling that suggests gas expulsion is restricted to the northern Barcoo Sub-basin (Kennard et al., 2004), indicate that charge from Jurassic gas-prone source rocks may be an issue in the sub-basin. Thinning of the Upper Jurassic–Holocene section to the south appears to be a key factor controlling maturity in the sub-basin (Kennard et al., 2004).

Absence of oil source rocks of suitable maturity is also a potential risk. The Upper Jurassic succession, the source rock for many North West Shelf oil accumulations, is generally thin in the Barcoo Sub-basin. The Lower Cretaceous succession contains oil-prone organic-rich rocks, and mature source rocks within this section provide the charge for the oil fields on the Yampi Shelf. However, in the Barcoo Sub-basin the section is immature to marginally mature.

4.3.3.5.2 Presence of Jurassic volcanic and related intrusive rocks

Igneous rocks have been intersected within the Jurassic succession in Arquebus 1 ST1, Lombardina 1, Warrabkook 1 and Omar 1 (Figure 4.13), and interpretation of seismic and magnetic data suggests they are widespread, especially in the western part of the sub-basin (Figure 4.16b). The risks associated with these rocks relate to the reduction of reservoir volume within mapped structures due to the presence of thick volcanic or intrusive units, thick igneous bodies acting as barriers to migrating hydrocarbons (Jason et al., 2006), and the deterioration of reservoir quality as a result of hydrothermal fluids.

4.3.3.5.3 Preservation of accumulations

Key risks for the large fault-reactivation anticlines along the boundary between the Barcoo Sub-basin and Leveque Shelf are timing of trap development relative to generation and expulsion, the lack of updip lateral seal and/or reactivation and breach by Pliocene faults (AGSO Browse Basin Project Team, 1997).

4.3.3.6 Overall prospectivity classification

Moderate–high

4.3.4 Exploration status

In the early 1970s, B.O.C. of Australia drilled Lynher 1 and Lombardina 1 (Figure 4.13) to test major late Miocene reactivation structures on the hanging wall of the large extensional fault system that forms the boundary between the Leveque Shelf and Barcoo Sub-basin; both wells were dry. In 1979–1980 Woodside drilled Barcoo 1 to test Upper Triassic and Lower–Middle Jurassic sandstones within a large northeast-trending anticline over the Barcoo fault trend, a play that had been proven in the gas discoveries at Scott Reef 1 and Brecknock 1, but which was, in this case, unsuccessful.

A subsequent hiatus in exploration in the Barcoo Sub-basin ended in the early 1990s with re-testing of reactivation structures along the boundary with the Leveque Shelf; Trochus 1 ST1 was drilled by Shell, and Amoco drilled Arquebus 1 ST 1 and Sheherazade 1. These wells were unsuccessful, although hydrocarbons were discovered on the adjacent Leveque Shelf at Psepotus 1 in 1998.

Renewed exploration in the Barcoo Sub-basin in the 2000s resulted in the drilling of three unsuccessful wells in the outboard part of the basin. South Galapagos 1 tested an inversion anticline in the southern part of the sub-basin without success (Antrim Energy, 2004). Warrabkook 1 was drilled to evaluate a postulated distal Cretaceous reservoir, as well as the reservoir potential of Plover Formation sandstones beneath Callovian volcanics. The targeted Cretaceous Jamison Formation reservoir was not present and the well intersected a thick succession of volcanics (with no Plover reservoirs) before reaching TD (Ellis, 2008). Omar 1 was drilled to evaluate a Plover Formation gas play; Woodside Petroleum (2011) reported that despite the presence of encouraging gas shows, reservoir quality was poor and the well was unsuccessful.

Exploration permits are currently held in the western Barcoo Sub-basin, and adjacent to the Calliance and Brecknock retention leases. In 2013, two exploration areas covering much of the central and eastern parts of the sub-basin were released for bidding.

4.3.5 Data

Key data sets for the Barcoo Sub-basin are listed in Table 4.9–Table 4.12. Nine wells have been drilled in the Barcoo Sub-basin, five of those along the NE trending inversion anticline that defines the eastern margin of the sub-basin and four in deeper water to the west (Figure 4.13 and Figure 4.17).

The sub-basin has a good, closely-spaced coverage of 2D seismic data (Figure 4.17). Key regional data sets include AGSO surveys 175, 119 and 130, and the PGS New Dawn survey. The northernmost part of the sub-basin, adjoining the Calliance and Brecknock fields, has good 3D seismic coverage provided by Woodside's Brecknock, Rosewall and Calliance, and Snarf-Dacey surveys. Woodside's large Omar 3D, acquired in 2008, is located within the centre of the sub-basin, and Bridge Oil's 1988 Lynher 3D overlies the southernmost part of the Barcoo fault system inversion anticline. The HBR03A 3D, acquired by BHP, is a key deepwater data set covering the boundary between the Barcoo Sub-basin, the Scott Plateau and the Seringapatam Sub-basin.

In 2014, Geoscience Australia released a new aeromagnetic data set that covers much of the Browse Basin, including the Barcoo Sub-basin. The data, which was acquired with a line spacing of 800 m and covers an area of 123,000 km^2, will be merged with older data to provide a more complete coverage of the basin. The data will be used in structural mapping and to analyse the distribution of igneous rocks within the basin (R. Hackney, Geoscience Australia, pers. comm., March 2014).

4.3.5.1 Confidence rating

High

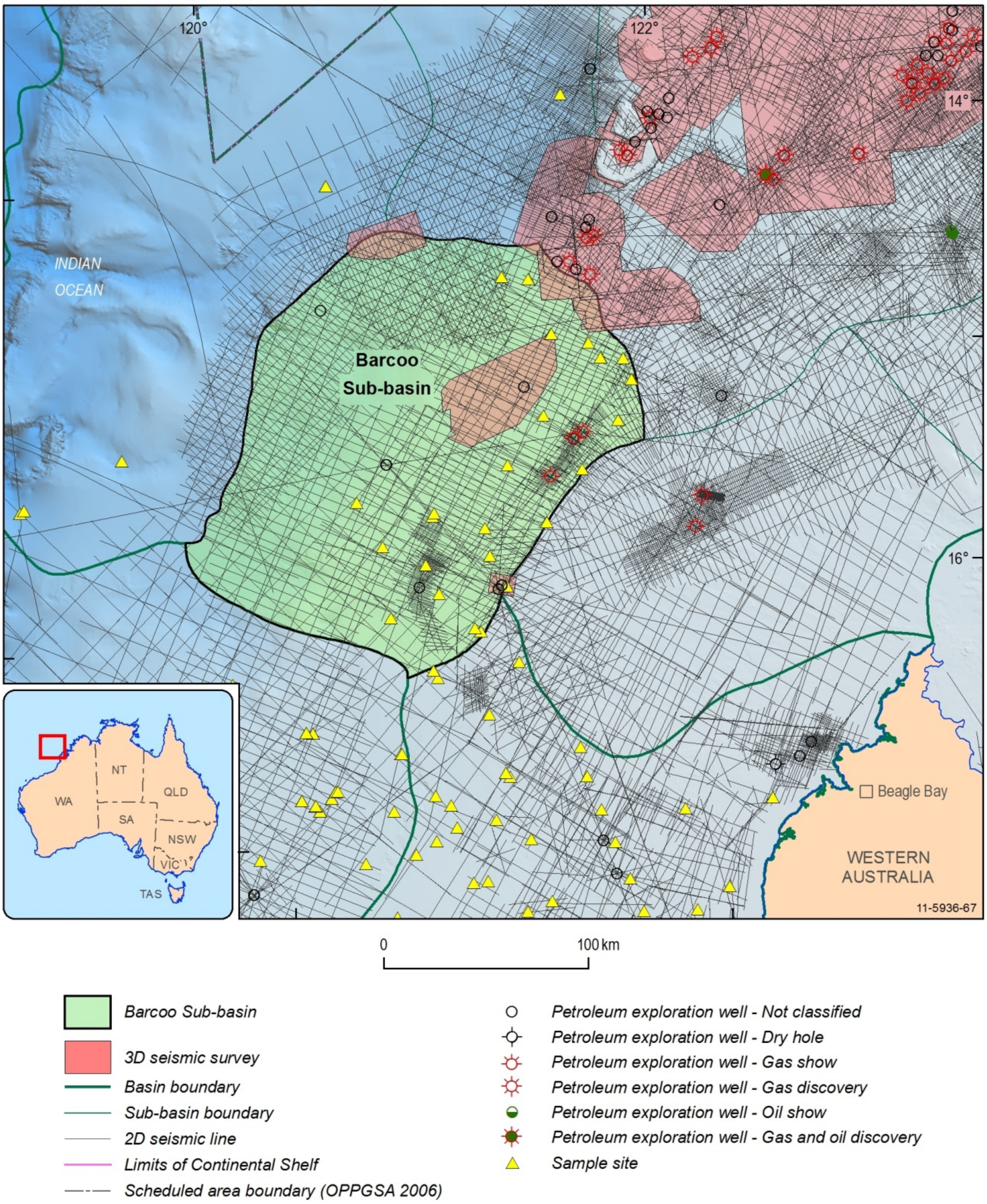

Figure 4.17: Seismic, well and sample distribution, Barcoo Sub-basin.

4.3.6 Issues and remaining questions

The key exploration issues in the Barcoo Sub-basin relate to source rocks, hydrocarbon charge and the impact of volcanic/intrusive rocks.

As a result of relatively sparse drilling in the Barcoo Sub-basin, uncertainties persist regarding:

- identification, characterisation, quality, maturity and distribution of potential source rocks, in particular those within the Upper Triassic and Lower–Middle Jurassic successions

- distribution and quality of potential reservoir facies within the Lower–Middle Jurassic Plover Formation and the Upper Jurassic–Lower Cretaceous succession
- distribution, geometry and thickness of volcanic and intrusive igneous rocks, including the identification of feeder systems and relationships with major structures

4.3.6.1 Recommendations

- Following on from the work of Boreham et al. (1997) and Kennard et al. (2004), understanding of source potential and charge in the sub-basin may be assisted by:
  - high resolution sampling and analysis of organic-rich rocks from the Barcoo Sub-basin and adjacent areas to identify and characterise potential source rocks, including their temporal and spatial variation
  - further detailed organic geochemical studies of Barcoo Sub-basin hydrocarbon shows and hydrocarbons from discoveries in adjacent areas to determine their likely source
  - detailed petroleum systems modelling constrained by these results and using the geological framework provided by the abundant 2D and 3D seismic data in the Barcoo Sub-basin.
- basin- to regional-scale palaeogeographic mapping using data in adjacent sub-basins, to assist in understanding the distribution and nature of potential source, reservoir and seal units in the Permian–Upper Jurassic succession
- basin- to regional scale structural mapping, analysis and modelling to better understand the structural evolution of the depocentre
- acquisition of additional aeromagnetic data with a line spacing of <800 m may assist in addressing specific issues regarding the distribution of igneous rocks and structure.

4.3.7 References

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4.3.8 Data Tables

Table 4.9: List of wells, Barcoo Sub-basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1971	Lynher 1	Exploration	B.O.C. of Australia	2725	Triassic	Dry	B.O.C. of Australia, 1971
1974	Lombardina 1	Exploration	B.O.C. of Australia	2855	Lower Jurassic	Gas show	B.O.C. of Australia, 1974
1980	Barcoo 1	Exploration	Woodside Petroleum Development	5109	Upper Triassic	Dry	Woodside Petroleum Development, 1980
1991	Trochus 1 ST1	Exploration	Shell Development (Australia)	1622	Lower Jurassic	Dry	Shell Development (Australia), 1991
1991	Arquebus 1 ST1	Exploration	Amoco Australia Exploration	3256	Lower Jurassic	Gas show	Reich, L., 1992
1993	Sheherazade 1	Exploration	Amoco Australia Exploration	2544	Lower Jurassic	Gas show	Pivnik, D., 1993
2004	South Galapagos 1	Exploration	Antrim Energy	3636	Jurassic	Dry	Antrim Energy, 2004
2008	Warrabkook 1	Exploration	BHP Billiton	3492	Jurassic	Dry	Ellis, 2008
2011	Omar 1	Exploration	Woodside Petroleum	5229	Jurassic	Dry	Woodside Petroleum, 2011

Table 4.10: Key seismic surveys, Barcoo Sub-basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1971	Petrel Roving 1971 (Deepwater)	Shell Development		
1988	Lynher 2D MSS	Bridge Oil	906	
1988	Olga MSS	Ampolex	382	
1988	Lynher 3D MSS	Bridge Oil	369 km^2	
1992	Elizabeth MSS	Ampolex	377	
1993	Survey 119	AGSO	3418	
1994	Survey 130	AGSO	4055	
1996	Survey 175 (Browse Basin High Resolution)	AGSO	5274	
1996	Lynne 2D MSS	Ampolex	1168	
1997	Brecknock 3D MSS	Woodside Offshore Petroleum	820 km^2	

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1998	BR98 (Browse 1998)	Veritas DGC	23,875	
1998	SPA Outer Browse (OB98)	Seismic Australia	3756	
1998	SPA Deepwater Canning	Seismic Australia	7863	
1998	Plumwood 2D MSS (P98)	Woodside Offshore Petroleum	1779	
2001	HBR2000A 2D MSS	BHP Petroleum	16,915	
2003	Floreana Plazas MSS (MGS 03)	Magellan Petroleum	875	
2003	HBR03A 3D MSS	BHP Petroleum	510 km^2	
2005–06	Snarf Dacey 3D MSS	Woodside Offshore Petroleum	1271 km^2	
2007	Deep Water Northwest Shelf MC2D (New Dawn) PhII	Petroleum Geo-Services Asia Pacific Pty Ltd	22,284 km (total)	
2007–08	Rosewall & Calliance 3D MSS	Woodside Offshore Petroleum	2888 km^2	
2008	Omar 3D MSS	Woodside Offshore Petroleum	1627 km^2	

Table 4.11: Key geological sampling surveys, Barcoo Sub-basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
1968	Northwest Shelf Sampling Survey 1	BMR	North West Shelf	Grab, dredge	Shelly calcarenites, gravels	Jones, 1973
1999	Franklin Cruise 4 (Survey ENO 4350)	University of Adelaide	North West Shelf	Benthic sled, dredge	Carbonate sediments	Bone et al, 1999
2013	Browse Basin 2013 Marine Survey	Geoscience Australia	Browse Basin	Grabs, dredges, vibracores	Marine sediments	In preparation

Table 4.12: Swath bathymetry surveys, Barcoo Sub-basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
2003	VANC11	SIO		
2005	VITAL	UKIEL		
2007	NW Bio (Legs 1-3)	CMAR		

4.4 Seringapatam Sub-basin and Scott Plateau (Browse Basin)

4.4.1 Summary

State(s)		Western Australia
Area (km^2)		~61,700
Water Depth (m)		~1050 to >5000
Maximum sediment thickness (m)		>5000
Age range		Carboniferous–Holocene
Basin	**Overlies**	Continental basement; ocean–continent transition
	Parent	Browse Basin
	Adjacent basins	Caswell Sub-basin, Barcoo Sub-basin, Roebuck Basin, Rowley Sub-basin
Basin type		Extensional, passive margin
Depositional setting, rock types		Marine and non-marine clastic sedimentary rocks and marine carbonates.
Petroleum prospectivity		Low–moderate
Confidence		*Low–medium*

4.4.2 Geology

The Browse Basin, located in the southern Timor Sea region of Australia's North West Shelf (Figure 4.18), contains two main depocentres—the Caswell and Barcoo sub-basins (Hocking et al., 1994; AGSO Browse Basin Project Team, 1997; Blevin et al., 1998; Struckmeyer et al., 1998). Seaward of these depocentres is a complex, deepwater, frontier region variously referred to (wholly or in part) as the Scott Plateau, Scott Sub-basin, Seringapatam Graben or Seringapatam Sub-basin (Hocking et al., 1994; Hoffman & Hill, 2004; Stagg & Exon, 1981; Struckmeyer et al., 1998).

The northernmost element of the deepwater Browse Basin is the Seringapatam Sub-basin (Figure 4.18). It contains a faulted, pre- to syn-breakup, Paleozoic(?) to Upper Jurassic section up to 4 s TWT thick, overlain by a thin Upper Jurassic–Cenozoic post-breakup succession (Figure 4.19 and Figure 4.20). The basin fill is characterised by extensive intrusive and extrusive igneous rocks.

The southern part of the deepwater Browse region is dominated by the Scott Plateau (Figure 4.18), a subsided marginal plateau, similar to the Exmouth Plateau or Ashmore Platform (Stagg & Exon, 1981; Hocking et al., 1994; Crawford & von Rad, 1994; Struckmeyer et al., 1998; Ellis, 2008). Hocking et al. (1994) defined the Scott Sub-basin as the basin underlying the Scott Plateau and separated it arbitrarily from a poorly-defined Seringapatam Sub-basin to the northeast. However, we contend that the widespread occurrence of igneous rocks makes it difficult to adequately characterise the sedimentary succession and define a sub-basin. Therefore, and in accordance with common usage, we refer to this area as the Scott Plateau.

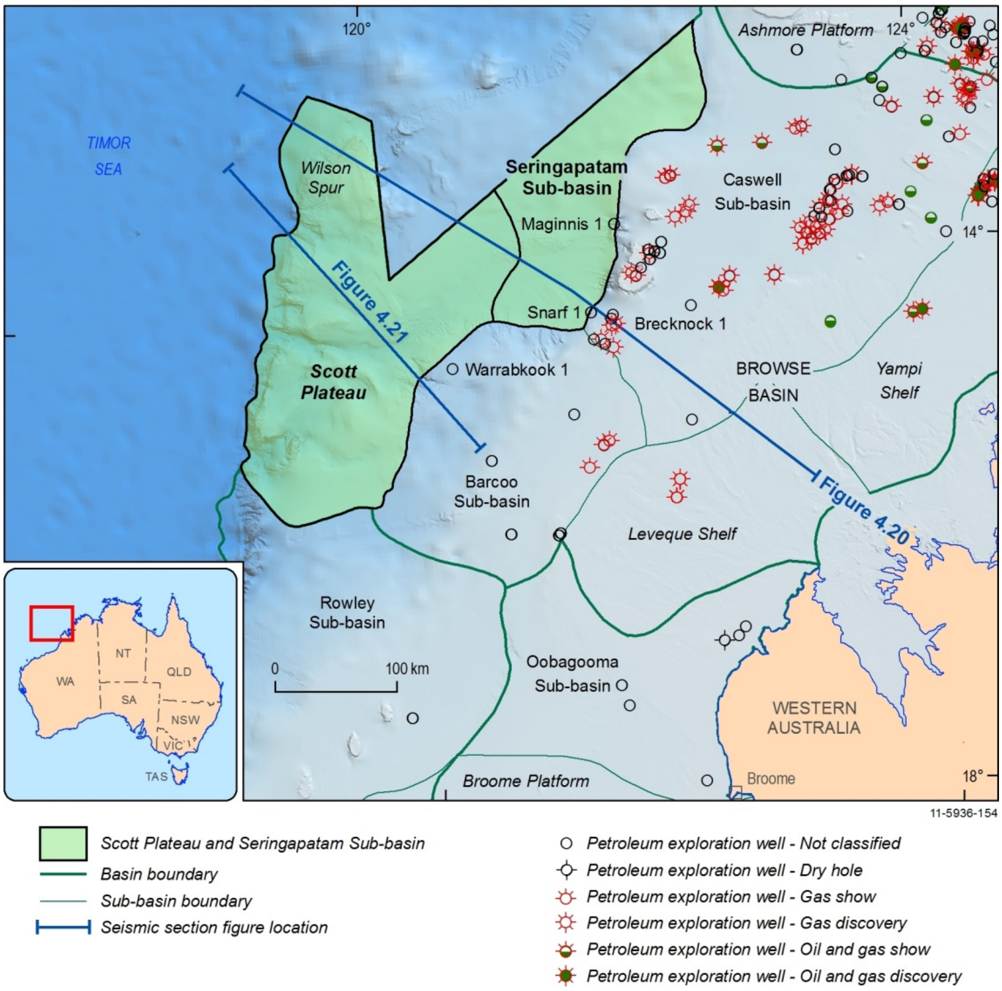

Figure 4.18: Structural elements map, Scott and Seringapatam sub-basins, Browse Basin.

The Seringapatam Sub-basin and Scott Plateau are exploration frontiers. Only one well, the unsuccessful Maginnis 1 (Figure 4.18), has been drilled in the region, a short distance seaward of the boundary between the Caswell and Seringapatam sub-basins (Locke, 2003). The Scott Plateau and the Seringapatam Sub-basin extend beyond Australian Marine Jurisdiction.

4.4.2.1 Structural geology

The Browse Basin was initiated in the Carboniferous–early Permian in response to north-northwest-oriented extension, and forms part of the larger Westralian Superbasin (Struckmeyer et al., 1998; Symonds et al., 1994). Contractional reactivation of Paleozoic faults in the Late Triassic–Early Jurassic led to partial inversion of half graben. A prolonged period of extension in the Early–Middle Jurassic preceded breakup in the Middle–Late Jurassic. The volume and widespread nature of igneous intrusive and extrusive rocks that accompanied Jurassic extension and breakup indicate that the outer Browse is a magma-rich (or “volcanic”) rifted margin.

The Scott Plateau is reported to contain a thick (>5 km) section of Paleozoic–Mesozoic rocks (Stagg & Exon, 1981; Symonds et al., 1994; Ellis, 2008; Hoffman & Hill, 2004). However, across much of the Scott Plateau, a thin Jurassic(?)–Cenozoic sedimentary section overlies a thick and extensive succession of igneous rocks that to a large extent obscures the underlying geology on seismic data

(Figure 4.21). The northeastern part of the Scott Plateau, which appears to be less affected by igneous rocks, consists of a broad platform characterised by rotated, planar normal faults ("domino faults"; Hoffman & Hill, 2004). The faulting affects a Triassic and older succession, with a thin syn-rift or immediate post-rift Jurassic succession preserved on the rotated hanging wall blocks; a distal Cretaceous–Cenozoic succession overlies this faulted terrane (Hoffman & Hill, 2004). This region is flanked to the west by the Wilson Spur, a 50 km wide elevated bathymetric feature at the seaward edge of the Scott Plateau, and to the east by the Seringapatam Sub-basin (Figure 4.20). Locally, simple half graben of probable Late Jurassic age that are bounded by large displacement, west-dipping normal faults are present on the inboard side of the northern and southern Wilson Spur.

The Scott Plateau appears to have undergone extreme crustal thinning during the Early–Middle Jurassic, prior to the localisation of extension initially in the Seringapatam Sub-basin, and then outboard of the Wilson Spur, where breakup was eventually located (Hoffman & Hill, 2004). On the faulted northeastern part of the Plateau (Figure 4.20), rotation of planar normal faults to low angles (15–25°) suggests up to 200% extension (Hoffman & Hill, 2004). Modelling results presented by Roberts et al. (2013), which include a suggested beta-factor of 5.0, support the interpretation of highly attenuated continental crust adjacent to the continent–ocean boundary for this part of the Scott Plateau. Roberts et al. (2013) postulated that the Scott Plateau inboard of the Wilson Spur may have been the location of failed Early–Middle Jurassic breakup. Breakup and the initiation of seafloor spreading in the Argo Abyssal Plain to the west of the Scott Plateau occurred in the Callovian and were accompanied by volcanism and igneous intrusions, and widespread erosion.

In the Seringapatam Sub-basin, widespread extensional faulting occurred in the Early–Middle and Late Jurassic (Struckmeyer et al., 1998; Jason et al., 2006; Hoffman & Hill, 2004). The sub-basin is highly faulted, with fault sets oriented northeast–southwest, east-southeast–west-northwest and east–west (Ellis, 2008). The locus of rifting appears to have been on the eastern side of the sub-basin, adjacent to the Caswell Sub-basin, where a deep but narrow rift basin formed; this feature is referred to as the "Seringapatam Graben" by Hoffman & Hill (2004). The age of the rift section is not well constrained, given the difficulties of carrying seismic interpretations across the relatively starved outer Caswell Sub-basin high. Hoffman & Hill (2004) proposed that extension within the graben continued from the Callovian to the Aptian.

During the Late Jurassic–Paleogene period of passive margin subsidence, the region underwent only minor structural reactivation, with episodes of minor inversion evident from structural restorations (Hoffman & Hill, 2004). Miocene convergence of the Australian and Eurasian plates led to some structural reactivation (Struckmeyer et al., 1998; Hoffman & Hill, 2004).

4.4.2.2 Basin evolution and depositional history

Deposition of the Lower–Middle Jurassic Plover Formation (Figure 4.19) extended into the deepwater depocentres of the Seringapatam Sub-basin, forming a depositional wedge that thins on to the Scott Plateau (Jason et al., 2006). In the Middle–Late Jurassic, extension became localised in the eastern Seringapatam Sub-basin. Deposition failed to keep pace with subsidence, resulting in the formation of a local sediment trap immediately outboard of the Caswell Sub-basin (Hoffman & Hill, 2004). This localised ponding isolated the Scott Plateau from sediment sources to the east (Hoffman & Hill, 2004). In the southern part of the Scott Plateau adjacent to the Barcoo Sub-basin, a wedge of reflective northwest-dipping strata that appears to be correlative with the Lower–Middle Jurassic Plover Formation is interpreted as a subaerial volcanic landward flow (Symonds et al., 1998).

Post-Jurassic deposition occurred in a distal, deepwater setting, and is likely to include turbidites. Initial sedimentation was confined to the Seringapatam Sub-basin, extending across the entire deepwater basin during the Cretaceous. Sedimentation was slow, and failed to keep pace with steady regional thermal subsidence. During the late Miocene, an increase in subsidence was matched by increased sediment supply from the adjacent shelf margin (Hoffman & Hill, 2004). This resulted in the deposition of a 1 km thick wedge of sediment that thins toward the west.

4.4.2.3 Level of knowledge

Understanding of the geology and evolution of the Seringapatam Sub-basin and Scott Plateau is based largely on a limited and variable grid of 2D seismic data. While seismic data density is good in the inboard parts of the Seringapatam Sub-basin, only a few lines have been acquired over much of the Scott Plateau (Figure 4.22). Only one well has been drilled in the Seringapatam Sub-basin—Maginnis 1 near the boundary with the Caswell Sub-basin (Figure 4.22). This well does not provide any useful insights into the pre-breakup section as it encountered only a thin Cretaceous Echuca Shoals Formation before intersecting a thick section of volcanic rocks (Jason et al., 2006).

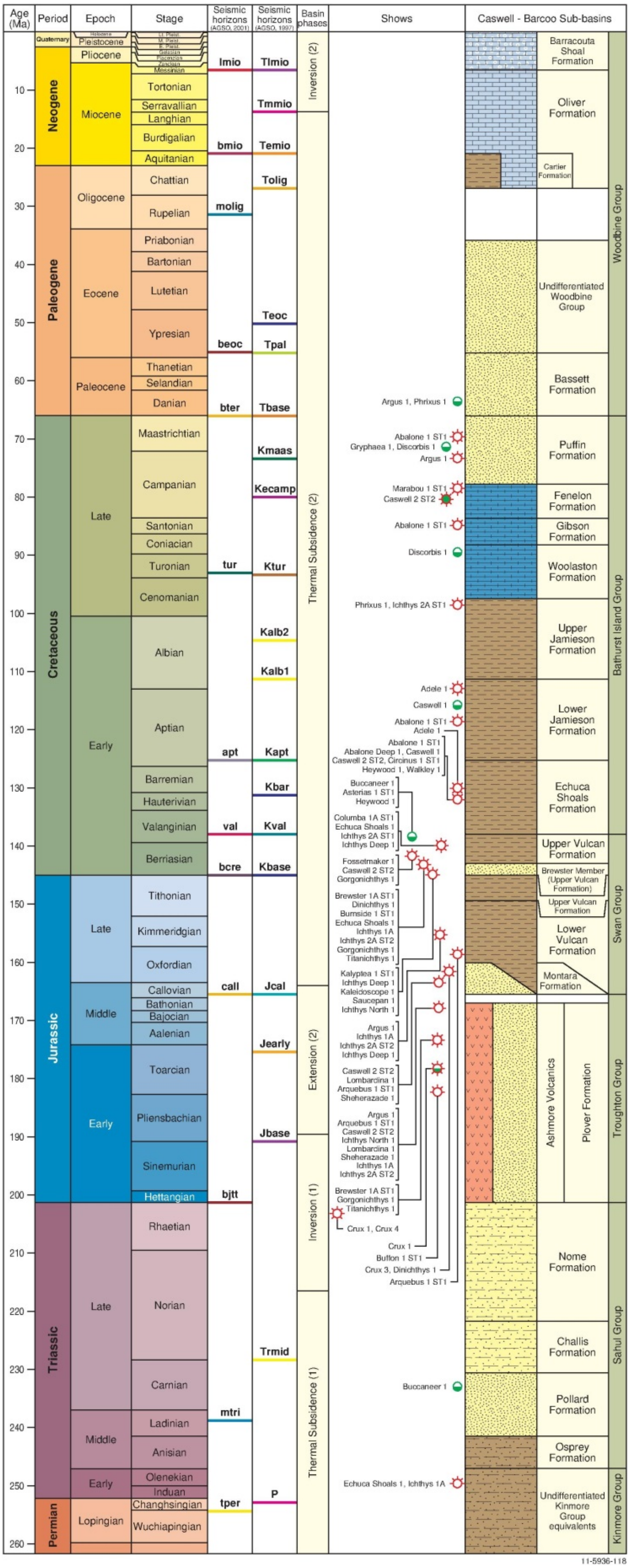

Figure 4.19: Stratigraphy of the Browse Basin. Geologic time scale after Gradstein et al. (2012).

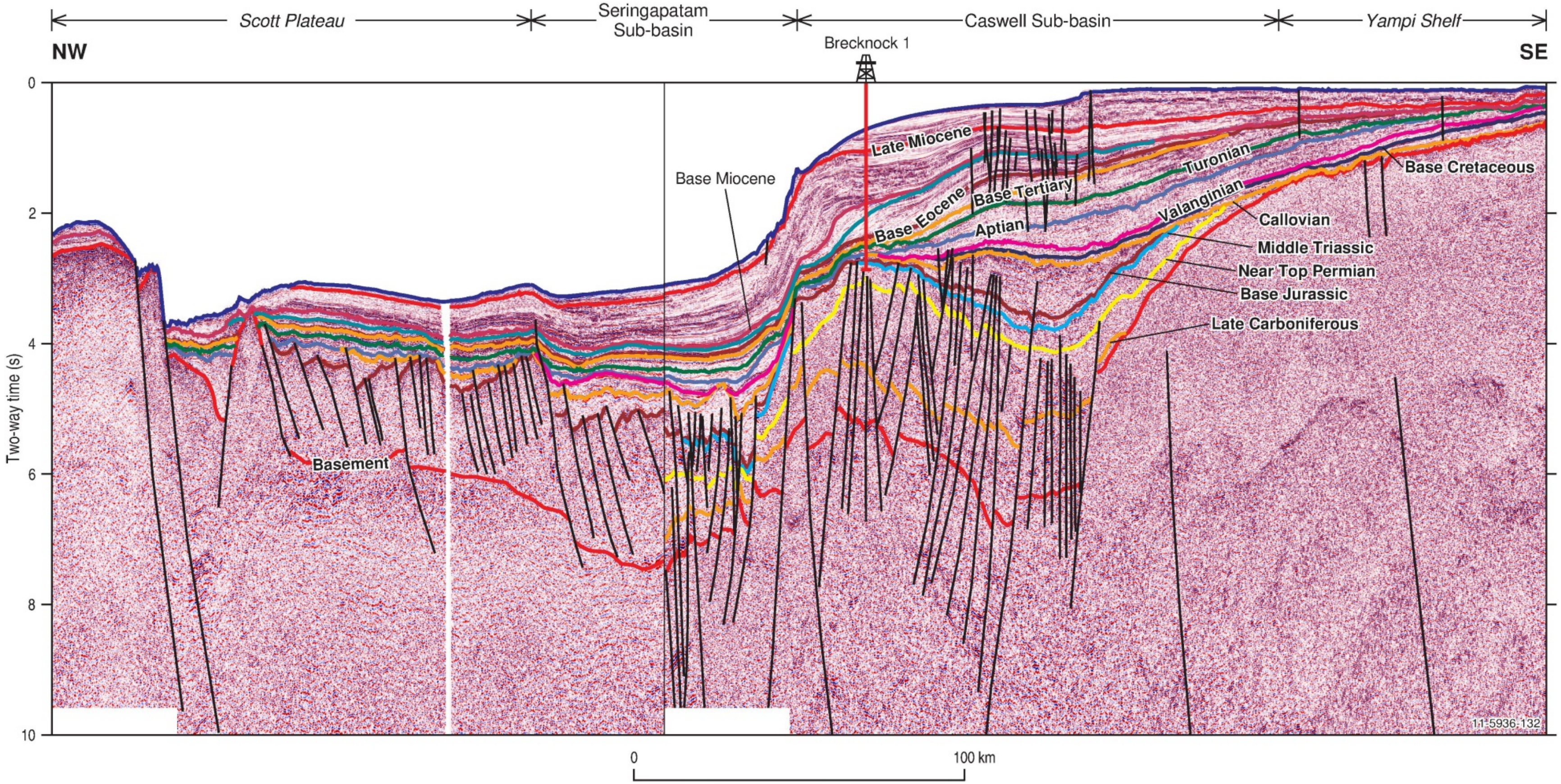

Figure 4.20: Seismic line across the Caswell and Seringapatam sub-basins and the Scott Plateau.

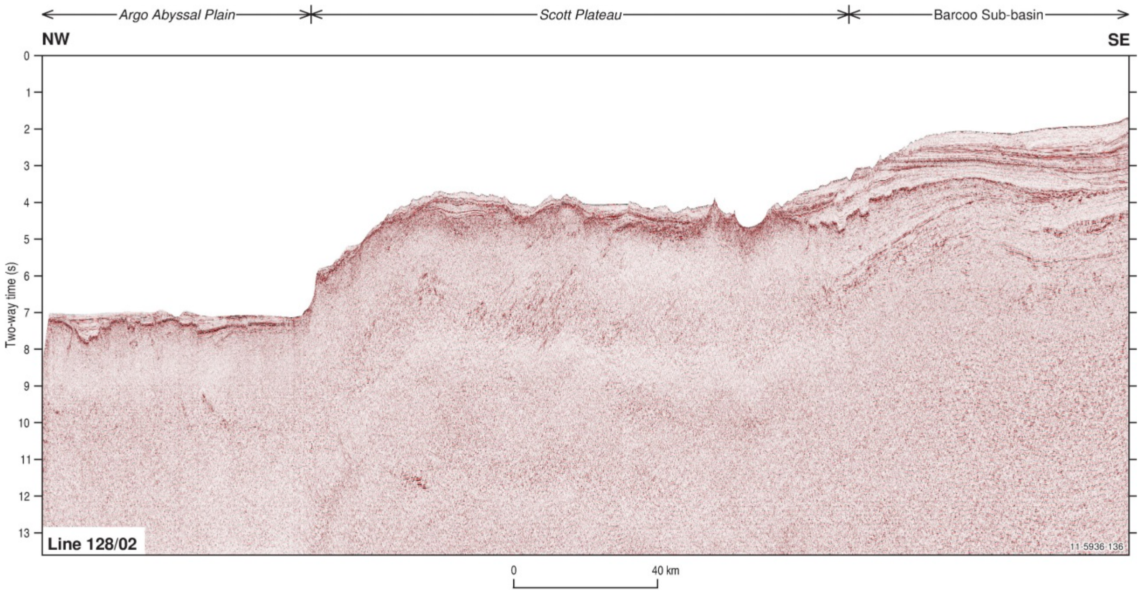

Figure 4.21: Seismic line across the southern Scott Plateau showing the effect of surface and near-surface igneous rocks on seismic data quality in this area.

4.4.3 Petroleum systems

The petroleum potential of the Seringapatam Sub-basin and Scott Plateau has not been tested. The most prospective section is likely to be the thick but narrow rift depocentre on the eastern side of the Seringapatam Sub-basin.

4.4.3.1 Source rocks

Models presented by Hoffman & Hill (2004) for the structural development of the Scott Plateau suggest that shallow-water source rocks (Plover Formation) may have accumulated during the pre- and early-rift stages, while thick syn- to immediately post-rift sequences (Vulcan Formation; Figure 4.19) may also have been deposited in the Late Jurassic restricted marine depocentres.

4.4.3.2 Generation and expulsion

Regional subsidence and thermal history modelling by Kennard et al. (2004) demonstrates that if Jurassic source rocks are present in the Seringapatam Sub-basin, they are mature for oil and gas generation. The modelling showed that any Plover Formation source rocks (Figure 4.19) in the inner Seringapatam Sub-basin would be dry gas mature, with expulsion occurring in the mid–Late Cretaceous and late Cenozoic. In addition, modelled oil expulsion from the Plover Formation is prolific on the inner margin of the Seringapatam Sub-basin, commencing in the early Cenozoic and peaking in the Neogene. Kennard et al. (2004) argued that elevated Grains with Oil Inclusions (GOI) results from North Scott Reef 1, Scott Reef 2A and Brecknock 1 may also be evidence of an early oil charge from the adjacent Seringapatam Sub-basin. The Upper Jurassic–Lower Cretaceous Vulcan Formation was modelled to be mature for oil and wet gas generation in the inner Seringapatam Sub-basin, but with little or no expulsion.

4.4.3.3 Reservoirs and seals

Little is known about the potential distribution of reservoir and seal facies in this region. Structural modelling implies that Late Jurassic–Cretaceous deposition took place in a distal deep-water environment (Hoffman & Hill, 2004), so it is likely that turbidite facies are present. Cenozoic overburden thins to the west which increases the chance of porosity preservation in Jurassic and Cretaceous reservoirs.

4.4.3.4 Play types

Hoffman & Hill (2004) identified a range of possible plays in the region, including Triassic–Jurassic fault blocks and inversion anticlines. In addition, submarine fans in the Echuca Shoals and Puffin formations (Figure 4.19) may be potential stratigraphic plays (Department of Resources, Energy & Tourism, 2011).

4.4.3.5 Critical risks

4.4.3.5.1 Presence of petroleum systems elements

The nature and age of the basin fill is poorly known due to the lack of well data. It follows that a key risk in this region relates to the presence of mature and generating source rocks, and adequate reservoir and seal facies. While modelling suggests oil and gas may have been generated and expelled from source rocks in the Plover Formation, charge from the Upper Jurassic Vulcan Formation is problematic.

4.4.3.5.2 Presence of Jurassic volcanic and related intrusive rocks

The results of Maginnis 1, and Warrabkook 1 in the Barcoo Sub-basin, confirm that the widespread presence of intrusive and extrusive igneous rocks (as suggested by seismic and magnetic data) is a major risk factor in the region. The risks associated with these rocks relate to the reduction of reservoir volume within mapped structures due to the presence of thick volcanic or intrusive units, thick igneous bodies acting as barriers to migrating hydrocarbons (Jason et al., 2006), and the deterioration of reservoir quality caused by hydrothermal fluids.

4.4.3.6 Overall prospectivity classification

Low–moderate

4.4.4 Exploration status

While exploration permits have been held over parts of the region in the past (Willis, 1988), little exploration had been carried out until 2000 when BHP Billiton Petroleum Pty. Ltd. (BHPB) was awarded five permits (WA-301-P, WA-302-P, WA-303-P, WA-304-P and WA-305-P) over the Seringapatam Sub-basin, Scott Plateau and adjacent areas of the Caswell and Barcoo sub-basins. As a result of that exploration program, two wells were drilled—Maginnis 1 in water depths of 1300 m on the Seringapatam/Caswell sub-basin boundary (Figure 4.22; Locke, 2003), and Warrabkook 1 in the Barcoo Sub-basin, in water depths of 1500 m (Ellis, 2008). Both wells were unsuccessful, intersecting thick breakup-related igneous units.

Exploration permits are currently held over much of the southern half of the Seringapatam Sub-basin. BHP Billiton Petroleum still hold WA-302-P, and Shell were awarded the large WA-477-P permit in 2012. The guaranteed work program for that permit includes the drilling of one well. In 2013, Woodside were awarded a permit covering part of the southern Scott Plateau (WA-495-P); the guaranteed work program includes the acquisition of 3D seismic data.

4.4.5 Data

Key data sets for the Seringapatam Sub-basin and Scott Plateau are listed in Table 4.13–Table 4.16.

The region has a variable 2D seismic coverage, ranging from good, high-quality, closely-spaced data to sparse regional scale lines and older, poorer quality data. Large areas of the Scott Plateau have no seismic coverage (Figure 4.22). Key regional data sets include AGSO surveys 130 and 119 and the PGS New Dawn MultiClient 2D seismic, gravity and magnetic survey (PGS, 2010).

BHPB's exploration program included a series of data acquisition surveys. The initial survey involved acquisition of 2D seismic data, and the acquisition and interpretation of 12 SAR scenes from RadarSat. The seismic survey (HBR2000A) consisted of 18,134 km of data over 302 lines across all five permits; line spacing was 1–15 km, with line density greatest in the eastern Seringapatam Sub-basin (BHP Billiton Petroleum Pty. Ltd., 2003). Seismic reflection data was acquired to 10 s TWT and data quality is excellent. Gravity (17,740 line-km) and magnetic data (17,230 line-km) were also acquired.

The initial surveys were followed by the HBR2001B survey which involved the acquisition of 25,000 line-km of airborne hyperspectral and aeromagnetic data (Ball AIMS, 2002; BHP Billiton Minerals Technology, 2004). A multibeam bathymetric survey (HBR2001C) was then undertaken to assess areas of potential hydrocarbon seepage (BHP Billiton Petroleum Pty. Ltd., 2002a). The final part of the program involved the collection of 400 sea-bed piston cores for geochemical analysis (head space gas and hydrocarbon biomarker analysis) and 33 temperature probes (survey HBR2002A; BHP Billiton Petroleum Pty. Ltd., 2002b). Logan et al. (2008) concluded that the results of the coring program did not provide any evidence of hydrocarbon seepage.

4.4.5.1 Confidence rating

Low–medium

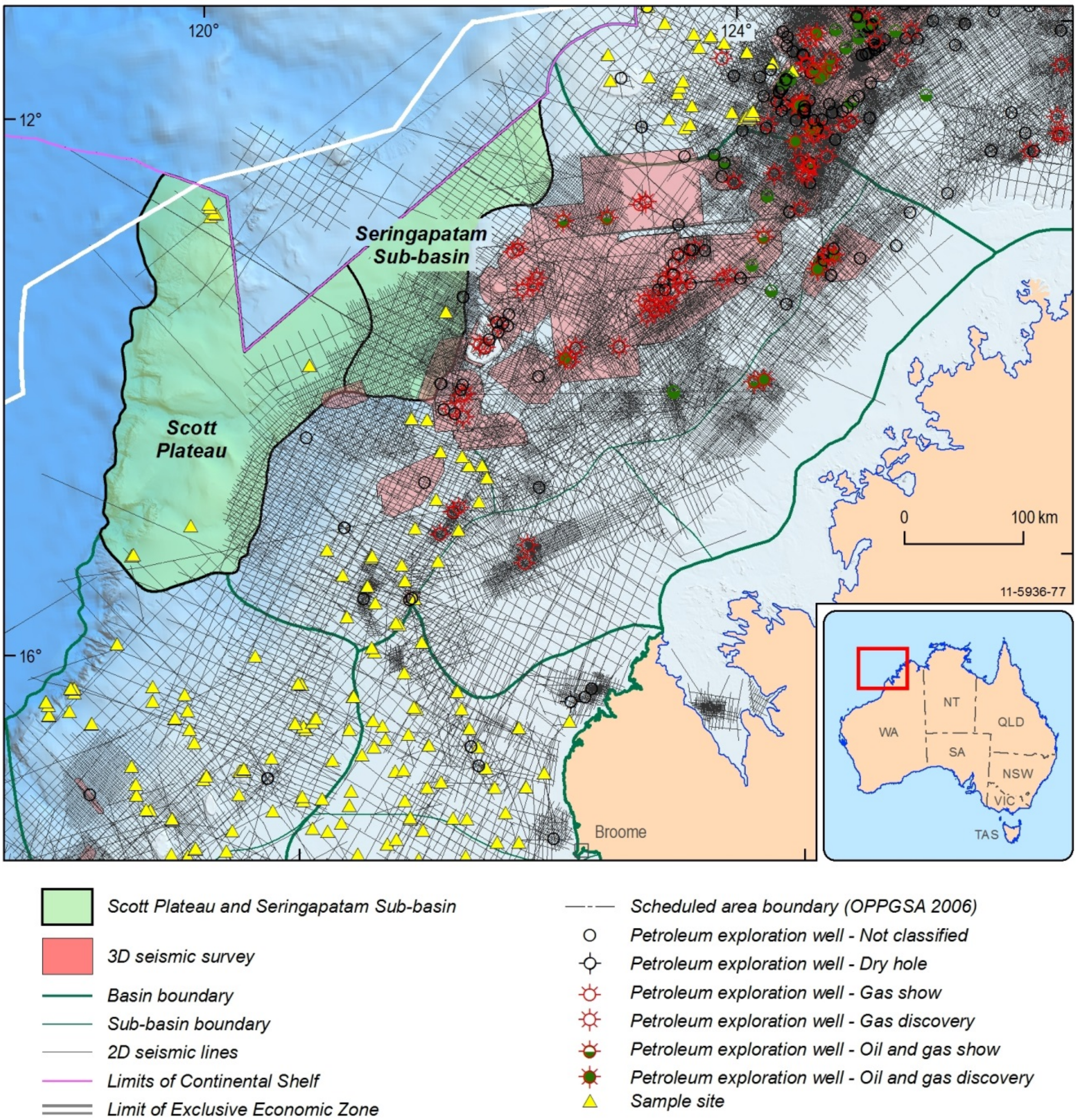

Figure 4.22: Seismic, well and sample distribution, Scott Plateau and Seringapatam Sub-basin.

4.4.6 Issues and remaining questions

The depocentres of the Seringapatam Sub-basin and Scott Plateau developed on highly thinned continental crust on a magma-rich rifted margin. As a consequence of this tectonic history, there are two key factors that impact the prospectivity of these basins:

- heat flow—key questions relate to how the timing, duration and magnitude of thermal events related to extension, rifting and magmatism affected or drove the development of petroleum systems in the area
- igneous rocks— key questions relate to the distribution, geometry and thickness of volcanic and intrusive igneous rocks, the identification of feeder systems and their relationships to major structures, and the impact of igneous rocks and hydrothermal fluids on reservoir quality

As a result of the paucity of drilling in the region, considerable uncertainty exists about most aspects of potential petroleum systems. These include:

- identification, character, quality, maturity, and distribution of potential source rocks
- generation, expulsion and volume of hydrocarbons
- distribution and nature of potential reservoir facies within the Lower–Middle Jurassic Plover Formation and the Upper Jurassic–Lower Cretaceous succession
- timing of key structuring events.

4.4.6.1 Recommendations

- integrated studies and modelling of the crustal and lithospheric structure, using newly acquired aeromagnetic data, recent high-quality seismic data and other geophysical data sets, to help constrain the timing and degree of crustal thinning, timing and extent of magmatism, heat flow history and subsidence
- integrated seismic and magnetic studies to map the distribution of volcanic rocks and related intrusive rocks, including feeder systems
- detailed organic geochemical studies of nearby hydrocarbon accumulations and shows to improve understanding of the origin of the hydrocarbons and any potential contribution from source rocks in the Seringapatam Sub-basin
- stratigraphic drilling of the Scott Plateau to determine the pre-breakup geology and magmatic history of this marginal plateau.

4.4.7 References

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4.4.8 Data Tables

Table 4.13: List of wells, Seringapatam Sub-basin and Scott Plateau.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
2003	Maginnis 1, 1A, 1A/ST1, 1A/ST2	Exploration	BHP Billiton Petroleum	4642.5	Jurassic	Dry	Locke, 2003

Table 4.14: Key seismic surveys, Seringapatam Sub-basin and Scott Plateau.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1971	Petrel Roving 1971 (Deepwater)	Shell Development		
1993	Survey 119	AGSO	3418	
1994	Survey 128	AGSO	3403	
1994	Survey 130	AGSO	4055	
1996	Survey 175 (Browse Basin High Resolution)	AGSO	5274	
1998	BR98 (Browse 1998)	Veritas DGC	23,875	
1998	P98	Woodside Offshore Petroleum	1779	
1998	SPA Outer Browse (OB98)	Seismic Australia	3756	
1998	SPA Deepwater Canning (DC98)	Seismic Australia	7863	
2001	HBR2000A 2D MSS	BHP Petroleum	16,915	
2003	HBR03A 3D MSS	BHP Petroleum	510 km^2	
2005–06	Snarf Dacey 3D MSS	Woodside Offshore Petroleum	1271 km^2	
2006	BKG06	Karoon Gas	915	
2007	Deep Water Northwest Shelf MC2D (New Dawn) PhII	Petroleum Geo-Services Asia Pacific Pty Ltd	22,284 km (total)	PGS, 2010

Table 4.15: List of key surveys involving geological sampling, Seringapatam Sub-basin and Scott Plateau.

Year	Survey	Operator	Region	Type	Rock types	Reference
1971	*Vema* Cruise 28, Leg 11 (ENO 19876)	Lamont Doherty Earth Observatory	Southeast Asia and NW Australia	Piston cores	Marine sediments	Frazer, 1971
1990	BMR Cruise 95: Triassic and Jurassic sequences of the Northern Exmouth plateau and Offshore Canning Basin	AGSO	Exmouth Plateau, Rowley Terrace–Scott Plateau	Dredges	Marine sediments, sedimentary rocks, volcanics	Exon & Ramsey, 1990a, b
	Scott Plateau and Java	BGR (Germany)	Northern Australia/Southeast Asia	Piston cores	Pelagic muds	
	Search for sediment from the last glacial maximum (Survey ENO 85163)	Australian National University	North West Shelf	Gravity and piston cores, grab samples	Seabed sediments	Opdyke, 1996

Table 4.16: Swath bathymetry surveys, Seringapatam Sub-basin and Scott Plateau.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1994	ADEDAV	AGSO/IFREMER		Petkovic et al., 1999
2001	WEPAMA	LOCEAN		
2003	VANC11	SIO		
2005	VITAL	UKIEL		

4.5 Rowley Sub-basin (Roebuck Basin)

4.5.1 Summary

State(s)		Western Australia
Area (km^2)		~64,000
Water Depth (m)		~10–5550
Maximum sediment thickness (m)		>6000
Age range		Permo-Carboniferous or older to Holocene
Basin	**Overlies**	Continental basement, extended continental crust
	Parent	Roebuck Basin
	Adjacent basins	Bedout Sub-basin, Browse Basin (Scott Plateau, Barcoo Sub-basin), offshore Canning Basin (Oobagooma Sub-basin, Broome Platform), Northern Carnarvon Basin (Beagle Sub-basin, Exmouth Plateau)
Basin type		Extensional, passive margin
Depositional setting, rock types		Marine and non-marine clastic sedimentary rocks and marine carbonates.
Petroleum prospectivity		**Moderate**
Confidence		*Medium*

4.5.2 Geology

The Roebuck Basin is located on the North West Shelf of Australia (Figure 4.23). It contains two main depocentres—the Rowley and Bedout sub-basins. The Bedout Sub-basin overlies, in part, the offshore extension of the Canning Basin. The Rowley Sub-basin lies seaward of the Bedout Sub-basin and covers an area of approximately 64,000 km^2. The Rowley Sub-basin is separated from the Beagle Sub-basin (Northern Carnarvon Basin) by the North Turtle Hinge Zone and Thouin Graben, and from the Bedout Sub-basin and Oobagooma Sub-basin (offshore Canning Basin) by the Bedout High and Oobagooma High, respectively (Figure 4.23). The sub-basin contains in excess of 6 km of Paleozoic–Middle Jurassic strata unconformably overlain by up to 2.5 km of Callovian–Holocene sediments (Figure 4.24 and Figure 4.25). The pre-breakup succession onlaps the Oobagooma High, Broome Platform and Bedout High to the east and southeast (Figure 4.25a and Figure 4.25b). This section forms a seaward-thickening wedge that is terminated at the escarpment defining the continent–ocean boundary (Smith et al., 1999). An unconformity at the top of the Paleozoic to Middle Jurassic section is overlain by prograding Callovian–Holocene sequences.

Figure 4.23: Structural elements map, Rowley Sub-basin.

Compared with the adjacent Northern Carnarvon and Browse basins, the Roebuck Basin is notable for its lack of exploration success. Only three wells have been drilled in the Rowley Sub-basin and there have been no hydrocarbon discoveries; however, the Phoenix 1 discovery in the adjacent Bedout Sub-basin provides evidence for the presence of active petroleum systems in the Roebuck Basin (Figure 4.23). The Rowley Sub-basin is subject to renewed exploration interest with drilling of several wells planned for 2014.

4.5.2.1 Structural geology

The Roebuck Basin forms the central element of the Westralian Superbasin. Inboard parts of the basin overlie the offshore continuation of the Canning Basin. The structural geology of the Canning Basin is dominated by northwest-oriented structures that reflect a Paleozoic regime of northeast–southwest intracratonic extension. Initiation of the Westralian Superbasin in the Pennsylvanian (late Carboniferous) was characterised by a change to northwest–southeast extension related to the separation of the Sibumasu terrane from Gondwana (Metcalfe, 1988; Smith et al., 1999). Fault systems within the Rowley Sub-basin reflect this stress regime and generally strike northeast–southwest. Compared with the adjacent Browse and Northern Carnarvon basins, however, the Rowley Sub-basin is only mildly structured.

The inboard margin of the sub-basin is marked by the Oobagooma and Bedout highs. The Oobagooma High comprises a region of uplifted and deformed rocks. It is characterised by seismic reflections that dip steeply to the west, which are interpreted to represent either highly rotated strata or igneous intrusions (Figure 4.25b). The Oobagooma High separates the strongly deformed rocks of the Oobagooma Sub-basin (the western, offshore extension of the Fitzroy Trough) from the unstructured, west-dipping and divergent half-graben fill of the Rowley Sub-basin. The deformed rocks of the Oobagooma High underlie the easternmost Rowley half graben with a distinct angular unconformity. To the south, the Bedout High forms a broad anticlinal feature that is onlapped by Triassic strata. The origin of the Oobagooma and Bedout highs is not well understood. Smith (1999) proposed that these structures formed to accommodate differential NE oriented extension during the Paleozoic, with the Bedout High subsequently reactivated during Westralian extension. Colwell & Stagg (1994) suggested the Bedout High is an intruded basement high underlain by magmatic upwelling and potentially partly thrust controlled, while others (Gorter, 1998; Becker et al., 2004) have suggested that the Bedout High is an impact structure. A strong magnetic anomaly is associated with the western flank of the Oobagooma High, suggesting it may be partly igneous in origin (Smith et al., 1999).

Structurally, the Rowley Sub-basin consists of a series of westward thickening extensional growth wedges overlain by a seaward dipping, relatively undeformed succession (Figure 4.25). In the central part of the Rowley Sub-basin, Permo-Carboniferous(?) to Early Triassic deposition was controlled by one or more large displacement, southeast to east-southeast-dipping normal faults. These faults bound a thick, divergent fill and offset a high amplitude basement reflector at a depth of about 8.5 s TWT. A parallel but smaller fault system inboard of the East Mermaid 1 well (Figure 4.23) bounds at least two connected half graben that contain up to 3 s TWT of basin fill. A distinct angular unconformity between flat-lying Upper Triassic–Lower Jurassic strata and the rotated and eroded hanging wall blocks of the half graben marks a phase of uplift and/or compressional deformation that could be attributable to either the late Permian Bedout Movement or the Middle Triassic Fitzroy Movement (Smith et al., 1999). Seismic data shows that a period of compressional deformation during the Triassic, which Smith et al. (1999) attributed the Fitzroy Movement (Forman & Wales, 1981), resulted in a moderate amount of inversion on some faults and the development of large folds.

The stratal geometry of the post-rift Triassic and Lower–Middle Jurassic succession suggests that accommodation during this period was controlled by prolonged thermal subsidence. Seismic data indicates that fault control on deposition at this time was minimal except along the outer margin of the basin. This region is characterised by a series of Middle Jurassic, large displacement, northwest-dipping normal faults; the most westward of these fault systems forms the ocean–continent boundary. Structuring of the Upper Triassic–Jurassic section also increases to the southwest, closer to the Northern Carnarvon Basin (e.g. at Whitetail 1; Figure 4.23).

The commencement of continental breakup in the Callovian was accompanied by uplift and erosion and the development of a regional scale unconformity; erosion is particularly prominent across the rotated footwall blocks of the outboard Middle Jurassic faults. During the Late Jurassic–Paleogene period of passive margin subsidence, the basin did not experience any significant deformation or structural reactivation.

Compared with the neighbouring Browse Basin, the Rowley Sub-basin does not appear to have been significantly affected by igneous activity. There are some seismic indications suggesting the presence of igneous intrusions (dykes and sills) within the Paleozoic–Triassic and Jurassic successions, particularly at the inboard edge of the sub-basin adjacent to the Oobagooma High, but they do not appear to be widespread or voluminous (Figure 4.25b).

4.5.2.2 Basin evolution and depositional history

As drilling in the Rowley Sub-basin is sparse, interpretation of the subsidence and depositional history of the basin is derived in part from the adjacent Bedout Sub-basin and offshore Canning Basin. Several authors have postulated the presence of an Ordovician–lower Carboniferous section equivalent to that in the Canning Basin underlying the sub-basin (Lipski, 1993; Kennard et al., 1994; Smith et al., 1999). However, the nature of the succession underlying the large half graben outboard of the Oobagooma High is difficult to resolve on seismic data.

The oldest section intersected by drilling is Rhaetian (latest Triassic); Huntsman 1, located in the western part of the sub-basin (Figure 4.23), reached total depth within the mudstone-dominated, marine to marginal marine Brigadier Formation (equivalent to the Bedout Formation; Figure 4.24; Woodside, 2007). This result, and correlation with wells drilled in the adjacent Bedout and Beagle sub-basins, provides an age-constraint for the post-rift (thermal sag) succession unconformably overlying the basal half graben. The rift succession is therefore likely to be either Permian–Triassic or Carboniferous–Permian in age. Several wells drilled in the offshore Canning Basin intersected Permian and Carboniferous, non-marine and glacially-influenced sediments. The overlying Triassic succession represents deposition during a widespread post-rift marine transgression.

The Triassic sediments are overlain by a thick Jurassic succession (Depuch Formation; Figure 4.24), which was intersected in both Huntsman 1 and East Mermaid 1 (Figure 4.23). The Jurassic succession accumulated in largely marine, marginal marine and deltaic environments; oolitic limestone within the lower Jurassic section indicates periods of quiet lagoonal deposition. The upper part of the Jurassic section is dominated by thick, delta-plain sandstone units.

Commencement of breakup in the Callovian resulted in the formation of a regional unconformity at the top of the Jurassic section. During the Cretaceous, post-breakup subsidence of the margin resulted in the deposition of a mudstone-rich to marly succession in shallow to increasingly deeper marine conditions (Figure 4.24). The overlying Cenozoic succession comprises a progradational calcilutite-dominated wedge.

4.5.2.3 Level of knowledge

Knowledge of the Rowley Sub-basin is poor to moderate. Geological understanding of the sub-basin is based on data provided by only three wells (Figure 4.23), interpretation of a variable quality seismic data set of moderate overall coverage (Figure 4.26), and correlation to adjacent basins/sub-basins that appear to have experienced different structural and stratigraphic histories. The early extensional depocentres have not been drilled and therefore interpretation of much of the basin fill is speculative.

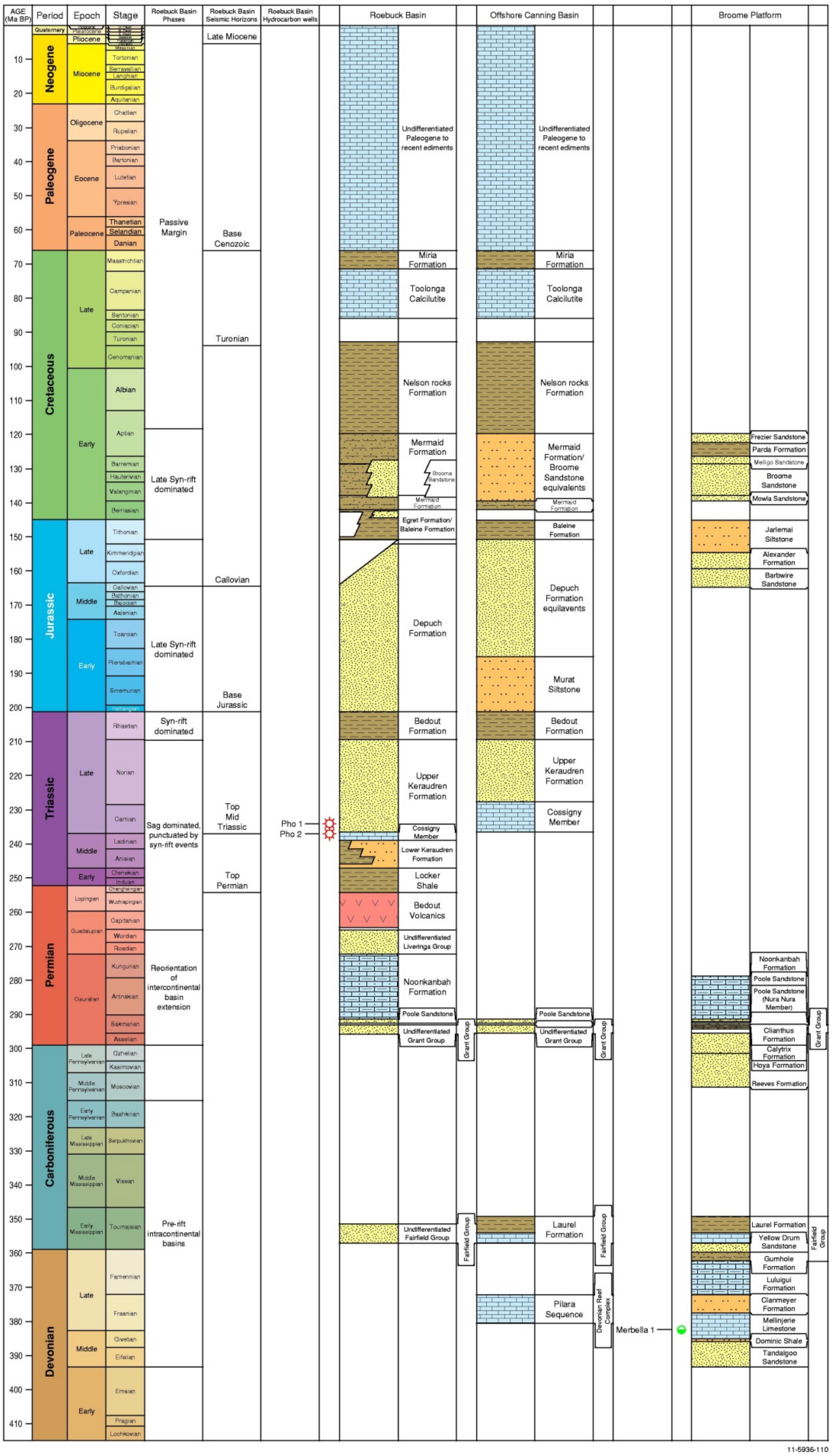

Figure 4.24: Stratigraphy of the Roebuck Basin. Geologic time scale after Gradstein et al. (2012).

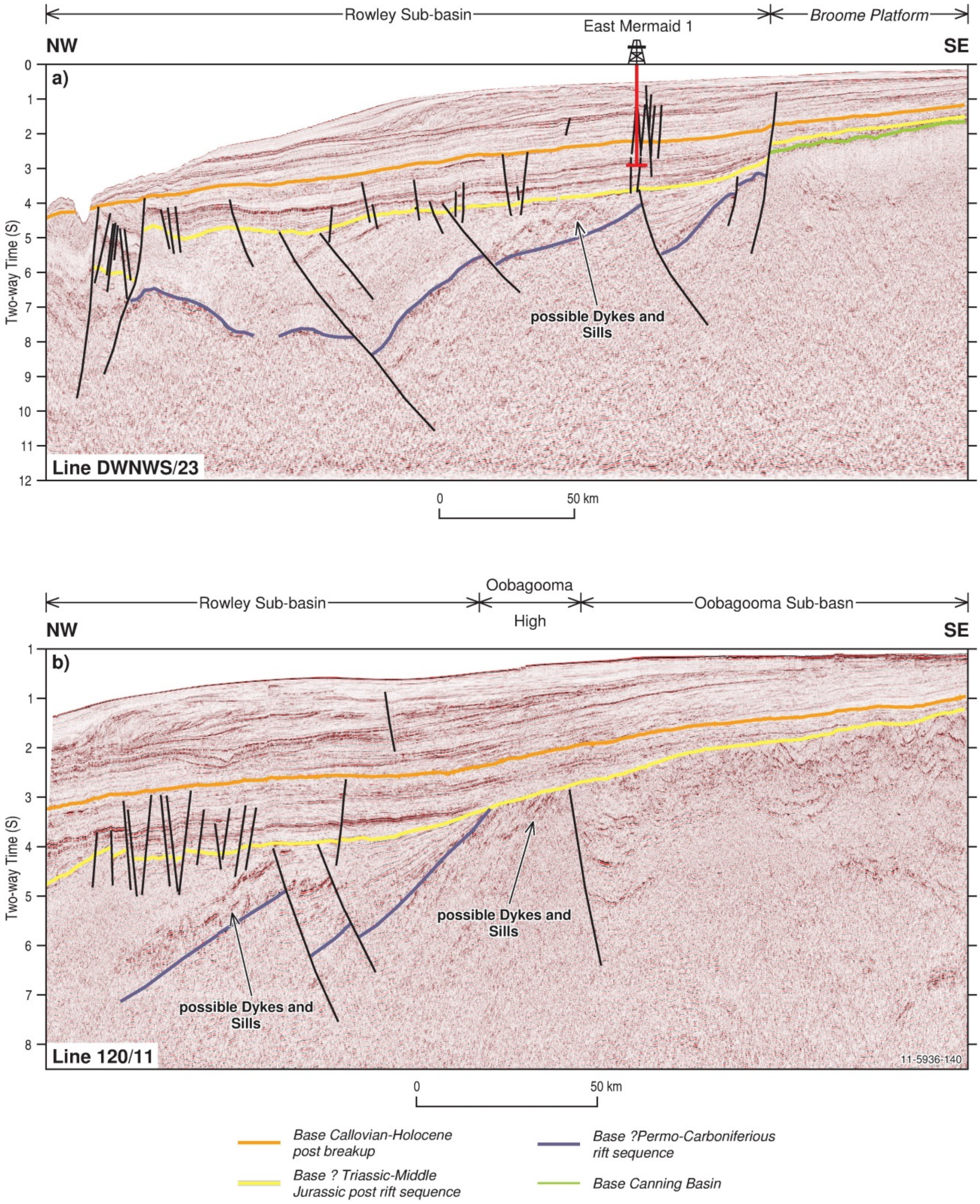

Figure 4.25: Seismic sections across the Rowley Sub-basin: a) transect across the central part of the sub-basin (seismic line courtesy of PGS); b) section across the Roebuck–offshore Canning basin boundary.

4.5.3 Petroleum systems

No commercial discoveries have been made in the Rowley Sub-basin and no significant hydrocarbons shows have been encountered in drilling. Early exploration campaigns conducted in the sub-basin, and the broader Roebuck Basin, focused on closures associated with large structural features such as the Bedout High and the East Mermaid anticlinal structure (Shell Development, 1973). Drilling by Woodside in the 2000s in the western Rowley Sub-basin tested Beagle Sub-basin style plays, but was also unsuccessful.

4.5.3.1 Source Rocks

Smith et al. (1999) identified the most prospective petroleum source rocks in the Rowley Sub-basin as transgressive shale and minor coal intervals within the Triassic succession (Locker Shale and Keraudren Formation; Figure 4.24; Esso, 1994; Smith et al., 1999; Woodside Energy Limited, 2001). The gas discovery in Phoenix 1 and the gas show in Phoenix 2 in the Bedout Sub-basin (Figure 4.23) are attributed to these source intervals. In the outer Rowley Sub-basin, these source rocks could be presently expelling liquids (Smith et al., 1999; O'Brien et al., 2003).

Numerous thin coaly and algal-rich mudstones and correlative pro-delta marine shales in the Depuch Formation, which is in part equivalent to the Legendre Formation in the Beagle Sub-basin (Figure 4.24), may also have source potential; these rocks may be early to late mature beneath the Oligocene carbonate wedge (Smith, 1999; Smith et al., 1999). Woodside (2003, 2007) identified the Middle Jurassic organic-rich rocks (equivalent to the Athol Formation of the Northern Carnarvon Basin) as a potential gas-prone source rock, with one unit (the "Picard Shale") having significant liquids potential.

Lower Cretaceous transgressive marine shales could potentially be mature beneath the thickest parts of the Cenozoic carbonate wedge (Smith et al., 1999). The source potential of the interpreted Permian and Carboniferous rift succession is unknown.

4.5.3.2 Generation and expulsion

Smith et al. (1999) showed that at East Mermaid 1 (Figure 4.23), the Jurassic succession reached early oil maturity in the Early Cretaceous, which suggests that the underlying Triassic succession is oil to possibly gas mature.

Petroleum systems modelling by Woodside (2007) for Triassic and Middle Jurassic source rocks in the outer part of the sub-basin demonstrated that the main phase of hydrocarbon generation took place during the Jurassic, with expulsion occurring at a slower rate during the Cretaceous, and no significant hydrocarbon generation during the Cenozoic.

4.5.3.3 Reservoirs and seals

Good quality reservoirs have been intersected in all three exploration wells in the sub-basin, which targeted Lower–Middle Jurassic sandstones. In Huntsman 1 (Figure 4.23), average porosities ranged from 20.8% in Lower–Middle Jurassic marine facies (Athol Formation equivalent) to 29.9% in Middle Jurassic deltaic sandstones (Depuch or Legendre Formation; Figure 4.24), with net:gross values around 75% (Woodside, 2007).

Within the older, undrilled section, potential reservoirs may be present within the Triassic Keruadren Formation and Locker Shale, and the underlying syn-rift succession (Figure 4.24; Lipski, 1993; Kennard et al., 1994; Smith et al., 1999). The Keraudren Formation and Locker Shale are likely to have higher porosity and permeability in the more shallowly buried areas where there is less potential for secondary carbonate and silica precipitation (Lipski, 1993).

Potential seal facies are present within the Lower–Middle Jurassic succession (e.g. Athol Formation equivalent), and Lower Cretaceous shales (e.g. Muderong/Baleine Formation) could provide seal for accumulations in the upper part of the Legendre/middle Depuch Formation (Figure 4.24; Woodside, 2003, 2007). Potential seals within the Triassic include intraformational shales in the Keraudren Formation (effective in Phoenix 1) as well as the Cossigny Member of the Keraudren Formation and the correlative Locker Shale (Lipski, 1993).

4.5.3.4 Play types

Compared with the adjacent, more successful hydrocarbon provinces of the Browse and Northern Carnarvon basins, the Rowley Sub-basin is not highly structured. The range of potential structural plays to be explored is consequently limited. Exploration has focused, without success, on Jurassic sandstones within structural traps, both inboard at East Mermaid 1 where a large anticlinal trend was the target, and outboard at Huntsman 1, which targeted a tilted fault block play (Figure 4.23). In the outboard parts of the sub-basin, where the post-breakup section thins and the Triassic and older section thickens, deeper plays within the Permian–Triassic section, and Jurassic fault blocks with access to hydrocarbons generated by Triassic or Permian source rocks may have some potential. The current phase of exploration by Woodside/Shell is focused on large anticlinal structures in the Triassic section (Woodside, 2012).

The potential also exists for a range of stratigraphic plays in the basin. For example, fluvio-deltaic sandstone bodies in the Jurassic Depuch Formation (Figure 4.24), charged from intraformational or underlying source rocks (Lipski, 1993; Smith et al., 1999), and onlap/pinchout plays associated with growth of Triassic anticlines. In addition, the Rhaetian reef play tested in the outer Exmouth Plateau at Tiberius 1 (Grain et al., 2013) may also be a viable exploration target along the outer margins of the Rowley Sub-basin where Late Triassic shelfal carbonates have been dredged (Colwell et al., 1994).

4.5.3.5 Critical risks

4.5.3.5.1 Presence of mature and generating source rocks and timing of charge

The nature and distribution of source rocks in the Rowley Sub-basin is poorly understood, so the presence of mature and generating source pods is a critical risk, particularly for plays dependent on charge from the Paleozoic–Triassic section.

Woodside (2003, 2007) indicated that a key risk in their exploration acreage was the timing of migration relative to trap formation; the failure of Huntsman 1 was attributed to maximum expulsion from source rocks in the area being too early for charge to be trapped (Woodside, 2007).

4.5.3.5.2 Seal quality

For targets within the Depuch Formation relying on seal by basal Lower Cretaceous mudstones (such as Whitetail 1), the thickness and quality of seal facies is a key risk (Woodside, 2003). The development of that seal relative to the timing hydrocarbon charge was also considered to be a potential risk (Woodside, 2007).

4.5.3.6 Overall prospectivity classification

Moderate

4.5.4 Exploration status

Only three wells have been drilled in the Rowley Sub-basin—East Mermaid 1, Whitetail 1 and Huntsman 1 (Figure 4.23). All wells were dry and the lack of exploration success, particularly compared with adjacent basins, has driven negative perceptions about the prospectivity of the area.

Exploration in the region commenced in the late 1960s. Two phases of exploration, in the early 1970s and 1980s, resulted in the drilling of a suite of wells across the Roebuck and offshore Canning basins; East Mermaid 1, drilled near the inboard margin of the Rowley Sub-basin was the furthest offshore of these wells, with most drilling concentrated in the Bedout and Oobagooma sub-basins. Exploration success in the region was limited a gas discovery in Triassic reservoirs at Phoenix 1 in the Bedout Sub-basin, gas shows at Phoenix 2, and oil indications within Paleozoic reservoirs at Perindi 1 in the offshore Canning Basin. In the more intensively explored Beagle Sub-basin to the southwest, oil was discovered in the Jurassic sandstones at Nebo 1 (Osborne, 1994) Drilling during this early phase of exploration was underpinned by the acquisition of several small 2D seismic grids and a few regional 2D surveys. In the late 80s to early 90s, more regional 2D seismic was acquired and the North West Shelf tie lines (surveys 95 and 120) were shot by AGSO.

In the late 1990s, Woodside commenced an exploration campaign in the western Rowley Sub-basin. Seismic acquisition included closely spaced 2D surveys and the first 3D grids in the basin, which were used to determine the Whitetail 1 and Huntsman 1 drilling targets. Several large multi-client surveys were also acquired during this period. Recently, seismic lines were acquired across the sub-basin by Petroleum Geo-Services (PGS) and Ion-GTX as part of large, regional surveys.

Exploration permits are currently held in the central Rowley Sub-basin, where a Woodside and Shell are undertaking an exploration campaign that includes the drilling of eight wells in the initial three-year term (Woodside, 2013). In 2012, the large (11,500 km^2) Curt 3D seismic survey was acquired over these permits. In 2013, Woodside and Shell were awarded an adjacent permit in the outer Rowley Sub-basin that extends into the Scott Plateau/Barcoo Sub-basin region of the Browse Basin. Current exploration permits also straddle the boundaries of the Rowley sub-basin with the Bedout Sub-basin (Apache) and Beagle Sub-basin (Karoon Gas and Repsol Exploration) and the offshore Canning basins (Pathfinder Energy).

4.5.5 Data

Key data sets for the Rowley Sub-basin are listed in Table 4.17–Table 4.20.

Three wells have been drilled in the Rowley Sub-basin, two of which are located in the western part of the basin adjacent to the Beagle Sub-basin (Figure 4.23); all were dry.

The sub-basin has a variable, widely (5–20 km) to closely-spaced (<1 km) coverage of 2D seismic data (Figure 4.26). Key regional data sets include AGSO's survey 120, and the PGS New Dawn survey. In the western part of the sub-basin, Woodside's Tarantula and Arachnid 2D surveys provide a good seismic coverage and the Huntsman and Whitetail surveys are the only 3D seismic datasets in the basin. The northeastern part of the sub-basin is covered by regional scale multi-client data.

During the 1990s, BMR/AGSO undertook geological sampling surveys along exposed slopes on the seaward edge of the sub-basin. These surveys obtained numerous samples from the Triassic to Cenozoic succession (Colwell et al., 1994). In 2006, Geoscience Australia conducted a hydrocarbon seepage survey over the Roebuck and offshore Canning Basins (Survey SS06/06; Jones et al., 2007); however, no definitive evidence of natural hydrocarbon seepage was detected.

4.5.5.1 Confidence rating

Medium

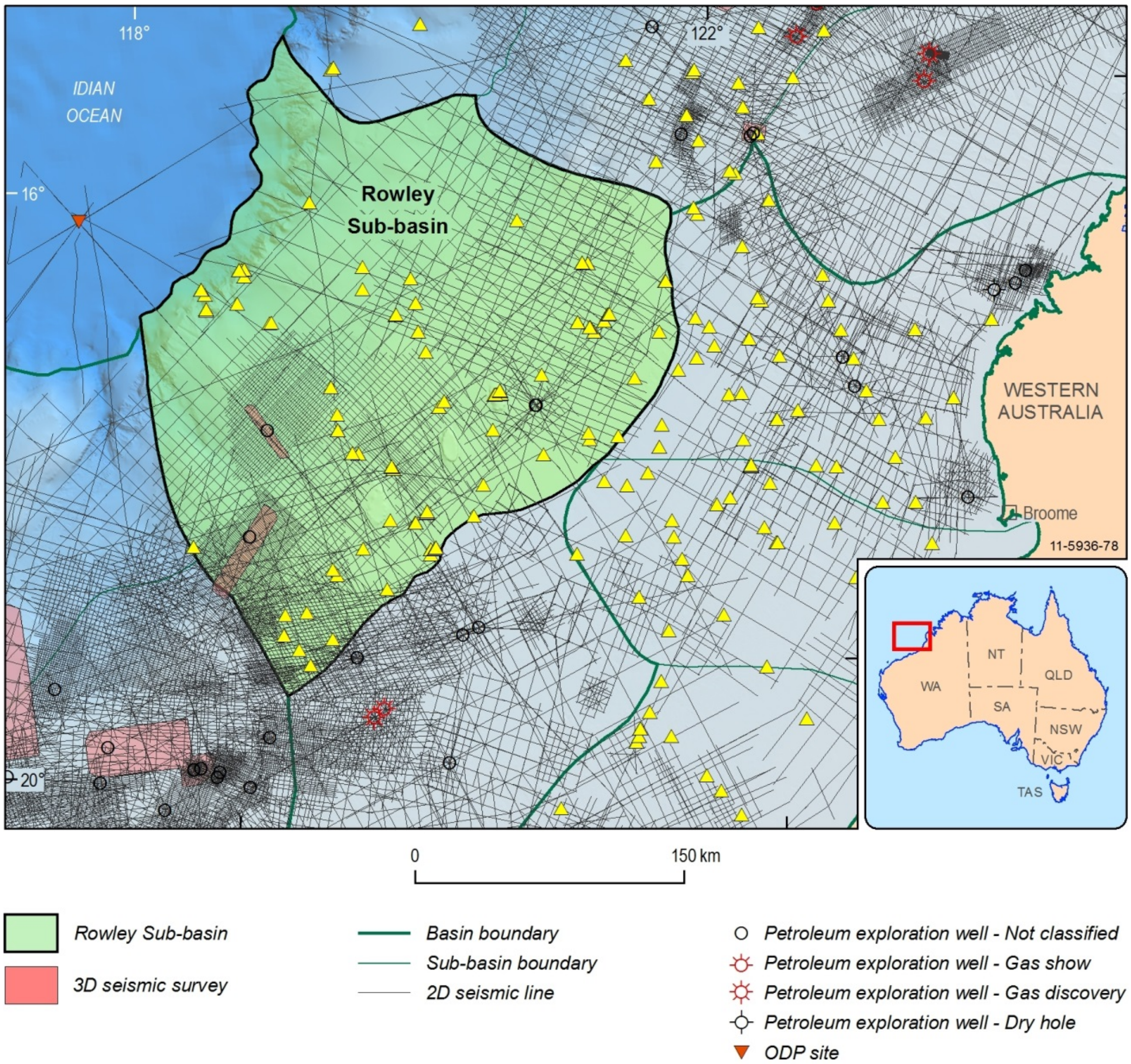

Figure 4.26: Seismic, well and sample distribution, Rowley Sub-basin.

4.5.6 Issues and remaining questions

Among the basins of the North West Shelf, the Roebuck Basin, and in particular the Rowley Sub-basin, stands out for the lack of exploration success. The key question regarding the prospectivity of the Rowley Sub-basin is why exploration in this area has been unsuccessful when the adjacent Browse and Northern Carnarvon basins are two of Australia's more important petroleum provinces.

The Rowley Sub-basin clearly has a different structural architecture, subsidence history and basin fill from the adjacent basins—it is relatively unstructured and the source rocks that are so prolific in the Northern Carnarvon and Browse basins do not appear to be effective here. Is the lack of success a function of the absence of those source rocks or is it a lack of effective migration pathways for generated hydrocarbons?

Advances in our understanding of the Rowley Sub-basin are likely to be made in the near future, as Woodside and Shell's current exploration program by Woodside and Shell in WA-462-P, WA-464-P and WA-466-P includes the acquisition of 3D seismic and the drilling of eight wells as part of the guaranteed work program.

At present, the main exploration issues in the Rowley Sub-basin concern the identification of large structural traps and characterisation of key petroleum systems elements.

4.5.6.1 Structure

Compared to adjacent basins, the Rowley Sub-basin is only mildly structured, which raises the following issues:

- The relatively minor amount of faulting may have limited effective migration pathways for generated hydrocarbons.
- A well-constrained velocity model is required to enable accurate depth mapping, which is critical to the identification of subtle structural or combined structural and stratigraphic prospects.

4.5.6.2 Petroleum Systems

As a result of sparse drilling in the Rowley Sub-basin, uncertainties persist regarding a range of key issues:

- identification, characterisation, quality, maturity and distribution of potential source rocks. The main source rock section in the Browse Basin is the Lower–Middle Jurassic Plover Formation. In the Rowley Sub-basin, much of the equivalent succession comprises a sand-rich deltaic system; however, more marine facies are present at the base of this succession. A better understanding of the distribution and depositional controls on these marine-influenced facies, and the potential of coaly facies within the overlying deltaic section is required. The maturity of these successions may also be an issue in the outer Rowley Sub-basin, seaward of the thickest part of the overlying Cretaceous–Cenozoic section. Another key uncertainty concerning source rocks is the unknown nature of the Triassic and older succession, and therefore their source potential.
- distribution and quality of potential seal facies within the Lower–Middle Jurassic and Lower Cretaceous successions
- timing of charge relative to trap formation and seal development.

4.5.6.3 Recommendations

With the prospect of eight new wells being drilled in the sub-basin within the next few years as part of the current Woodside/Shell work program, some of these issues will undoubtedly be addressed. Additional work that could lead to an improvement in the understanding of the basin includes:

- acquisition of wide-angle refraction seismic data to better constrain depth conversion
- dredge sampling of Triassic and Jurassic sequences exposed by faulting and uplift along the seaward margin of the basin. This could provide additional data on the facies and prospectivity in distal parts so the basin and would supplement sampling originally undertaken by BMR in the early 1990s
- further detailed organic geochemical studies of hydrocarbon shows and hydrocarbons from discoveries in adjacent areas to determine their likely source and the application of these results to analysis of the Rowley Sub-basin succession
- regional palaeogeographic and structural studies to help identify broader controls on deposition and key differences in basin history along the margin, and provide insights into the likely distribution of facies.

4.5.7 References

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4.5.8 Data Tables

Table 4.17: List of wells, Rowley Sub-basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1973	East Mermaid 1	Exploration	Shell Development	4067	Lower Jurassic	Dry	Shell Development, 1973
2003	Whitetail 1	Exploration	Woodside	2504	Jurassic	Dry	Woodside, 2003
2006	Huntsman 1	Exploration	Woodside	4375	Upper Triassic	Dry	Woodside, 2007

Table 4.18: Key seismic surveys, Rowley Sub-basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
2002	Whitetail 3D MSS	Woodside Offshore Petroleum	555 km^2	
2002	Huntsman 3D MSS	Woodside Offshore Petroleum	255 km^2	
2001–02	Browse 2001 2D MSS	Veritas DGC	6400	
2001	Araneus 2D MSS	Woodside Offshore Petroleum	1800	
1999–2000	Tarantula 2D MSS	Woodside Offshore Petroleum	13,143	
1999–2000	Arachnid 2D MSS	Woodside Offshore Petroleum	1766	
1998–1999	Browse 1998 SPEC MSS	Veritas DGC	23,875	
1998	SPA Outer Browse 98 4SL_97-8 MSS	Seismic Australia	3755	
1998	SPA 3SL_97-8 Deepwater Canning 2D MSS	Seismic Australia	7863	
1998	Beagle Deep Multi Client MSS	Nopec	10,249	
1995	OBS NW Shelf (Survey 168)	AGSO	2764	
1994	NW Margin Transect (Survey 128)	AGSO	3403	
1993	S NW Shelf 3 (Survey 120)	AGSO	4052	
1992	C92A MSS	Esso	2768	
1990	Canning–Exmouth (Survey 95)	BMR	2085	

Table 4.19: List of key geological sampling surveys, Rowley Sub-basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
1968	Northwest Shelf Sampling Survey 1	BMR	North West Shelf	Grab, dredge	Shelly calcarenites, gravels	Jones, 1973
1990	BMR Cruise 95: Triassic and Jurassic sequences of the Northern Exmouth plateau and Offshore Canning Basin	AGSO	Exmouth Plateau, Rowley Terrace–Scott Plateau	Dredges	Marine sediments, sedimentary rocks, volcanics	Exon & Ramsey, 1990a, b
2006	Central NWS seepage	Geoscience Australia	Rowley Sub-basin and offshore Canning Basin	Grab, dredge, water column		Jones et al., 2007

Table 4.20: Swath bathymetry surveys, Rowley Sub-basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1994	ADEDAV	AGSO/IFREMER		Petkovic et al., 1999
2003	VANC11	SIO		
2006	Central NWS (Rowley Shoals)	GA		Jones et al., 2007
2007	NW Bio (Legs 1–3)	CMAR		

4.6 Offshore Canning Basin

4.6.1 Summary

State(s)		Western Australia
Area (km^2)		~75,050
Water Depth (m)		30–450
Maximum sediment thickness (m)		~10,000
Age range		Ordovician(?) to Holocene
Basin	**Overlies**	Continental basement
	Adjacent basins	Onshore Canning Basin, Roebuck Basin (Bedout Sub-basin, Rowley Sub-basin), Browse Basin (Barcoo Sub-basin, Leveque Shelf), Northern Carnarvon Basin (Lambert Shelf)
Basin type		Extensional
Depositional setting, rock types		Marine and non-marine clastic sedimentary rocks and marine carbonates.
Petroleum prospectivity		Moderate
Confidence		*Low–medium*

4.6.2 Geology

The offshore continuation of the Canning Basin, in northwestern Western Australia, contains three main depocentres—Oobagooma Sub-basin, Broome Platform and Willara Sub-basin (Figure 4.27). The offshore portion of the basin contains up to 10 km of presumed Ordovician to Cenozoic marine and non-marine siliciclastics and marine carbonates.

The Early Ordovician to Early Cretaceous Canning Basin (Figure 4.28) occupies about 506,000 km^2, of which 430,000 km^2 is onshore. Upper Cretaceous and Tertiary sediments are restricted to the offshore portion of the basin and pinch-out landward. The onshore part of the basin has a maximum sediment thickness of over 15 km concentrated in two northwest trending depocentres. The northernmost of these is the Fitzroy Trough–Gregory Sub-basin complex, while the southernmost is the Willara Sub-basin–Kidson Sub-basin complex. The offshore extension of the Fitzroy Trough is the Oobagooma Sub-basin (Hocking et al., 1994).

Only six wells have been drilled in the offshore Canning Basin (Figure 4.27); no discoveries have been made and it remains an exploration frontier.

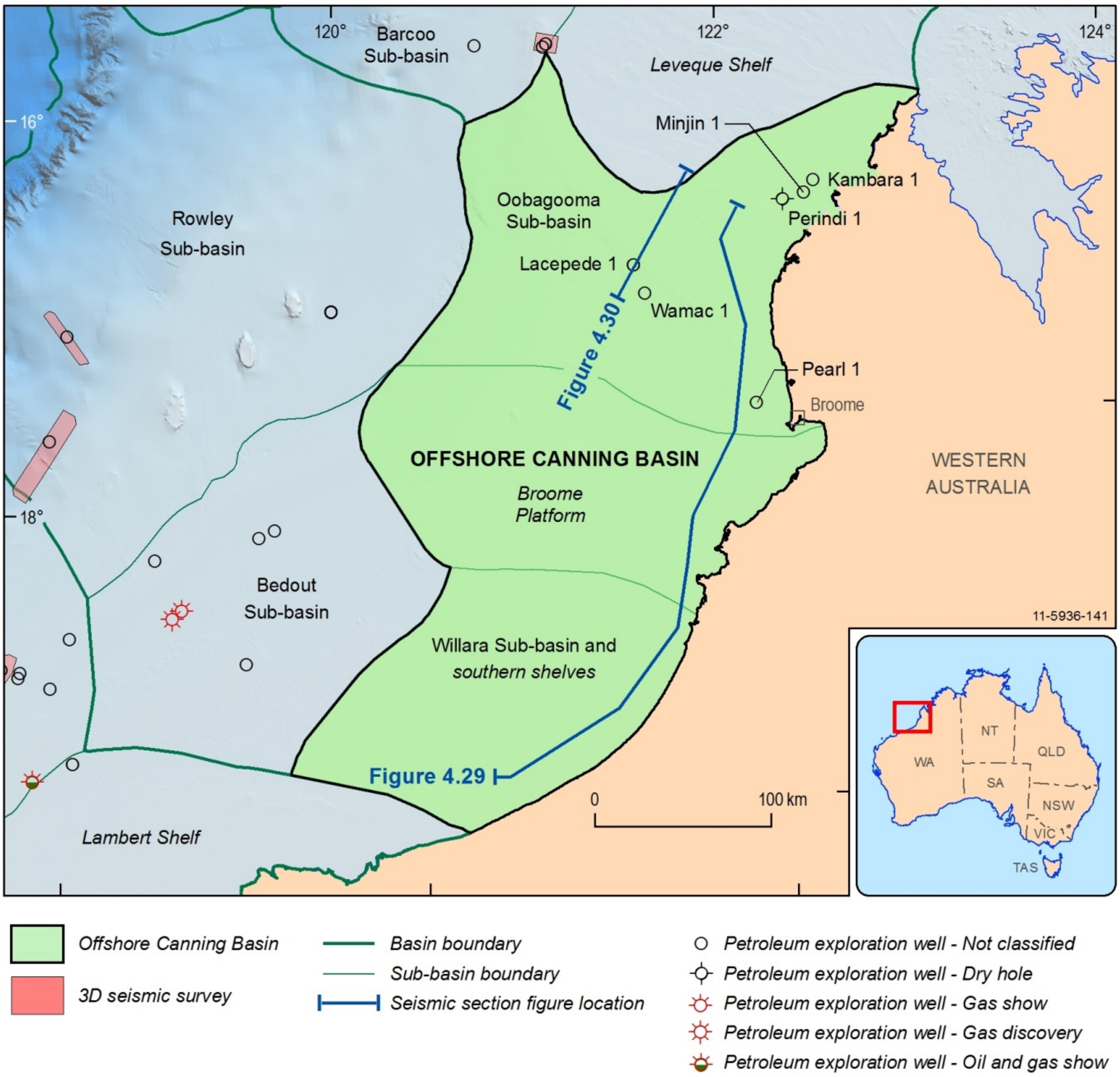

Figure 4.27: Structural elements map, offshore Canning Basin.

4.6.2.1 Structural geology

The two main Paleozoic depocentres of the offshore Canning Basin are the Oobagooma Sub-basin (the offshore continuation of the Fitzroy Trough and Pender Terrace) in the north and a southern depocentre comprising the offshore extensions of the Willara Sub-basin, Samphire Graben, Wallal Platform and Wallal Embayment (Smith, 1999). These depocentres are separated by the west-northwest-trending, only mildly deformed, structural high of the Broome Platform (Figure 4.27 and Figure 4.29). The deformed Paleozoic section is overlain by a westward thickening wedge of Triassic to Cenozoic rocks (Figure 4.30). In the south, the offshore Canning is contiguous with the Bedout Sub-basin of the Roebuck Basin.

The Oobagooma Sub-basin is composed largely of a northwest-trending, fault-bounded, deformed and partially-inverted graben, and is approximately 150 km long and 100 km wide (Figure 4.27). The structural style of the sub-basin margin changes from an asymmetrical, southwestward-thickening half graben onshore (Drummond et al., 1991), to a more symmetrical graben in the near offshore

(Figure 4.29; Smith et al., 1999). The Paleozoic basin-bounding and intra-basin faults trend northwest to north-northwest. The change in structural orientation occurs adjacent to the Oobagooma High, an asymmetric high that marks the boundary between the Oobagooma and Rowley sub-basins (Figure 4.27; Smith, 1999).

The sub-basin contains a Permian–Devonian and possibly older succession up to 5.5 km thick overlain by approximately 4.5 km of Mesozoic–Cenozoic sediments (Smith, 1999). The Paleozoic succession is strongly deformed (Figure 4.29 and Figure 4.30) and appears to have undergone multiple phases of compression or transpression, the most important being the Middle–Late Triassic Fitzroy Movement (Forman & Wales, 1981; Smith, 1999). In the western half of the sub-basin, the pre-Jurassic section is extensively intruded by igneous dykes and sills of probable Permian age (Reeckmann & Mebberson, 1984). The latest phase of compression/transpression occurred in the late Cenozoic; deformation extends to near the surface and probably reflects the same phase of Miocene deformation that affected the Browse Basin and formed the large inversion anticlines on the eastern margin of the Barcoo Sub-basin. Reverse movement on basin-bounding and intra-basinal faults during this event resulted in the development of a series of inversion anticlines. A prominent intra-basinal pop-up structure in the easternmost part of the sub-basin may be related to the formation of a new strike-slip fault during the Miocene event, or reactivation of an earlier formed strike-slip fault identified by Zhan & Mory (2013).

The Oobagooma High is a 25 km wide north–south-oriented elongate feature (Figure 4.27), which separates the Oobagooma Sub-basin from the Rowley Sub-basin at the Paleozoic level (Smith et al, 1999). A strong magnetic anomaly on the western flank of the Oobagooma High suggests that it may be associated with igneous rocks. The structural formation of the Oobagooma and Bedout highs appear to be related, although the mechanism is uncertain. Smith (1999) suggested that these structures formed to accommodate differential northeast oriented extension during the Paleozoic. Various theories have been proposed for the formation of the Bedout High, including compressional faulting, igneous intrusion and/or magmatic underplating and asteroid impact (Colwell & Stagg, 1994; Gorter, 1998; Becker et al., 2004).

The Broome Platform (Figure 4.27 and Figure 4.29) is a long-lived uplifted area of shallow basement, capped by a thin succession of Ordovician, Devonian and Permian rocks (around 1–2 km thick) that dips gently to the southeast (Kennard et al., 1994). The platform is flanked on its northern margin by the fault-bounded Jurgurra Terrace.

The offshore continuation of the Willara Sub-basin and flanking terraces contains a Paleozoic sedimentary section; sparse, poor quality seismic data suggests that this section is about 2 km thick, but the maximum sediment thickness is not known. This depocentre has not been drilled but is inferred to contain a succession similar to that intersected onshore. The onshore Willara Sub-basin contains an Ordovician–Devonian succession, which accumulated in a series of half graben, unconformably overlain by Permian Grant Group glacial sediments (Romine et al., 1994). The Paleozoic rocks are in turn unconformably overlain by a Jurassic–Cretaceous succession that thickens offshore.

4.6.2.2 Basin evolution and depositional history

The basin was initiated during an Early Ordovician phase of extension and rapid subsidence that led to deposition of the Nambeet, Willara, Goldwyer and Nita formations under marine and supratidal conditions (Kennard et al., 1994; Romine et al., 1994). Rifting was followed by a prolonged sag stage characterised by widespread evaporitic and playa conditions in the Late Ordovician and Silurian (Carribuddy Group, including Bongabinni Formation; Kennard et al., 1994).

In the earliest Devonian, a period of minor folding, regional uplift and erosion was followed by the accumulation of laterally extensive aeolian and terrestrial deposits. A major phase of extension, rifting and rapid subsidence occurred in the Middle Devonian. The period of thermal subsidence that followed this extension was interrupted by at least two extensional tectonic pulses marked by influxes of conglomerates along the northern margins of the basin. Deposition during the Late Devonian was marked by the development of an extensive reef complex. Mixed carbonate–clastic deposition continued into the Carboniferous with the deposition of the Fairfield Group (including the Laurel Formation; Figure 4.28), which was succeeded in turn by deposition of the fluvio-deltaic Anderson Formation; thickening of this unit into bounding faults on the southern side of the Fitzroy Trough indicates renewed extension (Kennard et al., 1994).

A mid-Carboniferous compressional event resulted in inversion on Devonian normal faults and development of a regional unconformity. Renewed extension and rapid subsidence coincided with the onset of glacial conditions in the early Permian and led to the deposition of the Grant Group (Figure 4.28; Kennard et al., 1994). The subsequent early Permian–Early Triassic sag phase commenced with a widespread post-glacial transgression (Poole Sandstone) followed by marine and non-marine deposition (Noonkanbah Formation, Liveringa Group, Blina Shale).

In the Middle–Late Triassic, the basin was affected by a regional compressional event, the Fitzroy Movement (Forman & Wales, 1981). This resulted in inversion and strike-slip movements on the basin-bounding faults and up to 3 km of uplift and erosion (Kennard et al., 1994). From the Middle Jurassic, passive margin subsidence led to the accumulation of a westward thickening wedge of fluvio-deltaic and marine sediments. A compressional/transpressional event in the Cenozoic resulted in further deformation of the offshore basin succession.

4.6.2.3 Level of knowledge

The level of knowledge of the offshore Canning Basin is poor to moderate. Understanding of the geology of the sub-basin is based on data provided by six wells in the Oobagooma Sub-basin, interpretation of a variable quality seismic data set of moderate–poor overall coverage (Figure 4.31), and correlation to the onshore basin.

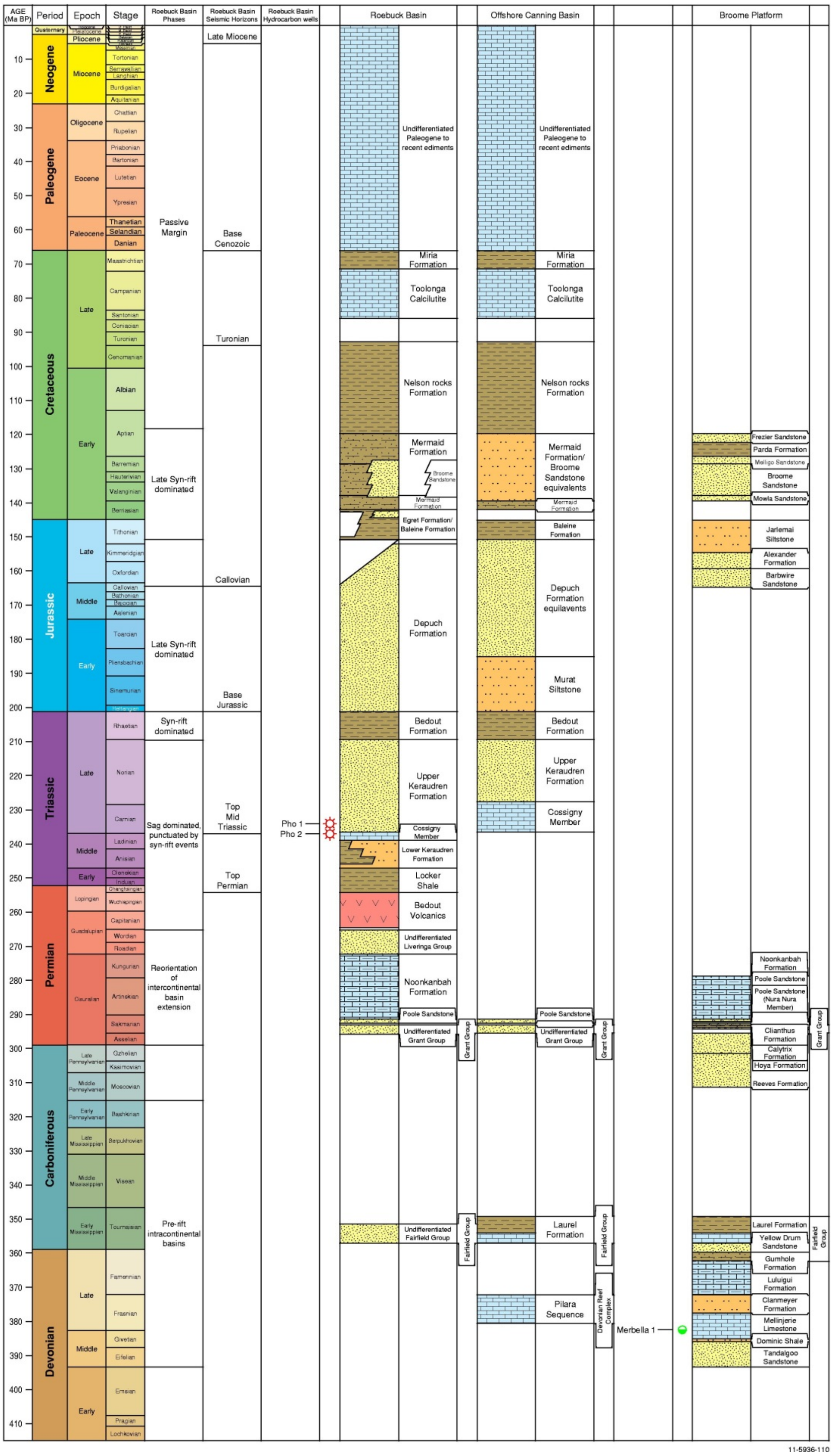

Figure 4.28: Stratigraphy of the Roebuck Basin, Oobagooma Sub-basin and Broome Platform. Geologic time scale after Gradstein et al. (2012).

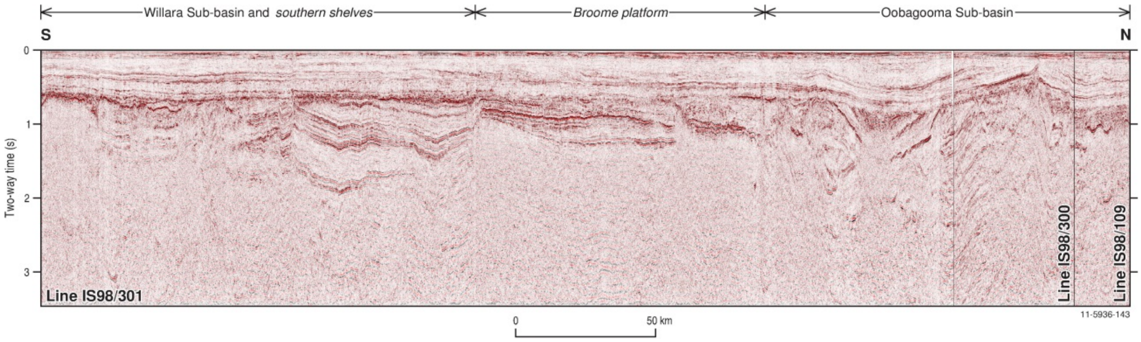

Figure 4.29: Seismic section across the offshore Canning Basin.

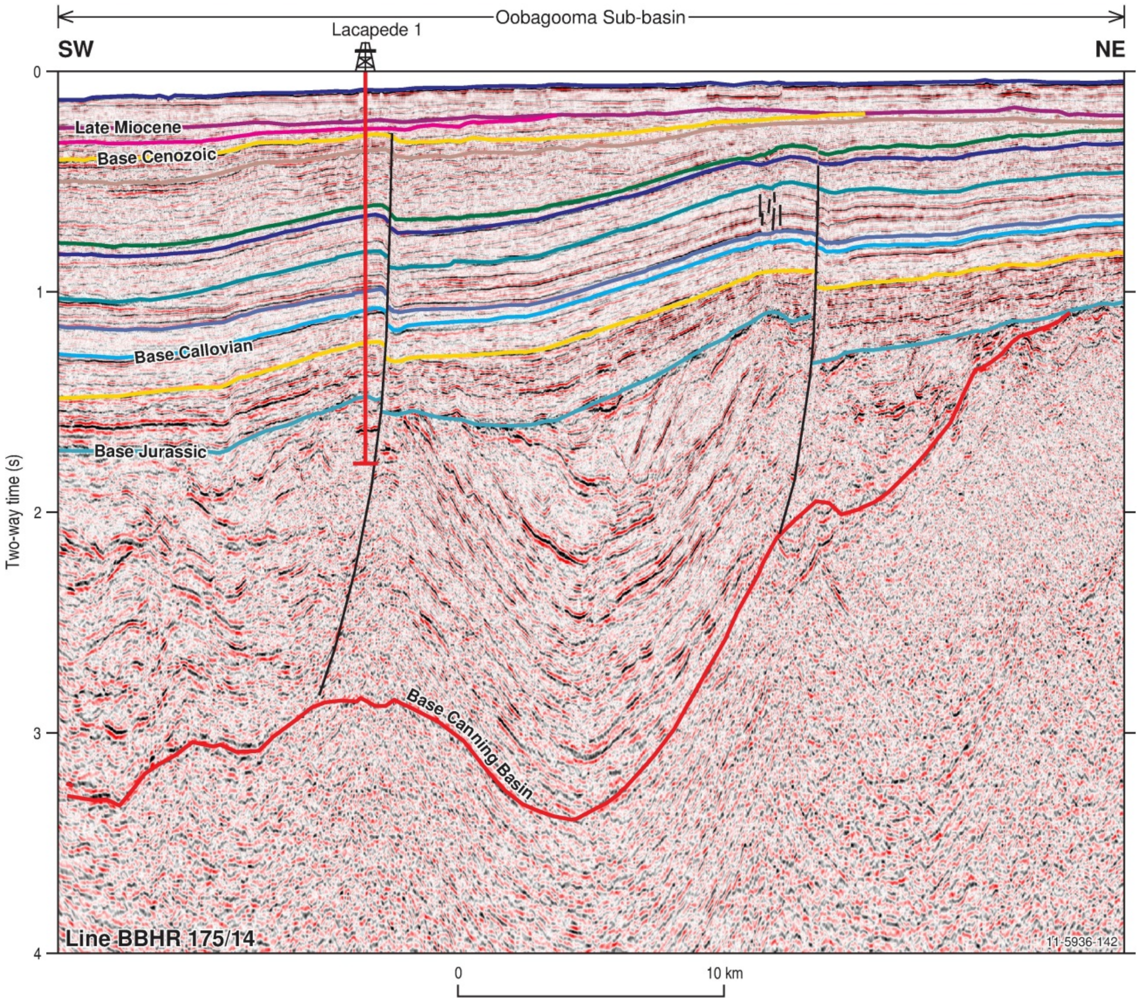

Figure 4.30: Seismic section. northern Oobagooma Sub-basin.

4.6.3 Petroleum systems

The petroleum potential of the offshore Canning Basin is considered to be poor compared to other basins on Australia's northwest margin, primarily due to the perceived absence, in this inboard location, of the Upper Jurassic and Lower Cretaceous source rocks typical of the Carnarvon and Bonaparte basins (Smith et al., 1999). Whilst the Mesozoic petroleum systems are unlikely to be developed in the offshore Canning Basin, there is potential for the Paleozoic petroleum systems that are successful in the onshore basin to be viable in the offshore continuation of the basin.

Limited drilling has showed that key Permian and Carboniferous sequences that contain reservoir and source facies onshore are present in the Oobagooma Sub-basin, and Devonian carbonate facies (reef and platform) have also been intersected. Seismic data indicates that the Willara Sub-basin succession, possibly including the succession containing rich Ordovician source rocks, also continues offshore.

The Paleozoic petroleum systems of the onshore Canning Basin are assigned to the Larapintine Supersystem (Bradshaw et al., 1994; Kennard et al., 1994):

- Larapintine 2 refers to accumulations sourced by oil-prone source rocks within the Ordovician Goldwyer and Bongabinni formations (Kennard et al., 1994; Ghori, 2013; Edwards et al., 2013);
- Larapintine 3 refers to oils sourced from the Upper Devonian Gogo Formation and/or the Luluigui and Clanmeyer formations (Figure 4.28; Ghori, 2013; Edwards et al., 2013);
- Larapintine 4 refers to hydrocarbons sourced from multiple source units within the lower Carboniferous Laurel and Anderson formations, and/or slightly older units within the Fairfield Group (Figure 4.28; Ghori, 2013; Edwards et al., 2013).

In the onshore Canning Basin, production is currently from Permo-Carboniferous sandstones (e.g. Lloyd and Sundown fields) and Devonian carbonates (Blina field) with many shows in Ordovician–Permian section.

4.6.3.1 Source Rocks

Ordovician Larapintine 2 source rocks include organic-rich source units within the Bongabinni Formation, which contains up to 60% TOC in the Willara Sub-basin, and the marine shales of the Goldwyer Formation (up to 5% TOC; Ghori, 2013). The Ordovician succession has not been drilled in the offshore Canning, but its presence at depth is inferred from seismic data. It is possible that this section may be overmature in the Oobagooma Sub-basin due to depth of burial and the local influence of extensive igneous intrusions. The Ordovivcian succession is, however, likely to be present at shallower depths in the southern depocentres (including the offshore continuation of the Willara Sub-basin).

Larapintine 3 and 4 source rocks have been geochemically typed, respectively, to accumulations at Blina and a suite of wells including Boundary, Lloyd, Kora, Meda and Sundown (Ghori, 2013; Edwards et al., 2013). Based on the results of drilling and seismic interpretation the Upper Devonian and lower Carboniferous Gogo and Laurel formations are likely to be present in the offshore Canning, and may contain potential source rocks.

Ghori (2013) noted that a working Permian petroleum system has not been identified in the onshore Canning Basin, although immature organic-rich rocks have been intersected in the Noonkanbah Formation. Offshore, in Kambara 1, immature potential source facies were also noted in the Liveringa

Group/Grant Group section (Figure 4.28; Reeckmann, 1983a). As the Jurassic–Cretaceous section thickens to the west, there is the potential for source rocks within the Permian section to be mature further basinward.

4.6.3.2 Generation and expulsion

Petroleum systems modelling by Ghori (2013) for the onshore Canning Basin succession suggests the timing of peak hydrocarbon generation from Ordovician source rocks varies from Carboniferous in the Fitzroy Trough to Cretaceous in the Willara Sub-basin. Ghori (2013) also proposed that peak generation from Gogo and Laurel source rocks in the Fitzroy Trough was during the Carboniferous–Permian. In the Oobagooma Sub-basin, modelling by Smith (1999) suggested that the Paleozoic section in Wamac 1 (interpreted as Carboniferous Anderson Formation by Reeckmann and Mebberson, 1984) entered the early oil window in the Cretaceous, and has stayed there since.

In the Oobagooma Sub-basin, widespread igneous intrusions have had a localised effect on maturity, bringing otherwise regionally immature sediments briefly into the oil window (Reeckmann & Mebberson, 1984; Holford et al., 2013). In Perindi 1, the thermal effect of a dolerite sill extended up to 500 m above the intrusion and 300 m below, which may explain oil indications in the well (Reeckmann & Mebberson, 1984). It has also been suggested that hydrothermal circulation systems utilised high porosity and permeability reservoirs to transfer heat from the intrusions distances in excess of 3 km (Reeckmann & Mebberson, 1984; Holford et al., 2013). Based on these studies, the extensive system of igneous sills, dykes and other intrusions is likely to have had a significant influence on maturity patterns in the in the eastern Oobagooma Sub-basin.

4.6.3.3 Reservoirs and seals

Good quality reservoirs, with average porosities of 20–30% and excellent permeability, were intersected in the upper Carboniferous–Permian Reeves Formation–Grant Group section in Pearl 1, Perindi 1 and Minjin 1 (Figure 4.28; Mah et al., 1983; Reeckmann, 1983b; Powis, 1984). In Wamac 1, low porosity and permeability in the Carboniferous Anderson Formation were attributed to the effects of igneous intrusions (Amax Petroleum, 1974). Three wells penetrated the Devonian succession, however significant vuggy and fracture porosity was only observed in Perindi 1 (Reeckmann, 1983b).

Excellent porosity and permeability were observed in sands (some unconsolidated) within the Jurassic and Cretaceous section.

Good seal quality was observed in Kambara 1 within the Permian Noonkanbah Formation and Poole Sandstone, middle Grant Group shales and most of the lower Carboniferous Laurel Formation (Figure 4.28; Reeckmann, 1983a).

4.6.3.4 Play types

In the Oobagooma Sub-basin, forced folds above igneous intrusions (Perindi 1 and Minjin 1), and potential Devonian reef plays (Kambara 1) were targeted unsuccessfully during exploration in the 1980s; modern seismic data would likely improve delineation of such targets. Fault-related structural plays, including tilted fault blocks and inversion-related structures are also potential targets in the Oobagooma Sub-basin.

In the Willara Sub-basin, simple fault-related traps are the most likely potential plays.

4.6.3.5 Critical risks

4.6.3.5.1 Presence of mature and generating source rocks and timing of charge

The presence of Ordovician sequences in the offshore Canning is inferred from correlation to the onshore basin. If they are present, they are potentially overmature in the Oobagooma Sub-basin, and under-mature in the offshore Willara Sub-basin. For effective source rocks in the Oobagooma Sub-basin, the timing of charge relative to deformation, uplift and erosion in the Triassic and later compressional reactivation in the Cenozoic, is critical.

4.6.3.5.2 Preservation of accumulations/structural complexity

Limited and variable quality seismic data indicates that the Oobagooma Sub-basin is structurally more complex than the onshore Fitzroy Trough. The sub-basin was affected not only by Paleozoic structuring and the Triassic Fitzroy Movement, but also Cenozoic compressional and/or transcurrent deformation. In addition, Permian igneous intrusions are widespread and abundant, particularly in the eastern part of the sub-basin. All these events have the potential to have compromised the preservation of hydrocarbon accumulations.

4.6.3.5.3 Distribution of igneous intrusions

In the Oobagooma Sub-basin the distribution of igneous intrusions and their effect on maturity, migration pathways and reservoir efficiency/quality is a critical risk. The effect of intrusions on local maturity and the use of high porosity and permeability sands by hydrothermal fluids has been demonstrated in the sub-basin (Reeckmann & Mebberson, 1984). Given the abundance of sills and dykes observed in seismic data, the effect of these intrusions on maturity and reservoir quality is likely to be significant, but difficult to predict. While some intrusions have generated forced folds that provide potential traps, laterally extensive sills are also likely to act as barriers and baffles to migrating fluids (Holford et al., 2013).

4.6.3.6 Overall prospectivity classification

Moderate

4.6.4 Exploration status

Until the mid-1980s, exploration in the northern onshore Canning Basin focused on plays reservoired in the Devonian reef complexes and overlying Permian and Carboniferous clastic units. Exploration resulted in limited success, with a series of small oilfields discovered, including Blina, which discovered an accumulation within the Upper Devonian Nullara Limestone and lower Carboniferous Yellow Drum Formation.

During this period the six offshore Canning wells were also drilled (Figure 4.31). In the early 1970s, two wells were drilled; Lacepede 1, 1A (B.O.C Australia) and Wamac 1 (Amax), both of which were dry. In the early 1980s, an exploration campaign by Esso Exploration and Production resulted in the drilling of three wells—Kambara 1, Perinidi 1 and Minjin 1. While none encountered significant hydrocarbons, oil and gas indications, including bitumen, were recorded at Perindi 1. The offshore Canning wells targeted a range of plays with closures in both Devonian and Permo-Carboniferous units. Some of the structures were attributed to underlying igneous intrusions.

After the failure of this phase of exploration, activity in the region ceased until Woodside were granted three permits in 2009. Despite announcing plans to acquire the Frederick 3D seismic survey in early 2013 (Woodside, 2012), Woodside surrendered the permits at the end of the three-year term (August 2013).

Recent discoveries in the onshore Canning Basin, including Buru's discovery of oil at Ungani, and the emerging shale gas play have changed perceptions of prospectivity for the onshore Canning Basin and revived exploration (Ghori, 2013). The application of similar exploration strategies to the offshore basin has yet to be tested.

4.6.5 Data

Key data sets for the offshore Canning Basin are listed in Table 4.21–Table 4.24.

Six wells have been drilled in the offshore Canning Basin, all in the Oobagooma Sub-basin (Figure 4.31); all were dry.

The basin has a variable, closely (<1 km) to widely-spaced (>20 km) coverage of 2D seismic data, ranging from sparse and poor data coverage over parts of the Broome Platform and offshore Willara Sub-basin to closely-spaced grids around wells in the eastern Oobagooma Sub-basin (Figure 4.31). Very little seismic data has been acquired in the past 15 years. Key regional data sets include the AGSO 120, JNOC JN88, and Seismic Australia LS98 surveys.

In 2006, Geoscience Australia conducted a hydrocarbon seepage survey over the Roebuck and offshore Canning Basins (Survey SS06/06; Jones et al., 2007), however, no definitive evidence of natural hydrocarbon seepage was detected. In 2007, a high-resolution aeromagnetic data set across the offshore Canning Basin was acquired by Geoscience Australia to improve understanding of the structural geology and distribution of igneous rocks in the basin (Foss et al., 2008).

4.6.5.1 Confidence rating

Low–medium

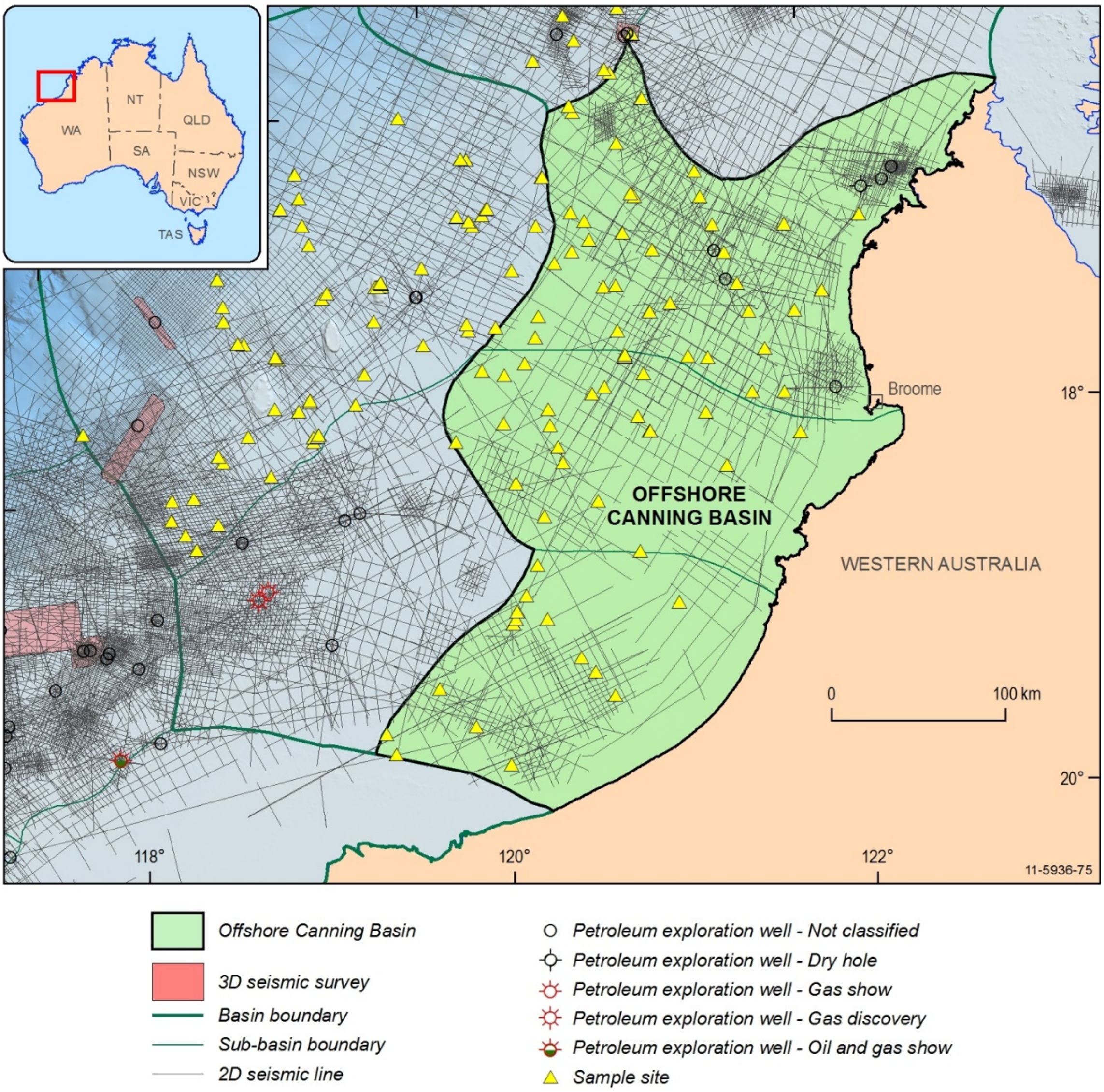

Figure 4.31: Seismic, well and sample distribution, offshore Canning Basin.

4.6.6 Issues and remaining questions

The main questions that need to be addressed in the offshore Canning Basin can be summarised as follows:

4.6.6.1 Petroleum Systems

- Are Ordovician source rocks present in the basin and what is their maturity?
- Can the Upper Devonian–lower Carboniferous sequences hosting Larapintine 3 and 4 source rocks be identified and what is their distribution?
- What is the timing of generation for key source rock units?

4.6.6.2 Structural and magmatic evolution

- What has been the impact of the various structural events on potential structural traps ?
- What is the distribution of sills, dykes and deeper igneous bodies?

4.6.6.3 Recommendations

A key to improving exploration outcomes in the offshore Canning Basin is new, high resolution 2D and 3D seismic data, which should enable a better understanding of the stratigraphy and structural geology of the basin, and the delineation of igneous intrusive bodies.

Additional work that could assist in improving understanding of the basin includes:

- use the wealth of new seismic data onshore to improve correlation from the better understood onshore succession to the Oobagooma Sub-basin
- further geochemical analyses to better understand the source and characteristics of hydrocarbons encountered in Perindi 1 and any relationships with onshore discoveries/petroleum systems
- regional palaeogeographic and structural studies to help identify broader controls on deposition and key differences in basin history along the margin.

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4.6.8 Data Tables

Table 4.21: List of wells, offshore Canning Basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1970	Lacepede 1, 1A	Exploration	B.O.C. of Australia Limited	2286	Permian	Dry	B.O.C. of Australia Limited, 1970
1973	Wamac 1	Exploration	Amax Petroleum	2764	?Carboniferous	Dry	Amax Petroleum, 1974
1982	Kambara 1	Exploration	Esso Exploration and Production Australia	3150	Devonian	Dry	Reeckmann, 1983a
1983	Pearl 1	Exploration	Home Energy Company Ltd.	2203	Carboniferous	Dry	Mah et al., 1983
1983	Perindi 1	Exploration	Esso Exploration and Production Australia	1846	Devonian	Dry	Reeckmann, 1983b
1984	Minjin 1	Exploration	Esso Exploration and Production Australia	1850	Devonian	Dry	Powis, 1984

Table 4.22: Key seismic surveys, offshore Canning Basin.

Year	Survey	Operator	Line-km	Reference
2010	Koolama 2D MSS	Woodside Offshore Petroleum	4102	
2003	Floreana Plazas MSS	Magellan Petroleum	875	
2001	Browse 2001 2D MSS	Veritas DGC	6400	
1998–99	Browse 1998 SPEC MSS	Veritas DGC	23,875	
1999	East Scott Plateau TQ2D MSS	NEPS ASA	2939	
1998	Leveque Shelf LS98 2D MSS	Seismic Australia	4987	
1998	SPA Outer Browse 98 4SL_97-8 MSS	Seismic Australia	3755	
1996	Browse Basin (Survey 175)	AGSO	5274	
1995	OBS NW Shelf (survey 168)	AGSO	2764	

Year	Survey	Operator	Line-km	Reference
1993	H93B MSS	Hadson Energy	7338	
1993	S NW Shelf 3 (Survey 120)	AGSO	4052	
1988	SPA 1SL-88-9 Scientific MSS (JN88)	JNOC	5088	

Table 4.23: List of key geological sampling surveys, offshore Canning Basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
1968	Northwest Shelf Sampling Survey 1	BMR	North West Shelf	Grab, dredge	Shelly calcarenites, gravels	Jones, 1973
2006	Central NWS seepage	Geoscience Australia	Rowley Sub-basin and offshore Canning Basin	Grab, dredge, water column		Jones et al., 2007

Table 4.24: Swath bathymetry surveys, offshore Canning Basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1999	Northern Aust Tropical Oceans	LDEO		
2003	VANC11	SIO		
2006	Central NWS (Rowley Shoals)	GA		Jones et al., 2007
2007	NW Bio (Legs 1–3)	CMAR		

5 Remote eastern and southeastern margin basins

From the Paleozoic to the Early Cretaceous, the southeastern Australian continental margin and Lord Howe Rise were part of the eastern Gondwana margin, located inboard of the convergent boundary with the Pacific Plate. The basins of Australia's remote eastern margin (Figure 5.1) evolved during the Cretaceous breakup of eastern Gondwana, which culminated in the opening of the Tasman Sea (85–52 Ma) and detachment of the Lord Howe Rise from eastern Australia. During the Early Cretaceous to Cenomanian, prior to breakup, regional extension and magmatism along the entire backarc area of the eastern Gondwana margin resulted in the formation of rift basins across the Lord Howe Rise. On the eastern margin of the Lord Howe Rise, a greater degree of crustal extension led to the development of the Fairway and New Caledonia basins over highly extended crust. A second phase of extension is interpreted to have taken place on the Lord Howe Rise during the Cenomanian–Campanian, in the lead up to the opening of the Tasman Sea. Rifting and deposition were terminated by localised basin inversion and erosion associated with continental breakup in the Campanian. From the Campanian to present, deposition has been controlled by thermal subsidence and accompanied by widespread mafic magmatism. Several phases of compression and uplift occurred during the Cenozoic.

Key references that discuss the geology and tectonic evolution of the remote eastern and southeastern margins are: Hayes & Ringis (1973), Wells & O'Brien (1994), Gaina et al. (1998), Sdrolias et al. (2001), Willcox et al. (2001), Willcox & Sayers (2002), Norvick et al. (2001, 2008), Stagg et al. (2002), van de Beuque et al. (2003), Stephenson & Burch (2004), Colwell et al. (2010), Higgins et al. (2011).

There has been no exploration activity in the remote eastern basins other than regional reconnaissance seismic surveys. In the inboard southeastern basins, exploration has been limited to the offshore Sydney Basin.

All remote eastern basins except the Gower Basin extend beyond Australian waters into New Zealand and/or French (New Caledonian) territory. This Record addresses the prospectivity of those parts of the remote eastern basins that are within the area defined by the limits of Australia's Continental Shelf.

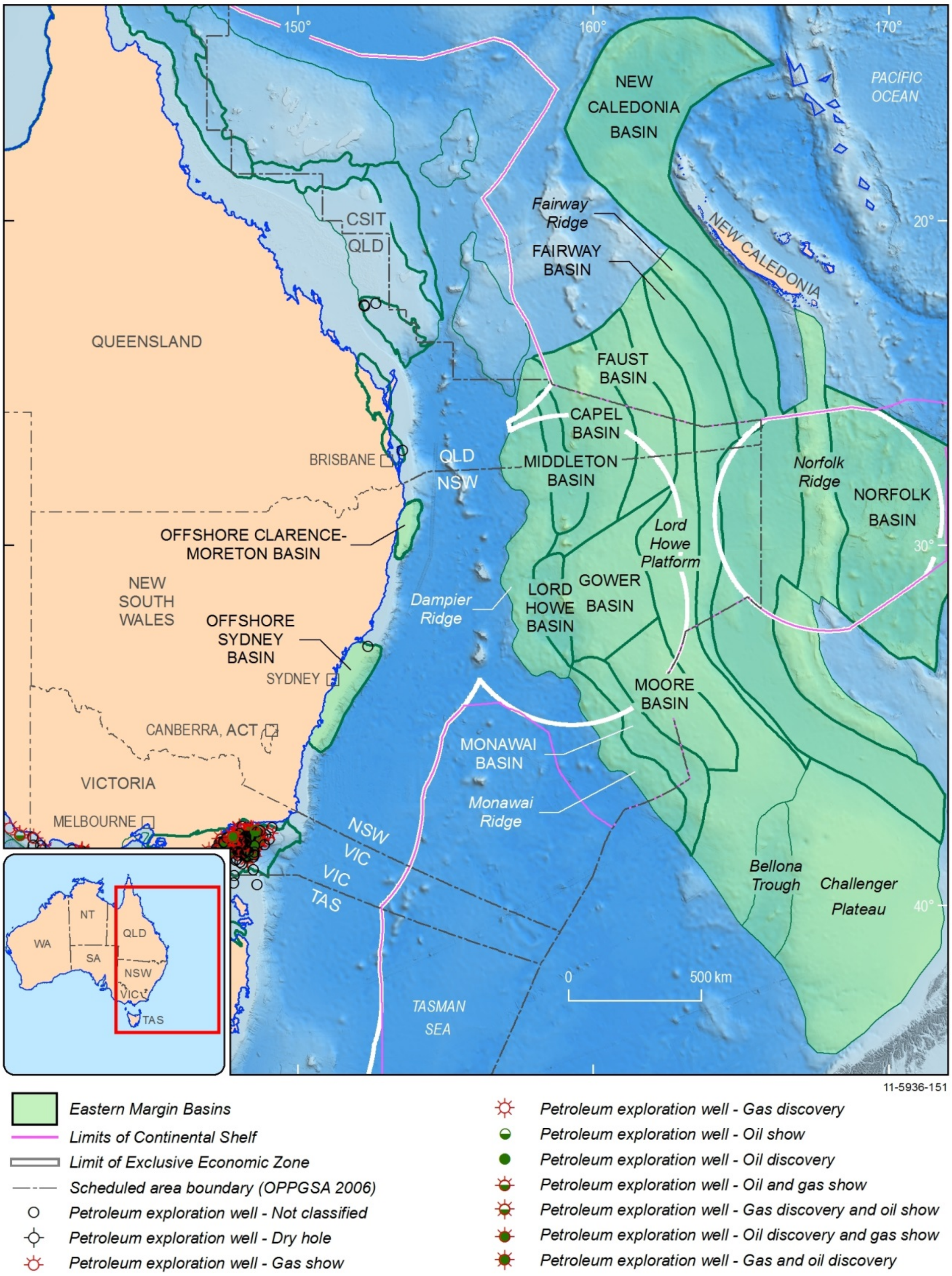

Figure 5.1: Basins of the remote eastern and southeastern Australian margin

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5.1 Capel Basin

5.1.1 Summary

State(s)		Commonwealth waters, France (New Caledonia)
Area (km^2)		90,700 (Australia); 125,900 (total)
Water Depth (m)		500–3000
Maximum sediment thickness (m)		>6000 (excluding underlying pre-rift succession)
Age range		?Early Cretaceous–Cenozoic
Basin	**Overlies**	Possible equivalents of Clarence-Moreton and Maryborough basins, New England Orogen, Whitsunday Volcanic Province
	Adjacent basins	Faust, Middleton, Lord Howe and Gower basins
Basin type		Extensional, sag
Depositional setting, rock types		Non-marine, deltaic, and marine clastic sedimentary rocks, bathyal biogenic (carbonate, siliceous) sedimentary rocks, volcanic, intrusive and volcaniclastic rocks
Petroleum prospectivity		Moderate
Confidence		*Medium–low*

5.1.2 Geology

The Capel Basin is located over the northern part of the Lord Howe Rise, in 500–3000 m water depth (Figure 5.2). It forms part of the Western Rift Province of the Lord Howe Rise (Stagg et al., 1999), a zone of deep and numerous extensional depocentres that trend north–south to northwest–southeast (van de Beuque et al., 2003). The basin covers an area of approximately 125,900 km^2, 70% of which is in Australian waters. It contains a ?Lower Cretaceous to Cenozoic succession with a maximum thickness of over 6000 m (Figure 5.3; Colwell et al., 2010; Higgins et al., 2011b; Petkovic et al., 2011). The Upper Cretaceous–Cenozoic succession within the basin is contiguous with the bathyal succession that blankets the entire Lord Howe Rise. The Capel Basin adjoins the Faust Basin to the east across a zone of basement highs, the Middleton–Lord Howe basins to the west across a major bathymetric scarp at the western edge of the Lord Howe Rise, and the Gower Basin to the south (van de Beuque et al., 2003).

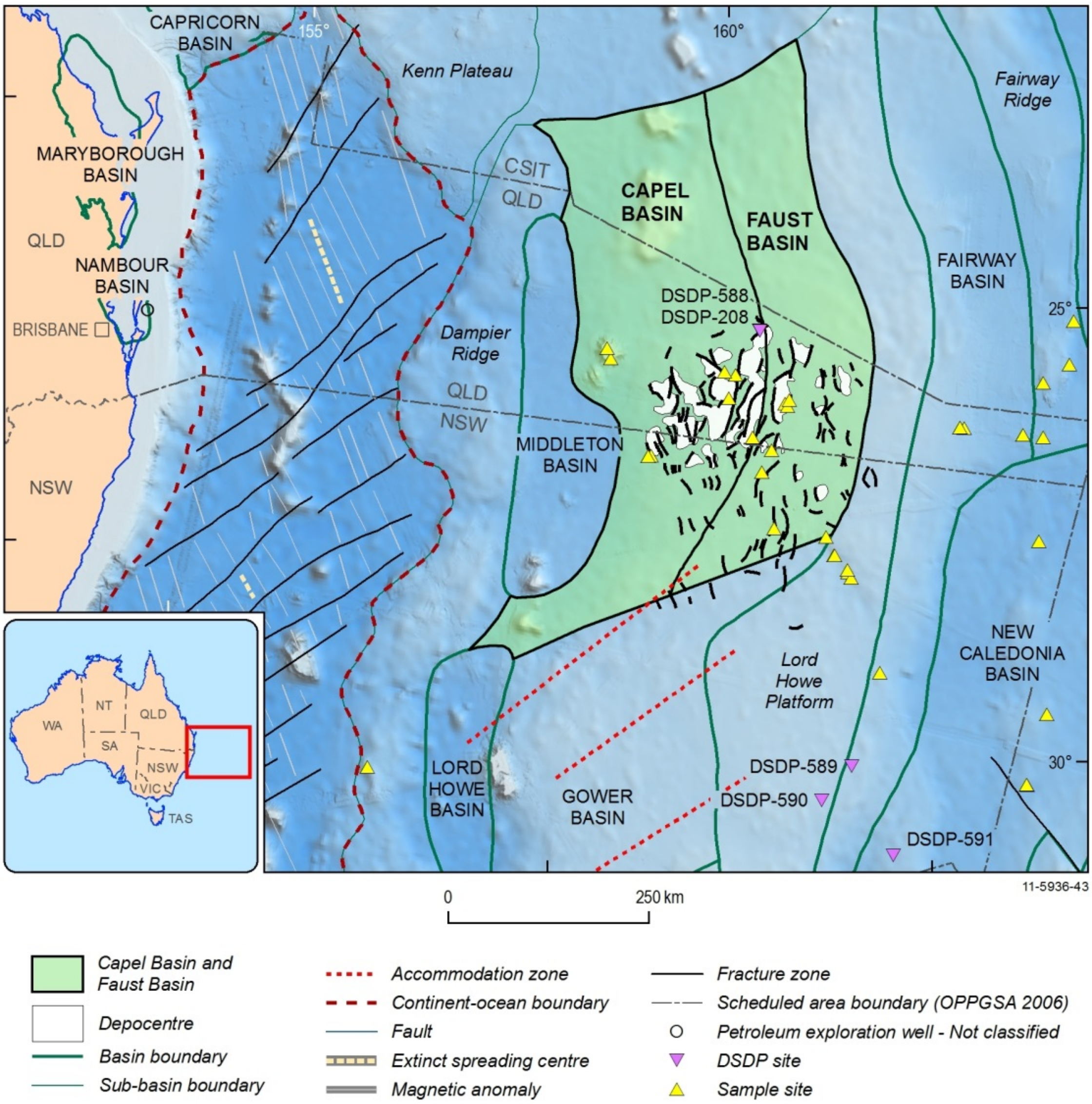

Figure 5.2: Structural elements map, Capel and Faust basins. Depocentre and fault locations after Colwell et al. (2010) and Higgins et al. (2011b).

5.1.2.1 Structural geology

The Capel Basin evolved during the Cretaceous breakup of eastern Gondwana that culminated with the opening of the Tasman Sea (85–52 Ma) and detachment of the Lord Howe Rise from eastern Australia (Hayes & Ringis, 1973; Gaina et al., 1998; Sdrolias et al., 2001). Crustal extension was most marked in the Western Rift Province of the Lord Howe Rise, which includes the Capel Basin, where the crustal thickness is generally 20 km or less (Shor et al., 1971). Two major phases of intracontinental extension resulted in the formation of generally north–south-trending major basement-involved faults, graben and half graben (Figure 5.2 and Figure 5.4; Colwell et al., 2010; Higgins et al., 2011b). In the western Capel Basin, the dominant structural trend is northwest–southeast, approximating the trend of the seafloor spreading axis in the Tasman Sea. The depocentres and major faults appear to be highly segmented and separated from each other by basement highs, many of which are interpreted to represent accommodation zones between fault segments. The extension-related structures have been modified by multiple episodes of compression, uplift and basin inversion during the Late Cretaceous–Neogene.

5.1.2.2 Basin evolution and depositional history

The main tectonostratigraphic phases within the Capel Basin have mostly been inferred from tectonic reconstructions and regional correlations. During the Paleozoic to the Early Cretaceous, the Lord Howe Rise was part of the eastern Gondwana margin located inboard of the convergent boundary with the Pacific Plate. Rocks forming the pre-rift basement to the Capel Basin are inferred to be equivalent to those of the New England Orogen, Clarence-Moreton Basin, Maryborough Basin and the early part of the Whitsunday Volcanic Province (Mortimer et al., 2008; Norvick et al., 2008; Colwell et al., 2010).

During the Early Cretaceous to Cenomanian, regional extension and magmatism, extending along the entire backarc area of the eastern Gondwana margin (Norvick et al., 2001, 2008), resulted in the formation of large north–south-trending graben and half graben in the Capel Basin (Colwell et al., 2010; Higgins et al., 2011b). The early rift section (Syn-rift 1 Megasequence; Figure 5.4) is up to 3 km thick and is interpreted to contain fluvio-lacustrine sediments, and volcaniclastic and igneous rocks (Colwell et al., 2010). Cessation of subduction along the eastern Gondwana–Pacific plate boundary resulted in regional uplift during the Cenomanian (Norvick et al., 2001, 2008; Willcox et al., 2001; Schellart et al., 2006; Waschbusch et al., 2009; Rey & Müller, 2010). Widespread inversion, folding and erosion within the Capel Basin is attributed to this event (Colwell et al., 2010).

A second phase of northeast–southwest crustal extension is interpreted to have taken place during the Cenomanian–Campanian, in the lead up to the opening of the Tasman Sea (Figure 5.3; Norvick et al., 2008). Major northwest–southeast-trending rift depocentres developed in the western part of basin, and the Early Cretaceous north–south-trending depocentres in the eastern part deepened (Colwell et al., 2010; Higgins et al., 2011b). In the deepest depocentres of the western Capel Basin, the Syn-rift 2 Megasequence is interpreted to contain over 2 km of fluvio-lacustrine to deltaic and shallow marine sediments (Figure 5.4). Much less deposition occurred elsewhere. Igneous activity was common through the Lord Howe Rise and surrounding regions (e.g. van der Lingen, 1973), and dredged rocks from the Lord Howe Platform to the east of the Capel Basin indicate magmas of alkalic intermediate composition (Higgins et al., 2011a). Rifting and deposition was terminated by localised basin inversion and erosion probably during the Campanian, associated with continental breakup and the opening of the Tasman Sea to the west (Norvick et al., 2008; Colwell et al., 2010).

During the Campanian–Maastrichtian, thermal subsidence resulted in deposition of a basal Post-rift Megasequence succession within the former rift depocentres (Figure 5.4). This section is interpreted to comprise fluvio-deltaic, marginal marine, shelf and bathyal clastic rocks. From the late Maastrichtian to the present, bathyal drape deposition of nannofossil/foraminiferal chalk and ooze has dominated (Colwell et al., 2010), accompanied by widespread intraplate mafic magmatism (Dadd et al., 2011; Rollet et al., 2012). Deposition was interrupted by compression and uplift during the Paleocene–Eocene, Eocene–Oligocene and possibly later, resulting in the reactivation of extensional faults, and basin inversion and erosion along depocentre margins (Colwell et al., 2010). The Eocene–Oligocene event was probably associated with a major change in the Pacific Plate motion (Müller et al., 2000; Veevers, 2000), obduction in New Caledonia (Aitchison et al., 1995) and an eastward relocation of the Australia–Pacific plate convergence (Sdrolias et al., 2001; Crawford et al., 2003).

5.1.2.3 Level of knowledge

As for most other basins of the region, the Capel Basin is a remote and under-explored deepwater frontier basin with a sparse coverage of regional 2D seismic reflection, gravity, magnetic and bathymetry data. Deep Sea Drilling Program (DSDP) holes 208 and 588, both drilled at the same location near the boundary between the Capel and Faust basins, provide the only stratigraphic control for the Maastrichtian–Holocene part of the sedimentary succession. No petroleum exploration wells have been drilled. Consequently, the geologic interpretation of the basin is largely inferred from regional tectonic reconstructions and correlations. Geoscience Australia's GA-302 2D seismic grid (20–40 km line spacing), acquired in 2006–2007, greatly improved data coverage over the Capel Basin, and enabled basin-wide interpretation of the seismic stratigraphy and structure. This interpretation indicates that the basin is potentially capable of generating and accumulating hydrocarbons.

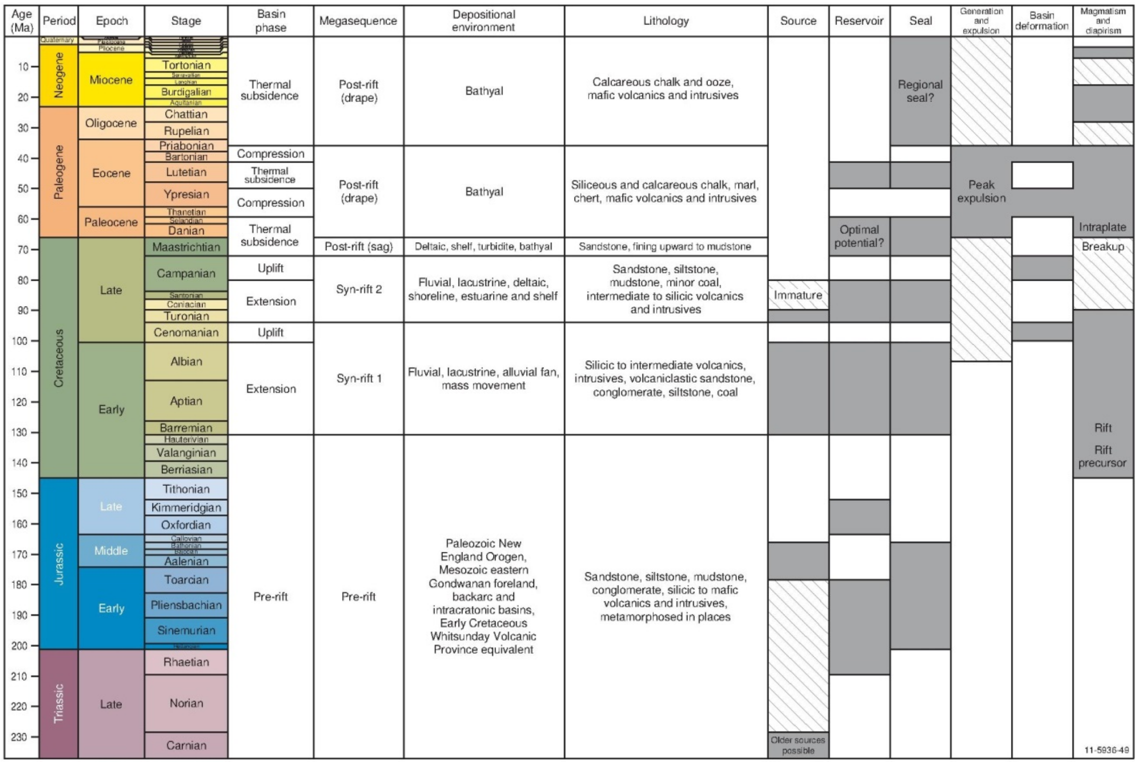

Figure 5.3: Stratigraphy of the Capel and Faust basins after Colwell et al. (2010). Predicted petroleum generation and expulsion after Funnell & Stagpoole (2011).

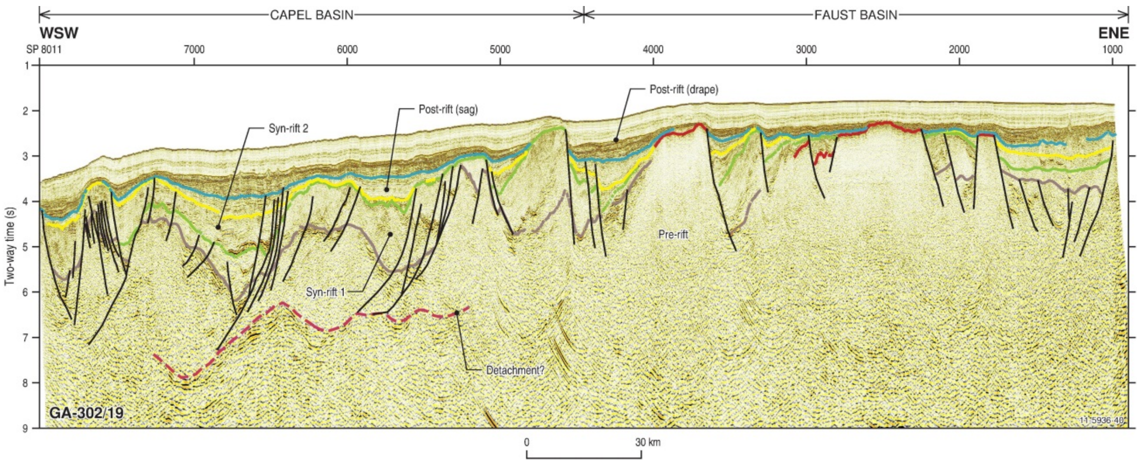

Figure 5.4: Geological cross-section of the Capel and Faust basins along seismic line GA-302/19 showing structural and stratigraphic relationships (after Colwell et al., 2010).

5.1.3 Petroleum systems

There are no known petroleum systems in the Capel Basin. Inferred stratigraphy and geologic evolution suggest however, that petroleum systems similar to those in onshore eastern Australia may be present in the region. Sediment thicknesses are sufficient in all major depocentres for oil and gas generation from pre-rift and Lower Cretaceous (Syn-rift 1) source rocks, if present (Funnell & Stagpoole, 2011). Previous works (e.g. Ramsay et al., 1997; Exon et al., 1998; Lafoy et al., 1998; Auzende et al., 2000) have speculated that bottom simulating reflectors (BSRs) seen on regional seismic data may indicate the occurrence of gas hydrates in the Lord Howe Rise and surrounding regions. However, a recent reappraisal based on newly acquired data has indicated that the BSRs are most likely to be an Opal-A/Opal-CT diagenetic boundary (Colwell et al., 2006; Nouzé et al., 2009).

5.1.3.1 Source rocks

Regional tectonic reconstructions (Mortimer et al., 2008; Norvick et al., 2008) and seismic character analysis indicate that pre-rift sediments that underlie parts of the Capel Basin may be equivalent to the successions in the Clarence-Moreton or Maryborough basins of eastern Australia. If so, gas-prone Middle–Upper Triassic to Lower Jurassic fluvio-lacustrine coal and mudstone source rocks, such as the Nymboida and Ipswich coal measures of the Clarence-Moreton Basin (Willis, 1985; Powell et al., 1993; O'Brien et al., 1994; Stewart & Alder, 1995), or the Tiaro Coal Measures of the Maryborough Basin (Lipski, 2001; Stephenson & Burch, 2004) may be present (Figure 5.3). Other possible source facies include equivalents of the oil-prone Middle–Upper Jurassic Walloon Coal Measures of the Clarence-Moreton Basin (Powell et al., 1993; O'Brien et al., 1994). Within the Syn-rift 1 Megasequence, non-marine deposition within compartmentalised rift depocentres may have resulted in deposition of Lower Cretaceous gas-prone fluvio-lacustrine coal and mudstone source rocks, analogous to the Strzelecki Group of the Gippsland Basin (Norvick et al., 2001; O'Brien et al., 2008) and the Eumeralla Supersequence in the Otway Basin (Edwards et al., 1999; Krassay et al., 2004; Boreham et al., 2004). Within the Syn-rift 2 Megasequence, there is the potential for Upper Cretaceous oil- and gas-prone fluvio-deltaic coal and mudstone source rocks similar to the Taniwha and Rakopi formations of the Taranaki Basin to be present (King & Thrasher, 1996; Norvick et al., 2001; Uruski & Baillie, 2004; Uruski, 2008).

5.1.3.2 Generation and expulsion

Multi-1D petroleum systems modelling predicts that interpreted Jurassic–Lower Cretaceous source rocks within the pre-rift and Syn-rift 1 successions would be oil and gas mature in all major depocentres, and overmature in the deeper parts of depocentres (Funnell & Stagpoole, 2011). Hydrocarbon generation and expulsion for these source rocks is expected from the Aptian to the present, with a peak during the Late Cretaceous to Middle Eocene (Figure 5.3). Upper Cretaceous source rocks that may be present within the Syn-rift 2 Megasequence are predicted to be oil- or gas-mature only within the deepest depocentre in the western part of the Capel Basin (Funnell & Stagpoole, 2011). Measurements in the Capel and Faust basins from the AUSFAIR survey indicate heat flow of over 60 mW/m^2 (Colwell et al., 2006), while measurements at DSDP 587 (northern Lord Howe Rise; Morin & von Herzen, 1986) and DSDP 206 (New Caledonia Basin; von Herzen, 1973) are in the range 56–58 mW/m^2. These results suggest above-average heat flow in the Capel Basin, which would have assisted the maturation of source rocks. Moreover, widespread Cenozoic magmatism may have enhanced the maturity of shallowly buried source rocks between the Eocene and present, if accompanied by elevated crustal heat flow (Funnell & Stagpoole, 2011). Hydrocarbon migration within the basin is likely to be complex, being controlled by the rugged basement topography of the compartmentalised depocentres, major north–south and northwest–southeast-trending faults; and facies variability within the Syn-rift 1, Syn-rift 2 and lower Post-rift megasequences.

5.1.3.3 Reservoirs

Potential reservoir sandstones may occur within the pre-rift, Syn-rift 1, Syn-rift 2 and the lower Post-rift successions (Figure 5.3). The pre-rift succession may include Upper Triassic–Jurassic quartzose fluvial sandstones, equivalent to those in the Clarence-Moreton and Maryborough basins (O'Brien et al., 1994; Lipski, 2001; Stephenson & Burch, 2004). Fluvial channel and alluvial fan sandstones are likely to occur within the Syn-rift 1 Megasequence, but they may have variable quality depending on the degree of volcaniclastic input and fluvial sorting achieved by small drainage systems associated with compartmentalised rift depocentres. Fluvial channel sandstones within the Syn-rift 2 Megasequence probably have better reservoir potential due to a lower volcaniclastic input and greater degree of sorting by axial fluvial systems. The best reservoir potential perhaps occurs within the upper Syn-rift 2 and the lower Post-rift successions, where early transgressive marine deposits are likely.

5.1.3.4 Seals

Analogy with the Clarence-Moreton and Maryborough basins implies that, within the pre-rift succession, potential intraformational seals could be provided by Lower–Upper Jurassic fluvio-lacustrine mudstones (O'Brien et al., 1994; Lipski, 2001; Stephenson & Burch, 2004). Intraformational seals may also be provided by potential fluvio-lacustrine mudstones within the Syn-rift 1 and Syn-rift 2 megasequences, and marine to deltaic mudstones within the upper Syn-rift 2 and lower Post-rift megasequences (Figure 5.3). Regional seal may be provided by the extensive and thick Oligocene–Holocene pelagic sediments (e.g. nannofossil ooze and foraminiferal chalk), although seal integrity may be compromised in places by intraplate magmatism, fluid migration and faulting (Rollet et al., 2012). Cretaceous–Holocene volcanic flows and sills may locally act as seals in parts of the syn-rift and Post-rift successions.

5.1.3.5 Play types

A range of structural and stratigraphic plays are possible in the Capel Basin. Potential structural play styles include tilted fault blocks and horsts, inversion and intra-basinal anticlines, and fault rollover structures. Tilted fault blocks within the pre-rift succession may also be potential plays. The high apparent facies variability and regional paleogeography also suggests the potential for stratigraphic (and combined structural-stratigraphic) plays in the Capel Basin, including fluvial channels, both proximal and distal marine sandstone facies, onlap and sub-unconformity plays. Stratigraphic trapping potential may be locally enhanced by Lower Cretaceous to Cenozoic volcanic flows and sills.

Hydrocarbon migration into structures near the edge of depocentres would be encouraged by major boundary faults and the basement topography, while vertical migration into intra-basin structures would be facilitated by the numerous extensional faults through the pre-rift and syn-rift successions. Given the peak in hydrocarbon generation and expulsion during the Late Cretaceous to Paleogene, plays reliant on pre-rift or Cretaceous intraformational seals may be more likely to be charged. However, the lateral extent and thickness of the intraformational seals are unknown, and preservation through the Cenozoic reactivation events may be a problem. The Maastrichtian–Holocene bathyal sediments are extensive and generally thick, but their potential as a regional seal remains untested. The bathyal succession also only attained substantial thickness after the Oligocene, so plays dependent on these sediments as seals would require sufficient hydrocarbon charge after the peak in generation and expulsion. Moreover, bathyal sediments thin over many of the major basement highs, precluding structures in these areas as viable plays.

5.1.3.6 Critical risks

There is no direct evidence for the presence of source rocks, reservoirs, seals and active petroleum systems in the Capel Basin. Nonetheless, the interpretation of recently acquired data, supplemented by regional reconstructions and analogues, suggest that petroleum system elements are likely to be present, and gas and oil generation and expulsion would be possible. Assuming the presence of source rocks, a key risk is the timing of main hydrocarbon charge (Late Cretaceous–Eocene) relative to the bathyal regional seal and overburden deposition (Oligocene–Holocene; Funnell & Stagpoole, 2011). Major structuring events during the Cenomanian, Campanian, Paleocene–Eocene and Eocene–Oligocene, and Cenozoic igneous activity and associated fluid migration, may pose a risk to preservation of earlier trapped hydrocarbons (Rollet et al., 2012). Effectiveness of the Oligocene–Holocene bathyal sediments as a regional seal remains untested, and no information exists on the distribution and effectiveness of intraformational seals. Multiple episodes of syn-rift and intraplate magmatism during the Cretaceous to Holocene may have a negative effect on reservoir quality through volcaniclastic input and hydrothermal alteration (Rollet et al., 2012).

5.1.3.7 Overall prospectivity classification

Moderate

5.1.4 Exploration status

The Capel Basin is a frontier basin. No exploration activity has taken place in the basin other than regional reconnaissance seismic surveys in the early 1970s by Shell International (MV *Petrel*) and Mobil. (see Data). Geoscience Australia, its predecessors the Australian Geological Survey Organisation (AGSO) and Bureau of Mineral Resources (BMR), as well as the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) have completed several data acquisition surveys over the Lord Howe Rise region, including the Capel Basin, since the 1970s for reconnaissance geological investigation, offshore hydrocarbon resource assessment and determination of maritime boundaries under the United Nations Convention on the Law of the Sea (UNCLOS).

5.1.5 Data

Although the Capel Basin probably has the best data coverage within the Lord Howe Rise region, the coverage is sparse when compared to most other Australian offshore basins. The only drilling within the basin consists of DSDP drill holes 208 and 588 (drilled at the same location). DSDP 208 penetrated a predominantly Cenozoic section of nannofossil/foraminiferal ooze before terminating in upper Maastrichtian rocks (The Shipboard Scientific Party, 1973). DSDP 588 consisted of four core holes at the DSDP 208 site, with DSDP 588C terminating in the Middle Eocene (The Shipboard Scientific Party, 1986). Key data sets for the Capel Basin are listed in Table 5.1–Table 5.5, and their location shown in Figure 5.5 and Figure 5.6.

Other data sets comprise regional 2D seismic, refraction seismic, gravity, magnetic and bathymetry data, and isolated rock samples. 2D seismic reflection data coverage over the northern Lord Howe Rise, including the Capel Basin, is sparse and variable in quality. Data from seven surveys completed over the basin during the 1970s are generally of poor quality. The joint Australian–French AGSO s206/FAUST 1 survey acquired 4564 line-km of moderate to high-quality data over the northern Tasman Sea region (Bernardel et al., 1999), of which about 500 km lie over the Capel Basin. Segments of lines s206-02 and s206-04 were subsequently reprocessed to image much of the basin succession and parts of the pre-rift basement. The Geoscience Australia GA-302 seismic survey provides the best data quality and density over the basin. The survey acquired approximately 6000 km of data with line spacing of 15–40 km in the central and southern parts of the Capel and Faust basins. The high-quality 106-fold data recorded to 12 s TWT enabled full imaging of the basin succession and the pre-rift basement for the first time (Kroh et al., 2007).

Seismic refraction data collected during several surveys (Table 5.3) contributed to a velocity model for the basin (Petkovic, 2010) that underpinned the geological interpretations recently completed by Geoscience Australia (e.g. Colwell et al., 2010; Higgins et al., 2011b). In addition, ocean-bottom seismometer (OBS) data has been collected in the French (New Caledonian) parts of the Capel, Faust, Fairway and New Caledonia basins (Klingelhoefer et al., 2007).

Potential field and bathymetry data coverage over the Capel Basin includes regional compilations derived from satellite, airborne and marine data e.g. Scripps Institution of Oceanography gravity (Sandwell & Smith, 1997), Danish National Space Centre DNSC08GRA gravity (Andersen et al., 2010), World Digital Magnetic Anomaly Map (WDMAM; Maus et al., 2007), Earth Magnetic Anomaly Grid 2 (EMAG2; Maus et al., 2009), and Geoscience Australia Bathymetry and Topography Grid of Australia AUSBATH09 (Whiteway, 2009). Shipboard gravity, magnetic and bathymetry data were acquired during the Geoscience Australia and Ifremer AUSFAIR MD-153 MV *Marion Dufresne* survey (Colwell et al., 2006), and Geoscience Australia GA 302 (Kroh et al., 2007) and GA 2436 RV *Tangaroa* (Heap et al., 2009) surveys. Recently, all shipboard gravity and magnetic data over the Lord Howe Rise region have been re-levelled and released as the Geoscience Australia Capel and Faust basins levelled potential field data set (Hackney, 2010). These revised data sets represent the highest-resolution and most complete gravity and magnetic data coverage currently available over the Capel Basin.

A few rock samples have been collected from the seafloor within, and in the vicinity of, the Capel Basin. These include continental rocks (conglomerate, sandstone, calcarenite, alkali intermediate–acid volcanics) dredged from the Lord Howe Platform to the east of the Capel and Faust basins during the BGR RV *Sonne* 36 (Röser & Shipboard Party, 1985) and Geoscience Australia/Ifremer AUSFAIR MD-153 (Colwell et al., 2006) surveys. In addition, predominantly upper Cenozoic mafic volcanic rocks and seafloor sediments were collected during the GA 2436 RV *Tangaroa* survey (in 2007; Dadd et al., 2011). The volcanic rocks from the Lord Howe Platform collected during the AUSFAIR MD-153 survey have subsequently been dated at 96.9 +/- 0.7 Ma (Cenomanian) and 74.1+/-0.7 Ma (Campanian; Higgins et al., 2011a). The extensive cover of bathyal ooze over the entire region severely limits sampling opportunities for older rocks.

5.1.5.1 Confidence rating

Medium–low

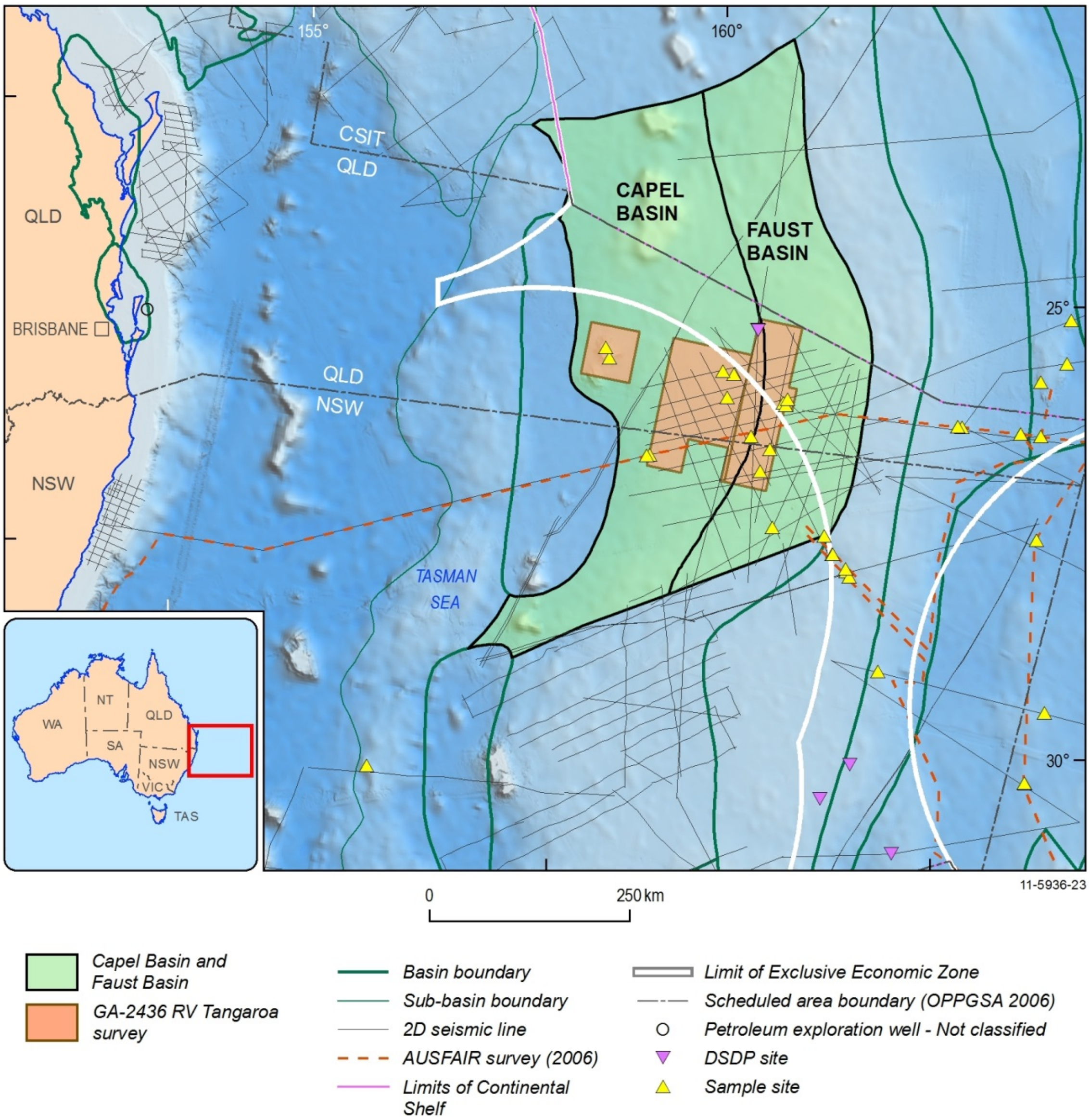

Figure 5.5: Seismic, well and sample distribution, Capel and Faust basins.

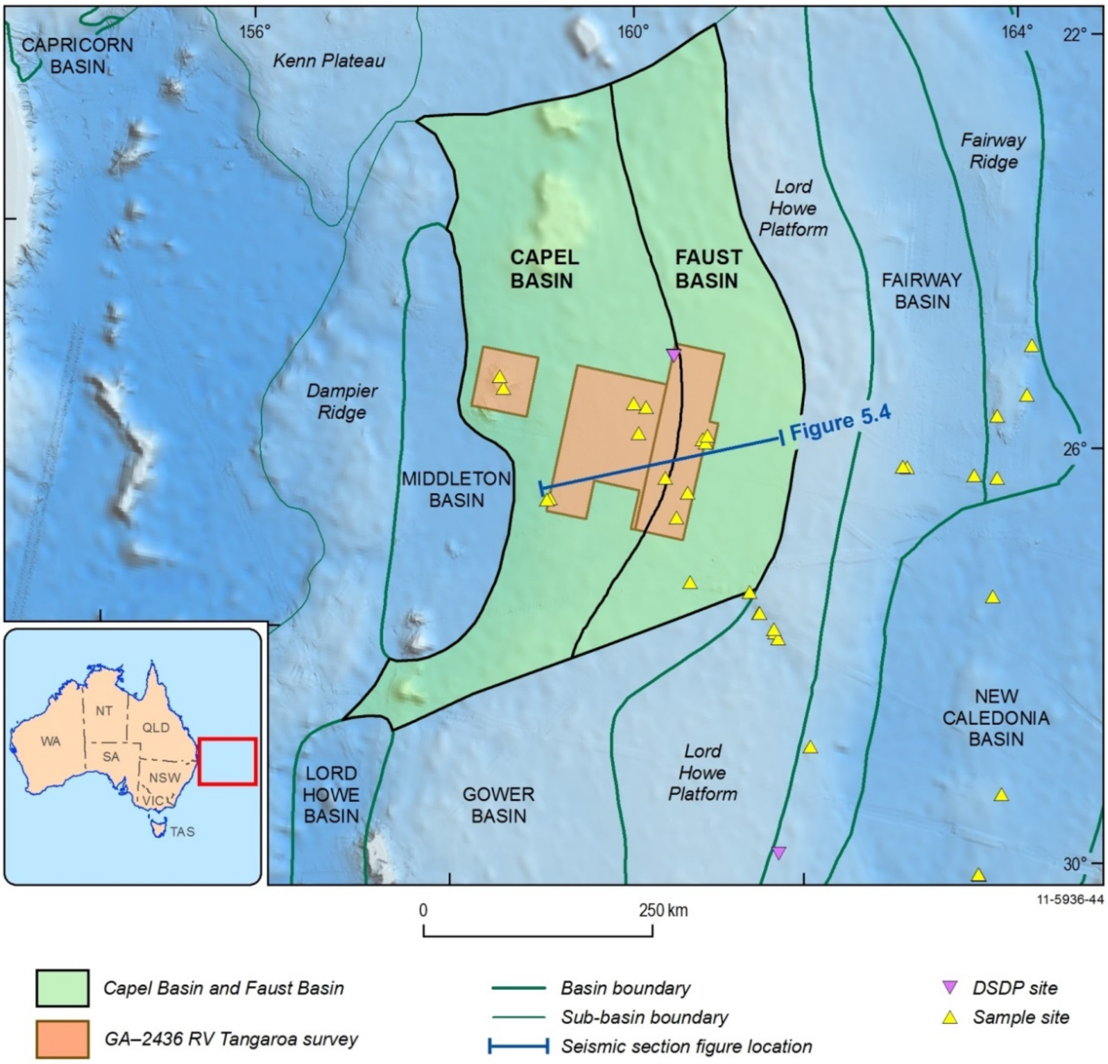

Figure 5.6: GA Survey 2436 and location of seismic line shown in Figure 5.4.

5.1.6 Issues and remaining questions

Lack of direct evidence for the composition and age of the basin succession and the basement, and particularly for the existence of source, reservoir, seal and active petroleum systems, is a major obstacle to understanding the region's petroleum prospectivity and reducing exploration risk.

A key issue for future exploration activity in this area is the remoteness from existing infrastructure and markets. Environmental sensitivities arising from proximity of the southwestern part of the Capel Basin to the Lord Howe Island World Heritage Area would also need to be considered.

5.1.6.1 Recommendations

Stratigraphic drilling with penetration at least to the lower Syn-rift 1 succession (and preferably deeper into the pre-rift succession) could address some of the key issues. Targeted seismic data acquisition (e.g. high density 2D or 3D reflection) would be recommended prior to any drilling attempts, in order to refine the interpretation of 3D architecture of the basin depocentres and the identification of drilling targets. Opportunities for dredge sampling of rock are limited due to the extensive and thick cover of Cenozoic bathyal sediments, and the paucity of canyons and scarp exposures, so carefully targeted deep coring could be useful.

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5.1.8 Data Tables

Table 5.1: List of wells, Capel Basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1971	DSDP 208	Scientific	Deep Sea Drilling Project	594	Late Maastrichtian	Nil	The Shipboard Scientific Party, 1973
1982	DSDP 588	Scientific	Deep Sea Drilling Project	236.0	Middle Miocene	Nil	The Shipboard Scientific Party, 1986
1982	DSDP 588A	Scientific	Deep Sea Drilling Project	344.4	Early Miocene	Nil	The Shipboard Scientific Party, 1986
1982	DSDP 588B	Scientific	Deep Sea Drilling Project	277.4	Middle Miocene	Nil	The Shipboard Scientific Party, 1986
1982	DSDP 588C	Scientific	Deep Sea Drilling Project	488.1	Middle Eocene	Nil	The Shipboard Scientific Party, 1986

Table 5.2: Key 2D seismic surveys, Capel Basin.

Year	Survey	Operator	Line-km	Reference
1971	MV *Petrel* Roving	Shell International	400	van de Beuque et al., 2003
1972	Mobil 1972	Mobil	800	Stagg et al., 2002
1972	BMR Continental Margin surveys 12, 13, 15	Bureau of Mineral Resources (BMR)	1800	van de Beuque et al., 2003
1998	AGSO 206 (FAUST 1)	Australian Geological Survey Organisation	500	Bernardel et al., 1999
2006/2007	GA-302	Geoscience Australia	2200	Kroh et al., 2007

Table 5.3: Refraction seismic and velocity surveys covering the Faust Basin.

Year	Survey	Operator	Location	Reference
1967	Scripps Institution of Oceanography two-ship refraction seismic survey	Scripps Institution of Oceanography	23 profiles over Southwest Pacific	Shor et al., 1971
1971	DSDP 208 sonobuoy refraction survey	Deep Sea Drilling Project	Capel Basin	The Shipboard Scientific Party, 1973
1978	RV *Sonne* 7 survey	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)	Lord Howe Rise region including two sites in Capel and Faust basins	Willcox et al., 1981

Year	Survey	Operator	Location	Reference
2004	ZoNéCo 11 OBS survey	Ifremer, Agence de Développement Economique de la Nouvelle Calédonie (ADECAL)	42 sites in French (New Caledonian) parts of Capel, Faust, Fairway and New Caledonia basins	Klingelhoefer et al., 2007
2006/2007	GA-302 sonobuoy refraction survey	Geoscience Australia	96 sites in Capel and Faust basins	Petkovic, 2010

Table 5.4: List of key surveys involving geological sampling.

Year	Survey	Operator	Region	Type	Rock types	Reference
1985	RV *Sonne* 36	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)	Lord Howe Platform	Dredge	Pebbly conglomerate, sandstone, calcarenite	Röser & Shipboard Party, 1985
2006	AUSFAIR MD-153 (RV *Marion Dufresne*)	Geoscience Australia, Ifremer	Capel, Faust and New Caledonia basins, Lord Howe Platform, Fairway Ridge	Dredge, giant piston core	Trachyte, latite, quartz–feldspathic conglomerate and sandstone, some with molluscan fossils, calcareous ooze, ferromanganese nodules and crust	Colwell et al., 2006; Higgins et al., 2011a
2007	GA-2436 RV *Tangaroa*	Geoscience Australia	Capel and Faust basins, Gifford Guyot	Dredge, piston and box cores, epibenthic sled, camera, CTD	Mafic volcanic rocks, pumice, ferromanganese nodules and crust, calcareous ooze and chalk	Heap et al., 2009; Dadd et al., 2011

Table 5.5: Swath bathymetry surveys.

Year	Survey name	Operator	Line-km/Area (km^2)	Reference
2001	Australian continental margin levelled gravity, magnetic and bathymetry	Geoscience Australia, Intrepid Geophysics		Petkovic et al., 2001
2006	AUSFAIR MD-153 (RV Marion Dufresne)	Geoscience Australia, Ifremer	Capel, Faust and New Caledonia basins, Fairway Ridge	Colwell et al., 2006
2007	GA-2436 RV *Tangaroa*	Geoscience Australia	39,870 km^2 over Capel and Faust basins, Gifford Guyot	Heap et al., 2009
2009	Bathymetry and Topography Grid of Australia AUSBATH09 (2009)	Geoscience Australia		Whiteway, 2009

5.2 Faust Basin

5.2.1 Summary

State(s)		Commonwealth waters, France (New Caledonia)
Area (km^2)		42,175 (Australia); 84,200 (total)
Water Depth (m)		1000–2000
Maximum sediment thickness (m)		>5000 (excluding underlying pre-rift succession)
Age range		?Early Cretaceous–Cenozoic
Basin	**Overlies**	Possible equivalents of Clarence-Moreton and/or Maryborough basins, Gympie Terrane or Murihiku/Maitai Supergroup, New England Orogen, Whitsunday Volcanic Province
	Adjacent basins	Faust, Middleton, Lord Howe and Gower basins
Basin type		Extensional, sag
Depositional setting, rock types		Non-marine, deltaic, and marine clastic sedimentary rocks, bathyal biogenic (carbonate, siliceous) sedimentary rocks, volcanic, intrusive and volcaniclastic rocks
Petroleum prospectivity		Low–moderate
Confidence		*Medium–low*

5.2.2 Geology

The Faust Basin is located over the northern part of the Lord Howe Rise, in 1000–2000 m of water (Figure 5.7). It is part of the Central Rift Province of the Lord Howe Rise (Stagg et al., 1999), and is characterised by small and shallow extensional depocentres that trend north–south to northwest–southeast (van de Beuque et al., 2003). The basin covers an area of approximately 84,200 km^2, half of which lies in Australian waters. It contains a ?Lower Cretaceous to Cenozoic succession with a maximum thickness of over 5000 m in the westernmost depocentres adjoining the Capel Basin (Figure 5.8; Colwell et al., 2010; Higgins et al., 2011b; Petkovic et al., 2011). However, extensive areas of basement high reduce the total sediment thickness to 2000 m or less in much of the southern and eastern parts of the basin. The Upper Cretaceous–Cenozoic succession within the basin is laterally contiguous with the bathyal succession that blankets the entire Lord Howe Rise. The Faust Basin adjoins the Capel Basin to the west across a prominent basement ridge, the Lord Howe Platform to the east, and the Gower Basin to the south (Stagg et al., 1999; van de Beuque et al., 2003).

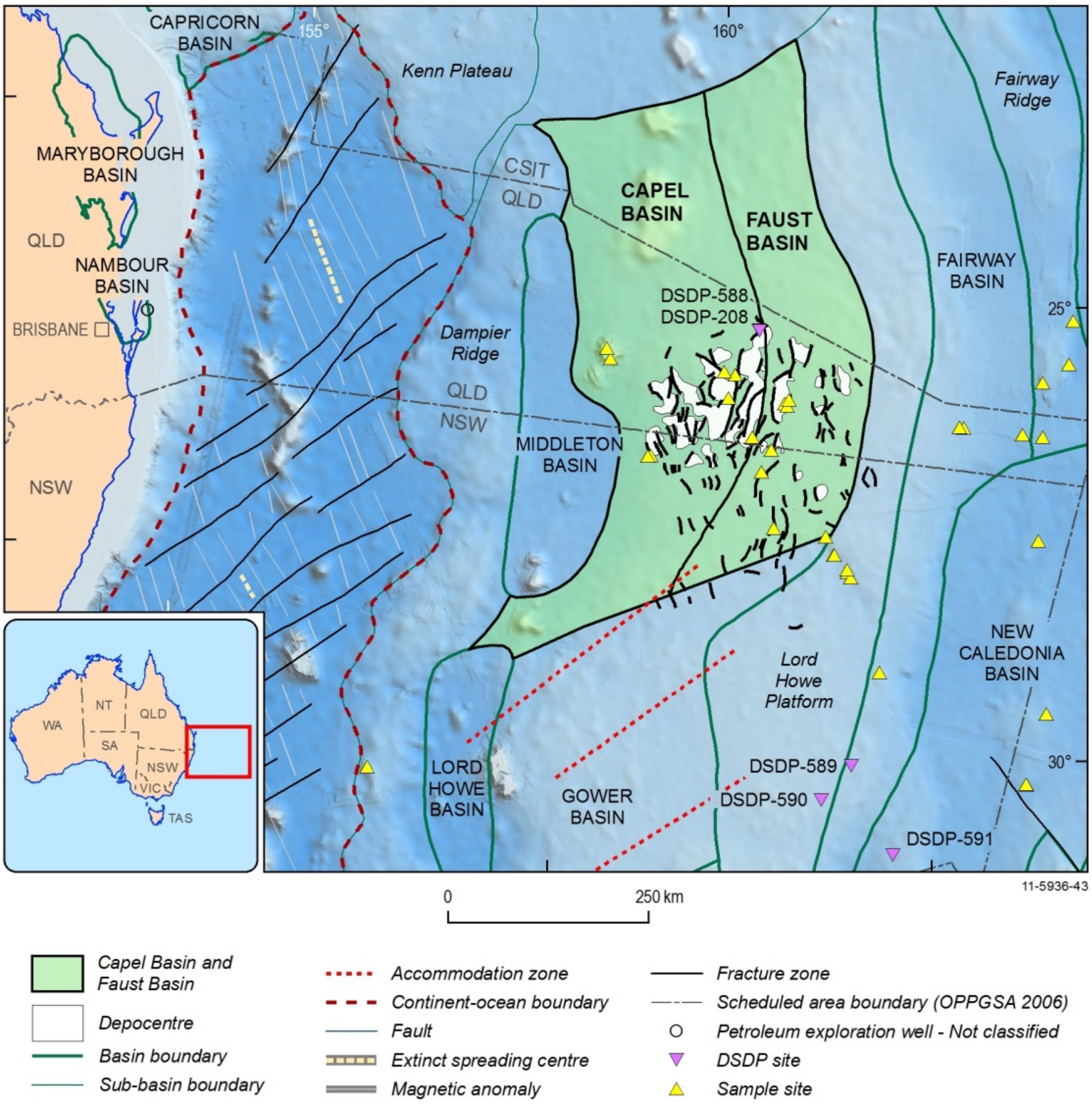

Figure 5.7: Structural elements map, Capel and Faust basins. Depocentre and fault locations after Colwell et al. (2010) and Higgins et al. (2011b).

5.2.2.1 Structural geology

The Faust Basin evolved during the Cretaceous breakup of eastern Gondwana that culminated with the opening of the Tasman Sea (85–52 Ma) and detachment of the Lord Howe Rise from eastern Australia (Hayes & Ringis, 1973; Gaina et al., 1998; Sdrolias et al., 2001). The Central Rift Province of the Lord Howe Rise, which includes the Faust Basin, experienced moderate crustal extension compared to the Western Rift Province. Seismic refraction data presented by Shor et al. (1971) indicate crustal thicknesses of 18–29 km beneath the Faust Basin. Two major phases of intracontinental extension resulted in the formation of generally north–south-trending major basement-involved faults, graben and half graben in the western part of the Faust Basin (Figure 5.7 and Figure 5.9; Colwell et al., 2010; Higgins et al., 2011b). In the eastern and southern parts, limited crustal extension formed several small northwest–southeast-trending depocentres, which align with the pre-rift regional structural trend (Higgins et al., 2011b). Extensive basement highs separate the depocentres. The extensional structures have been modified by multiple episodes of compression, uplift and basin inversion during the Late Cretaceous–Neogene.

5.2.2.2 Basin evolution and depositional history

In the absence of direct evidence, the main tectonostratigraphic phases within the Faust Basin have mostly been inferred from tectonic reconstructions and regional correlations. During the Paleozoic to the Early Cretaceous, the Lord Howe Rise was part of the eastern Gondwana margin located inboard of the convergent boundary with the Pacific Plate. Rocks forming the pre-rift basement to the Faust Basin are inferred to be equivalent to those of the New England Orogen, Clarence-Moreton Basin, Maryborough Basin, Gympie Terrane or the Maitai/Murihiku supergroups, and the early part of the Whitsunday Volcanic Province (Mortimer et al., 2008; Norvick et al., 2008; Colwell et al., 2010).

During the Early Cretaceous to Cenomanian, regional extension and magmatism, extending along the entire backarc area of the eastern Gondwana margin (Norvick et al., 2001, 2008), formed large north–south-trending graben and half graben in the Capel and westernmost Faust basins (Colwell et al., 2010; Higgins et al., 2011b). The lower syn-rift succession (the Syn-rift 1 Megasequence; Figure 5.9) is interpreted to contain up to 3 km of fluvio-lacustrine sediments, and volcaniclastic and igneous rocks (Colwell et al., 2010). In the eastern and southern Faust Basin, limited extension resulted in smaller depocentres with thinner successions. Cessation of subduction along eastern Gondwana–Pacific plate boundary resulted in regional uplift during the Cenomanian (Norvick et al., 2001, 2008; Willcox et al., 2001; Schellart et al., 2006; Waschbusch et al., 2009; Rey & Müller, 2010). Widespread inversion, folding and erosion within the Faust Basin is attributed to this event (Colwell et al., 2010).

A second phase of northeast–southwest crustal extension is interpreted to have taken place during the Cenomanian–Campanian, in the lead up to the opening of the Tasman Sea (Figure 5.8; Norvick et al., 2008). This event mainly affected the western Faust basin, where extension continued in the Early Cretaceous north–south-trending depocentres (Colwell et al., 2010; Higgins et al., 2011b). Some of the smaller depocentres in the eastern Faust Basin also continued to grow, possibly due to the influence of rifting in the Fairway and New Caledonia basins to the east (Collot et al., 2009). A thin (generally less than 1 km) succession accumulated (Syn-rift 2 Megasequence) and is interpreted to consist of predominantly fluvio-lacustrine sediments with increasing marine influence (Figure 5.9; Colwell et al., 2010). During this period, igneous activity was common through the Lord Howe Rise and surrounding regions (e.g. van der Lingen, 1973), and dredged rocks from the Lord Howe Platform to the east of the Faust Basin indicate magmas of alkalic intermediate composition (Higgins et al., 2011a). Rifting and deposition was terminated by localised basin inversion and erosion probably during the Campanian, associated with continental breakup and the opening of the Tasman Sea to the west (Norvick et al., 2008; Colwell et al., 2010).

During the Campanian–Maastrichtian, thermal subsidence resulted in deposition of the basal Post-rift Megasequence within the former rift depocentres (Figure 5.9). This section is interpreted to comprise fluvio-deltaic, marginal marine, shelf and bathyal clastic rocks. From the late Maastrichtian to the present, bathyal drape deposition of pelagic chalk and ooze has dominated (the main part of Post-rift Megasequence; Colwell et al., 2010), accompanied by widespread intraplate mafic magmatism (Dadd et al., 2011). Deposition was interrupted by compression and uplift during the Paleocene–Eocene, Eocene–Oligocene and possibly later, resulting in the reactivation of extensional faults, and basin inversion and erosion along depocentre margins (Colwell et al., 2010). The Eocene–Oligocene event was probably associated with a major change in the Pacific Plate motion (Müller et al., 2000; Veevers, 2000), obduction in New Caledonia (Aitchison et al., 1995) and an eastward relocation of the Australia–Pacific plate convergence (Sdrolias et al., 2001; Crawford et al., 2003).

5.2.2.3 Level of knowledge

The Faust Basin is a remote and under-explored deepwater frontier basin with a sparse coverage of regional 2D seismic reflection, gravity, magnetic and bathymetry data. There are no wells within the basin. Deep Sea Drilling Program (DSDP) holes 208 and 588, located within the adjacent Capel Basin near the boundary with the Faust Basin, provide stratigraphic control for the Maastrichtian–Holocene section. The geologic interpretation of the basin is, therefore, mostly based on regional tectonic reconstructions and correlations. Geoscience Australia seismic survey GA 302 2D (20–40 km line spacing), greatly improved data coverage over the Faust Basin, and enabled basin-wide interpretation of the seismic stratigraphy and structure. The geological interpretations suggest that the deepest depocentres are potentially capable of generating and accumulating hydrocarbons.

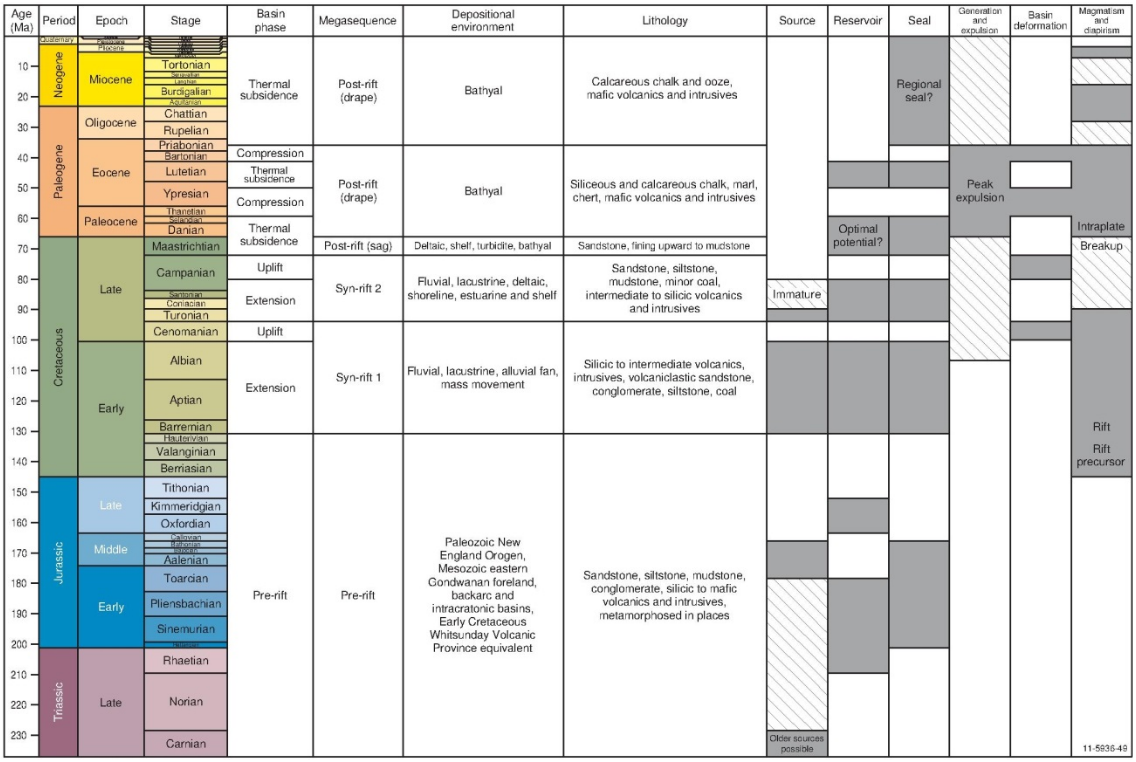

Figure 5.8: Stratigraphy of the Capel and Faust basins after Colwell et al. (2010). Predicted petroleum generation and expulsion after Funnell & Stagpoole (2011).

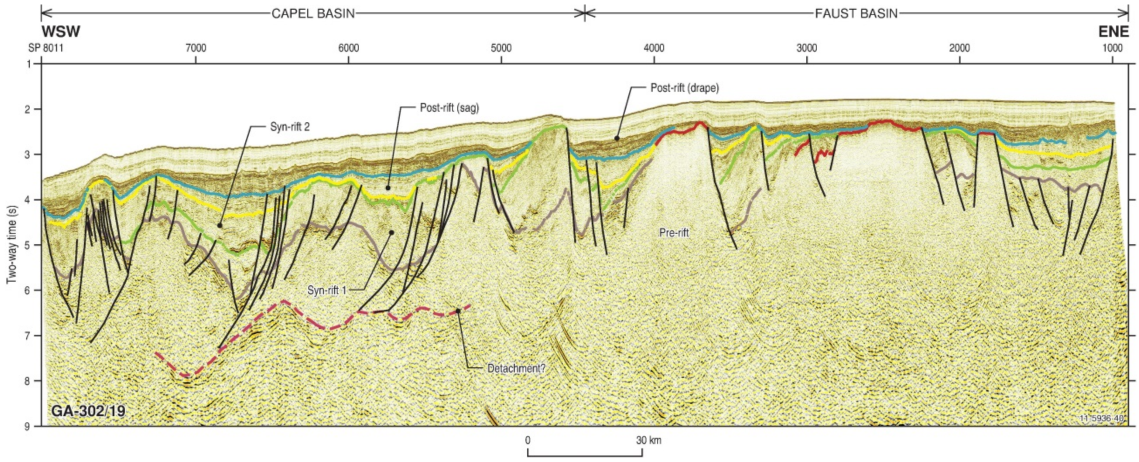

Figure 5.9: Geological cross-section of the Capel and Faust basins along seismic line GA-302/19 showing structural and stratigraphic relationships (after Colwell et al., 2010).

5.2.3 Petroleum systems

Despite the lack of evidence for active petroleum systems in the Faust Basin, the inferred stratigraphy and geologic evolution indicate that petroleum systems similar to those in onshore eastern Australia may be present in the region. The largest depocentres contain sufficiently thick sediments for oil and gas generation from pre-rift and Lower Cretaceous (Syn-rift 1) source rocks, if present (Funnell & Stagpoole, 2011). Some previous works (e.g. Ramsay et al., 1997; Exon et al., 1998; Lafoy et al., 1998; Auzende et al., 2000) have speculated that bottom simulating reflectors (BSRs) seen on regional seismic data may indicate the occurrence of gas hydrates in the Lord Howe Rise and surrounding regions. A recent reappraisal based on newly acquired data has indicated that the BSRs are more likely to be an Opal-A/Opal-CT diagenetic boundary (Colwell et al., 2006; Nouzé et al., 2009).

5.2.3.1 Source rocks

Regional tectonic reconstructions (Mortimer et al., 2008; Norvick et al., 2008) and seismic character analysis indicate that pre-rift sediments underlying the deeper depocentres of the Faust Basin may be equivalent to the successions in the Clarence-Moreton or Maryborough basins of eastern Australia. If so, gas-prone Middle–Upper Triassic to Lower Jurassic fluvio-lacustrine coal and mudstone source rocks, such as the Nymboida and Ipswich coal measures of the Clarence-Moreton Basin (Willis, 1985; Powell et al., 1993; O'Brien et al., 1994; Stewart & Alder, 1995), or the Tiaro Coal Measures of the Maryborough Basin (Lipski, 2001; Stephenson & Burch, 2004), may be present (Figure 5.8). Other possible source facies include equivalents of the oil-prone Middle–Upper Jurassic Walloon Coal Measures of the Clarence-Moreton Basin (Powell et al., 1993; O'Brien et al., 1994) or the Jurassic coals within the Murihiku Supergroup in New Zealand (Uruski & Baillie, 2004; Uruski, 2006, 2008). Within the syn-rift succession, non-marine deposition within compartmentalised rift depocentres may have resulted in deposition of Lower Cretaceous gas-prone fluvio-lacustrine coal and mudstone source rocks, analogous to the Strzelecki Group of the Gippsland Basin (Norvick et al., 2001; O'Brien et al., 2008) and the Eumeralla Supersequence in the Otway Basin (Edwards et al., 1999; Krassay et al., 2004; Boreham et al., 2004). Fluvio-deltaic coal and mudstone source rocks akin to the Taniwha and Rakopi formations of the Taranaki Basin (King & Thrasher, 1996; Norvick et al., 2001; Uruski & Baillie, 2004; Uruski, 2008) may occur within the upper Syn-rift 2 Megasequence, but would be immature given the shallow burial depths.

5.2.3.2 Generation and expulsion

Multi-1D petroleum systems modelling suggests Jurassic–Lower Cretaceous source rocks that may be present within the pre-rift and Syn-rift 1 successions are predicted to be oil or gas mature within the deepest depocentres in the westernmost parts of the basin (Funnell & Stagpoole, 2011). Hydrocarbon generation and expulsion for these source rocks is expected from the Aptian to the present, with a peak during the Late Cretaceous to Middle Eocene (Figure 5.8). However, in most other parts of the basin, the sediment thickness is insufficient for hydrocarbon generation. Measurements in the Capel and Faust basins from the AUSFAIR survey indicate heat flow of over 60 mW/m^2 (Colwell et al., 2006), while measurements at DSDP 587 (northern Lord Howe Rise; Morin & von Herzen, 1986) and DSDP 206 (New Caledonia Basin; von Herzen, 1973) are in the range 56–58 mW/m^2. These results suggest above-average heat flow in the Faust Basin, which would have assisted the maturation of source rocks. Moreover, widespread Cenozoic magmatism may have enhanced the maturity of shallowly buried source rocks between the Eocene and present, if accompanied by elevated crustal heat flow (Funnell & Stagpoole, 2011). Hydrocarbon migration within the basin is likely to be complex, being controlled by: the high degree of compartmentalisation of depocentres; major north–south and northwest–southeast-trending faults, and; facies variability within the Syn-rift 1, Syn-rift 2 and lower Post-rift megasequences.

5.2.3.3 Reservoirs

Potential reservoir sandstones may occur within the pre-rift, Syn-rift 1, Syn-rift 2 and the lower Post-rift successions (Figure 5.8). The pre-rift succession may include Upper Triassic–Jurassic quartzose fluvial sandstones, equivalent to those in the Clarence-Moreton and Maryborough basins (O’Brien et al., 1994; Lipski, 2001; Stephenson & Burch, 2004). Fluvial channel and alluvial fan sandstones are likely to occur within the Syn-rift 1 Megasequence, but they may vary in quality depending on the degree of volcaniclastic input and fluvial sorting achieved by small drainage systems associated with compartmentalised rift depocentres. Fluvial channel sandstones within the Syn-rift 2 Megasequence probably have better reservoir potential because of a lower volcaniclastic input and greater degree of sorting by axial fluvial systems. The best reservoir potential perhaps occurs within the upper Syn-rift 2 and the lower Post-rift successions, where early transgressive marine deposits are likely.

5.2.3.4 Seals

Analogy with the Clarence-Moreton and Maryborough basins suggests that within the pre-rift succession, potential intraformational seals may be provided by Lower–Upper Jurassic fluvio-lacustrine mudstones (O’Brien et al., 1994; Lipski, 2001; Stephenson & Burch, 2004). Intraformational seals may also be provided by potential fluvio-lacustrine mudstones within the Syn-rift 1 and Syn-rift 2 megasequences, and marine to deltaic mudstones within the upper Syn-rift 2 and lower Post-rift megasequences (Figure 5.8). Regional seal may be provided by the extensive and thick Oligocene–Holocene pelagic chalk and ooze, although seal integrity may be compromised in places by intraplate magmatism, fluid migration and faulting (Rollet et al., 2012). Cretaceous–Holocene volcanic flows and sills may locally act as seals in parts of the syn-rift and Post-rift successions.

5.2.3.5 Play types

A range of structural and stratigraphic plays are possible in the Faust Basin. Potential structural play styles include tilted fault blocks and horsts, inversion and intra-basinal anticlines, and fault rollover structures. Tilted fault blocks within the pre-rift succession may also be potential plays. The high apparent facies variability and regional palaeogeography also suggests the potential for stratigraphic (and combined structural–stratigraphic) plays in the Faust Basin, including fluvial channels, both proximal and distal marine sandstone facies, onlap and sub-unconformity plays. Stratigraphic trapping potential may be locally enhanced by Lower Cretaceous to Cenozoic volcanic flows and sills.

Only a small proportion of structures present, however, are likely to offer viable potential plays, due to the restricted lateral extent of source kitchen areas and the baffling effect of extensive basement highs. Given the peak in hydrocarbon generation and expulsion during the Late Cretaceous to Paleogene, plays reliant on pre-rift or Cretaceous intraformational seals are more likely to be charged. However, the lateral extent and thickness of the intraformational seals are unknown, and preservation through the Cenozoic reactivation events may be a problem. The Maastrichtian–Holocene bathyal sediments are extensive and generally thick, but their potential as a regional seal remains untested. The bathyal succession also only attained substantial thickness after the Oligocene, so plays dependent on these sediments as seals would require sufficient hydrocarbon charge after the peak in generation and expulsion. Moreover, bathyal sediments thin over many of the major basement highs, precluding structures in these areas from being viable plays.

5.2.3.6 Critical risks

There is no direct evidence for the presence of source rocks, reservoirs, seals and active petroleum systems in the Faust Basin. Furthermore, there may be insufficient sediment thickness for hydrocarbon generation and expulsion in some areas of the basin. Nonetheless, the interpretation of recently acquired data, supplemented by regional reconstructions and analogues, shows that petroleum system elements are likely to be present, and that potential source rocks would be oil or gas-mature within the deepest depocentres. Assuming the presence of source rocks, a key risk is the timing of main hydrocarbon charge (Late Cretaceous–Eocene) relative to the bathyal regional seal and overburden deposition (Oligocene–Recent). Moreover, the limited area of potential source kitchens and extensive basement highs may result in insufficient charge. Major structuring events during the Cenomanian, Campanian, Paleocene–Eocene and Eocene–Oligocene, and Cenozoic igneous activity and associated fluid migration, may pose a risk to preservation of earlier trapped hydrocarbons. Effectiveness of the Oligocene–Holocene bathyal sediments as a regional seal remains untested, and no information exists on the distribution and effectiveness of intraformational seals. Multiple episodes of syn-rift and intraplate magmatism during the Cretaceous to Holocene may have a negative effect on reservoir quality through volcaniclastic input and hydrothermal alteration.

5.2.3.7 Overall prospectivity classification

Low–moderate

5.2.4 Exploration status

The Faust Basin is a frontier basin in terms of exploration status. No exploration activity has taken place other than reconnaissance seismic surveys in the early 1970s by Shell International (MV *Petrel*) and Mobil in the French (New Caledonian) part of the basin. Geoscience Australia, its predecessors Australian Geological Survey Organisation (AGSO) and Bureau of Mineral Resources (BMR), as well as the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) have completed several data acquisition surveys over the Lord Howe Rise region, including the Faust Basin, since the 1970s for reconnaissance geological investigation, offshore hydrocarbon resource assessment and determination of maritime boundaries under the United Nations Convention on the Law of the Sea (UNCLOS).

5.2.5 Data

The Faust Basin, together with the Capel Basin, has the best data coverage within the Lord Howe Rise region. Nevertheless, it is a sparsely surveyed frontier area with no stratigraphic control, other than the DSDP drill holes 208 and 588 drilled at the same location in the adjoining Capel Basin. DSDP 208 penetrated a predominantly Cenozoic section of nannofossil/foraminiferal ooze before terminating in an upper Maastrichtian section (The Shipboard Scientific Party, 1973). DSDP 588 consisted of four core holes at the DSDP 208 site, with DSDP 588C terminating in the Middle Eocene rocks (The Shipboard Scientific Party, 1986). Key data sets for the Faust Basin are listed in Table 5.6–Table 5.10, and their location shown in Figure 5.10 and Figure 5.11.

Other data sets comprise regional 2D seismic, refraction seismic, gravity, magnetic and bathymetry data, and isolated rock samples. 2D seismic reflection data coverage over the northern Lord Howe Rise, including the Faust Basin, is sparse and variable in quality. Data from seven surveys completed over the basin during the 1970s are generally of poor quality. The joint Australian–French AGSO s206/FAUST 1 survey acquired 4564 line-km of moderate to high-quality data over the northern Tasman Sea region (Bernardel et al., 1999), of which about 400 km lie over the Faust Basin. Segments of lines s206-02 and s206-04 were subsequently reprocessed to image much of the basin succession and parts of the pre-rift basement. The Geoscience Australia GA 302 seismic survey provides the best data quality and density over the basin. The survey acquired about 6000 km of data over 23 lines with spacing of 15–40 km in the central and southern parts of the Capel and Faust basins. The high-quality 106-fold data recorded to 12 s TWT enabled full imaging of the basin succession and the pre-rift basement for the first time (Kroh et al., 2007).

Seismic refraction data collected in the vicinity of the Faust Basin during several surveys (Table 5.8), contributed to a velocity model for the basin (Petkovic, 2010) that underpinned the geological interpretations recently completed by Geoscience Australia (e.g. Colwell et al., 2010; Higgins et al., 2011b). In addition, ocean-bottom seismometer (OBS) refraction data were acquired in the French (New Caledonian) parts of the Capel, Faust, Fairway and New Caledonia basins (Klingelhoefer et al., 2007).

Potential field and bathymetry data coverage over the Faust Basin includes regional compilations derived from satellite, airborne and marine data (Sandwell & Smith, 1997; Andersen et al., 2010; Maus et al., 2007, 2009; Whiteway, 2009). Shipboard gravity, magnetic and bathymetry data were acquired during the Geoscience Australia and Ifremer AUSFAIR MD-153 MV *Marion Dufresne* survey (Colwell et al., 2006), and Geoscience Australia GA-302 (Kroh et al., 2007) and GA-2436 RV *Tangaroa* (Heap et al., 2009) surveys. Recently, all shipboard gravity and magnetic data over the Lord Howe Rise region have been re-levelled and released as the Geoscience Australia Capel and Faust basins levelled potential field data (Hackney, 2010). These revised data sets represent the highest-resolution and most complete gravity and magnetic data coverage currently available over the Faust Basin.

A few rock samples have been collected from the seafloor within, and in the vicinity of, the Faust Basin. These include continental rocks (conglomerate, sandstone, calcarenite, alkali intermediate–acid volcanics) dredged from the Lord Howe Platform immediately to the east of the Faust Basin during the BGR RV *Sonne* 36 (Röser & Shipboard Party, 1985) and Geoscience Australia/Ifremer AUSFAIR MD-153 (Colwell et al., 2006) surveys. In addition, predominantly upper Cenozoic mafic volcanic rocks and seafloor sediments were collected during the GA-2436 RV *Tangaroa* survey (Dadd et al., 2011). The volcanic rocks from the Lord Howe Platform collected during the AUSFAIR MD-153 survey have subsequently been dated at 96.9 +/- 0.7 Ma (Cenomanian) and 74.1+/-0.7 Ma (Campanian; Higgins et al., 2011a). The extensive cover of bathyal ooze over the entire region severely limits sampling opportunities for older rocks. A complete list of sampling surveys can be found in Table 5.9.

5.2.5.1 Confidence rating

Medium–low

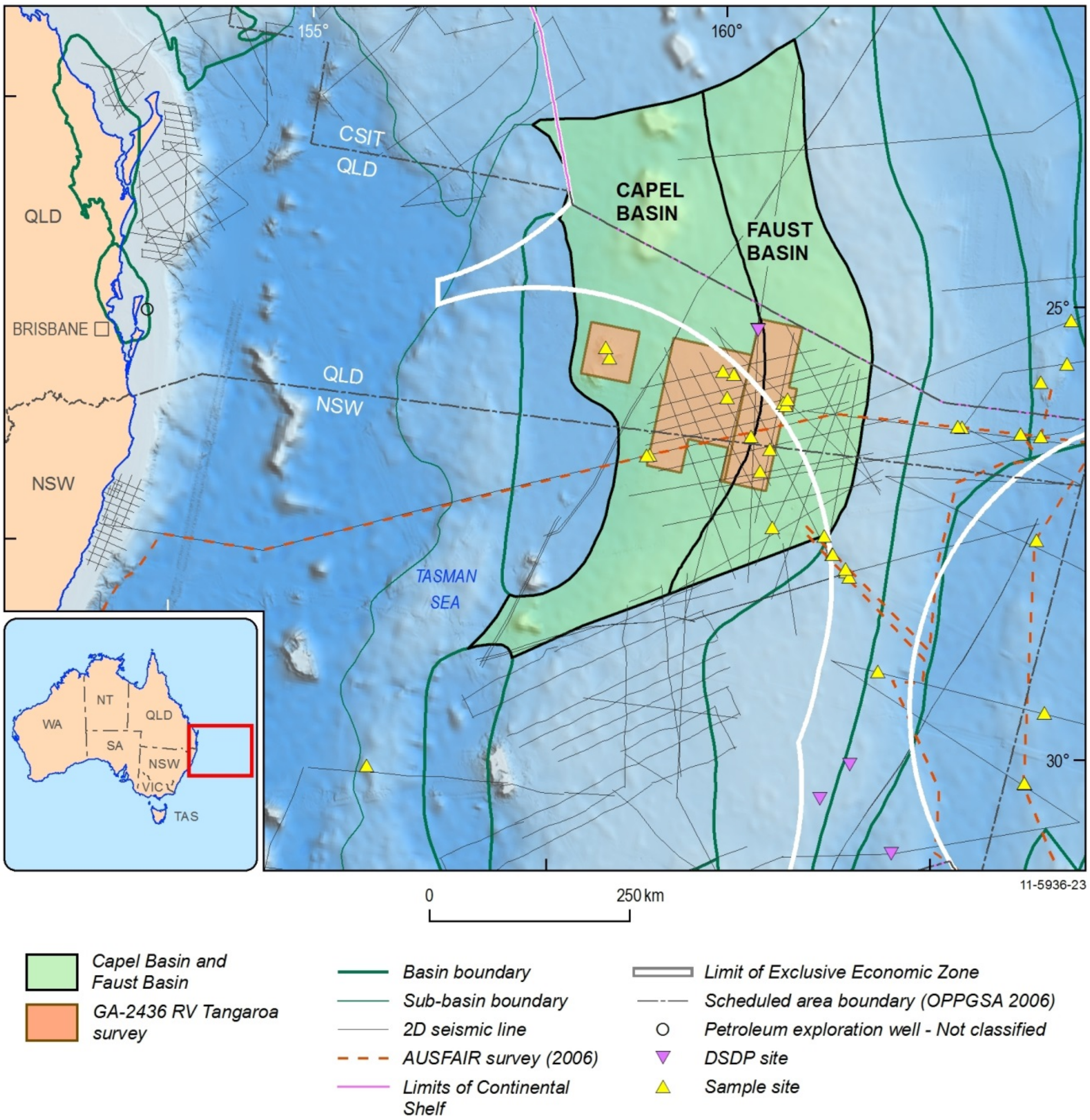

Figure 5.10: Seismic, well and sample distribution, Capel and Faust basins.

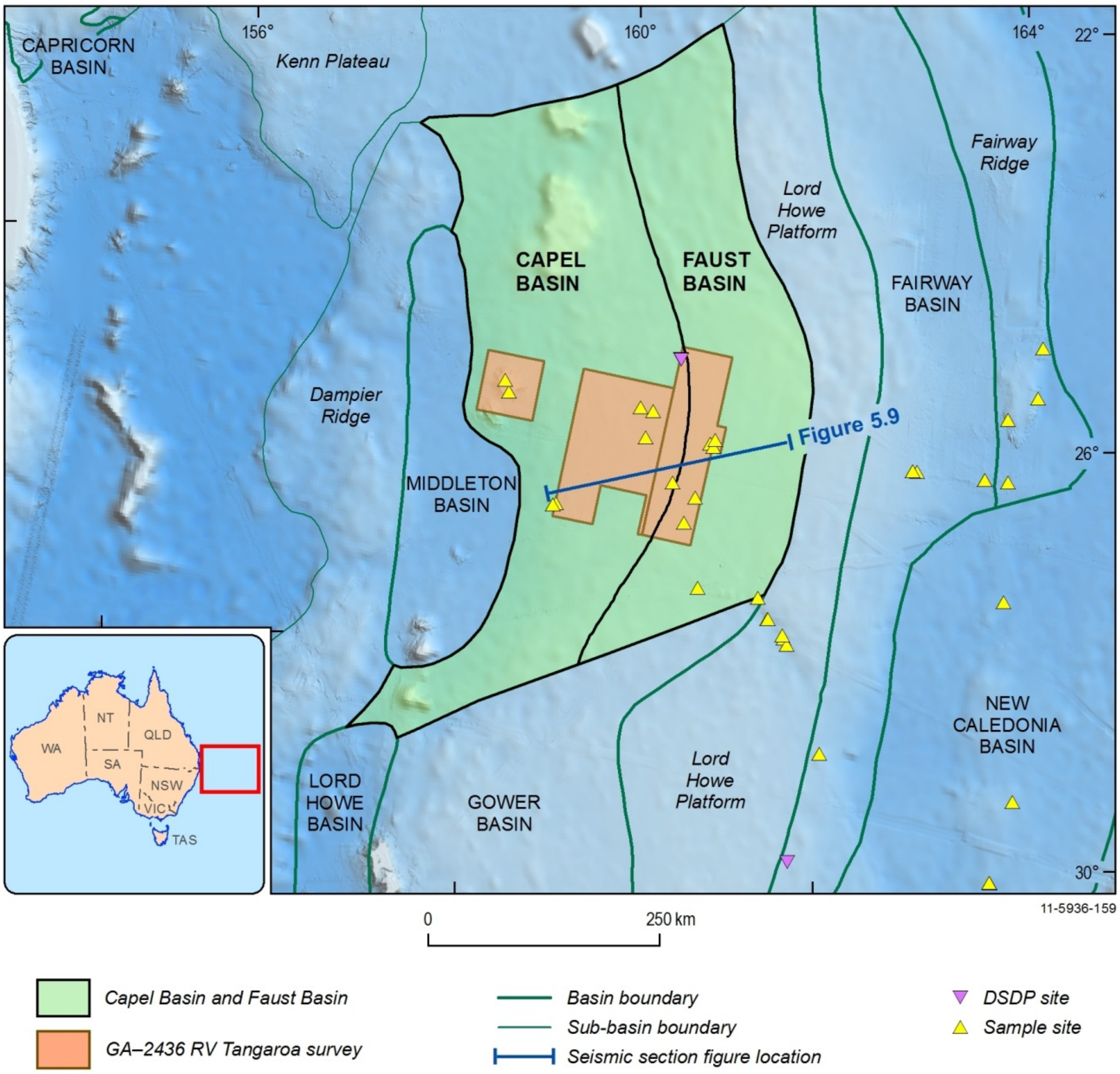

Figure 5.11: GA Survey 2436 and location of seismic line shown in Figure 5.9.

5.2.6 Issues and remaining questions

Lack of direct evidence for the composition and age of basin succession and the basement, and particularly for the existence of source, reservoir, seal and active petroleum systems, is a major obstacle to improving the understanding of the region's petroleum prospectivity and reducing exploration risk.

Compared to the neighbouring Capel and Gower basins, the Faust Basin has fewer depocentres with sufficient thickness of sediment for hydrocarbon generation. Given the remoteness from existing infrastructure and markets, the Faust Basin is likely to offer secondary targets to exploration activity focused on the more prospective areas of the Lord Howe Rise.

5.2.6.1 Recommendations

Stratigraphic drilling over a target that allows penetration at least to the lower Syn-rift 1 section (and preferably deeper into the pre-rift sedimentary section) could address some of the key issues. Targeted seismic data acquisition (e.g. high-density 2D or 3D reflection) would be recommended prior to any drilling attempts, in order to refine the interpretation of 3D architecture of the basin depocentres and the identification of drilling targets. The extensive and thick cover of Cenozoic bathyal sediments, and the paucity of canyons and scarp exposures, limits opportunities for the collection of dredged rocks samples. Carefully targeted deep coring may be a viable alternative to dredging.

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5.2.8 Data Tables

Table 5.6: List of wells drilled close to the Faust Basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1971	DSDP 208	Scientific	Deep Sea Drilling Project	594	Late Maastrichtian	Nil	The Shipboard Scientific Party, 1973
1982	DSDP 588	Scientific	Deep Sea Drilling Project	236.0	Middle Miocene	Nil	The Shipboard Scientific Party, 1986
1982	DSDP 588A	Scientific	Deep Sea Drilling Project	344.4	Early Miocene	Nil	The Shipboard Scientific Party, 1986
1982	DSDP 588B	Scientific	Deep Sea Drilling Project	277.4	Middle Miocene	Nil	The Shipboard Scientific Party, 1986
1982	DSDP 588C	Scientific	Deep Sea Drilling Project	488.1	Middle Eocene	Nil	The Shipboard Scientific Party, 1986

Table 5.7: Key 2D seismic surveys, Faust Basin.

Year	Survey	Operator	Line-km	Reference
1971	MV *Petrel* Roving	Shell International	150	van de Beuque et al., 2003; Sutherland et al., 2012
1972	Mobil 1972	Mobil	140	Stagg et al., 2002; Sutherland et al., 2012
1998	AGSO 206 (FAUST 1)	Australian Geological Survey Organisation	950	Bernardel et al., 1999
2006/2007	GA-302	Geoscience Australia	3100	Kroh et al., 2007

Table 5.8: Refraction seismic and velocity surveys covering the Faust Basin.

Year	Survey	Operator	Location	Reference
1967	Scripps Institution of Oceanography two-ship refraction seismic survey	Scripps Institution of Oceanography	23 profiles over Southwest Pacific	Shor et al., 1971
1971	DSDP 208 sonobuoy refraction survey	Deep Sea Drilling Project	Capel Basin	The Shipboard Scientific Party, 1973
1978	RV *Sonne* 7 survey	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)	Lord Howe Rise region including two sites in Capel and Faust basins	Willcox et al., 1981

Year	Survey	Operator	Location	Reference
2004	ZoNéCo 11 OBS survey	Ifremer, Agence de Développement Economique de la Nouvelle Calédonie (ADECAL)	42 sites in French (New Caledonian) parts of Capel, Faust, Fairway and New Caledonia basins	Klingelhoefer et al., 2007
2006/2007	GA-302 sonobuoy refraction survey	Geoscience Australia	96 sites in Capel and Faust basins	Petkovic, 2010

Table 5.9: List of key surveys involving geological sampling.

Year	Survey	Operator	Region	Type	Rock types	Reference
1985	RV *Sonne* 36	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)	Lord Howe Platform	Dredge	Pebbly conglomerate, sandstone, calcarenite	Röser & Shipboard Party, 1985
2006	AUSFAIR MD-153 (RV *Marion Dufresne*)	Geoscience Australia, Ifremer	Capel, Faust and New Caledonia basins, Lord Howe Platform, Fairway Ridge	Dredge, giant piston core	Trachyte, latite, quartz–feldspathic conglomerate and sandstone, some with molluscan fossils, calcareous ooze, ferromanganese nodules and crust	Colwell et al., 2006; Higgins et al., 2011a
2007	GA-2436 RV *Tangaroa*	Geoscience Australia	Capel and Faust basins, Gifford Guyot	Dredge, piston and box cores, epibenthic sled, camera, CTD	Mafic volcanic rocks, pumice, ferromanganese nodules and crust, calcareous ooze and chalk	Heap et al., 2009; Dadd et al., 2011

Table 5.10: Swath bathymetry surveys.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
2001	Australian continental margin levelled gravity, magnetic and bathymetry	Geoscience Australia, Intrepid Geophysics		Petkovic et al., 2001
2006	AUSFAIR MD-153 (RV *Marion Dufresne*)	Geoscience Australia, Ifremer	Capel, Faust and New Caledonia basins, Fairway Ridge	Colwell et al., 2006
2007	GA-2436 RV *Tangaroa*	Geoscience Australia	39,870 km^2 over Capel and Faust basins, Gifford Guyot	Heap et al., 2009
2009	Bathymetry and Topography Grid of Australia AUSBATH09 (2009)	Geoscience Australia		Whiteway, 2009

5.3 Gower Basin

5.3.1 Summary

State(s)		Commonwealth waters, NSW
Area (km^2)		106,000
Water Depth (m)		750–3000
Maximum sediment thickness (m)		>4000 (excluding underlying probable pre-rift succession)
Age range		?Late Jurassic–Cenozoic
Basin	**Overlies**	Possible equivalents of New England Orogen, Sydney Basin, Gympie Terrane or Murihiku/Maitai Supergroup, Whitsunday Volcanic Province
	Adjacent basins	Capel, Faust, Lord Howe, Moore and Monawai basins, Lord Howe Platform,
Basin type		Extensional, sag
Depositional setting, rock types		Non-marine, deltaic, and marine clastic sedimentary rocks, bathyal biogenic (carbonate, siliceous) sedimentary rocks, volcanic, intrusive and volcaniclastic rocks
Petroleum prospectivity		Moderate–low
Confidence		*Low–medium*

5.3.2 Geology

The Gower Basin is located over the central segment of the Lord Howe Rise, in water depths of 750–3000 m (Figure 5.12). It straddles the Central Rift and Western Rift provinces of the Lord Howe Rise (Stagg et al., 1999) and is characterised by north-northwest trending extensional depocentres offset by northeast-trending accommodation zones (Willcox & Sayers, 2001, 2002). The basin covers an area of approximately 106,000 km^2 and contains an ?Upper Jurassic to Cenozoic succession generally 1500 to 3000 m thick, but attaining a maximum thickness of over 4000 m in the largest depocentres (Figure 5.13; Willcox & Sayers, 2001, 2002). Together with the adjacent Capel Basin, the Gower Basin represents the area of greatest sediment accumulation within the Lord Howe Rise. The depocentres are separated by basement horsts that are thinly mantled by predominantly Cenozoic bathyal sediments. The Gower Basin adjoins the Capel and Faust basins to the north across a major structural offset along the Barcoo–Elizabeth–Fairway Lineament. It adjoins the Lord Howe Platform to the east, the Lord Howe Basin to the west, and the Moore and Monawai basins to the south (Stagg et al., 1999).

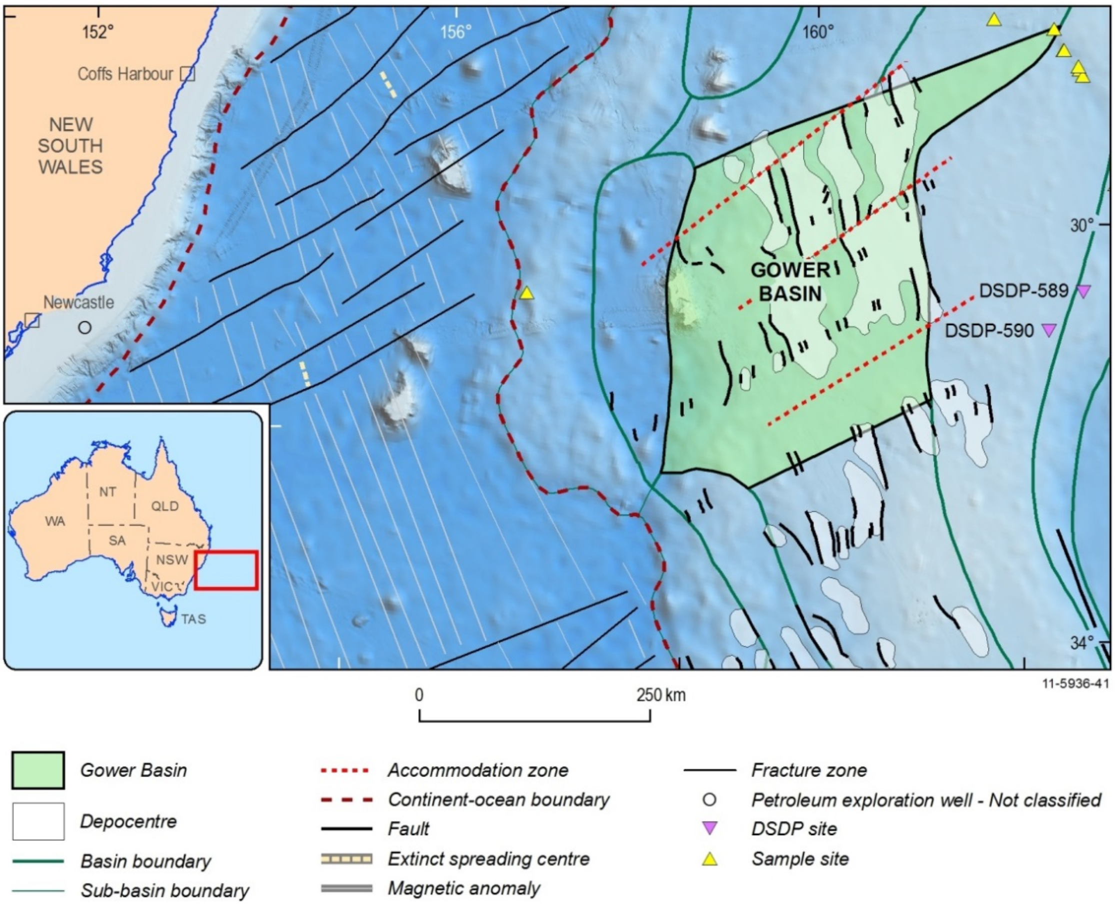

Figure 5.12: Structural elements map, Gower Basin. Depocentre locations based on Willcox & Sayers (2002) and interpretation of regional seismic, gravity and magnetic data.

5.3.2.1 Structural geology

The Gower Basin evolved during the Cretaceous breakup of eastern Gondwana that culminated with the opening of the Tasman Sea (85–52 Ma) and detachment of the Lord Howe Rise from eastern Australia (Hayes & Ringis, 1973; Gaina et al., 1998; Sdrolias et al., 2001). The Central Rift and Western Rift provinces of the Lord Howe Rise, including the Gower Basin, experienced varying degrees of crustal extension prior to the breakup. Seismic refraction data from immediately to the north in the Capel and Faust basins indicate crustal thicknesses of 18–29 km (Shor et al., 1971). Two major syn-rift phases resulted in the formation of north-northwest trending major basement-involved faults, graben and half graben, mainly in the central and eastern parts of the Gower Basin (Figure 5.12 and Figure 5.14). The western part of the basin, along the boundary with the Lord Howe Basin, is dominated by a broad ridge of basement and/or volcanic rocks with minor development of depocentres. Syn-rift structuring has been overprinted by the effects of post-rift inversion, post-breakup thermal subsidence, and Cenozoic compressive folding.

5.3.2.2 Basin evolution and depositional history

The geologic evolution of the Gower Basin (Figure 5.13) has been reconstructed through inference from seismic interpretation, tectonic reconstructions and regional correlations. Pre-breakup palaeogeography of eastern Gondwana indicates that the southern boundary of the Gower Basin was situated close to the northern edge of the Gippsland Basin, implying that the two basins share a similar early evolutionary history (Willcox & Sayers, 2001, 2002).

From the Paleozoic to the Early Cretaceous, the Lord Howe Rise was part of the eastern Gondwana margin located inboard of the convergent boundary with the Pacific Plate. The basement rocks underlying the Gower Basin (Megasequence GB11; Willcox & Sayers, 2001, 2002) are inferred to be equivalent to those of the New England Orogen, Sydney Basin, Gympie Terrane or the Maitai/Murihiku supergroups, and the early part of the Whitsunday Volcanic Province (Norvick et al., 2001, 2008; Willcox & Sayers, 2001, 2002; Mortimer et al., 2008; Colwell et al., 2010).

In the latest Jurassic to the earliest Cretaceous, crustal extension between the Lord Howe Rise and the Australian continent resulted in the onset of rifting in the Gower Basin (Willcox & Sayers, 2001, 2002; Norvick et al., 2001, 2008). Extension was accompanied by regional magmatism that extended along the entire backarc area of the eastern Gondwana margin (Norvick et al., 2001, 2008). In the Gower Basin, a thick syn-rift succession attaining a maximum thickness of 4000 m was deposited within the rift depocentres. Deposition was initially dominated by volcanics (megasequence GB10; Willcox & Sayers, 2001, 2002), and was succeeded by widespread and potentially non-marine volcaniclastic deposition (megasequences GB8 and GB9; Willcox & Sayers, 2001, 2002). These megasequences are interpreted to be analogous to the Lower Cretaceous Strzelecki Group of the Gippsland Basin, the Otway Group of the Durroon Sub-Basin (Bass Basin), and the uppermost Jurassic Casterton Formation in the Otway Basin (Willcox & Sayers, 2001, 2002).

Syn-rift deposition was terminated in the Cenomanian by regional uplift that resulted in inversion, folding, transpression and erosion (unconformity U8; Willcox & Sayers 2001, 2002). This event is recognised over much of the Lord Howe Rise and eastern and southern Australia, and has been attributed to the cessation of subduction along eastern Gondwana–Pacific plate boundary (Norvick et al., 2001, 2008; Willcox et al., 2001; Schellart et al., 2006; Waschbusch et al., 2009; Rey & Müller, 2010).

A second phase of crustal extension resulted in the deposition of up to 600 m of sediments. This succession (megasequence GB7) is interpreted to comprise Cenomanian–Campanian coastal to restricted marine sediments analogous to the Golden Beach and Emperor subgroups of the Gippsland Basin (Norvick et al., 2001, 2008; Willcox & Sayers, 2001, 2002). The onset of seafloor spreading in the Tasman Sea during the Campanian resulted in the transient uplift of the Gower Basin (unconformity U7; Willcox & Sayers, 2001, 2002), followed by thermal subsidence. Initial deposition during this phase was probably coastal to marginal marine, but bathyal conditions were established by the Maastrichtian (megasequences GB4–GB6; Willcox & Sayers, 2001, 2002). These sediments attain a thickness of up to 1800 m within topographic lows overlying the syn-rift depocentres. A prominent unconformity (U5) at the top of this succession is likely to reflect a major change in regional tectonics during the Eocene associated with a shift in the motion of the Pacific Plate (Müller et al., 2000; Veevers, 2000), obduction in New Caledonia (Aitchison et al., 1995) and an eastward relocation of the Australia–Pacific plate convergence (Sdrolias et al., 2001; Crawford et al., 2003).

The Gower Basin entered an oceanic phase from the Oligocene onward, characterised by the deposition of a bathyal succession up to 850 m thick comprising laterally continuous pelagic carbonate oozes and clays (megasequences GB1–GB4; Willcox & Sayers, 2001, 2002). Compressive stresses propagating from plate convergence to the northeast of the region resulted in ongoing gentle folding of strata from the Miocene until Holocene times (Willcox & Sayers, 2001, 2002).

5.3.2.3 Level of knowledge

The Gower Basin is a remote and under-explored deepwater frontier basin with a sparse coverage of regional 2D seismic reflection, gravity, magnetic and bathymetry data (Figure 5.15). No petroleum exploration wells have been drilled within the basin. The nearest drilling locations are Deep Sea

Drilling Program (DSDP) sites 208 and 588, in the adjacent Capel Basin, which provide stratigraphic control for the Maastrichtian–Holocene section, and DSDP site 206 in the New Caledonia Basin, which provides information on the lower Paleocene–Holocene section. The geologic interpretation of the basin is based mainly on inferences from seismic data, regional tectonic reconstructions and correlations. The key seismic reflection data set covering the basin is the RV *Sonne* 36 survey (Röser & Shipboard Party, 1985; Willcox & Sayers, 2002). This data set is of sufficient quality and coverage to reveal the gross-scale basement topography and stratigraphy of the basin, but lacks resolution to fully reveal the stratigraphic detail or structure within individual depocentres. As such, the level of geological knowledge of the basin is intermediate between the better-studied Capel and Faust basins to the north, and the poorly known Moore and Monawai basins to the south.

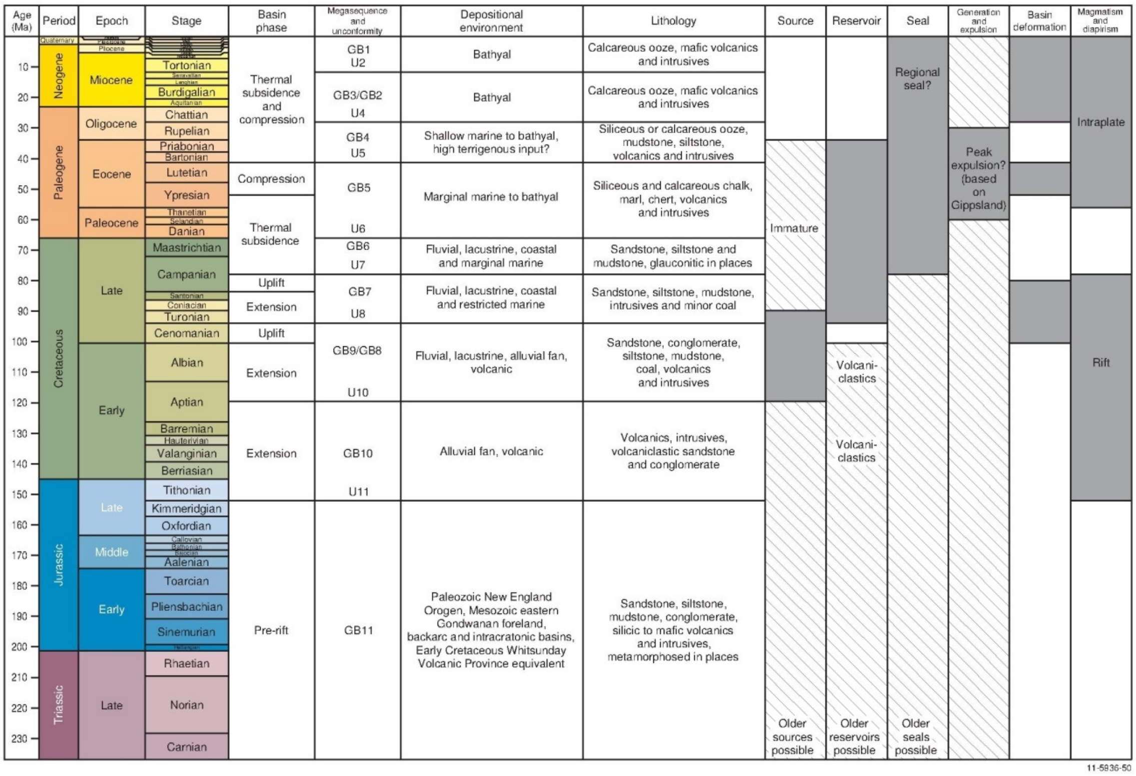

Figure 5.13: Stratigraphy of the Gower Basin based on Norvick et al. (2001, 2008) and Willcox & Sayers (2002).

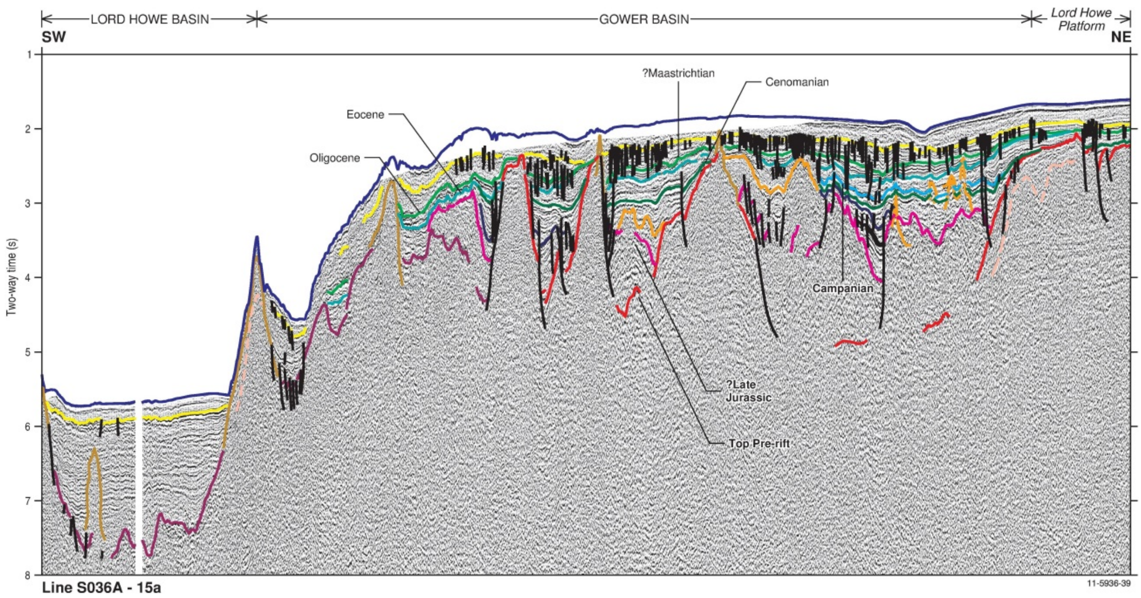

Figure 5.14: Geological cross-section of the Gower Basin along regional seismic line SO36A-15 and 15a showing structural and stratigraphic relationships (after Willcox & Sayers, 2002). Line location shown on Figure 5.16.

5.3.3 Petroleum systems

There is no evidence for active petroleum systems in the Gower Basin. The geological evolution and stratigraphy inferred from regional comparison and seismic data indicate that it is possible that petroleum systems similar to those proven in onshore eastern Australia are present in the region. Based on the results of basin modelling in the neighbouring Capel and Faust basins (Funnell & Stagpoole, 2011), it is likely that the largest depocentres of the Gower Basin contain sufficiently thick sediments for oil and gas generation from potential source rocks in the pre-rift to lower syn-rift successions. Bottom simulating reflectors (BSRs) have been identified on regional seismic data in the adjacent Monawai Basin (Stagg et al., 2002) and several previous works (e.g. Ramsay et al., 1997; Exon et al., 1998; Lafoy et al., 1998; Auzende et al., 2000) have speculated that the reflectors may indicate the occurrence of gas hydrates over the Lord Howe Rise. However, a recent reappraisal based on newly acquired data has indicated that the BSRs are most likely to be an Opal-A/Opal-CT diagenetic boundary (Colwell et al., 2006; Nouzé et al., 2009).

5.3.3.1 Source rocks

If the Gower Basin has a similar early history to the Gippsland Basin on the conjugate eastern Australian margin, gas-prone, fluvio-lacustrine coal and mudstone source rocks equivalent to the Strzelecki Group (Norvick et al., 2001; O'Brien et al., 2008) may occur within the Lower Cretaceous syn-rift succession (Figure 5.13). Gas- and oil-prone coastal plain mudstone and marine shale source rocks, equivalent to sources within the Golden Beach and Emperor subgroups in the Gippsland Basin, may also occur in the Upper Cretaceous syn-rift succession of the Gower Basin (Willcox & Sayers, 2001, 2002). Possible restricted marine conditions during the early post-rift phase (to the Maastrichtian) may have resulted in deposition of oil-prone marine shales, although they are likely to be too shallowly buried for hydrocarbon generation (Willcox & Sayers, 2001, 2002).

Regional tectonic reconstructions by Norvick et al., (2001, 2008) suggest that the central part of the Lord Howe Rise, in the vicinity of the Gower Basin, may be underlain by the offshore continuation of the Permian–Triassic Sydney Basin of eastern Australia. The most likely source rocks in the offshore

Sydney Basin are gas- and condensate-prone upper Permian coals and carbonaceous shales (Stewart & Alder, 1995), and it is possible that these potential source rocks also occur in the pre-rift sedimentary section underlying the Gower Basin.

5.3.3.2 Generation and expulsion

A sediment thickness of over 4000 m in the deepest depocentres indicates that parts of the Gower Basin would be capable of generating hydrocarbons, if suitable source rocks are present. Heat flow measurements over the southern Lord Howe Rise by Grim (1969) indicated very high values of 97–100 mW/m^2, while those in the Capel and Faust basins to the north were over 60 mW/m^2 (Colwell et al., 2006), and measurements at DSDP 587 (northern Lord Howe Rise; Morin & von Herzen, 1986) and DSDP 206 (New Caledonia Basin; von Herzen, 1973) were in the range 56–58 mW/m^2. These results suggest potentially elevated heat flow in the vicinity of the Gower Basin, which would have assisted the maturation of source rocks. The elevated heat flow may be related to the Neogene intraplate magmatism associated with the Lord Howe and Tasmantid hotspot chains to the west of the Gower Basin (Willcox & Sayers, 2001, 2002).

5.3.3.3 Reservoirs

Potential reservoir rocks in the Gower Basin may occur within the syn-rift and early post-rift megasequences (Figure 5.13) as interbedded sandstones in fluvial, coastal plain and shallow marine successions (Willcox & Sayers, 2001, 2002). Potential reservoir rocks may also occur within the pre-rift section as quartzose sandstones equivalent to those within the Triassic Hawkesbury Sandstone and Narrabeen Group of the Sydney Basin (Stewart & Alder, 1995).

5.3.3.4 Seals

A regional seal may be provided by the extensive and thick Oligocene–Holocene pelagic ooze, while volcanic flows and sills within the pre-rift and syn-rift successions have potential to act as local seals (Willcox & Sayers, 2001, 2002). Fluvio-deltaic to shallow marine shales, equivalent to parts of the Triassic Narrabeen and Wianamatta groups of the Sydney Basin, may also provide seals within the pre-rift succession (Stewart & Alder, 1995).

5.3.3.5 Play types

The polyphase evolutionary history of the Gower Basin has resulted in a range of potential play types. Potential play styles include: Cretaceous rift margin fault traps; Cenomanian inversion-related anticlinal and transpressional structures; Late Cretaceous syn-rift compaction, drape and pinchout features; basin margin pinchouts of syn-rift and post-rift strata; drape and compactional anticlines over basement; and anticlines associated with accommodation and transfer zones, potentially fed by relay structures (Willcox & Sayers, 2001, 2002). Shale or salt diapirs and Eocene carbonate mounds have also been interpreted, but these features are more likely to be volcanic in origin (Willcox & Sayers, 2001, 2002).

5.3.3.6 Critical risks

As for all other basins of the Lord Howe Rise region, the most significant uncertainty in the Gower Basin is the existence of viable source rocks, reservoirs, seals and active petroleum systems. Insufficient sediment thickness for hydrocarbon generation and expulsion is also a significant risk outside the largest depocentres. However, pre-breakup palaeogeographic proximity of the basin to the Gippsland Basin raises the possibility that petroleum system elements are present, and seismic data reveals areas of sufficient sediment thickness for hydrocarbon generation. Assuming the presence of source rocks, a key risk is the insufficient thermal maturation of source rocks arising from the comparatively thin overburden accumulation during the post-rift phase. Although the total sediment thickness is sufficient for hydrocarbon generation in the larger depocentres, the best (i.e. marine) source rock intervals are likely to occur in the upper syn-rift to lower post-rift levels, while source rocks may be poorly developed within the lower syn-rift succession due to a high volcaniclastic input (Willcox & Sayers, 2001, 2002). Thus, the effective source rocks may be insufficiently buried. Other potential risks include the timing of hydrocarbon charge relative to the deposition of the regional seal and overburden (Oligocene–Holocene), insufficient charge due to a limited extent of potential source kitchens within compartmentalised depocentres and extensive areas of basement high and breaching of early-formed accumulations and seals due to post-rift structuring.

5.3.3.7 Overall prospectivity classification

Moderate–low

5.3.4 Exploration status

The Gower Basin is a frontier basin. No exploration activity has taken place other than reconnaissance seismic surveys in the early 1970s by Shell International (MV Petrel) and Mobil. Geoscience Australia, its predecessors, the Australian Geological Survey Organisation (AGSO) and Bureau of Mineral Resources (BMR), as well as the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) have completed several data acquisition surveys over the Lord Howe Rise region, including the Gower Basin, since the 1970s for reconnaissance geological investigation, offshore hydrocarbon resource assessment and determination of maritime boundaries under the United Nations Convention on the Law of the Sea (UNCLOS).

5.3.5 Data

In comparison with other areas of the Lord Howe Rise region, the Gower Basin has a moderate data coverage; key data sets for the Gower Basin are listed in Table 5.11–Table 5.14 and locations shown on Figure 5.15. Nevertheless, it is a sparsely surveyed frontier area with no stratigraphic control, other than the DSDP drill holes 208 and 588 in the adjoining Capel Basin, and DSDP 206 drilled in the nearby New Caledonia Basin. DSDP 208 penetrated a predominantly Cenozoic section of nannofossil/foraminiferal ooze before terminating in upper Maastrichtian sediments (The Shipboard Scientific Party, 1973b). DSDP 588 consisted of four core holes at the DSDP 208 site, with DSDP 588C terminating in the Middle Eocene section (The Shipboard Scientific Party, 1986). DSDP 206 penetrated a nannofossil ooze-dominated Cenozoic section (The Shipboard Scientific Party, 1973a).

The main data set covering the Gower Basin is regional seismic reflection data from the BGR RV *Sonne* 36 survey in 1985. 3660 line-km of 2D data were acquired in collaboration with the BMR, mostly over the northern Gower Basin (Röser & Shipboard Party, 1985). The data is of moderate to good quality, enabling the gross-scale basement topography and stratigraphy to be imaged (Willcox & Sayers, 2002). However, the data set lacks the resolution to reveal the detailed stratigraphy of individual depocentres or deeply buried sections. Lines from the Shell International MV *Petrel*, Mobil and BMR RV *Rig Seismic* 46 surveys also traverse the basin, but the data is of poor to moderate quality, and the coverage within the basin in each case is less than 300 line-km. Portions of the GA 302 seismic survey and AGSO 206 survey extend into the northernmost parts of the Gower Basin.

Although the data quality is excellent, these data sets do not cover the Gower Basin sufficiently to be useful in the study of the basin.

Other relevant data sets comprise seismic refraction, gravity, magnetic and bathymetry data, and isolated rock samples. Sonobuoy seismic refraction data were collected in the vicinity of the Gower Basin during the BGR/BMR RV *Sonne* 7 Survey (Willcox et al., 1981). Sonobuoy data were collected at over 40 locations within the GA 302 seismic reflection survey grid. The velocity data acquired contributed to a velocity model (Petkovic, 2010) that underpinned the geological interpretation of the Capel and Faust basins (Colwell et al., 2010; Higgins et al., 2011b).

Potential field and bathymetry data coverage over the Gower Basin includes regional compilations derived from satellite, airborne and marine data (Sandwell & Smith, 1997; Andersen et al., 2010; Maus et al., 2007, 2009; Whiteway, 2009). Shiptrack gravity and magnetic data levelled in 2001 by Geoscience Australia (Petkovic et al., 2001) have recently been improved by re-levelling with data acquired over the northern Lord Howe Rise region during the GA 302 and GA 2436 RV *Tangaroa* surveys. This revised Geoscience Australia Capel and Faust basins levelled potential field data (Hackney, 2010) represents the highest-resolution gravity and magnetic data coverage currently available over the Gower Basin.

A few rock samples have been collected from the seafloor in the vicinity of the Gower Basin. These include continental sedimentary and igneous rocks dredged from the Lord Howe Platform immediately to the northeast of the Gower Basin during the BGR RV Sonne 36 (Röser & Shipboard Party, 1985) and Geoscience Australia/Ifremer AUSFAIR MD-153 (Colwell et al., 2006) surveys, and predominantly upper Cenozoic mafic volcanic rocks and seafloor sediments collected during the GA-2436 RV Tangaroa survey in the Capel and Faust basins to the north (Dadd et al., 2011). Basement rocks, including mid-Permian granite, were also dredged from the Dampier Ridge to the west of the Gower Basin during the RV Sonne 36 survey (Röser & Shipboard Party, 1985; McDougall et al., 1994). The extensive cover of bathyal ooze over the entire region severely limits sampling opportunities for older rocks.

5.3.5.1 Confidence rating

Low–medium

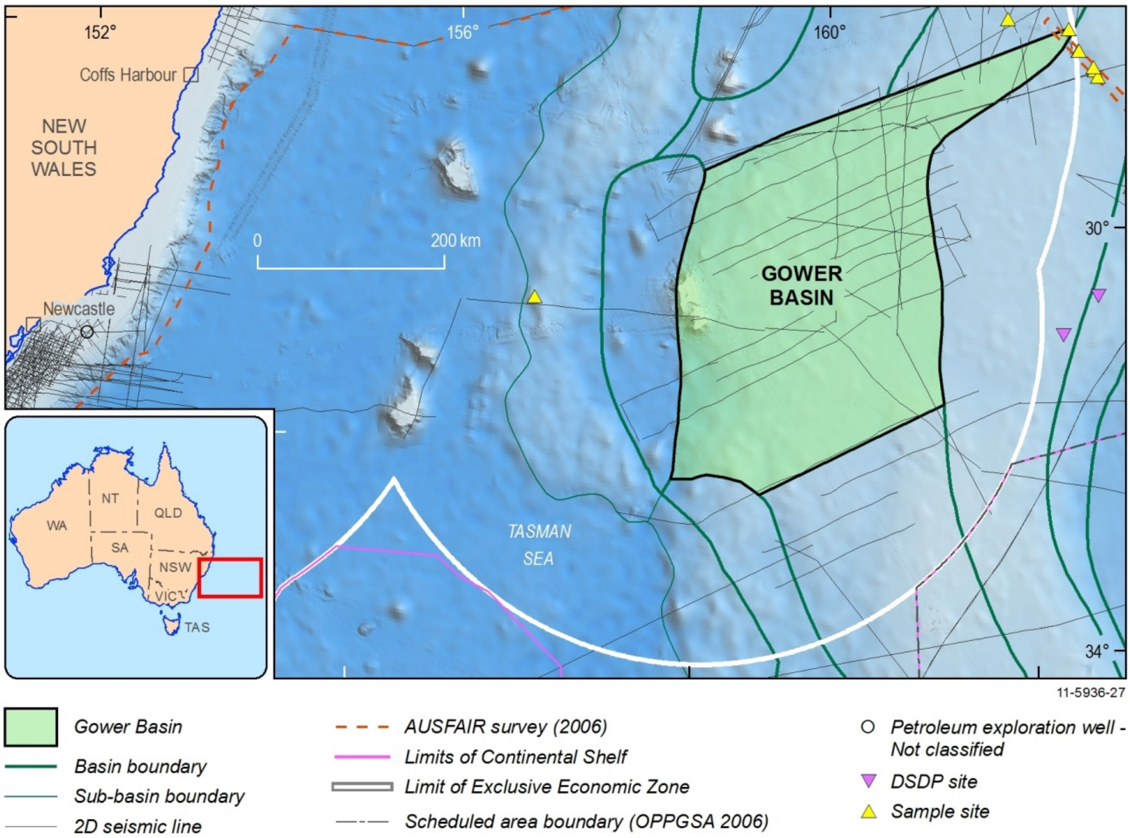

Figure 5.15: Seismic, well and sample distribution.

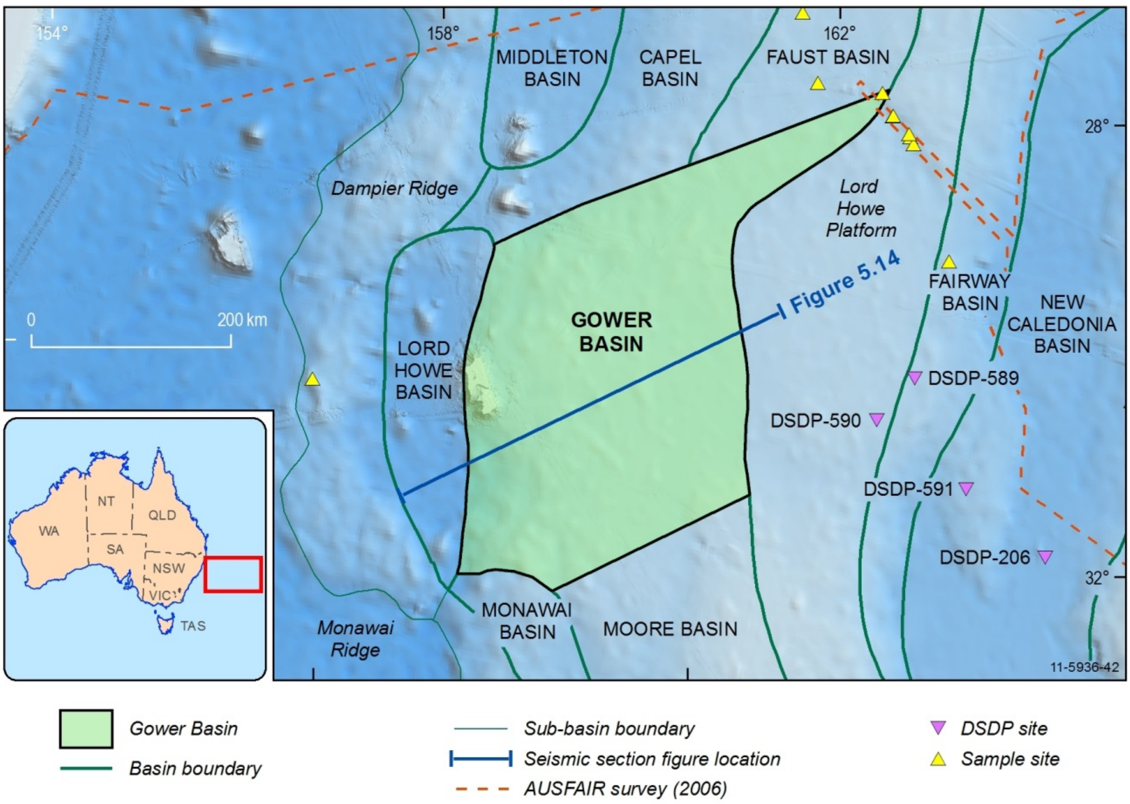

Figure 5.16: Location of seismic cross-section in Figure 5.14.

5.3.6 Issues and remaining questions

Lack of direct evidence for the composition and age of the basin succession and basement, and particularly for the existence of source, reservoir, seal and active petroleum systems, is a major obstacle to understanding the region's petroleum prospectivity.

Available data nevertheless indicate that the Gower Basin contains several large depocentres with sediment thickness sufficient for hydrocarbon generation. The Gower Basin represents a high-priority target within the region for further data acquisition, detailed geological studies and petroleum prospectivity assessment.

5.3.6.1 Recommendations

Stratigraphic drilling over a target that allows penetration at least to the lower syn-rift section (and preferably deeper into the pre-rift sedimentary section) could address some of the key issues. Acquisition of seismic reflection data on a 2D grid, followed by targeted high density 2D or 3D surveys, would be necessary prior to any drilling attempts, in order to improve the definition of the basin structure and stratigraphy. Petroleum generation and expulsion modelling, based on newly acquired seismic data, would contribute to a preliminary assessment of the petroleum prospectivity of the basin.

5.3.7 References

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5.3.8 Data Tables

Table 5.11: Key 2D seismic surveys, Gower Basin.

Year	Survey	Operator	Line-km	Reference
1971	MV *Petrel* Roving	Shell International	270	van de Beuque et al., 2003
1972	Mobil 1972	Mobil	260	Stagg et al., 2002
1985	RV *Sonne* 36	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)	3660	Röser & Shipboard Party, 1985
1985	RV *Rig Seismic* 46	Bureau of Mineral Resources	230	Whitworth & Willcox, 1985
1998	AGSO 206 (FAUST 1)	Australian Geological Survey Organisation	50	Bernardel et al., 1999
2006/2007	GA 302	Geoscience Australia	280	Kroh et al., 2007

Table 5.12: Refraction seismic and velocity surveys covering the Gower Basin.

Year	Survey	Operator	Location	Reference
1967	Scripps Institution of Oceanography two-ship refraction seismic survey	Scripps Institution of Oceanography	23 profiles over Southwest Pacific, including two stations northeast of Gower Basin	Shor et al., 1971
1978	RV *Sonne* 7 survey	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)	Lord Howe Rise region including Gower, Capel and Faust basins, Dampier Ridge and Lord Howe Platform	Willcox et al., 1981

Table 5.13: List of key surveys involving geological sampling, Gower Basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
1985	RV *Sonne* 36	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)	Lord Howe Platform and Dampier Ridge	Dredge	Pebbly conglomerate, sandstone, calcarenite (Lord How Platform), granite, gabbro, feldspathic sandstone (Dampier Ridge)	Röser & Shipboard Party, 1985; McDougall et al., 1994

Year	Survey	Operator	Region	Type	Rock types	Reference
2006	AUSFAIR MD-153 (RV *Marion Dufresne*)	Geoscience Australia, Ifremer	Capel, Faust and New Caledonia basins, Lord Howe Platform, Fairway Ridge, far northeastern Gower Basin	Dredge, giant piston core	Trachyte, latite, quartz–feldspathic conglomerate and sandstone, some with molluscan fossils, calcareous ooze, ferromanganese nodules and crust	Colwell et al., 2006; Higgins et al., 2011a

Table 5.14: Swath bathymetry surveys, Gower Basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
2001	Australian continental margin levelled gravity, magnetic and bathymetry	Geoscience Australia, Intrepid Geophysics		Petkovic et al., 2001
2006	AUSFAIR MD-153 (RV *Marion Dufresne*)	Geoscience Australia, Ifremer	Capel, Faust and New Caledonia basins, Fairway Ridge	Colwell et al., 2006
2009	Bathymetry and Topography Grid of Australia AUSBATH09 (2009)	Geoscience Australia		Whiteway, 2009

5.4 Moore Basin

5.4.1 Summary

State(s)		Commonwealth waters, New Zealand
Area (km^2)		43,700 (Australia); 81,800 (total)
Water Depth (m)		1000–2500
Maximum sediment thickness (m)		>4000 (excludes pre-rift succession)
Age range		?Cenomanian–Cenozoic
Basin	**Overlies**	Possible equivalents of New England and/or Lachlan orogens, Sydney Basin, Gympie Terrane or Murihiku/Maitai Supergroup, Whitsunday Volcanic Province
	Adjacent basins	Gower Basin, Monawai Basin, Lord Howe Platform
Basin type		Extensional, sag
Depositional setting, rock types		Non-marine, deltaic, and marine clastic sedimentary rocks, bathyal biogenic (carbonate, siliceous) sedimentary rocks, volcanic, intrusive and volcaniclastic rocks
Petroleum prospectivity		Low–moderate
Confidence		*Low*

5.4.2 Geology

The Moore Basin is located within the Central Rift Province (Stagg et al., 1999) of the southern Lord Howe Rise, in water depths of 1000–2500 m (Figure 5.17). The basin contains extensional depocentres that trend roughly northwest, offset by northeast-trending structural lineaments (Stagg et al., 2002). The basin covers an area of approximately 81,800 km^2, just over 50% of which lies in Australian waters. It contains a ?Cenomanian to Cenozoic succession generally 1500 to 3000 m thick (Figure 5.18; Stagg et al., 2002). In the largest depocentres, the sediment thickness may exceed 4000 m, although the deeper sections are poorly imaged by the existing seismic data. Basement horsts, thinly mantled by predominantly Cenozoic bathyal sediments, compartmentalise the depocentres. The Moore Basin adjoins the Gower Basin to the north, the Lord Howe Platform to the northeast, and the Monawai Basin to the west (Stagg et al., 1999).

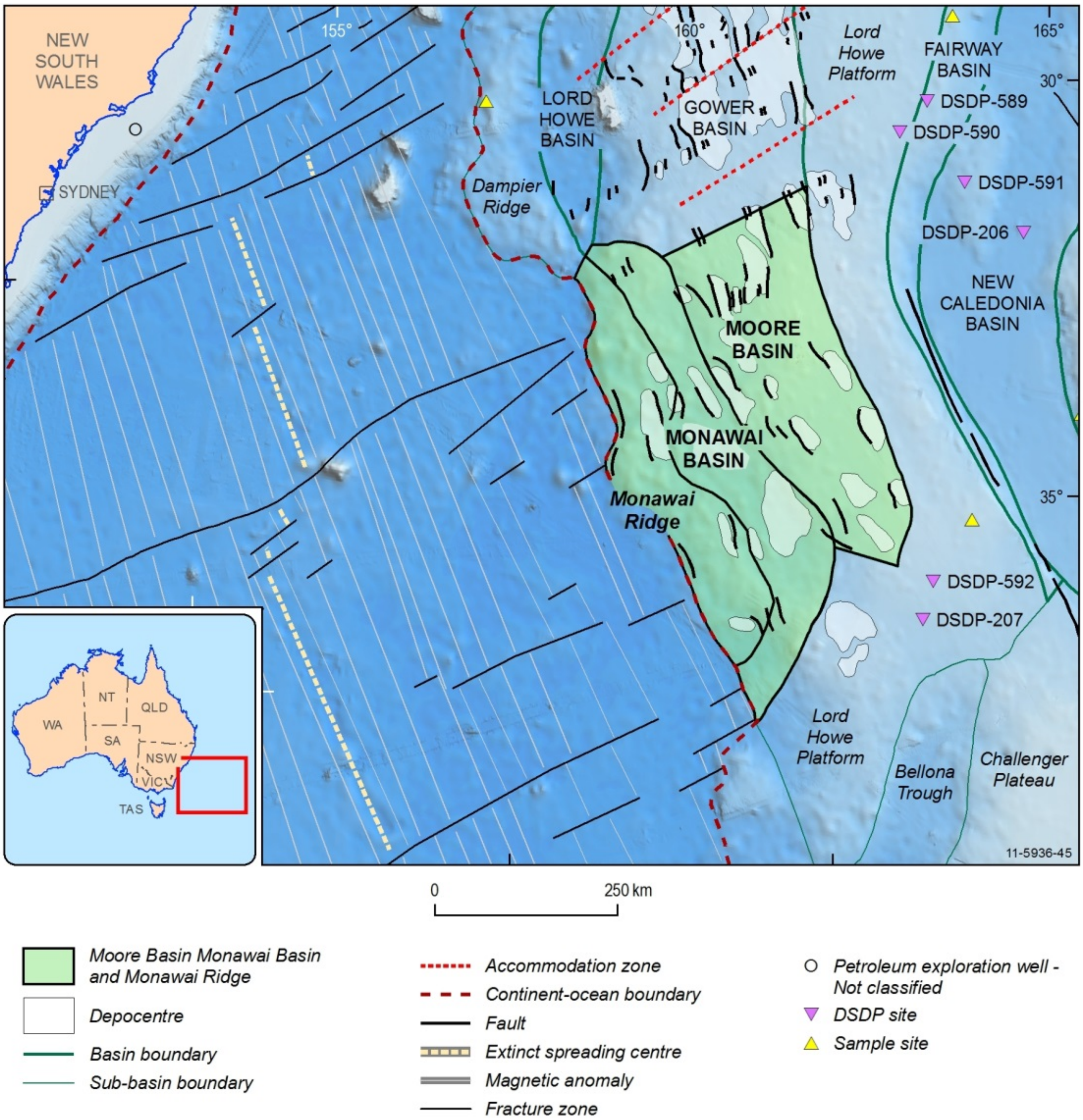

Figure 5.17: Structural elements map, Moore Basin. Depocentre locations based on Stagg et al. (2002), Willcox & Sayers (2002) and interpretation of regional seismic, gravity and magnetic data.

5.4.2.1 Structural geology

As for the other basins of the Lord Howe Rise, the Moore Basin evolved during the Cretaceous breakup of the eastern Gondwana, in the lead up to the opening of the Tasman Sea (85–52 Ma) (Hayes & Ringis, 1973; Gaina et al., 1998; Sdrolias et al., 2001). The Central Rift Province of the Lord Howe Rise, which includes the Moore Basin, experienced varying degrees of crustal extension prior to breakup. Gravity modelling over the southern Lord Howe Rise (Zhu & Symonds, 1994), in addition to seismic refraction data from the Faust Basin to the north (Shor et al., 1971), indicate a crustal thickness of 18–28 km beneath the Moore Basin. Rifting resulted in northwest-trending horsts that are downfaulted to the west, and intervening graben and half graben (Figure 5.19). Compared to the adjacent Monawai Basin (within the Western Rift Province of the Lord Howe Rise; Stagg et al., 1999), the Moore Basin appears to have more laterally confined depocentres, separated from each other by broad basement horsts. Truncation and folding of syn-rift strata indicate one or more phases of post-rift compressive structuring between the Late Cretaceous and the Cenozoic.

5.4.2.2 Basin evolution and depositional history

In the absence of deep drilling data the geologic evolution of the Moore Basin can only be inferred from sparse seismic and geophysical data sets, tectonic reconstructions and regional basin correlations. Reconstructions suggest that the southern Lord Howe Rise, including the Moore and Monawai basins, was located adjacent to the Gippsland Basin of southeastern Australia prior to the opening of the Tasman Sea (Norvick et al., 2001, 2008). As such, the Gippsland Basin may provide an analogue for the early evolutionary stages of the Moore Basin (Stagg et al., 2002). However, the Moore Basin did not experience the substantial post-rift sediment loading experienced in the Gippsland Basin (Rahmanian et al., 1990).

From the Paleozoic to the Early Cretaceous, the Lord Howe Rise was located inboard of the eastern Gondwana–Pacific convergent plate boundary. The pre-rift basement to the Moore Basin could be equivalent to rocks of the New England and/or Lachlan orogens, Sydney Basin, Gympie Terrane or the Maitai/Murihiku supergroups (Norvick et al., 2001, 2008; Willcox & Sayers, 2001, 2002; Mortimer et al., 2008; Colwell et al., 2010; Stagg et al., 2002). On the Challenger Plateau to the southeast of the Lord Howe Rise, a Carboniferous granite sample was dredged which may support the presence of a New England Orogen basement (Tulloch et al., 1991). On the other hand, the DSDP 207 drill hole immediately southeast of the Moore Basin encountered rhyolitic rocks of Cenomanian age (93.7 +/- 1.0 Ma; van der Lingen, 1973; McDougall & van der Lingen, 1974). Correlation of the drill hole with seismic reflection data indicates that the seismic 'basement' may represent early rift volcanics rather than the pre-rift basement in some areas of the basin (Stagg et al., 2002). It is also possible that the basement comprises rift-precursor volcanic and volcaniclastic rocks related to the latest Jurassic–Early Cretaceous extension and regional magmatism that extended along the entire backarc area of the eastern Gondwana margin (Bryan et al., 1997, 2000; Norvick et al., 2001, 2008; Stagg et al., 2002; Tulloch et al., 2009).

The syn-rift succession in the Moore Basin has been inferred by Stagg et al. (2002) to be of Cenomanian–Campanian age, through correlation with the Gippsland Basin. The succession is equivalent to the GB7 Megasequence in the Gower Basin (Willcox & Sayers, 2001, 2002) and the Syn-rift 2 Megasequence of the Capel and Faust basins (Colwell et al., 2010). The succession is generally 500 m to a little over 1000 m thick in the depocentres, attaining a maximum thickness of approximately 2000 m in the deepest depocentres. Studies in the Gower (Norvick et al., 2001; Willcox & Sayers, 2001, 2002), Capel and Faust (van de Beuque et al., 2003; Norvick et al., 2008; Colwell et al., 2010) basins to the north indicate that older syn-rift (and pre-rift) sediments may underlie this succession, but have not been imaged by the existing seismic reflection data. Much of the syn-rift succession in the Moore Basin is likely to comprise non-marine, paralic to shallow marine, clastic sediments analogous to the Golden Beach and Emperor sub-groups of the Gippsland Basin, or their correlatives in the Bass and Otway basins (Norvick et al., 2001, 2008; Stagg et al., 2002). The upper boundary of the succession is typically erosional and is thought to correspond to the breakup unconformity associated with the onset of seafloor spreading in the Tasman Sea during the Campanian (Stagg et al., 2002). Widespread igneous activity is likely to have accompanied the breakup, as indicated by seismic reflectors suggestive of volcanic flows and sills (Stagg et al., 2002).

The overlying post-rift succession can be subdivided into three distinct parts on the basis of their seismic character. The DSDP drilling sites over the Lord Howe Rise and New Caledonia Basin (e.g. sites 206 and 207) provide direct stratigraphic control for the post-rift succession. The Campanian–lower Eocene sequence was deposited in topographic lows controlled by syn-rift structures, probably under shallow marine conditions (Stagg et al., 2002). It is equivalent to the GB5 and GB6 megasequences in the Gower Basin (Willcox & Sayers, 2001, 2002). An Eocene regional unconformity that is observed throughout the Lord Howe Rise region (Stagg et al., 2002) may correspond to a major change in regional tectonics associated with a change in the motion of the Pacific Plate (Müller et al., 2000; Veevers, 2000), obduction in New Caledonia (Aitchison et al., 1995) and an eastward relocation of the Australia–Pacific plate convergence (Sdrolias et al., 2001; Crawford et al., 2003). The lower Eocene–Oligocene sequence is more laterally continuous, reflecting deposition within an open marine environment. It is dominated by foraminiferal nannofossil chalk, ooze and chert (Stagg et al., 2002). The top of the succession is defined by another regional unconformity that reflects changes in oceanic circulation following the opening of the Southern Ocean and the Tasman Sea (Stagg et al., 2002).

The Oligocene–Holocene succession is composed of foraminiferal nannofossil ooze, and mirrors the establishment of bathyal conditions across the Lord Howe Rise during this period. Intraplate volcanism was common over the southern Lord Howe Rise during the post-rift phase, particularly around the Eocene–Oligocene boundary, and throughout the Neogene (Stagg et al., 2002).

5.4.2.3 Level of knowledge

The Moore Basin is a remote and under-explored deepwater frontier basin with a sparse coverage of regional 2D seismic reflection, gravity, magnetic and bathymetry data (Figure 5.20). No petroleum exploration wells have been drilled within the basin. The nearest drilling locations are Deep Sea Drilling Program (DSDP) sites 207 and 592, over the Lord Howe Platform to the southeast of the Moore Basin, and DSDP sites 206 and 589 to 591 in the New Caledonia Basin to the northeast. These drilling sites collectively provide stratigraphic control on the Cenomanian–Holocene section. The interpretation of the pre-rift to lower syn-rift successions relies entirely on inferences from seismic data, regional tectonic reconstructions and correlations. Regional scale seismic reflection data sets (including the AGSO 114 and RV *Rig Seismic* 46 surveys) reveal the gross-scale structural architecture and stratigraphy of the basin, but do not fully resolve the stratigraphy or basement structure within individual depocentres. It is likely that the seismic data do not fully image the deeper parts of the basin succession or the pre-rift basement. The Moore and Monawai basins are within an area of the Lord Howe Rise with the least coverage of seismic reflection data. As such, these basins have the lowest level of geological knowledge amongst the basins of the Lord Howe Rise, and further data acquisition is required for a preliminary assessment of their geology and petroleum prospectivity.

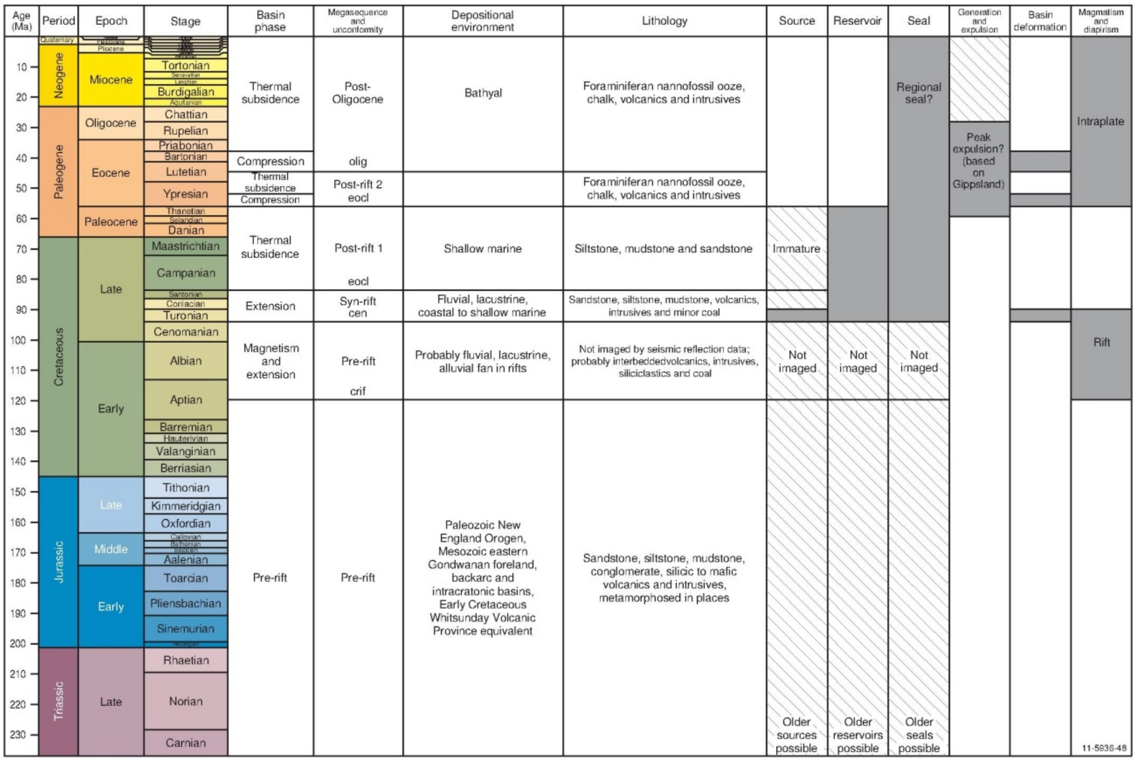

Figure 5.18: Stratigraphy of the Moore and Monawai basins, including sequence stratigraphy and tectonic events (after Norvick et al., 2001, 2008; Stagg et al., 2002).

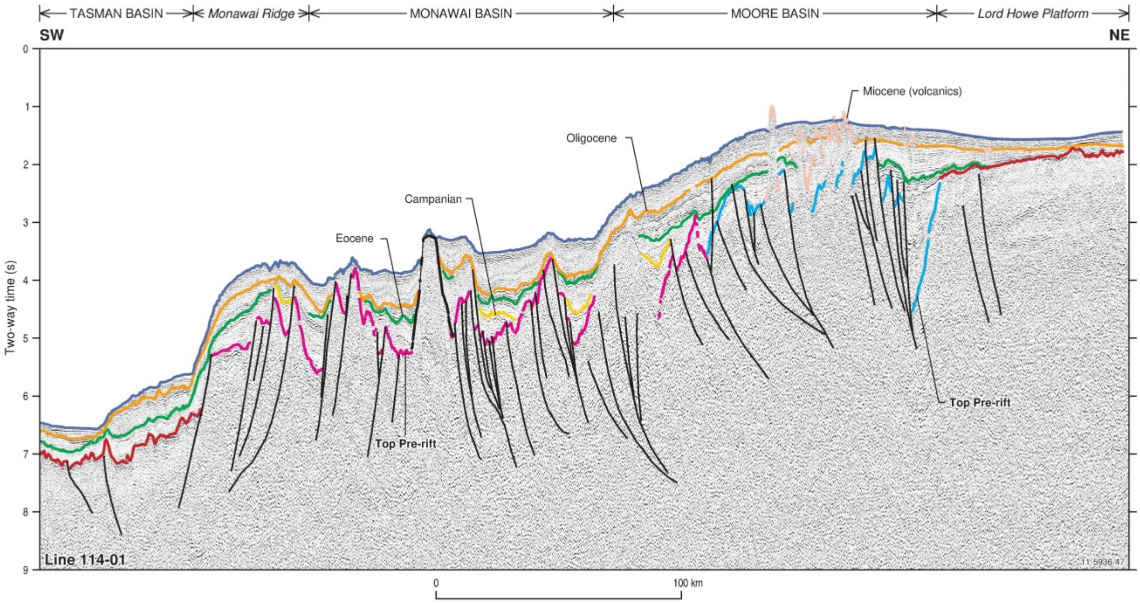

Figure 5.19: Geological cross-section along regional seismic line AGSO 114-01 showing structural and stratigraphic relationships (after Stagg et al., 2002). Location of line is shown in Figure 5.21.

5.4.3 Petroleum systems

Given the lack of data, the presence of an active petroleum system in the Moore Basin cannot be confirmed. Inferences from regional comparison and seismic data suggest it is possible that petroleum systems similar to those proven in onshore eastern Australia are present in the region. Results of basin modelling in the Capel and Faust basins in the northern part of the Lord Howe Rise (Funnell & Stagpoole, 2011) reveal that the sediment thickness in many depocentres within the Moore Basin may not be sufficient for hydrocarbon generation. However, it is also likely that the sediment thicknesses are considerably greater than indicated by the existing data, particularly in the larger depocentres, so a firm conclusion cannot be drawn. Bottom simulating reflectors (BSRs) have been identified on regional seismic data in the adjacent Monawai Basin (Stagg et al., 2002), and several authors (e.g. Ramsay et al., 1997; Exon et al., 1998; Lafoy et al., 1998; Auzende et al., 2000) have speculated that these reflectors indicate the widespread occurrence of gas hydrates over the Lord Howe Rise. However, a recent reappraisal based on newly acquired data has indicated that the BSRs are most likely to be an Opal-A/Opal-CT diagenetic boundary (Colwell et al., 2006; Nouzé et al., 2009).

5.4.3.1 Source rocks

Assuming that the Moore Basin has a similar early history to the Gippsland Basin on the conjugate eastern Australian margin, it is possible that gas- and oil-prone coastal plain and shallow marine mudstones, equivalent to the Golden Beach and Emperor sub-groups of the Gippsland Basin, may provide potential source rocks within the inferred Upper Cretaceous syn-rift succession (Figure 5.18). More widespread marine conditions during the post-rift phase (to the Maastrichtian) may have been conducive to the deposition of oil-prone marine source rocks, although they are likely to be immature for hydrocarbon generation given the shallow burial depths (Stagg et al., 2002). Source rock maturity may not be a significant concern if the inferred Upper Cretaceous syn-rift sediments are underlain by Upper Jurassic to Lower Cretaceous pre-rift and lower syn-rift successions. If potential source rocks are present within these successions, they are more likely to be fluvio-lacustrine coal and mudstones, similar to those found within the Strzelecki Group of the Gippsland Basin (Norvick et al., 2001; O'Brien et al., 2008).

Regional tectonic reconstructions by Norvick et al. (2001, 2008) show that the boundary between the New England and Lachlan orogens of eastern Australia (or their equivalents) underlies the Moore Basin. If this is correct, it is plausible that the offshore continuation of the Permian–Triassic Sydney Basin may also be present in the area. Stewart & Alder (1995) consider the gas- and condensate-prone upper Permian coals and carbonaceous shales as the most promising candidates for source rocks in the offshore Sydney Basin.

5.4.3.2 Generation and expulsion

A maximum total sediment thickness of over 4 km implies that the deepest depocentres of the Moore Basin may be capable of generating hydrocarbons, if suitable source rocks are present. Other areas of the basin may also contain sufficient sediment thickness, but the lack of seismic resolution at depth precludes confirmation. Heat flow measurements over the southern Lord Howe Rise by Grim (1969) indicated very high values of 97–100 mW/m^2, but the calculated heat flow at the DSDP 206 site in the nearby New Caledonia Basin (von Herzen, 1973) was 58 mW/m^2. These results indicate potentially elevated heat flow in the vicinity of the Moore Basin, which could have assisted the maturation of source rocks. The elevated heat flow may be related to the Neogene intraplate magmatism associated with the Lord Howe and Tasmantid hotspot chains to the west of the Lord Howe Rise (Stagg et al., 2002).

5.4.3.3 Reservoirs

Potential reservoir rocks in the Moore Basin may occur within the syn-rift and lower post-rift megasequences as interbedded sandstones of fluvial to shallow marine origins (Figure 5.18; Stagg et al., 2002). Potential reservoir rocks may also occur within the pre-rift section as quartzose sandstones equivalent to those within the Triassic Hawkesbury Sandstone and Narrabeen Group of the Sydney Basin (Stewart & Alder, 1995).

5.4.3.4 Seals

A regional seal may be provided by the extensive and thick Oligocene–Holocene pelagic ooze. Marine, coastal and lacustrine mudstones within the syn-rift and lower post-rift successions, and volcanic flows and sills within the pre-rift and syn-rift successions, have potential to act as local seals (Stagg et al., 2002). Fluvio-deltaic to shallow marine shales, equivalent to parts of the Triassic Narrabeen and Wianamatta groups of the Sydney Basin, may also provide seals within the pre-rift succession (Stewart & Alder, 1995).

5.4.3.5 Play types

Seismic reflection data reveal a range of potential play types within the Moore Basin, including: fault blocks, anticlines, transpressional structures and stratigraphic traps (Stagg et al., 2002). Compressional tectonics has resulted in localised fault reversal and anticlinal deformation during the Cenozoic, creating additional potential trapping structures. Multiple episodes of magmatism during the syn-rift and post-rift phases may also have produced further potential plays and enhanced source rock maturation (Stagg et al., 2002).

5.4.3.6 Critical risks

As in other parts of the Lord Howe Rise, there is a lack of direct evidence for active petroleum systems and a paucity of geological data; hence, the presence of viable source rocks, reservoirs and seals are key uncertainties in the Moore Basin. The pre-breakup palaeogeographic proximity to the Gippsland and Sydney basins, however, suggests that the Moore Basin may contain viable petroleum system elements. Insufficient sediment thickness for hydrocarbon generation and expulsion is also a potential risk, although maximum sediment thicknesses are likely to be greater than predicted by the existing data. The Moore Basin has experienced multiple phases of igneous activity, implying that the degradation of reservoirs and trapped hydrocarbons may be a risk. An additional risk to prospectivity is posed by Cenozoic tectonic reactivation, which may have resulted in late-stage trap breach.

5.4.3.7 Overall prospectivity classification

Low–moderate

5.4.4 Exploration status

No exploration activity has taken place in the Moore Basin other than the reconnaissance seismic surveys in the early 1970s by Shell International (MV *Petrel*) and Mobil. Geoscience Australia and its predecessors, the Australian Geological Survey Organisation (AGSO) and Bureau of Mineral Resources (BMR), have completed several data acquisition surveys over the southern Lord Howe Rise region, including the Moore Basin, since the 1980s for reconnaissance geological investigation, offshore hydrocarbon resource assessment and determination of maritime boundaries under the United Nations Convention on the Law of the Sea (UNCLOS).

5.4.5 Data

The Moore Basin is a frontier area with very sparse data coverage. Key data sets for the Moore Basin are listed in Table 5.15–Table 5.19 and their locations shown on Figure 5.20. There are no sufficiently deep drill holes that provide stratigraphic control for the basin succession. The nearest drilling sites are the DSDP sites 207 and 592 over the Lord Howe Platform to the southeast, and DSDP 206 and

589 to 591 in the New Caledonia Basin to the northeast (Figure 5.21). DSDP 207 penetrated a Cenozoic section of nannofossil ooze and over 150 m of Upper Cretaceous volcanics (The Shipboard Scientific Party, 1973b). The drill hole terminated in rhyolitic flows and pumiceous lapilli tuffs that have been dated at 93.7 +/- 1.1 Ma (Cenomanian; McDougall & van der Lingen, 1974). DSDP 206 penetrated a nannofossil ooze-dominated Cenozoic section, terminating in calcic claystone and limestone (The Shipboard Scientific Party, 1973a).

Several regional seismic reflection lines traverse the Moore Basin (Table 5.16). Of these, the most useful are those acquired during the AGSO 114 survey. Approximately 3190 line-km of data were recorded as part of a geological framework study to support Australia's extended continental shelf claims under the United Nations Convention on the Law of the Sea (UNCLOS; Marshall et al., 1994). Of this, approximately 950 line-km was acquired over the Moore Basin, although much of this is outside of the Australian maritime jurisdiction. The data is of good quality, enabling the gross-scale basement topography and stratigraphy to be imaged in many places (Stagg et al., 2002). However, the data set lacks the resolution to reveal the detailed stratigraphy of individual depocentres or deeply buried sections. Lines from the Shell International MV *Petrel*, Mobil, BMR RV *Rig Seismic* 46 and AGSO 177 surveys also traverse the basin, but the data quality is poor to moderate and/or the surveys do not provide a significant coverage of the Moore Basin.

Other data sets include velocity, heat flow, gravity, magnetic and bathymetry data, and isolated rock samples. Sonobuoy seismic refraction data were collected in the vicinity of the Moore Basin during the Mobil (Bentz, 1974) and BGR/BMR RV *Sonne* 7 (Willcox et al., 1981) surveys. To the north of the Moore Basin, sonobuoy data were collected by the Scripps Institution of Oceanography over the northern Lord Howe Rise and the Tasman Sea (Shor et al., 1971), and at over 40 locations over the Capel and Faust basins during the GA 302 seismic reflection survey.

Two heat flow measurements were acquired in the northern Moore Basin and the southwestern Gower Basin; the anomalously high values of 97 to 100 mWm^{-2} may reflect the effects of Neogene intraplate igneous activity in the region (Grim, 1969; Stagg et al., 2002).

Potential field and bathymetry data coverage over the southern Lord Howe Rise region includes regional compilations derived from satellite, airborne and marine data (Sandwell & Smith, 1997; Andersen et al., 2010; Maus et al., 2007, 2009; Whiteway, 2009). Additionally, shiptrack gravity and magnetic data were levelled in 2001 by Geoscience Australia (Petkovic et al., 2001).

A few rock samples have been collected from the seafloor near the Moore Basin (Table 5.19). These include mid-Permian granite, gabbro and sandstone from the Dampier Ridge to the northwest (Röser & Shipboard Party, 1985), Upper Cretaceous coaly sandstone and carbonaceous mudstone (Launay et al., 1977; Herzer et al., 1997, 1999) from the West Norfolk Ridge to the east, and Carboniferous granite from the Challenger Plateau to the southeast (Tulloch et al., 1991). Continental sedimentary and igneous rocks were dredged from the Lord Howe Platform to the north during the BGR RV *Sonne* 36 (Röser & Shipboard Party, 1985) and Geoscience Australia/Ifremer AUSFAIR MD-153 (Colwell et al., 2006) surveys. The volcanic rocks collected during the MD-153 survey have subsequently been dated as Cenomanian (Higgins et al., 2011). Other dredge samples collected in the vicinity of the Moore Basin are mostly Cenozoic bathyal sediments and volcanic rocks. As in the other parts of the Lord Howe Rise, the extensive blanket of bathyal ooze restricts sampling opportunities for older rocks.

5.4.5.1 Confidence rating

Low

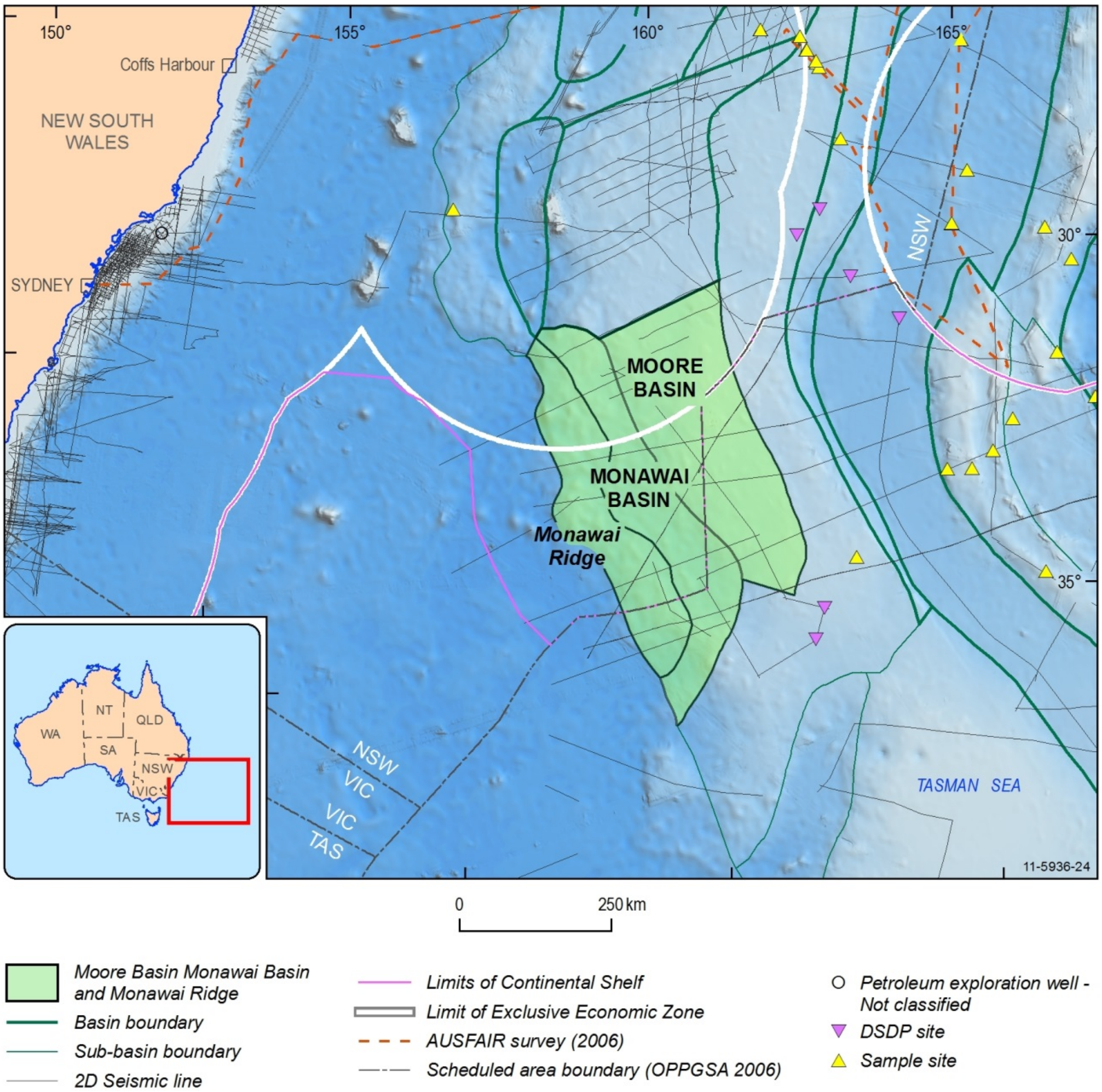

Figure 5.20: Seismic, well and sample distribution.

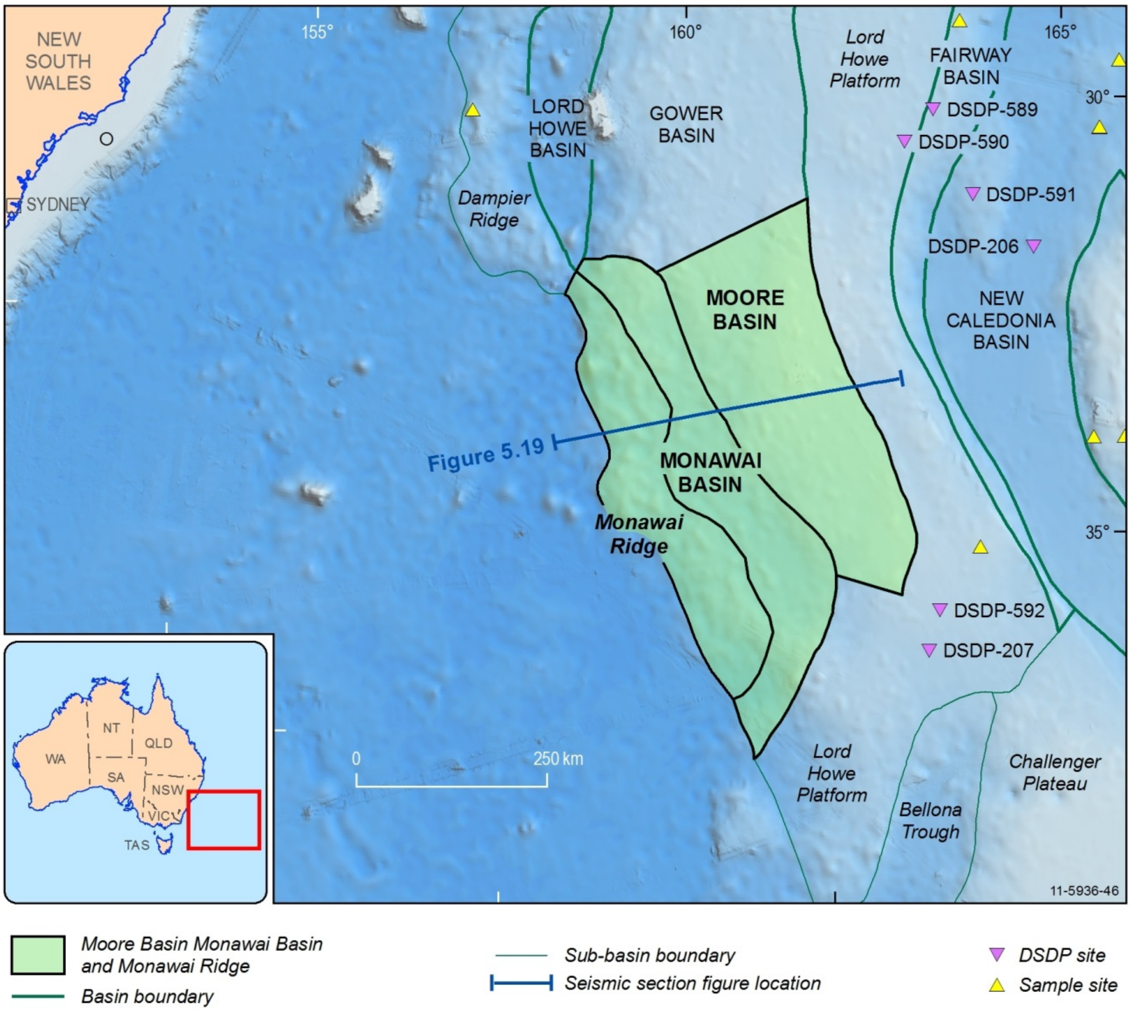

Figure 5.21: Location of nearby well control and seismic line shown in Figure 5.19.

5.4.6 Issues and remaining questions

The Moore Basin is one of the least understood basins within the Lord Howe Rise region. There is insufficient data to confidently map sediment thickness and distribution. Furthermore, there is no direct control on the composition and age of the basin succession or the basement, which precludes the assessment of potential for source, reservoir, seal and active petroleum systems.

Nevertheless, the existing data, in conjunction with the results of petroleum prospectivity studies of other basins in the Lord Howe Rise region, suggest that the Moore Basin contains depocentres with sufficient sediment thickness for hydrocarbon generation. Further studies are required to reduce exploration risk in the southern Lord Howe Rise region, including the Moore Basin. Depending on the results, these studies could significantly enhance the long-standing industry interest in the Lord Howe Rise region.

5.4.6.1 Recommendations

Acquisition of more reconnaissance-level data will be required to improve the understanding of the region's petroleum prospectivity and to reduce exploration risk. High-quality regional 2D reflection seismic surveys could image the full sedimentary succession and basement structure. The results of these regional surveys could then inform the design of targeted high-density 2D or 3D seismic surveys. Basin stratigraphy and facies distribution could then be mapped, which would in turn inform a preliminary assessment of petroleum prospectivity. Given the limited opportunity for dredge sampling of pre-Cenozoic rocks in the region, deep stratigraphic drilling remains the only viable means of testing the interpretations.

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5.4.8 Data Tables

Table 5.15: List of wells drilled close to the Moore Basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1971	DSDP 207	Scientific	Deep Sea Drilling Project	513	Cenomanian	Nil	The Shipboard Scientific Party, 1973b
1982	DSDP 592	Scientific	Deep Sea Drilling Project	388.5	Middle Late Eocene	Nil	The Shipboard Scientific Party, 1986

Table 5.16: Key 2D seismic surveys, Moore Basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1971	MV *Petrel* Roving	Shell International	240	van de Beuque et al., 2003; Sutherland et al., 2012
1972	Mobil 1972	Mobil	360	Stagg et al., 2002; Sutherland et al., 2012
1985	RV *Rig Seismic* 46	Bureau of Mineral Resources	430	Whitworth & Willcox, 1985
1992	AGSO 114	Australian Geological Survey Organisation	950	Marshall et al., 1994
1996	AGSO 177	Australian Geological Survey Organisation	60	Ramsay et al., 1997

Table 5.17: Refraction seismic and velocity surveys covering the Moore Basin.

Year	Survey	Operator	Location	Reference
1967	Scripps Institution of Oceanography two-ship refraction seismic survey	Scripps Institution of Oceanography	23 profiles over Southwest Pacific, including two stations northeast of Gower Basin	Shor et al., 1971
1972	Mobil 1972	Mobil	One station to southeast of Moore Basin, three stations in southern New Caledonia Basin, four stations without positioning data	Bentz, 1974; Stagg et al., 2002
1978	RV *Sonne* 7 survey	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)	Lord Howe Rise region, including two stations in Moore Basin, two stations in Monawai and one station each over nearby Gower Basin, Dampier Ridge and Lord Howe Platform	Willcox et al., 1981

Table 5.18: Key geological sampling surveys in areas adjacent to the Moore Basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
1975	GEORSTOM III Sud	Office de la recherche scientifique et technique outre-mer (ORSTOM)	Norfolk Ridge, Reinga Basin and Lord Howe Platform	Dredge	Mudstone, limestone, organic shale, basalt, gabbro, hyaloclastic breccia	Launay et al., 1977; Herzer et al., 1997, 1999
1985	RV *Sonne* 36	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)	Lord Howe Platform and Dampier Ridge	Dredge	Pebbly conglomerate, sandstone, calcarenite (Lord Howe Platform), granite, gabbro and feldspathic sandstone (Dampier Ridge)	Röser & Shipboard Party, 1985; McDougall et al., 1994
1987	CH8701	Department of Scientific & Industrial Research (DSIR)	Challenger Plateau	Dredge	Granite	Tulloch et al., 1991
1993	RE9302	Institute of Geological & Nuclear Sciences (IGNS)	Norfolk, West Norfolk, Wanganella and Three Kings ridges,	Dredge	Carbonaceous sandstone and mudstone, bryozoan/foraminiferan limestone, calcareous volcaniclastic sandstone, lapilli tuff	Herzer et al., 1997, 1999
2006	AUSFAIR MD-153 (RV *Marion Dufresne*)	Geoscience Australia, Ifremer	Capel, Faust and New Caledonia basins, Lord Howe Platform, Fairway Ridge, far northeastern Gower Basin	Dredge, giant piston core	Trachyte, latite, quartz–feldspathic conglomerate and sandstone, some with molluscan fossils, calcareous ooze, ferromanganese nodules and crust	Colwell et al., 2006; Higgins et al., 2011

Table 5.19: Swath bathymetry surveys, Moore Basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
2001	Australian continental margin levelled gravity, magnetic and bathymetry	Geoscience Australia, Intrepid Geophysics		Petkovic et al., 2001
2006	AUSFAIR MD-153 (RV *Marion Dufresne*)	Geoscience Australia, Ifremer	Capel, Faust and New Caledonia basins, Fairway Ridge	Colwell et al., 2006
2009	Bathymetry and Topography Grid of Australia AUSBATH09 (2009)	Geoscience Australia		Whiteway, 2009

5.5 Monawai Basin

5.5.1 Summary

State(s)		Commonwealth waters, New Zealand
Area (km^2)		37,000 (Australia); 54,900 (total)
Water Depth (m)		1500–4000
Maximum sediment thickness (m)		>3000 (excludes pre-rift succession)
Age range		?Cenomanian–Cenozoic
Basin	**Overlies**	Possible equivalents of Lachlan Orogen, New England Orogen, Sydney Basin, Whitsunday Volcanic Province equivalent
	Adjacent basins	Gower, Moore and Lord Howe basins Lord Howe Platform, Monawai Ridge, Dampier Ridge,
Basin type		Extensional, sag
Depositional setting, rock types		Non-marine, deltaic, and marine clastic sedimentary rocks, bathyal biogenic (carbonate, siliceous) sedimentary rocks, volcanic, intrusive and volcaniclastic rocks
Petroleum prospectivity		Low–moderate
Confidence		*Low*

5.5.2 Geology

The Monawai Basin is located within the Western Rift Province of the southern Lord Howe Rise (Stagg et al., 1999). The basin covers an area of approximately 54,900 km^2, of which approximately 70% is in Australian waters, in water depths 1500–4000 m (Figure 5.22). The ?Cenomanian to Cenozoic sedimentary fill is generally 1500 to 3000 m thick (Figure 5.23; Stagg et al., 2002) and likely to exceed 4000 m in places, although the deeper sections are poorly imaged by the existing seismic data. Basement horsts and tilted fault blocks define the extent of individual extensional depocentres, which trend roughly northwest–southeast and are offset by northeast-trending structural lineaments (Stagg et al., 2002). The Monawai Basin adjoins the Gower Basin to the north, the Moore Basin to the northeast, the Lord Howe Platform to the southeast, the Monawai Ridge to the west, and the Dampier Ridge and Lord Howe Basin to the extreme northwest (Figure 5.22; Stagg et al., 1999). A major structural hinge separates the Monawai Basin from the Moore Basin, across which the water depth increases toward the Monawai Basin, and the regional seafloor profile changes from gently convex in the Moore Basin to concave or flat in the Monawai Basin.

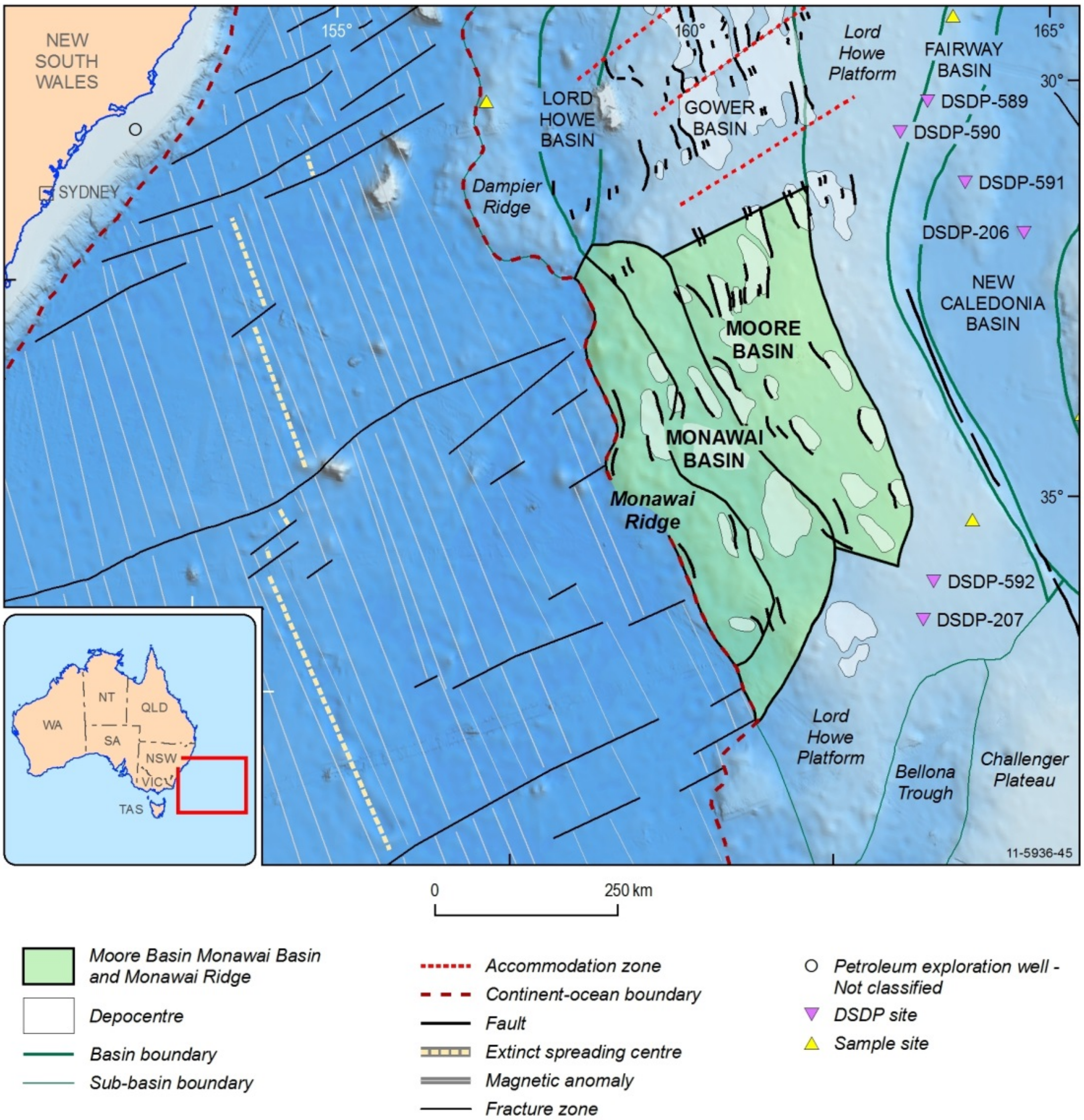

Figure 5.22: Structural elements map, Moore Basin. Depocentre locations based on Stagg et al. (2002), Willcox & Sayers (2002) and interpretation of regional seismic, gravity and magnetic data.

5.5.2.1 Structural geology

The Monawai Basin, in common with the other basins of the Lord Howe Rise, evolved during the Cretaceous breakup of eastern Gondwana and the opening of the Tasman Sea (85–52 Ma; Hayes & Ringis, 1973; Gaina et al., 1998; Sdrolias et al., 2001). The area occupied by the Western Rift Province of the Lord Howe Rise, including the Monawai Basin, experienced significant crustal extension in the lead up to the breakup. Gravity modelling over the southern Lord Howe Rise (Zhu & Symonds, 1994), and additional evidence from seismic refraction data acquired over the Faust Basin of the northern Lord Howe Rise (Shor et al., 1971), indicate a crustal thickness of 18–20 km beneath the Monawai Basin. Rifting resulted in northwest-trending horsts and tilted fault blocks that are generally downfaulted to the west, and intervening graben and half graben (Figure 5.24). Within the Monawai Basin, many of the horsts and fault blocks have been mantled by post-rift sediments 1.5 to 2.5 km thick, such that the depocentres are laterally confined by the most prominent basement highs. Erosional truncation and folding of syn-rift strata indicate one or more phases of post-rift compressive structuring between the Late Cretaceous and the Cenozoic.

5.5.2.2 Basin evolution and depositional history

Given the lack of sufficiently deep drilling data, the evolution of the Monawai Basin can only be inferred from seismic and geophysical data sets, tectonic reconstructions and regional basin correlations. Reconstructions indicate that the Monawai Basin was located adjacent to the Gippsland Basin of southeastern Australia prior to the opening of the Tasman Sea (Norvick et al., 2001, 2008). The Gippsland Basin may, therefore, provide a partial analogue for the early evolutionary stages of the Monawai Basin (Stagg et al., 2002). However, the southern Lord Howe Rise differs from the Gippsland Basin in the lack of major post-rift sediment loading that significantly contributed to petroleum generation in the Gippsland Basin (Rahmanian et al., 1990).

From the Paleozoic to the Early Cretaceous, the Lord Howe Rise was located inboard of the eastern Gondwana–Pacific convergent plate boundary. Palaeogeographic reconstructions suggest that the pre-rift basement to the Monawai Basin is most likely to be the Lachlan Orogen, although rocks of the New England Orogen and the Permian–Triassic Sydney Basin may also be represented especially beneath the northern part of the basin (Norvick et al., 2001, 2008; Willcox & Sayers, 2001, 2002; Mortimer et al., 2008; Colwell et al., 2010). On the Challenger Plateau to the southeast of the Lord Howe Rise, dredge sampling of Carboniferous granite (Tulloch et al., 1991) suggests continuity of the Lachlan Orogen with the New Zealand Western Province (Cooper & Tulloch, 1992; Mortimer, 2004). The DSDP 207 drill hole to the east of the Monawai Basin encountered rhyolitic rocks of Cenomanian age (93.7 +/- 1.0 Ma; van der Lingen, 1973; McDougall & van der Lingen, 1974). Correlation of the drill hole with seismic reflection data indicates that the seismic 'basement' may represent early rift volcanics rather than the pre-rift basement in some areas of the basin (Stagg et al., 2002). It is also possible that the basement comprises rift-precursor volcanic and volcaniclastic rocks related to the latest Jurassic–Early Cretaceous extension and regional magmatism that extended along the entire backarc area of the eastern Gondwana margin (Bryan et al., 1997, 2000; Norvick et al., 2001, 2008; Stagg et al., 2002; Tulloch et al., 2009).

The syn-rift succession in the Monawai Basin has is inferred to be Cenomanian–Campanian through correlation with the Gippsland Basin (Figure 5.23; Stagg et al., 2002). The succession is equivalent to the GB7 Megasequence in the Gower Basin (Willcox & Sayers, 2001, 2002) and the Syn-rift 2 Megasequence of the Capel and Faust basins (Colwell et al., 2010). The succession is generally 500 m to over 1000 m thick in the depocentres. It is likely that the full thickness of this succession is not imaged by seismic reflection data due to the relatively thick post-rift sediment cover and the presence of volcanics. Moreover, studies in the Gower (Norvick et al., 2001; Willcox & Sayers, 2001, 2002), Capel and Faust (van de Beuque et al., 2003; Norvick et al., 2008; Colwell et al., 2010) basins to the north suggest that older syn-rift (and pre-rift) sediments possibly underlie this succession. Much of the syn-rift succession in the Moore Basin is likely to comprise non-marine, paralic to shallow marine, clastic sediments analogous to the Golden Beach and Emperor sub-groups of the Gippsland Basin, or their correlatives in the Bass and Otway basins (Norvick et al., 2001, 2008; Stagg et al., 2002). The upper boundary of the succession is typically erosional and is thought to correspond to the breakup unconformity associated with the onset of seafloor spreading in the Tasman Sea during the Campanian (Stagg et al., 2002). Widespread igneous activity accompanied breakup, as indicated by seismic reflectors suggestive of volcanic flows and sills (Stagg et al., 2002). A possible seaward-dipping reflector sequence (SDRS) has been identified on seismic reflection data at one location in the southern Monawai Basin (Stagg et al., 2002), implying that the basin may be situated along a failed breakup axis.

The overlying post-rift succession can be subdivided into three distinct sequences on the basis of seismic character. The DSDP drilling sites over the Lord Howe Rise and New Caledonia Basin (e.g. sites 206 and 207) provide direct stratigraphic control for this succession. The Campanian–lower Eocene sequence was deposited in the topographic lows controlled by syn-rift structures, probably under shallow marine conditions (Stagg et al., 2002). It is equivalent to the GB5 and GB6 megasequences in the Gower Basin (Willcox & Sayers, 2001, 2002). An Eocene regional unconformity observed throughout the Lord Howe Rise region (Stagg et al., 2002) may correspond to a major change in regional plate tectonics (Müller et al., 2000; Veevers, 2000; Aitchison et al., 1995; Sdrolias et al., 2001; Crawford et al., 2003). The lower Eocene–Oligocene sequence is more laterally continuous, reflecting deposition within an open marine environment. It is dominated by foraminiferal nannofossil chalk, ooze and chert (Stagg et al., 2002). The top of the succession is defined by another regional unconformity that probably reflects changes in oceanic circulation following the opening of the Southern Ocean and the Tasman Sea (Stagg et al., 2002). The Oligocene–Holocene succession is composed of foraminiferal nannofossil ooze, reflecting the establishment of bathyal conditions across the Lord Howe Rise during this period. Intraplate volcanism appears to have been relatively common over the southern Lord Howe Rise during the post-rift phase, particularly around the Eocene–Oligocene boundary, and throughout the Neogene (Stagg et al., 2002).

5.5.2.3 Level of knowledge

The Monawai Basin is a remote and under-explored deepwater frontier basin with a sparse coverage of regional 2D seismic reflection, gravity, magnetic and bathymetry data (Figure 5.25). No petroleum exploration wells have been drilled within the basin. The nearest drilling locations are Deep Sea Drilling Program (DSDP) sites 207 and 592, over the Lord Howe Platform to the east of the Monawai Basin, and DSDP sites 206 and 589 to 591 in the New Caledonia Basin to the northeast (Figure 5.26). These drilling sites collectively provide stratigraphic control on the Cenomanian–Holocene section. The interpretation of the pre-rift to lower syn-rift successions relies entirely on inferences from seismic data, regional tectonic reconstructions and correlations. Regional scale seismic reflection data sets (including the AGSO 114 and RV *Rig Seismi*c 46 surveys) reveal the gross-scale structural architecture and stratigraphy of the basin, but do not fully resolve the stratigraphy or basement structure within individual depocentres. It is likely that the seismic data do not fully image the deeper parts of the basin succession or the pre-rift basement. The Monawai and Moore basins are within an area of the Lord Howe Rise with the least coverage of seismic reflection data. As such, these basins have the lowest level of geological knowledge amongst the basins of the Lord Howe Rise, and further data acquisition is required for a preliminary assessment of their geology and petroleum prospectivity.

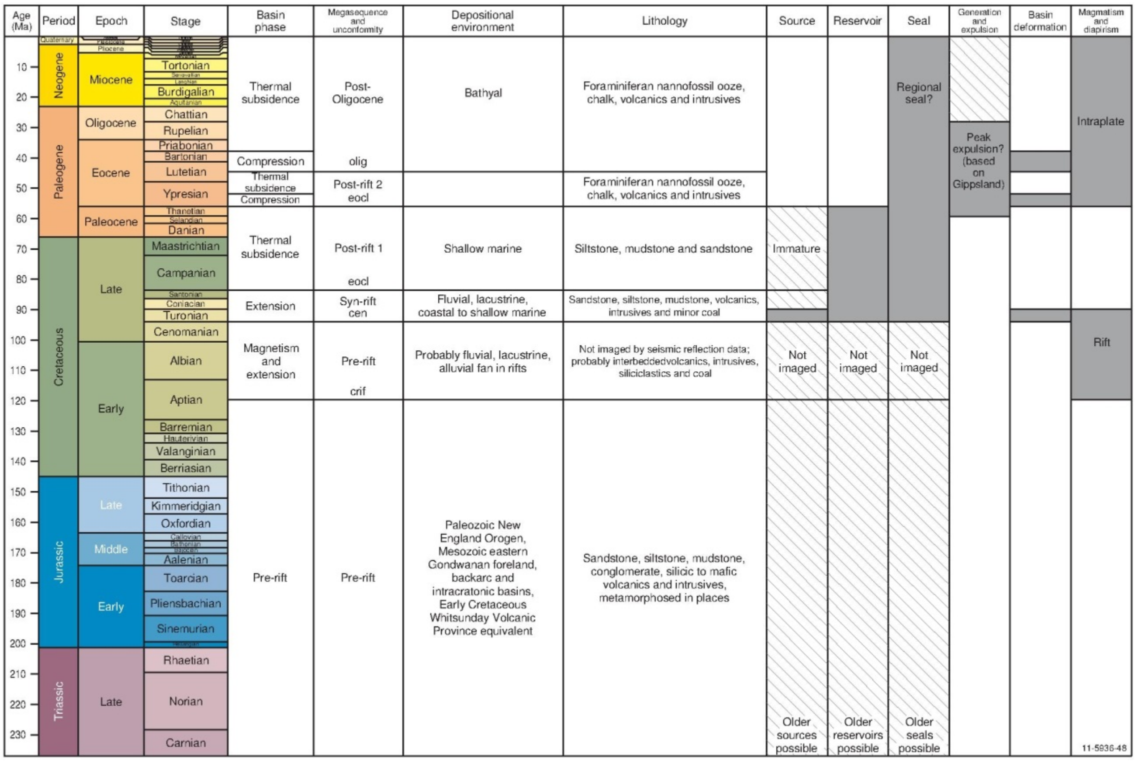

Figure 5.23: Stratigraphy of the Monawai and Moore basins, including sequence stratigraphy and tectonic events (after Norvick et al., 2001, 2008; Stagg et al., 2002).

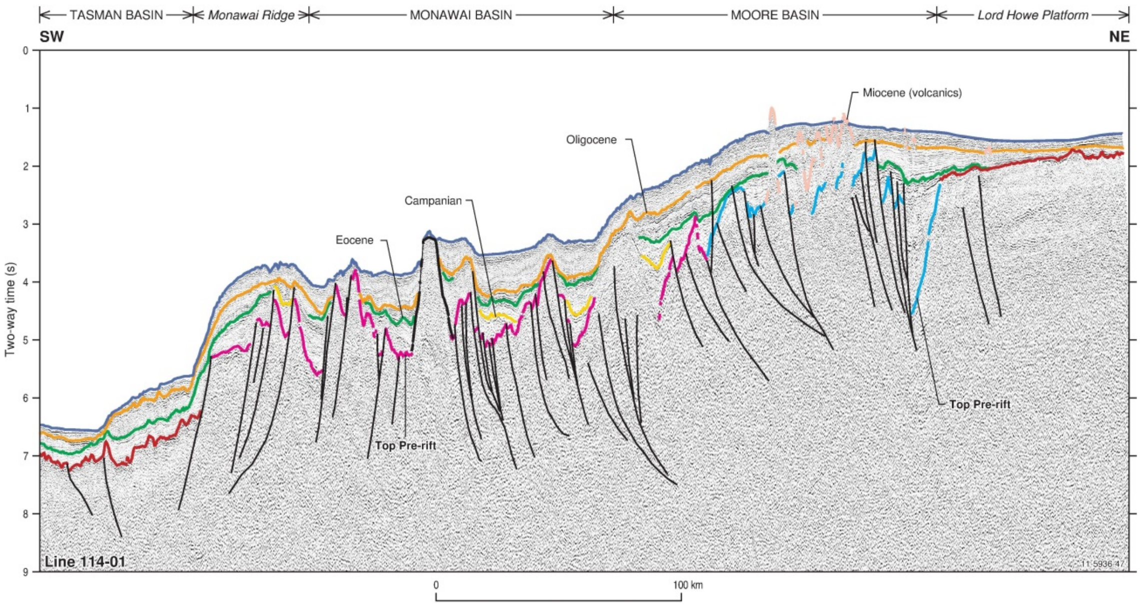

Figure 5.24: Geological cross-section along regional seismic line AGSO 114-01 showing structural and stratigraphic relationships (after Stagg et al., 2002). Location of line shown in Figure 5.26.

5.5.3 Petroleum systems

Given the lack of data, the presence of an active petroleum system in the Monawai Basin cannot be confirmed. The geological evolution and stratigraphy inferred from regional comparison and seismic data imply that petroleum systems similar to those proven in onshore eastern Australia could be present in the region. Results of basin modelling in the Capel and Faust basins in the northern part of the Lord Howe Rise (Funnell & Stagpoole, 2011) suggest that the sediment thickness across much of the Monawai Basin may not be sufficient for hydrocarbon generation. However, it is likely that the sediment thicknesses are considerably greater than indicated by the existing data, particularly in the larger depocentres. Bottom simulating reflectors (BSRs) have been identified on seismic data in the northern Monawai Basin (Stagg et al., 2002), and several previous works (e.g. Ramsay et al., 1997; Exon et al., 1998; Lafoy et al., 1998; Auzende et al., 2000) have speculated that these reflectors indicate the widespread occurrence of gas hydrates over the Lord Howe Rise. However, a recent reappraisal based on newly acquired data has indicated that the BSRs are most likely to be an Opal-A/Opal-CT diagenetic boundary (Colwell et al., 2006; Nouzé et al., 2009).

5.5.3.1 Source rocks

Assuming that the Monawai Basin has a similar early history to the Gippsland Basin on the conjugate eastern Australian margin, it is possible that gas- and oil-prone coastal plain and shallow marine mudstones, equivalent to the Golden Beach and Emperor sub-groups of the Gippsland Basin, may provide potential source rocks within the inferred Upper Cretaceous syn-rift succession (Figure 5.23). Widespread marine conditions during the post-rift phase (to the Maastrichtian) may have been conducive to the deposition of oil-prone marine source rocks, although they are likely to be immature for hydrocarbon generation given the shallow burial depths (Stagg et al., 2002). Source rock maturity may not be a significant concern if the inferred Upper Cretaceous syn-rift sediments are underlain by Upper Jurassic to Lower Cretaceous pre-rift and lower syn-rift successions. If potential source rocks are present within these successions, they are likely to be fluvio-lacustrine coal and mudstones, such as those found within the Strzelecki Group of the Gippsland Basin (Norvick et al., 2001; O’Brien et al., 2008).

Regional tectonic reconstructions by Norvick et al., (2001, 2008) show that the boundary between the New England and Lachlan orogens of eastern Australia (or their equivalents) underlies the northern part of the Monawai Basin. If this is the case, it is also plausible that the offshore continuation of the Permian–Triassic Sydney Basin may be present in the area. Stewart & Alder (1995) consider the gas- and condensate-prone upper Permian coals and carbonaceous shales as the most promising candidates for source rocks in the offshore Sydney Basin.

5.5.3.2 Generation and expulsion

If the total sediment thickness exceeds 4 km, as hinted by the seismic reflection data, the deepest depocentres of the Monawai Basin may be capable of generating hydrocarbons if suitable source rocks are present. Other areas of the basin may also contain sufficient sediment thickness, but the lack of seismic imaging at depth precludes confirmation. Heat flow measurements over the southern Lord Howe Rise by Grim (1969) indicated very high values of 97–100 mW/m^2, while the calculated heat flow at the DSDP 206 site in the nearby New Caledonia Basin (von Herzen, 1973) was 58 mW/m^2. These results indicate the potential for elevated heat flow in the Monawai Basin, which could have assisted the maturation of source rocks. High heat flow may be related to Neogene intraplate magmatism associated with the Lord Howe and Tasmantid hotspot chains to the west of the Lord Howe Rise (Stagg et al., 2002).

5.5.3.3 Reservoirs

Potential reservoir rocks in the Monawai Basin may occur within the syn-rift and lower post-rift megasequences as interbedded sandstones of fluvial to shallow marine origins (Figure 5.23; Stagg et al., 2002). Potential reservoir rocks may also occur within the pre-rift section as quartzose sandstones equivalent to those within the Triassic Hawkesbury Sandstone and Narrabeen Group of the Sydney Basin (Stewart & Alder, 1995).

5.5.3.4 Seals

A regional seal may be provided by the extensive and thick Oligocene–Holocene pelagic ooze. Marine, coastal and lacustrine mudstones within the syn-rift and lower post-rift successions, and volcanic flows and sills within the pre-rift and syn-rift successions, have potential to act as local seals (Stagg et al., 2002). Fluvio-deltaic to shallow marine shales, equivalent to parts of the Triassic Narrabeen and Wianamatta groups of the Sydney Basin, may also provide seals within the pre-rift succession (Stewart & Alder, 1995).

5.5.3.5 Play types

Seismic reflection data indicate a range of potential play types within the Monawai Basin, including: fault blocks, anticlines, transpressional structures and stratigraphic traps (Stagg et al., 2002). Compressional tectonics has resulted in localised fault reversal and anticlinal deformation during the Cenozoic, creating additional potential trapping structures. Multiple episodes of magmatism during the syn-rift and post-rift phases may also have produced further plays and enhanced source rock maturation (Stagg et al., 2002).

5.5.3.6 Critical risks

As in other parts of the Lord Howe Rise, there is a lack of direct evidence for active petroleum systems and a paucity of geological data. Hence, the presence of viable source rocks, reservoirs and seals are key uncertainties in the Monawai Basin. The pre-breakup palaeogeographic proximity to the Gippsland Basin, and possibly the Sydney Basin, suggests that the Monawai Basin may nevertheless contain viable petroleum system elements. Insufficient sediment thickness for hydrocarbon generation and expulsion is also a potential risk, although maximum sediment thicknesses are likely to be greater than suggested by the existing data. The Monawai Basin has experienced multiple phases of igneous activity, implying that the degradation of reservoirs and trapped hydrocarbons may be a risk. An additional risk to prospectivity is posed by Cenozoic tectonic reactivation, which may have resulted in late-stage trap breach.

5.5.3.7 Overall prospectivity classification

Low–Moderate

5.5.4 Exploration status

The Monawai Basin is a frontier basin in terms of petroleum exploration. No exploration activity has taken place other than the reconnaissance seismic surveys in the early 1970s by Shell International (MV *Petrel*) and Mobil. Geoscience Australia and its predecessors, the Australian Geological Survey Organisation (AGSO) and Bureau of Mineral Resources (BMR), have completed several data acquisition surveys over the southern Lord Howe Rise region, including the Monawai Basin, since the 1980s for reconnaissance geological investigation, offshore hydrocarbon resource assessment and determination of maritime boundaries under the United Nations Convention on the Law of the Sea (UNCLOS).

5.5.5 Data

The Monawai Basin is a frontier area with very sparse data coverage. Key data sets for the Monawai Basin are listed in Table 5.20–Table 5.24, and their locations shown in Figure 5.25 and Figure 5.26.

There are no sufficiently deep drill holes that provide stratigraphic control for the basin succession. The nearest drilling sites are the DSDP sites 207 and 592 over the Lord Howe Platform to the east. DSDP 207 penetrated a Cenozoic section of nannofossil ooze and over 150 m of Upper Cretaceous volcanics (The Shipboard Scientific Party, 1973). The drill hole terminated in rhyolitic flows and pumiceous lapilli tuffs that have been dated at 93.7 +/- 1.1 Ma (Cenomanian; McDougall & van der Lingen, 1974).

Several regional seismic reflection surveys traverse the Monawai Basin, amounting to over 900 line-km and located mostly within the Australian maritime jurisdiction (Table 5.21). Of these, the most significant are the AGSO 114 and 177 surveys that acquired approximately 3190 line-km and 5714 line-km of data, respectively. Both surveys were completed in collaboration with New Zealand as part of geological framework studies to support extended continental shelf claims under the United Nations Convention on the Law of the Sea (UNCLOS; Marshall et al., 1994; Ramsay et al., 1997). The data is of good quality, enabling the gross-scale basement topography and stratigraphy to be imaged in many places (Stagg et al., 2002). However, the data set lacks the resolution to reveal the detailed stratigraphy of individual depocentres or deeply buried sections. Lines from the Shell International MV *Petrel* and BMR RV *Rig Seismic* 46 surveys also traverse the basin, but the data quality is poor to moderate and the surveys do not provide a significant coverage of the basin.

Other data sets include seismic refraction, heat flow, gravity, magnetic and bathymetry data, and isolated rock samples. Sonobuoy seismic refraction data were collected in the vicinity of the Monawai Basin during the Mobil (Bentz, 1974) and BGR/BMR RV *Sonne* 7 (Willcox et al., 1981) surveys. To the north of the Monawai Basin, sonobuoy data have been collected over the northern Lord Howe Rise and Tasman Sea (Shor et al., 1971), and at over 40 locations over the Capel and Faust basins during the GA 302 seismic reflection survey.

High heat flow measurements acquired in the nearby Moore and Gower basins may reflect the effects of Neogene intraplate igneous activity in the region (Grim, 1969; Stagg et al., 2002).

Potential field and bathymetry data coverage over the southern Lord Howe Rise region includes regional compilations derived from satellite, airborne and marine data (Sandwell & Smith, 1997; Andersen et al., 2010; Maus et al., 2007, 2009; Whiteway, 2009). Additionally, shiptrack gravity and magnetic data were levelled in 2001 by Geoscience Australia (Petkovic et al., 2001).

A few rock samples have been collected from the seafloor near the Monawai Basin. These include mid-Permian granite, gabbro and sandstone from the Dampier Ridge to the northwest (Röser & Shipboard Party, 1985) and Carboniferous granite from the Challenger Plateau to the southeast (Tulloch et al., 1991). As in the other parts of the Lord Howe Rise, the extensive blanket of bathyal ooze restricts sampling opportunities for older rocks.

5.5.5.1 Confidence rating

Low

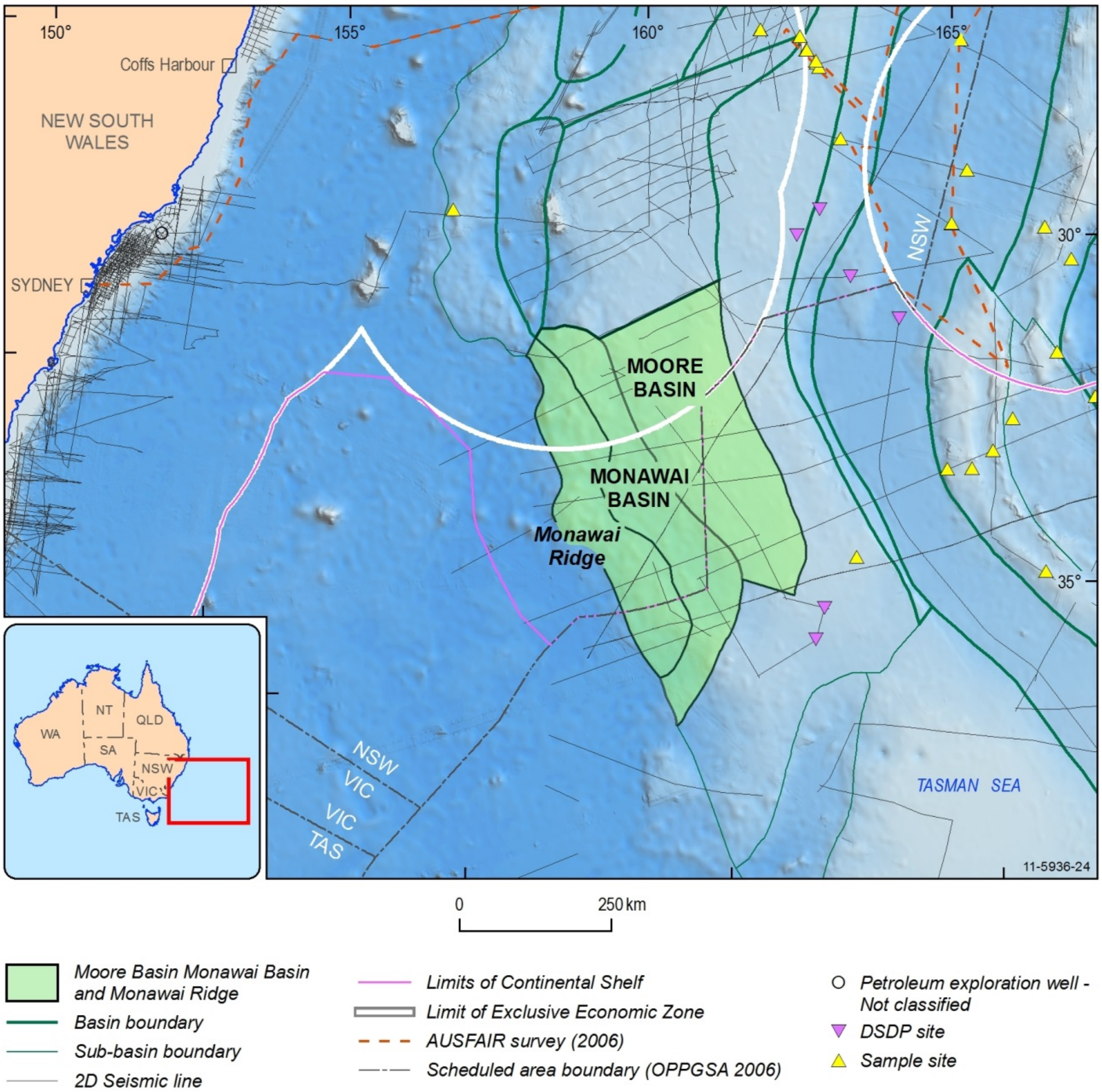

Figure 5.25: Seismic, well and sample distribution.

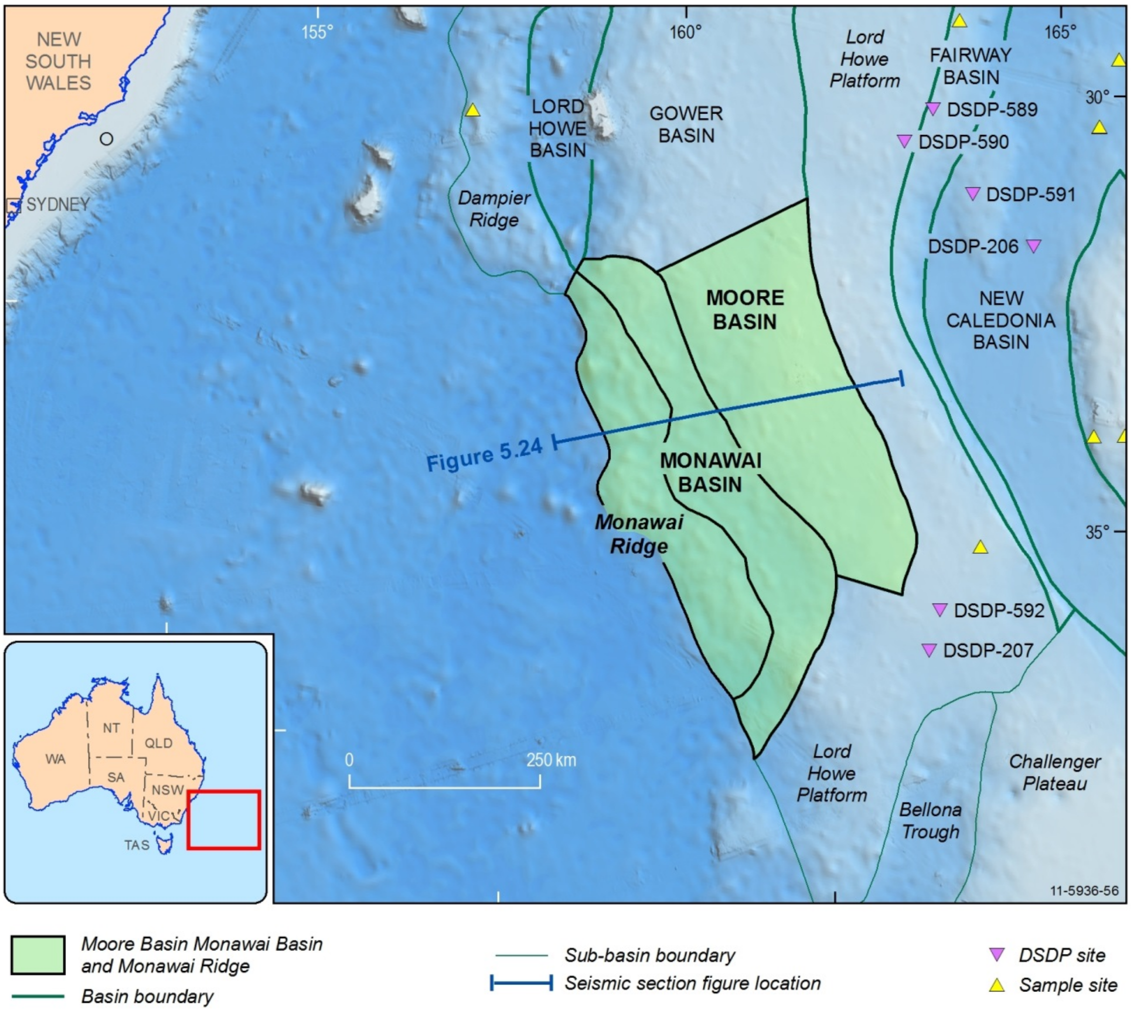

Figure 5.26: Location of nearby well control and seismic line shown in Figure 5.24.

5.5.6 Issues and remaining questions

Together with the adjacent Moore Basin, the Monawai Basin is one of the least understood basins within the Lord Howe Rise region. The poor coverage and quality of the existing data do not permit a definitive determination of the sediment thickness and distribution. There is no direct control on the composition and age of the basin succession or the basement, which precludes the assessment of potential for source, reservoir, seal and active petroleum systems.

Nevertheless, the existing data, in conjunction with the results of petroleum prospectivity studies of other basins in the Lord Howe Rise region, suggest that the Monawai Basin may contain large depocentres with sufficient sediment thickness for hydrocarbon generation. Further studies are required to reduce exploration risk in the southern Lord Howe Rise region, including the Monawai Basin. Depending on the results, these studies could enhance the long-standing industry interest in the Lord Howe Rise region.

5.5.6.1 Recommendations

Additional reconnaissance-level data acquisition will be required to improve the understanding of the region's petroleum prospectivity and to reduce exploration risk. High-quality regional 2D reflection seismic surveys could vastly improve the imaging of the full sedimentary succession and basement structure. The results of these regional surveys could then inform the design of targeted high-density 2D or 3D seismic surveys. This data would in turn support detailed interpretation of the basin stratigraphy and potential facies distribution, and thus a preliminary assessment of the petroleum prospectivity. Given the limited opportunity for the dredge sampling of pre-Cenozoic rocks in the region, deep stratigraphic drilling remains the only viable means of testing the interpretations.

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5.5.8 Data Tables

Table 5.20: List of wells located close to Monawai Basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1971	DSDP 207	Scientific	Deep Sea Drilling Project	513	Cenomanian	Nil	The Shipboard Scientific Party, 1973
1982	DSDP 592	Scientific	Deep Sea Drilling Project	388.5	Middle Late Eocene	Nil	The Shipboard Scientific Party, 1986

Table 5.21: Key 2D seismic surveys, Monawai Basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1971	MV *Petrel* Roving	Shell International	170	van de Beuque et al., 2003; Sutherland et al., 2012
1985	RV *Rig Seismic* 46	Bureau of Mineral Resources	120	Whitworth & Willcox, 1985
1992	AGSO 114	Australian Geological Survey Organisation	360	Marshall et al., 1994
1996	AGSO 177	Australian Geological Survey Organisation	280	Ramsay et al., 1997

Table 5.22: Refraction seismic and velocity surveys covering the Monawai Basin and adjacent areas.

Year	Survey	Operator	Location	Reference
1967	Scripps Institution of Oceanography two-ship refraction seismic survey	Scripps Institution of Oceanography	23 profiles over Southwest Pacific, including two stations northeast of Gower Basin	Shor et al., 1971
1972	Mobil 1972	Mobil	One station to southeast of Moore Basin, three stations in southern New Caledonia Basin, four stations without positioning data	Bentz, 1974; Stagg et al., 2002
1978	RV *Sonne* 7 survey	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)	Lord Howe Rise region, including two stations in Moore Basin, two stations in Monawai and one station each over nearby Gower Basin, Dampier Ridge and Lord Howe Platform	Willcox et al., 1981

Table 5.23: Key geological sampling surveys in areas adjacent to the Monawai Basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
1975	GEORSTOM III Sud	Office de la recherche scientifique et technique outre-mer (ORSTOM)	Norfolk Ridge, Reinga Basin and Lord Howe Platform	Dredge	Mudstone, limestone, organic shale, basalt, gabbro, hyaloclastic breccia	Launay et al., 1977; Herzer et al., 1997, 1999
1985	RV *Sonne* 36	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)	Lord Howe Platform and Dampier Ridge	Dredge	Pebbly conglomerate, sandstone, calcarenite (Lord Howe Platform), granite, gabbro and feldspathic sandstone (Dampier Ridge)	Röser & Shipboard Party, 1985; McDougall et al., 1994
1987	CH8701	Department of Scientific and Industrial Research (DSIR)	Challenger Plateau	Dredge	Granite	Tulloch et al., 1991
1993	RE9302	Institute of Geological and Nuclear Sciences (IGNS)	Norfolk, West Norfolk, Wanganella and Three Kings ridges,	Dredge	Carbonaceous sandstone and mudstone, bryozoal/foraminiferal limestone, calcareous volcaniclastic sandstone, lapilli tuff	Herzer et al., 1997, 1999
2006	AUSFAIR MD-153 (RV *Marion Dufresne*)	Geoscience Australia, Ifremer	Capel, Faust and New Caledonia basins, Lord Howe Platform, Fairway Ridge, far northeastern Gower Basin	Dredge, giant piston core	Trachyte, latite, quartz–feldspathic conglomerate and sandstone, some with molluscan fossils, calcareous ooze, ferromanganese nodules and crust	Colwell et al., 2006; Higgins et al., 2011

Table 5.24: Swath bathymetry data sets relevant to the Monawai Basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
2001	Australian continental margin levelled gravity, magnetic and bathymetry	Geoscience Australia, Intrepid Geophysics		Petkovic et al., 2001
2006	AUSFAIR MD-153 (RV *Marion Dufresne*)	Geoscience Australia, Ifremer	Capel, Faust and New Caledonia basins, Fairway Ridge	Colwell et al., 2006
2009	Bathymetry and Topography Grid of Australia AUSBATH09 (2009)	Geoscience Australia		Whiteway, 2009

5.6 Fairway Basin

5.6.1 Summary

State(s)		Commonwealth waters; basin continues into French(New Caledonia) and New Zealand jurisdictions
Area (km^2)		51,040 (Australia); 130,800 (total)
Water Depth (m)		1500–3000
Maximum sediment thickness (m)		5000 (excludes pre-rift succession)
Age range		Late Cretaceous (or earlier)–Cenozoic
Basin	**Overlies**	Possible equivalents of Teremba-Murihiku-Brook Street terranes, Cretaceous magmatic arc
	Adjacent basins	Lord Howe Platform, Fairway Ridge, New Caledonia Basin, Challenger Plateau
Basin type		Extensional, sag
Depositional setting, rock types		Non-marine, deltaic, and marine clastic sedimentary rocks, bathyal biogenic (carbonate, siliceous) sedimentary rocks, volcanic, intrusive and volcaniclastic rocks
Petroleum prospectivity		Low–moderate
Confidence		*Low*

5.6.2 Geology

The Fairway Basin is a northwest to north-northwest-trending structural element located along the eastern flanks of the Lord Howe Rise, extending over 1700 km through the Australian, French (New Caledonian) and New Zealand marine jurisdictions in 1500–3000 m water depth (Figure 5.27). The basin covers an area of approximately 130,800 km^2 and contains an Upper Cretaceous (or older) to Cenozoic succession (Figure 5.28) with a maximum thickness of approximately 5000 m (Lafoy et al., 2005; Exon et al., 2007; Collot et al., 2009). The northern Fairway Basin is separated from the New Caledonia Basin by the northwest-trending Fairway Ridge. According to a recent revision of the regional tectonic elements (Lafoy et al., 2005; Exon et al., 2007; Collot et al., 2009), the Fairway Basin is considered to be contiguous with northwesterly extension of the offshore Taranaki Basin, which is variably known as the Aotea Basin (Exon et al., 2007) and the Deepwater Taranaki Basin (Baillie & Uruski, 2004).

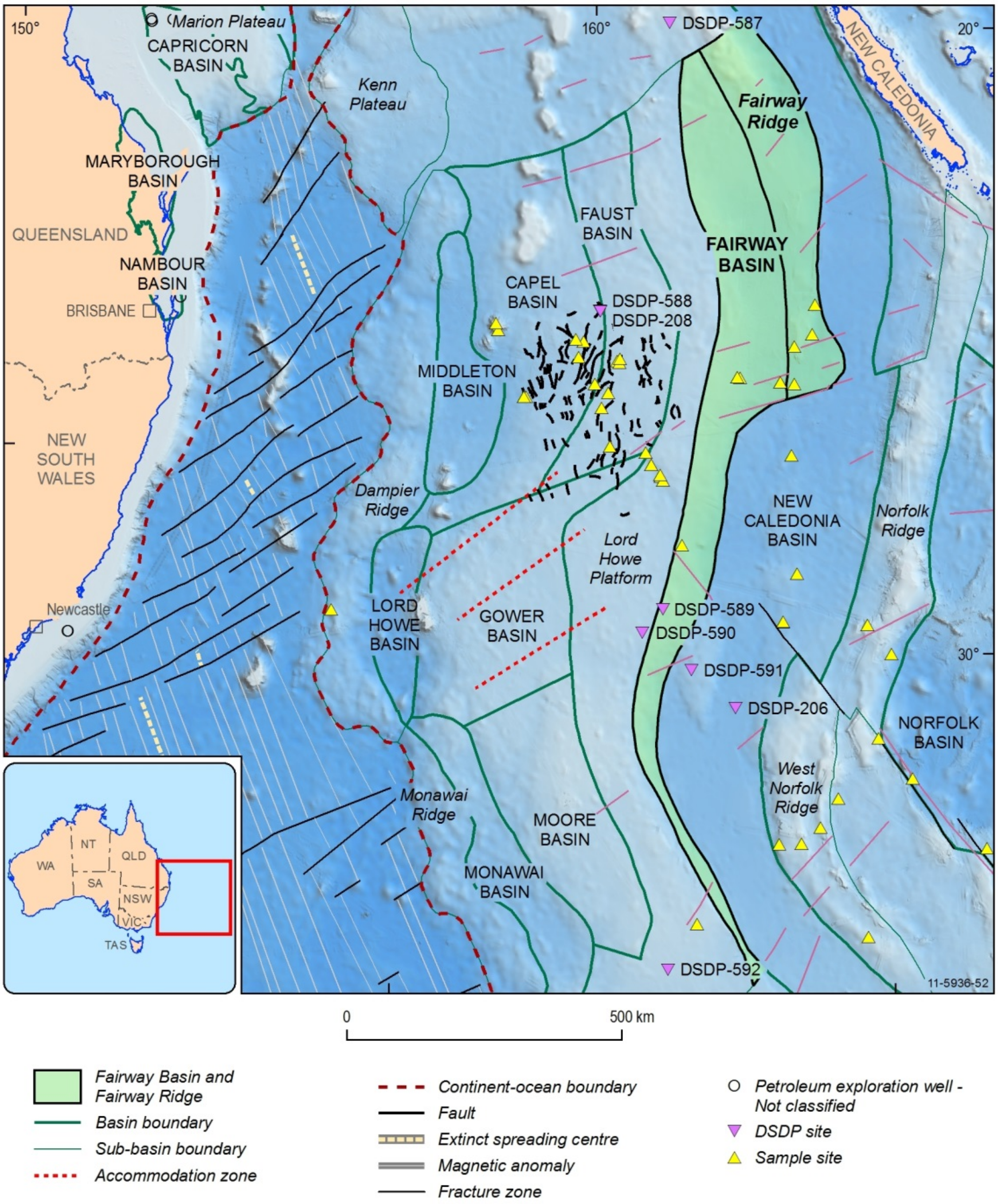

Figure 5.27: Structural elements map, Fairway Basin and surrounding regions (location of lineaments and faults east of the Lord Howe Platform based on Collot et al., 2009).

5.6.2.1 Structural geology

The Fairway Basin occupies the transition between the regional structural high of the Lord Howe Rise and the New Caledonia Basin (Figure 5.29). The seafloor above the Fairway Basin slopes gently eastward to the Fairway Ridge and the New Caledonia Basin. The steeply sloping western boundary with the Lord Howe Rise is marked by sediment slumps. An extension of the Barcoo–Elizabeth–Fairway Lineament originating in the Tasman Sea separates the Fairway and New Caledonia Basins into northern and central–southern segments. The northern segment is mostly within the French (New

Caledonian) maritime jurisdiction and is characterised by a northwest–southeast structural trend. The central–southern segment is mostly within Australian and New Zealand jurisdictions and exhibits a north-northwest to northwest trend. In addition, an extension of the Vening–Meinesz Fracture Zone intersects the central part of the Fairway Basin and sinistrally offsets the eastern flank of the Lord Howe Rise.

The Fairway Basin evolved during the Cretaceous breakup of eastern Gondwana that culminated with the opening of the Tasman Sea (85–52 Ma) and detachment of the Lord Howe Rise from eastern Australia (Hayes & Ringis, 1973; Gaina et al., 1998; Sdrolias et al., 2001). The basin underwent a greater degree of crustal extension than the Lord Howe Rise, such that the basin is now underlain by highly extended continental crust between 12 and 15 km thick (Shor et al., 1971; Klingelhoefer et al., 2007). Rifting created multiple graben and half graben that have been buried by post-rift deposition. The northern segment is characterised by shallower water depths (1500–2500 m) and comparatively thick (4000–5000 m) syn- and post-rift sediments. The central–southern segment generally lies at water depths of over 2500 m and sediment thicknesses are 2000 m or less.

5.6.2.2 Basin evolution and depositional history

As for other basins in the region, the Fairway Basin is not constrained by deep drilling data. The tectonic phases described herein are inferred mainly from the interpretation of reflection seismic and geophysical data, in combination with regional tectonic reconstructions and correlations. During the Paleozoic to the Early Cretaceous, the area presently occupied by the Fairway and New Caledonia basins and the eastern Lord Howe Rise was part of the eastern Gondwana margin located inboard of the convergent boundary with the Pacific Plate. It is likely that this area was in a forearc position relative to the subduction-related magmatic arc for much of this time (Mortimer et al., 2008), until the arc migrated eastwards over the area during the Early Cretaceous (Collot et al., 2009). The regionally pervasive curvilinear trend of the eastern flanks of the Lord Howe Rise and the New Caledonia Basin probably reflects the trend of the magmatic arc (Collot et al., 2009). Given this pre-rift history, the basement to the Fairway Basin may include the rocks equivalent to the Permian–Jurassic Teremba Terrane in New Caledonia and their New Zealand correlatives, the Murihiku and Brook Street terranes (Norvick et al., 2008; Collot et al., 2009).

During the Early Cretaceous–Cenomanian widespread extension and magmatism affected the backarc area of the eastern Gondwana margin, including parts of eastern Australia and the Lord Howe Rise (Bryan et al., 1997; Norvick et al., 2001, 2008). Numerous rift depocentres are inferred to have formed over the Lord Howe Rise during this time (Willcox et al., 2001; Willcox & Sayers, 2002; van de Beuque et al., 2003; Colwell et al., 2010). However, in the Fairway Basin, there is no convincing evidence to suggest significant rifting during the Early Cretaceous, probably reflecting the area’s proximity to an active arc.

A change in regional plate dynamics is believed to have resulted in subduction roll-back and the eventual cessation of subduction along eastern Gondwana–Pacific margin around the Cenomanian (Norvick et al., 2001, 2008; Willcox et al., 2001; Schellart et al., 2006; Collot et al., 2009; Waschbusch et al., 2009; Rey & Müller, 2010). Rifting along the axis of the Early Cretaceous arc (Collot et al., 2009) resulted in the formation of extensional depocentres in the Fairway and New Caledonia basins during the Late Cretaceous (Lafoy et al., 2005; Exon et al., 2007; Collot et al., 2009). Associated syn-rift deposition was probably dominated by non-marine to marine siliciclastics and laterally confined by the fault-bounded margins of individual depocentres (van de Beuque et al., 2003; Exon et al., 2004a). Progradational shelf wedges and aggradational coastal plain successions are apparent at the basin margins on reflection seismic data (Collot et al., 2012; Rouillard et al., 2012). The Cretaceous succession is generally 500–1000 m thick (Exon et al., 2004a). Auzende et al. (2000b) interpreted mud or salt diapirs within the Upper Cretaceous syn-rift succession in the northern Fairway Basin. Alternatively, the apparently diapiric structures could be volcanic build-ups.

A period of thermal subsidence that commenced towards the end of the Late Cretaceous resulted in deposition of a laterally extensive succession that blanketed the structurally confined rift depocentres. The post-rift succession comprises two parts. A Paleocene–Eocene section that includes chalk, radiolarite, chert and claystone (evidence from a dredge sample during the FAUST 3/GA 232 survey) is over 1000 m thick above the syn-rift depocentres. An extensive Oligocene–Holocene section of probable chalk, nannofossil ooze and minor volcaniclastic turbidite is generally between 400 and 800 m thick (van de Beuque et al., 2003; Exon et al., 2004a, 2007). During the Eocene–Oligocene, the region experienced compressive tectonism that culminated with the obduction event in New Caledonia (Aitchison et al., 1995). Initial uplift, accompanied by subaerial erosion of the structural highs, gentle folding of the basin sediments and fault reversal, was followed by flexural subsidence of the Fairway and New Caledonia basins and continued uplift of the flanking structural highs (Exon et al., 2007; Collot et al., 2008). Likely turbidite channels and basin-floor fans are apparent on reflection seismic data about the Eocene–Oligocene unconformity, probably sourced from the erosion of uplifted structural highs nearby (Collot et al., 2012; Rouillard et al., 2012). Tectonism during this time is related to an overall reorganisation of the Pacific Plate boundaries and dynamics (Müller et al., 2000; Veevers, 2000; Sdrolias et al., 2001; Crawford et al., 2003). Since the Oligocene, the Fairway and New Caledonia basins and the Lord Howe Rise have experienced rapid thermal subsidence, possibly enhanced by a crustal detachment beneath the New Caledonia Basin (Sutherland et al., 2010). Cenozoic intraplate magmatism has produced isolated volcanic build-ups within, and in the vicinity of, the Fairway Basin (Exon et al., 2004a, b).

5.6.2.3 Level of knowledge

As for most other basins in the region, the Fairway Basin is a remote and under-explored deepwater frontier basin with a sparse coverage of regional 2D seismic reflection, gravity, magnetic and bathymetry data (Figure 5.30). Stratigraphic control for the latest Cretaceous to Cenozoic successions is provided via ties to the Deep Sea Drilling Program (DSDP) holes 208 and 588, both drilled at the same location near the boundary between the Capel and Faust basins. No petroleum exploration wells have been drilled, and the syn-rift and pre-rift successions remain unconstrained. The geologic interpretation of the basin is largely inferred from regional tectonic reconstructions and correlations. A few recent marine surveys, some within the Australian jurisdiction, have contributed to improving the geological knowledge of the area. The Geoscience Australia survey GA 232 filled a gap in regional seismic data coverage in the central segment of the Fairway and New Caledonia basins and recovered rock and core samples that provide information on the magmatic and depositional history. The French–New Caledonian ZoNéCo 11 survey acquired deep reflection and refraction seismic data to image the crustal structure of the northern segment. The Australian–French AUSFAIR–ZoNéCo 12 survey acquired shallow core samples in the northern and central segments to test for the occurrence of gas hydrates in the sub-bottom sediments and to measure heat flow. The survey also recovered rock samples from the nearby Fairway Ridge and the Lord Howe Platform that have constrained the timing of Late Cretaceous magmatism and marine deposition in the region.

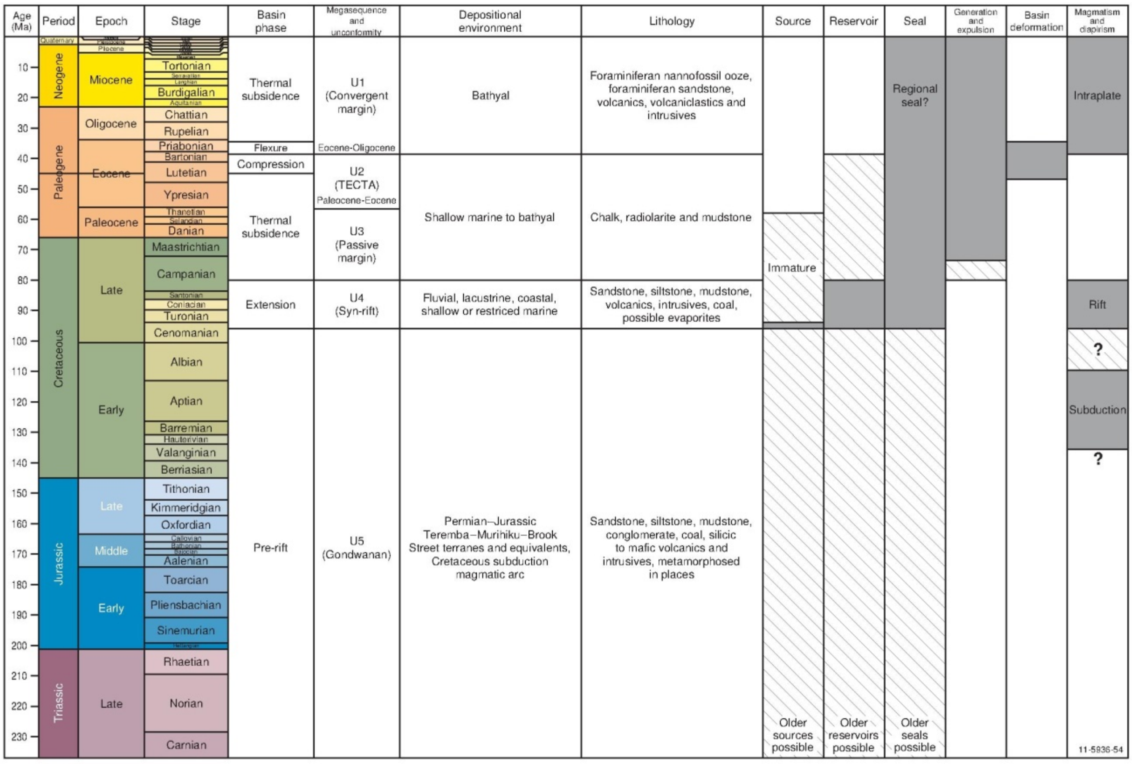

Figure 5.28: Stratigraphy of the Fairway and New Caledonia basins based on Lafoy et al. (2005), Exon et al. (2007), Collot et al. (2008, 2009), Norvick et al. (2008). Megasequence nomenclature after Collot et al. (2012) and predicted petroleum generation and expulsion after Vially et al. (2003).

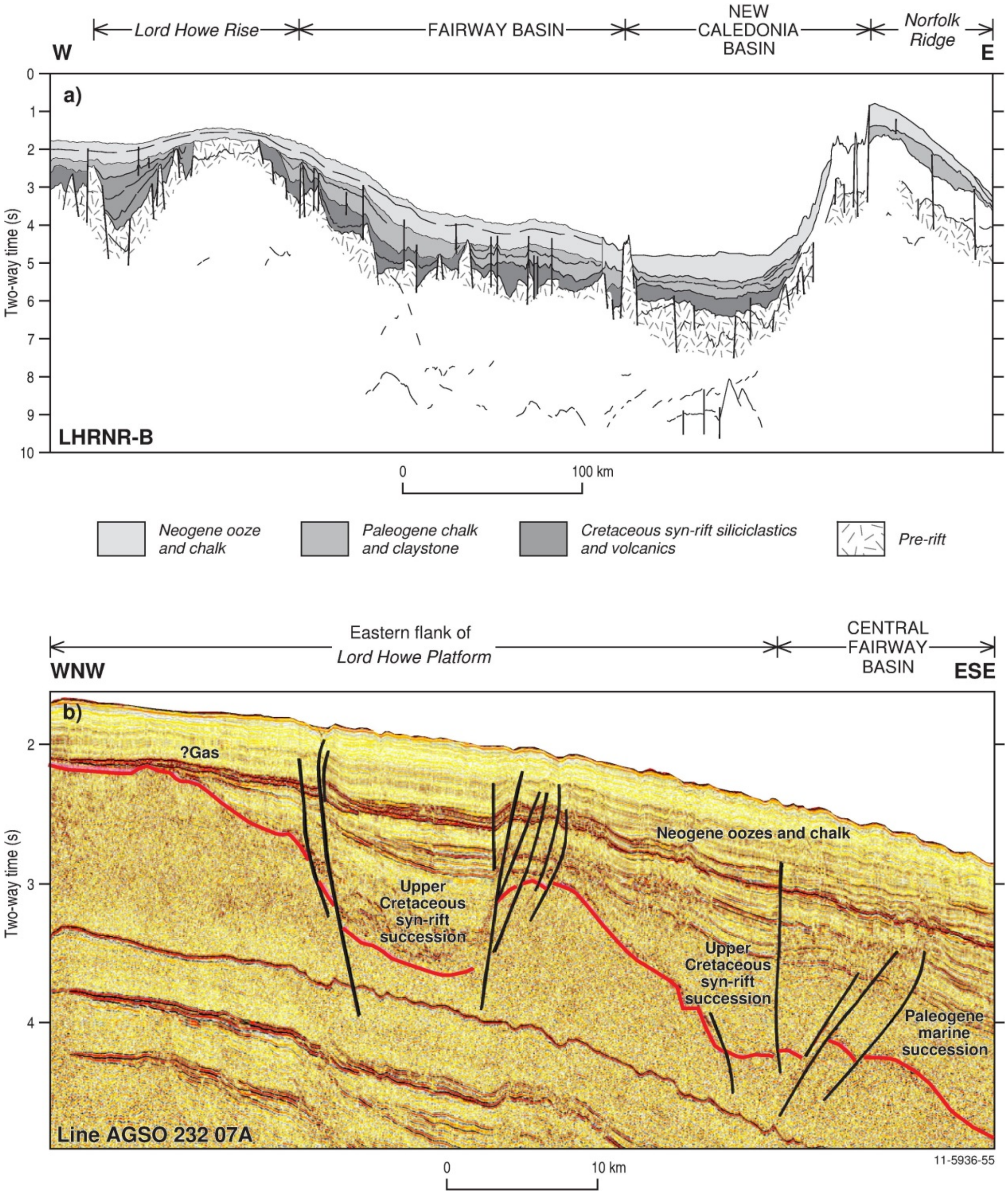

Figure 5.29: a) Geological cross-section of the northern Fairway and New Caledonia basins along regional seismic reflection line AGSO 177 LHRNR-B; b) Details of seismic reflection line FAUST 3/GA-232 07A showing structural and stratigraphic relationships (after Exon et al., 2004a). Location of profiles shown on Figure 5.31.

5.6.3 Petroleum systems

Much of the petroleum interest in the basin has arisen from the possibility of vast gas hydrate occurrences within the post-rift succession. This interpretation was based on the identification of bottom simulating reflectors (BSRs) in regional seismic data that exhibit a positive polarity and are located at 500–700 m below the seafloor (Ramsay et al., 1997; Exon et al., 1998; Lafoy et al., 1998; Auzende et al., 2000b). However, a recent reappraisal based on newly acquired data has indicated that the BSRs are most likely to be an Opal-A/Opal-CT diagenetic boundary (Colwell et al., 2006; Nouzé et al., 2009).

Inferred stratigraphy and geologic evolution suggest, however, that conventional petroleum systems similar to those proven in New Zealand or onshore eastern Australia may be present in the Fairway and New Caledonia basins. The basins are structurally contiguous and share a similar stratigraphy with the offshore Taranaki Basin, a proven oil- and gas-producing basin. Although the massive Neogene sediment loading experienced in the shallow-water Taranaki Basin is absent, basin modelling indicates that, in some areas, the Fairway and New Caledonia basins have sufficient sediment thickness for hydrocarbon generation, if suitable source rocks are present (Vially et al., 2003). Synthetic aperture radar (SAR) satellite imagery has previously indicated the presence of third-order slicks at the sea surface in the southern Fairway Basin (van de Beuque et al., 2003).

5.6.3.1 Source rocks

Seismic reflection data indicate widespread presence of coaly rocks in the New Caledonia, Deepwater Taranaki and Reinga basins and over the West Norfolk Ridge that correlate with the Upper Cretaceous Rakopi Formation, the principal source of oil in the shallow-water Taranaki Basin (Uruski, 2008). Cenomanian coal measures have been sampled from the West Norfolk Ridge (Herzer et al., 1997, 1999) and Upper Cretaceous coal is also known from onshore New Caledonia (Paris & Lille, 1977; Paris, 1981). Coaly potential source rocks could also occur within the pre-rift succession forming the basement to the basins, e.g. the inferred continuation of the Permian–Jurassic Murihiku Terrane from New Zealand (Figure 5.28). Deposition within fault-bounded depocentres may also have produced organic-rich marine potential source rocks in the Upper Cretaceous syn-rift succession (Exon et al., 2007).

5.6.3.2 Generation and expulsion

Sediment thickness in parts of the Fairway Basin appears to be sufficient for oil and gas generation, if viable source rocks are present within the Cretaceous syn-rift succession (van de Beuque et al., 2003; Vially et al., 2003). 1D source rock maturity modelling indicates that Cretaceous coals would be capable of generation and expulsion from the late Campanian onward (Vially et al., 2003). Measurements taken during the joint French–Australian MD-153 AUSFAIR–ZoNéCo 12 survey over the Fairway and Capel basins, at the DSDP 587 site over northern Lord Howe Rise, and at the DSDP 206 site in the New Caledonia Basin indicate heat flow of 48–75 mW/m^2 (von Herzen, 1973; Morin & von Herzen, 1986; Colwell et al., 2006; Harmegnies & Foucher, 2006). These results potentially suggest above-average heat flow in parts of the region, which may have assisted the maturation of source rocks. Upward hydrocarbon migration within the basin may have been assisted by the numerous small-scale faults and fluid escape features that are apparent above diapiric structures on seismic reflection data (Auzende et al., 2000b).

5.6.3.3 Reservoirs

Potential reservoir formations within the Fairway Basin may include Cretaceous to Paleogene fluvial, deltaic and marine sandstones (Figure 5.28). Shelf wedges and coastal plain successions within the Cretaceous syn-rift sequence, and turbidite channels and basin-floor fans about the Eocene–Oligocene unconformity, may contain significant sand bodies. There is also potential for reservoir sandstones within the pre-rift section, although the lack of imaging and direct evidence precludes further assessment.

5.6.3.4 Seals

Regional seal could be provided by the extensive and thick Oligocene–Holocene nannofossil/foraminiferal chalk and ooze, although seal integrity may be compromised in places by fluid migration, small-scale faulting and magmatism. There is also potential for more localised seals within the fine-grained facies of the Cretaceous–Paleogene successions. If the diapiric structures observed on reflection seismic data are fed by mud or salt within the Cretaceous syn-rift succession, this would imply a comparatively widespread distribution of potential seal facies, at least within the syn-rift succession. The pre-rift section may also contain potential seals, although no data is available to support this.

5.6.3.5 Play types

Likely play types in the Fairway Basin include horsts, tilted fault blocks and associated drapes within the Cretaceous syn-rift succession, mud or salt diapirs within the Cretaceous–Paleogene section, anticlines associated with the Eocene–Oligocene tectonism, and drapes (induced by compaction and differential subsidence) within the post-rift succession. Stratigraphic traps associated with transgressive–regressive cycles within the coastal plain, progradational wedge, and turbidite/basin-floor fan systems are also likely.

5.6.3.6 Critical risks

As for the other basins of the Lord Howe Rise and surrounding regions, there is a lack of direct evidence for active petroleum systems and a paucity of geological data. Consequently, the presence of viable source, reservoir and seal facies are key uncertainties in the Fairway Basin. Despite these uncertainties, the available data, interpreted in light of regional tectonic reconstructions and basin analogues, indicate that petroleum system elements are likely to be present, and that gas and oil generation and expulsion would be possible in the deepest depocentres if suitable source rocks are present. Assuming the presence of source rocks, a key risk is the timing of main hydrocarbon charge (Late Cretaceous–Eocene) relative to deposition of the bathyal regional seal and overburden (Oligocene–Holocene). The major Eocene–Oligocene structuring event and Cenozoic igneous activity, fluid migration and small-scale faulting, may pose a risk to preservation of earlier trapped hydrocarbons. Effectiveness of the Oligocene–Holocene bathyal sediments as a regional seal remains untested, and no information exists on the distribution and effectiveness of intraformational seals.

5.6.3.7 Overall prospectivity classification

Low–moderate

5.6.4 Exploration status

The only exploration activities in the Fairway Basin have been a series of regional reconnaissance seismic surveys conducted in the early 1970s by Shell International (MV *Petrel* survey) and Mobil, and the AUSTRADEC I and II and WNC80 surveys (Table 5.26). Data coverage over the Fairway and New Caledonia basins has been significantly improved through a series of marine reconnaissance surveys since the 1990s funded by the governments of France and New Caledonia which acquired bathymetric, reflection seismic, gravity, magnetic, biological and geological sample data. This programme was complemented by the French–Australian FAUST (France–Australia Seismic Transect) collaborative programme that acquired several regional reflection seismic lines across the Lord Howe Rise, Fairway and New Caledonia basins. Marine surveys specifically aimed at the definition of maritime boundaries under the United Nations Convention on the Law of the Sea (UNCLOS), such as the NOUCAPLAC programme in New Caledonia and many of the Australian Geological Survey Organisation (AGSO) and Geoscience Australia (GA) surveys, have also contributed to the regional data coverage.

5.6.5 Data

Together with the Capel and Faust basins of the northern Lord Howe Rise, the northern Fairway Basin has the best data coverage within the region (Figure 5.30). Key data sets are listed in Table 5.25–Table 5.29. The density of data coverage is nevertheless sparse when compared to most other Australian offshore basins. Stratigraphic control for the latest Cretaceous to Cenozoic successions is provided via reflection seismic ties to the Deep Sea Drilling Program (DSDP) holes 208 and 588, both drilled at the same location near the boundary between the Capel and Faust basins. DSDP 208 penetrated an upper Maastrichtian–Holocene section of nannofossil/foraminiferal ooze (The Shipboard Scientific Party, 1973). DSDP 588 consisted of four core holes at the DSDP 208 site, with DSDP 588C terminating in the Middle Eocene (The Shipboard Scientific Party, 1986a). DSDP sites 589 and 590, located further south in the central Fairway Basin and adjacent Lord Howe Rise, do not provide any information on the deeper basin as they only penetrated the Miocene–Holocene succession of calcareous biogenic sediments (The Shipboard Scientific Party, 1986b, 1986c).

Other data sets comprise regional 2D seismic reflection, velocity, gravity, magnetic, bathymetry and heat flow data, and rock and shallow sediment samples. The northern Fairway Basin and the adjacent Fairway Ridge have a regional-scale 2D seismic reflection data coverage, although data quality is variable. Most data from surveys acquired in the 1970s and 1980s are generally of poor to moderate quality. However, data quality for the ZoNéCo and FAUST surveys is good to moderate. The FAUST 1 survey (run in conjunction with AGSO 206 survey) acquired 4564 line-km of high-quality data over the northern Tasman Sea region (Bernardel et al., 1999), approximately 730 km of which is located over the Fairway Basin and Ridge. FAUST 1 remains the only deep seismic reflection data available over the Fairway Basin (Lafoy et al., 2005). The ZoNéCo 5 survey acquired approximately 5400 line-km of six-channel data over the northern Fairway Basin and Ridge to map the distribution of BSRs imaged by the FAUST 1 seismic reflection data (Auzende et al., 2000a; Brodien et al., 2003; Sutherland et al., 2012). The FAUST 3 survey (run in conjunction with the GA 232 survey) acquired a total of 2795 line-km of 24-channel seismic reflection data, of which approximately 870 km are over the northern and central Fairway Basin and the Fairway Ridge. Together with the data from the Ifremer's NOUCAPLAC 2 survey, and the AGSO 177 survey, these lines provide across-strike imaging of the area.

The central and southern parts of the Fairway Basin are very sparsely covered by reflection seismic data. Apart from the FAUST 3/GA 232 survey, the only seismic reflection data in the area are derived from parts of the AGSO 114 survey.

The most significant velocity data sets in the northern and central Fairway and New Caledonia basins have been derived from a two-ship seismic refraction survey of the southwest Pacific, with two transects across the Fairway and New Caledonia basins (Shor et al., 1971), and the ocean-bottom seismometer (OBS) survey along two transects during the ZoNéCo 11 survey (Klingelhoefer et al., 2007). In the nearby Capel and Faust basins of the northern Lord Howe Rise, velocity data were also collected at the DSDP 208 site (The Shipboard Scientific Party, 1973), and sonobuoy data were collected within the GA-302 seismic reflection survey grid (Petkovic, 2010).

Potential field and bathymetry data coverage over the southern Lord Howe Rise region includes regional compilations derived from satellite, airborne and marine data (Sandwell & Smith, 1997; Andersen et al., 2010; Maus et al., 2007, 2009; Whiteway, 2009). In addition, shipboard gravity, magnetic and bathymetry data were acquired during the ZoNéCo, AGSO/GA, FAUST and NOUCAPLAC surveys undertaken in the area, although the details have not been listed here.

Heat flow data available for the Fairway Basin and the surrounding regions are derived from the joint French–Australian MD-153 AUSFAIR–ZoNéCo 12 survey over the Fairway and Capel basins, DSDP 587 site on the northern Lord Howe Rise, and DSDP 206 site in the New Caledonia Basin. The results indicate a range of values between 48 and 75 mW/m^2, which are normal to above average heat flow values for a rifted margin setting (von Herzen, 1973; Morin & von Herzen, 1986; Colwell et al., 2006; Harmegnies & Foucher, 2006).

Although a number of rock and sediment samples have been collected by dredging and shallow seabed coring from the Fairway Basin, and the nearby Lord Howe Rise and New Caledonia Basin, the majority are of Neogene age. However, the MD-153 AUSFAIR–ZoNéCo 12 survey recovered continental rocks (conglomerate, sandstone, alkali intermediate–acid volcanics) from the central New Caledonia Basin—the northern West Norfolk Ridge in the revised nomenclature of Lafoy et al. (2005), Exon et al. (2007) and Collot et al. (2009)—and the central Lord Howe Platform (Colwell et al., 2006). The volcanic rocks from the Lord Howe Platform have subsequently been dated at 96.9 +/- 0.7 Ma (Cenomanian) and 74.1+/-0.7 Ma (Campanian; Higgins et al., 2011). Similar alkali volcanic rocks have been noted as clasts in a pebble conglomerate sample dredged from the central New Caledonia Basin that also contains abundant mollusc fossils. Assuming that the clasts are of similar age to the dated volcanic rocks, the samples in combination provide a constraint on the timing of initial marine deposition in the region. In addition, lower Eocene chalk/radiolarite was dredged from the Fairway Ridge during the FAUST 3/GA 232 survey (Exon et al., 2004a). Late Paleogene to Neogene intraplate volcanic rocks have been sampled during a number of marine surveys, including the ZoNéCo 5 survey from the northern Lord Howe Platform adjoining the northern Fairway Basin (Exon et al., 2004b), FAUST 3/GA 232 from the central Lord Howe Platform (Exon et al., 2004a), and GA 2436 RV *Tangaroa* survey from the Capel and Faust basins (Dadd et al., 2011).

5.6.5.1 Confidence rating

Low

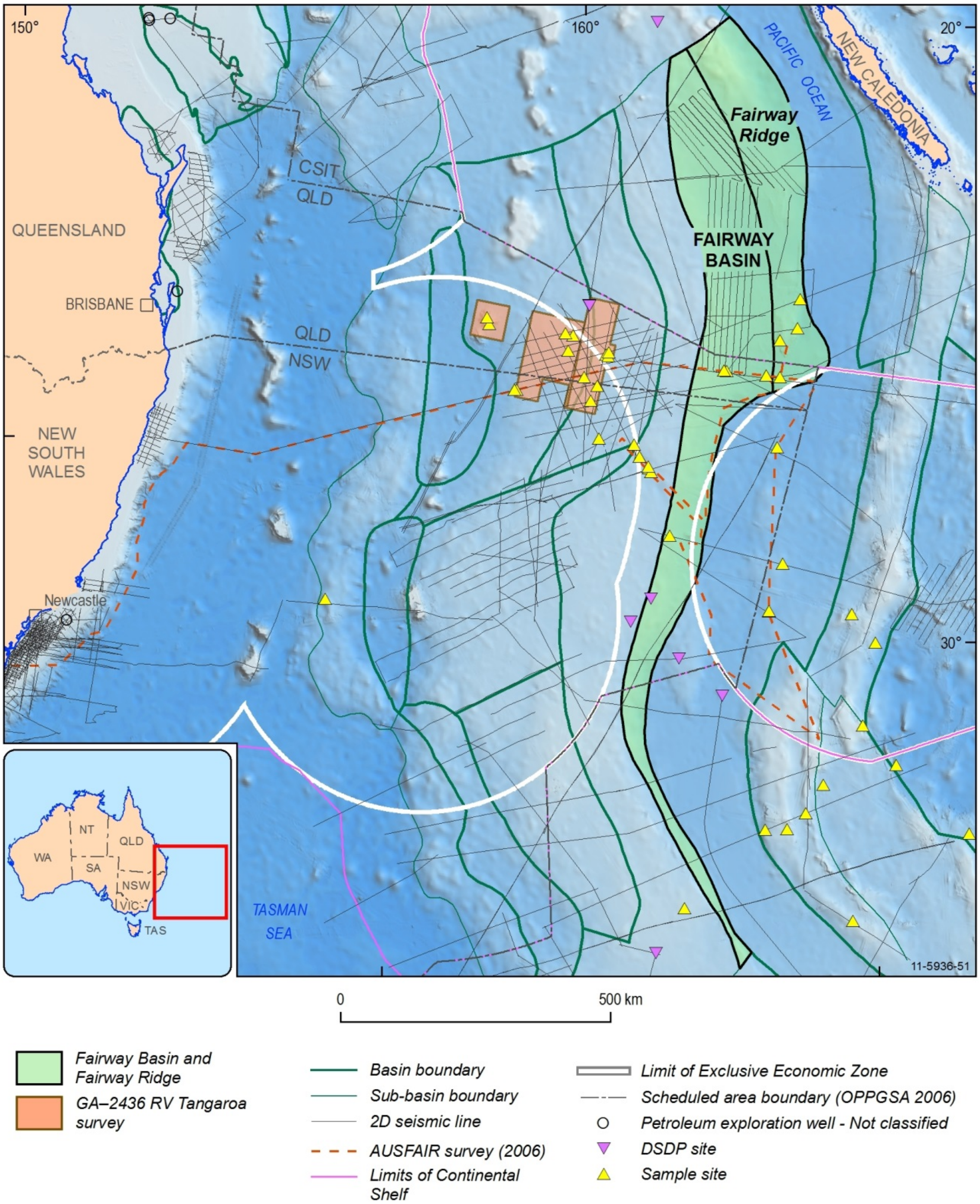

Figure 5.30: Seismic, well and sample distribution.

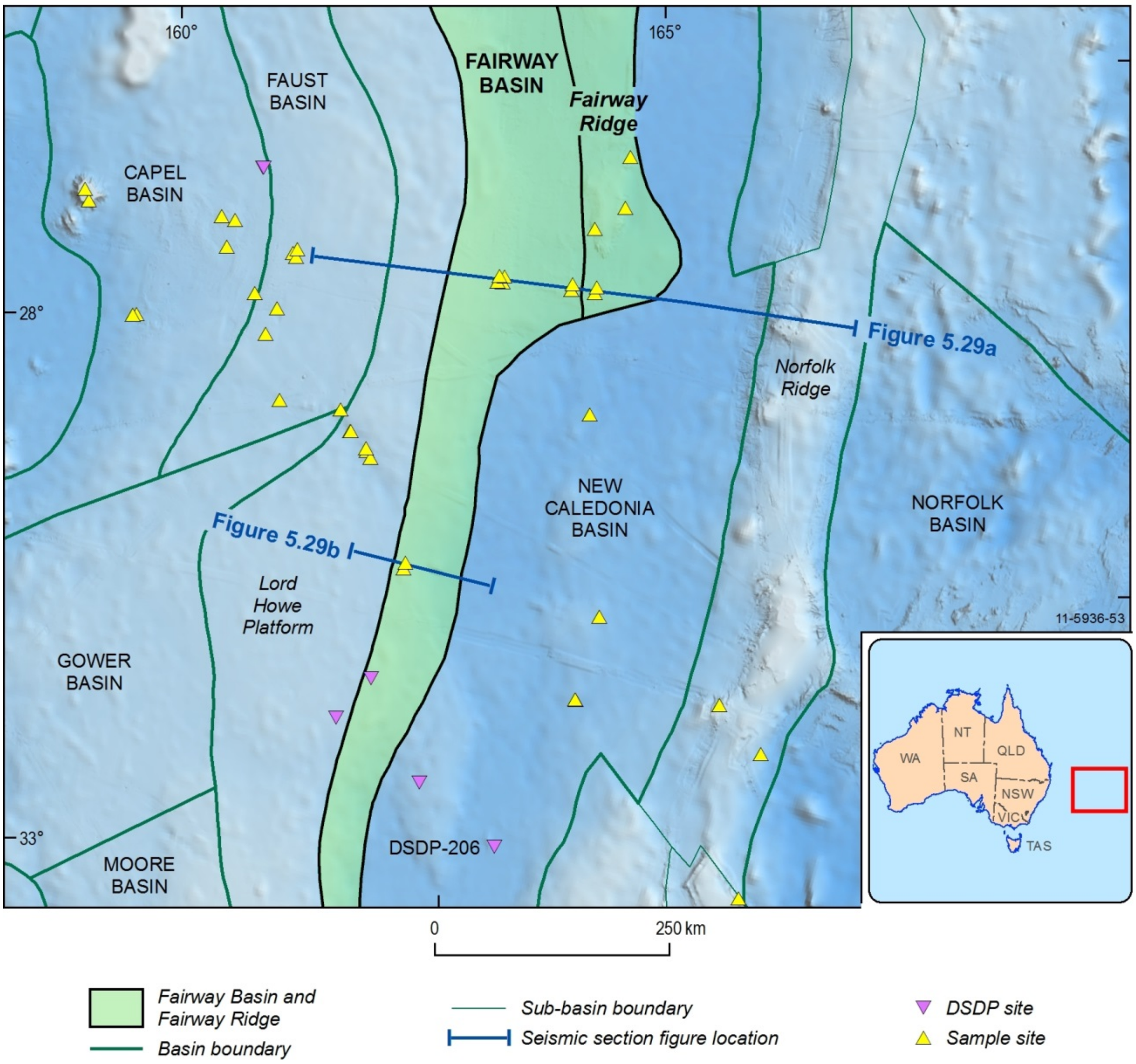

Figure 5.31: Location of seismic line and cross-section shown in Figure 5.29.

5.6.6 Issues and remaining questions

The comparatively high density of data coverage, in addition to ongoing scientific work being led by New Caledonia (France), has improved geological understanding in the northern Fairway Basin. However, a lack of direct evidence for the composition and age of the basin succession and basement, and particularly for the existence of source, reservoir, seal and active petroleum systems, remains a major obstacle to improving the understanding of the region's petroleum prospectivity and reducing exploration risk.

A key issue for future exploration activity in the Fairway Basin is the remoteness from existing infrastructure. Environmental sensitivities arising from proximity to the Coral Sea would also need to be considered. However, the northern Fairway Basin is well placed as a potential 'entry point' for the exploration of the vast frontier Lord Howe Rise region, given its relative proximity to the New Caledonia and the associated infrastructure.

5.6.6.1 Recommendations

Targeted stratigraphic drilling that is sufficiently deep to penetrate at least the syn-rift (and preferably deeper into the pre-rift) section is required. The density of existing reflection seismic data within the New Caledonian jurisdiction is sufficient to identify suitable areas for drilling, although further high-density 2D or 3D reflection data would be required to refine the identification of drilling targets.

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5.6.8 Data Tables

Table 5.25: List of wells located in or close to Fairway Basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1971	DSDP 208	Scientific	Deep Sea Drilling Project	594	Late Maastrichtian	Nil	The Shipboard Scientific Party, 1973
1982	DSDP 588	Scientific	Deep Sea Drilling Project	236.0	Middle Miocene	Nil	The Shipboard Scientific Party, 1986a
1982	DSDP 588A	Scientific	Deep Sea Drilling Project	344.4	Early Miocene	Nil	The Shipboard Scientific Party, 1986a
1982	DSDP 588B	Scientific	Deep Sea Drilling Project	277.4	Middle Miocene	Nil	The Shipboard Scientific Party, 1986a
1982	DSDP 588C	Scientific	Deep Sea Drilling Project	488.1	Middle Eocene	Nil	The Shipboard Scientific Party, 1986a
1982	DSDP 589	Scientific	Deep Sea Drilling Project	36.1	Latest Pliocene	Nil	The Shipboard Scientific Party, 1986b
1982	DSDP 590	Scientific	Deep Sea Drilling Project	26.2	Early Quaternary	Nil	The Shipboard Scientific Party, 1986c
1982	DSDP 590A	Scientific	Deep Sea Drilling Project	280.8	Middle Late Miocene	Nil	The Shipboard Scientific Party, 1986c
1982	DSDP 590B	Scientific	Deep Sea Drilling Project	499.1	Earliest Miocene	Nil	The Shipboard Scientific Party, 1986c

Table 5.26: Key 2D seismic surveys, Fairway Basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1971	MV *Petrel* Roving	Shell International	180	van de Beuque et al., 2003; Sutherland et al., 2012
1972	Mobil 1972	Mobil	650	Stagg et al., 2002; Sutherland et al., 2012
1972	AUSTRADEC 1	Comité d'Etudes Petrolières Marines (CEPM)	240	Brodien et al., 2003; Sutherland et al., 2012
1973	AUSTRADEC 2	Comité d'Etudes Petrolières Marines (CEPM)	430	Brodien et al., 2003; Sutherland et al., 2012
1981	WNC80	Elf	350	Brodien et al., 2003; Sutherland et al., 2012
1992	AGSO 114	Australian Geological Survey Organisation	50	Marshall et al., 1994
1996	AGSO 177	Australian Geological Survey Organisation	220	Ramsay et al., 1997
1998	FAUST 1/AGSO 206 (FAUST 1)	Ifremer, Australian Geological Survey Organisation	730	Bernardel et al., 1999
1999	ZoNéCo 5	Ifremer, Agence de developpement économique de la Nouvelle-Calédonie (ADECAL)	5400	Auzende et al., 2000a; Brodien et al., 2003; Sutherland et al., 2012

Year	Survey	Operator	Line-km/Area (km^2)	Reference
2001	FAUST 3/GA-232	Ifremer, Geoscience Australia	870	Exon et al., 2004a
2004	NOUCAPLAC 2	Ifremer	450	Sutherland et al., 2012

Table 5.27: Refraction seismic and velocity surveys covering the Fairway Basin and adjacent areas.

Year	Survey	Operator	Location	Reference
1967	Scripps Institution of Oceanography two-ship refraction seismic survey	Scripps Institution of Oceanography	23 profiles over Southwest Pacific	Shor et al., 1971
1971	DSDP 208 sonobuoy refraction survey	Deep Sea Drilling Project	Capel Basin	The Shipboard Scientific Party, 1973
2004	ZoNéCo 11 OBS survey	Ifremer, Agence de Développement Economique de la Nouvelle-Calédonie (ADECAL)	42 sites in French (New Caledonian) parts of Capel, Faust, Fairway and New Caledonia basins	Klingelhoefer et al., 2007
2006/2007	GA-302 sonobuoy refraction survey	Geoscience Australia	96 sites in Capel and Faust basins	Petkovic, 2010

Table 5.28: List of key surveys involving geological sampling relevant to the Fairway Basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
1985	RV *Sonne* 36	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)	Lord Howe Platform	Dredge	Pebbly conglomerate, sandstone, calcarenite	Röser & Shipboard Party, 1985
2001	FAUST 3/GA-232	Ifremer, Geoscience Australia	Fairway and New Caledonia basins, Fairway Ridge, Lord Howe Platform	Dredge, gravity core	Quaternary foraminiferal nannofossil ooze, foraminiferal sand, Miocene basalt, Eocene chalk/radiolarite,	Exon et al., 2004a
2006	AUSFAIR MD-153 (RV *Marion Dufresne*)	Geoscience Australia, Ifremer	Capel, Faust and New Caledonia basins, Lord Howe Platform, Fairway Ridge	Dredge, giant piston core	Trachyte, latite, quartz–feldspathic conglomerate and sandstone, some with molluscan fossils, calcareous ooze, ferromanganese nodules and crust	Colwell et al., 2006; Higgins et al., 2011
2007	GA-2436 RV *Tangaroa*	Geoscience Australia	Capel and Faust basins, Gifford Guyot	Dredge, piston and box cores, epibenthic sled, camera, CTD	Mafic volcanic rocks, pumice, ferromanganese nodules and crust, calcareous ooze and chalk	Heap et al., 2009; Dadd et al., 2011

Table 5.29: Swath bathymetry data sets relevant to the Fairway Basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
2001	Australian continental margin levelled gravity, magnetic and bathymetry	Geoscience Australia, Intrepid Geophysics		Petkovic et al., 2001
2009	Bathymetry and Topography Grid of Australia AUSBATH09 (2009)	Geoscience Australia		Whiteway, 2009

5.7 New Caledonia Basin

5.7.1 Summary

State(s)		Commonwealth waters; basin continues into French (New Caledonia) and New Zealand jurisdictions
Area (km^2)		150,760 (Australia); 665,600 (total)
Water Depth (m)		2000–4000
Maximum sediment thickness (m)		4000 (excludes pre-rift succession)
Age range		?Late Cretaceous–Cenozoic
Basin	**Overlies**	Possible equivalents of Teremba-Murihiku-Brook Street terranes, ?Cretaceous arc, Late Cretaceous–Early Eocene oceanic crust
	Adjacent basins	Northern and southern New Caledonia Basin, Fairway Ridge, Fairway Basin, Norfolk and West Norfolk ridges, Deepwater Taranaki Basin
Basin type		Extensional, sag
Depositional setting, rock types		Non-marine, deltaic, and marine clastic and bathyal biogenic sedimentary rocks, volcanic, intrusive and volcaniclastic rocks
Petroleum prospectivity		Low
Confidence		*Low*

5.7.2 Geology

The New Caledonia Basin is an elongated, 2000 km long, north to northwest-trending structural element located between the Fairway Basin and Fairway Ridge to the west and the New Caledonia–Norfolk Ridge–West Norfolk Ridge system to the east (Figure 5.32). Water depths range between 2000–4000 m in most parts and the basin covers an area of approximately 665,600 km^2 over Australian, French (New Caledonian) and New Zealand marine jurisdictions (Figure 5.1). This report addresses the central (Australian) portion of the New Caledonia Basin, which covers approximately 150,760 km^2.

The New Caledonia Basin contains a dominantly Upper Cretaceous to Cenozoic succession (Figure 5.33). In the southern, New Zealand, segment of the basin (Deepwater Taranaki Basin), a Middle Jurassic to Lower Cretaceous syn-rift succession is present (Baillie & Uruski, 2004; Uruski, 2008). Maximum sediment thickness varies from 4000 m in the central segment to 8000–9000 m in the northern and southern segments (Baillie & Uruski, 2004; Lafoy et al., 2005; Exon et al., 2007; Uruski, 2008; Collot et al., 2009).

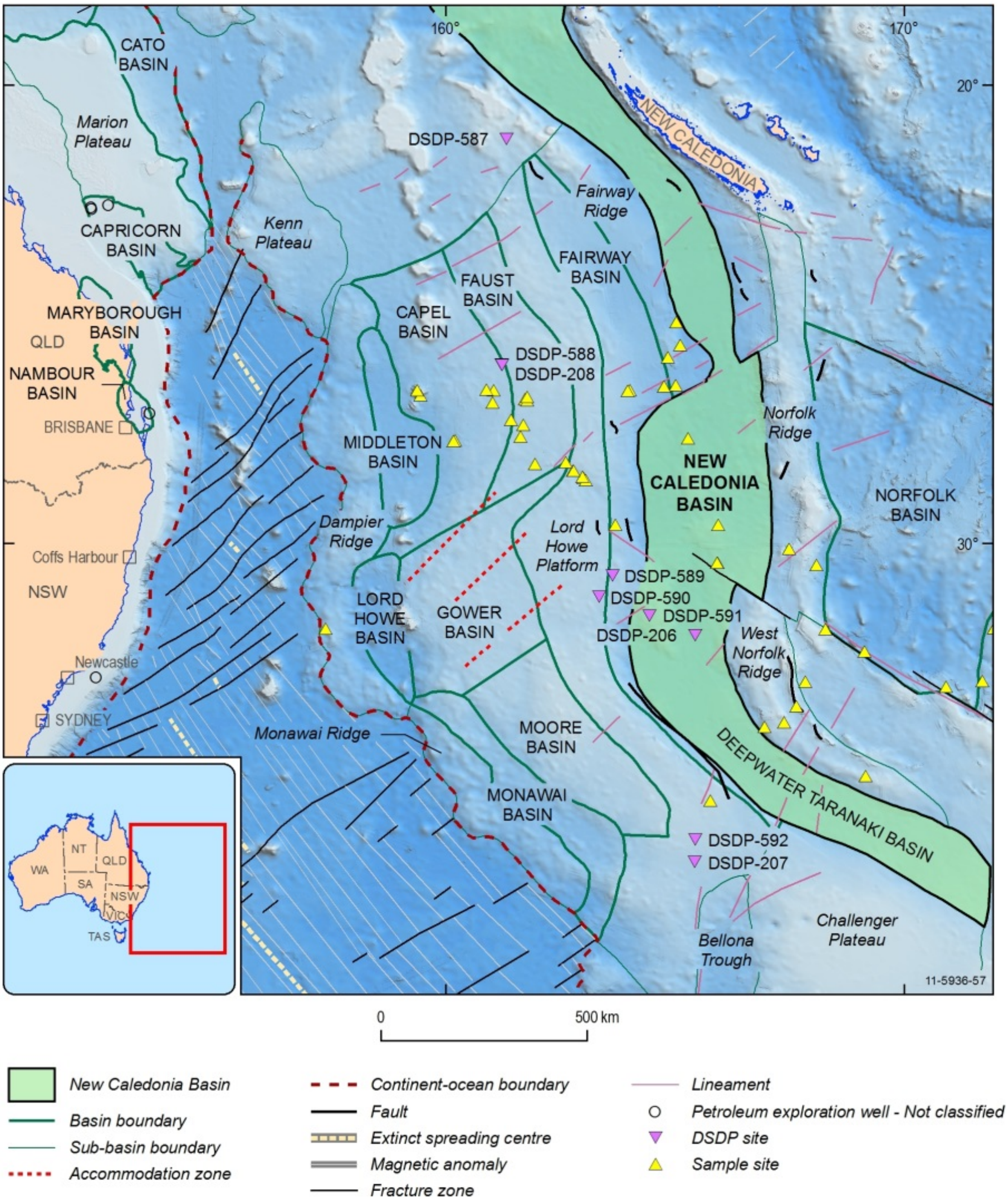


Figure 5.32: Structural elements map, New Caledonia Basin and surrounding regions (location of lineaments and faults east of the Lord Howe Platform based on Collot et al., 2009).

5.7.2.1 Structural geology

The New Caledonia Basin represents a major regional structural low (Figure 5.34a). The basin evolved during the Cretaceous breakup of eastern Gondwana that culminated with the opening of the Tasman Sea (85–52 Ma) and detachment of the Lord Howe Rise from eastern Australia (Hayes & Ringis, 1973; Gaina et al., 1998; Sdrolias et al., 2001). Rifting created multiple graben and half graben that have subsequently been buried by thick post-rift deposition (Figure 5.34b).

The New Caledonia Basin is subdivided into northern, central and southern (Deepwater Taranaki Basin) segments, based on the nature of the underlying crust. The northern segment lies within the French (New Caledonian) maritime jurisdiction and is characterised by a northwest structural trend. It is underlain by crust 10–14 km thick that may be of extended continental or atypical (possibly serpentinised upper mantle) origin (Shor et al., 1971; Lafoy et al., 2005; Klingelhoefer et al., 2007). The central segment is mostly within Australian jurisdiction and exhibits a rough north–south trend. A west-northwest-trending fault system immediately to the south of the island of New Caledonia marks the boundary between the northern and central segments (Lafoy et al., 2005; Collot et al., 2009). A southwest-trending extension of the Barcoo–Elizabeth–Fairway Lineament originating in the Tasman Sea dextrally offsets the central segment. The crust underlying the central segment is approximately 8–9 km thick and exhibits oceanic characteristics, implying that this part of the New Caledonia Basin has formed through seafloor spreading (Shor et al., 1971; Lafoy et al., 2005; Klingelhoefer et al., 2007). The southern segment has a northwest trend and lies mostly within the New Zealand jurisdiction. An extension of the Vening–Meinesz Fracture Zone, which sinistrally offsets the eastern flank of the Lord Howe Rise, delineates the boundary between the central and southern segments of the New Caledonia Basin. The crust beneath the basin is approximately 18 km thick and consistent with an extended continental origin (Zhu & Symonds, 1994).

5.7.2.2 Basin evolution and depositional history

Although there are no deep drilling data within the New Caledonia Basin, a number of petroleum exploration wells drilled in the offshore Taranaki and Northland basins provide ties to reflection seismic data and thus, stratigraphic control, in the southern segment of the New Caledonia (Deepwater Taranaki) Basin. However, a paucity of reflection seismic coverage, in combination with reflector discontinuities across structural highs, means that the stratigraphy of the central and northern segments of the New Caledonia Basin can only be inferred from seismic character and stratigraphic comparisons with the southern segment, geophysical data sets such as gravity and magnetic anomalies, and tectonic reconstructions.

During the Paleozoic to the Early Cretaceous, the area presently occupied by the Fairway and New Caledonia basins and the eastern Lord Howe Rise was part of the eastern Gondwana margin located inboard of the convergent boundary with the Pacific Plate. It is likely that this area was in a forearc position relative to the magmatic arc for much of this time (Mortimer et al., 2008), until the arc migrated over the area during the Early Cretaceous (Collot et al., 2009). The regionally pervasive curvilinear trend of the eastern flanks of the Lord Howe Rise and the New Caledonia Basin probably reflects the trend of the magmatic arc (Collot et al., 2009). Given this pre-rift history, the basement to the New Caledonia Basin may include the rocks equivalent to the Permian–Jurassic Teremba Terrane in New Caledonia and their New Zealand correlatives, the Murihiku and Brook Street terranes (Norvick et al., 2008; Collot et al., 2009). At Waka Nui 1 in the Northland Basin to the southeast of the New Caledonia Basin, Middle Jurassic coal measures of the Murihiku Supergroup were encountered at the bottom of the well (Milne & Quick, 1999). These rocks appear to correlate with the earliest deposits within graben and half graben in the southern segment of the New Caledonia Basin, indicating that rifting was initiated in the Middle Jurassic (Baillie & Uruski, 2004; Uruski, 2008).

During the Early Cretaceous widespread extension and magmatism affected the backarc area of the eastern Gondwana margin, including parts of eastern Australia and the Lord Howe Rise (Bryan et al., 1997; Norvick et al., 2001, 2008). In the southern New Caledonia Basin, the Jurassic rift depocentres continued to develop, accumulating a Middle Jurassic to Lower Cretaceous non-marine syn-rift succession (Baillie & Uruski, 2004; Uruski, 2008; Uruski et al., 2008). By the end of Early Cretaceous, the area experienced initial marine transgression, as the Taranaki Delta developed at the head of the southern New Caledonia Basin (Baillie & Uruski, 2004; Uruski, 2008). In the northern and central New Caledonia Basin, there is insufficient evidence to support widespread Early Cretaceous syn-rift deposition, possibly because of the area's proximity to the eastern Gondwanan subduction arc.

A change in the regional plate dynamics is believed to have resulted in roll-back and eventual cessation of subduction along the eastern Gondwana–Pacific margin around the Cenomanian (Norvick et al., 2001, 2008; Willcox et al., 2001; Schellart et al., 2006; Collot et al., 2009; Waschbusch et al., 2009; Rey & Müller, 2010). Rifting along the axis of the Early Cretaceous subduction arc (Collot et al., 2009) resulted in the widespread formation of extensional depocentres in the Fairway, New Caledonia, Reinga, Northland and Taranaki basins during the Late Cretaceous (King & Thrasher, 1996; Baillie & Uruski, 2004; Lafoy et al., 2005; Exon et al., 2007; Uruski, 2008; Collot et al., 2009; Stagpoole et al., 2009). Associated syn-rift deposition was probably dominated by non-marine to marine siliciclastics and laterally confined by the fault-bounded margins of individual depocentres in the northern and central segments of the New Caledonia Basin (van de Beuque et al., 2003; Exon et al., 2004; Collot et al., 2012). Progradation of small coastal plain and shelf wedges locally fed by the erosion of structural highs has been interpreted in seismic reflection profiles (Collot et al. 2012; Rouillard et al., 2012). Late Cretaceous deposition in the southern New Caledonia Basin was dominated by laterally extensive deltaic and distal marine facies, and extensive coal measures (Baillie & Uruski, 2004; Uruski, 2008; Collot et al., 2009; Stagpoole et al., 2009; Sutherland et al., 2010).

Thermal subsidence from the late Campanian onward resulted in a marine transgression across most of the New Caledonia Basin that blanketed the earlier syn-rift sediments. Deposition during this time occurred under generally deepening conditions with a diminishing clastic sediment supply (Uruski, 2008). In the southern New Caledonia Basin, deposition was characterised by progressively deeper marine conditions and by the Eocene–Oligocene, carbonate deposition had become significant (Baillie & Uruski, 2004; Uruski, 2008; Uruski et al., 2008).

A similar progression in facies is inferred for much of the central and northern New Caledonia Basin, although the onset of carbonate deposition was probably earlier due to the smaller siliciclastic sediment supply. In the central segment, oceanic crust was emplaced during the Paleocene (Lafoy et al., 2005), presumably associated with deep marine deposition.

During the Eocene–Oligocene, the region experienced compression that culminated with the obduction event in New Caledonia (Aitchison et al., 1995). Tectonism during this time is related to an overall reorganisation of the Pacific Plate boundaries and dynamics (Müller et al., 2000; Veevers, 2000; Sdrolias et al., 2001; Crawford et al., 2003). There was widespread uplift in the New Caledonia Basin and the Lord Howe Rise region, resulting in the subaerial erosion of structural highs, reversal of syn-rift faults, and gentle folding of the basin sediments (Collot et al., 2008, 2012; Uruski, 2008). Overthrusting of the allochthon in onshore New Caledonia caused flexural subsidence in the northern New Caledonia Basin around the late Eocene, while uplift continued on the flanking structural highs, feeding sediment to turbidite channels and fans in the nearby depocentres (Collot et al., 2008, 2012; Rouillard et al., 2012). The New Caledonia Basin and the Lord Howe Rise region experienced up to 2000 m of rapid subsidence after the Eocene accompanied by a regional marine transgression and widespread bathyal deposition (King & Thrasher, 1996; Collot et al., 2008, 2012; Uruski, 2010; Rouillard et al., 2012; Sutherland et al., 2010). The rapid subsidence was focused along the axis of the New Caledonia Basin and resulted in onlap of the Eocene–Oligocene unconformity by flat-lying Oligocene–Recent strata. This succession is thick in the northern New Caledonia Basin due to the eastward flexural tilting related to obduction (Collot et al., 2008; Sutherland et al., 2010). Cenozoic magmatism has resulted in isolated flows, intrusions and build-ups mainly near the margins of the New Caledonia Basin (Exon et al., 2004; Stagpoole et al., 2009). Although many of these are of intraplate nature, numerous subduction-related volcanic features exist along the northeastern margin of the southern New Caledonia Basin, attributed to Miocene plate convergence along the Northland Peninsula (Stagpoole et al., 2009).

5.7.2.3 Level of knowledge

Most of the New Caledonia Basin is a remote and under-explored deepwater frontier basin with a sparse coverage of regional 2D seismic reflection, gravity, magnetic and bathymetry data (Figure 5.35). In the southern segment of the basin, stratigraphic control is provided by ties of reflection seismic data to exploration wells in the shallow-water Taranaki and Northland basins and DSDP 206 site (Figure 5.36). In the central and northern segments, however, interpretations are based largely on inferences from seismic character, regional tectonic reconstructions and basin analogues, as the existing data coverage does not permit a reliable direct correlation with the southern segment. A few recent marine surveys over the northern and central segments have led to an increase in geological knowledge of these areas. Geoscience Australia survey GA 232 filled a gap in regional seismic data coverage over the central segment, and recovered rock and core samples that provide information on the magmatic and depositional history. The French–New Caledonian ZoNéCo 11 survey acquired deep reflection and refraction seismic data to image crustal structure. The Australian–French AUSFAIR–ZoNéCo 12 survey acquired shallow core samples to test for the occurrence of gas hydrates in the sub-bottom sediments and to measure heat flow.

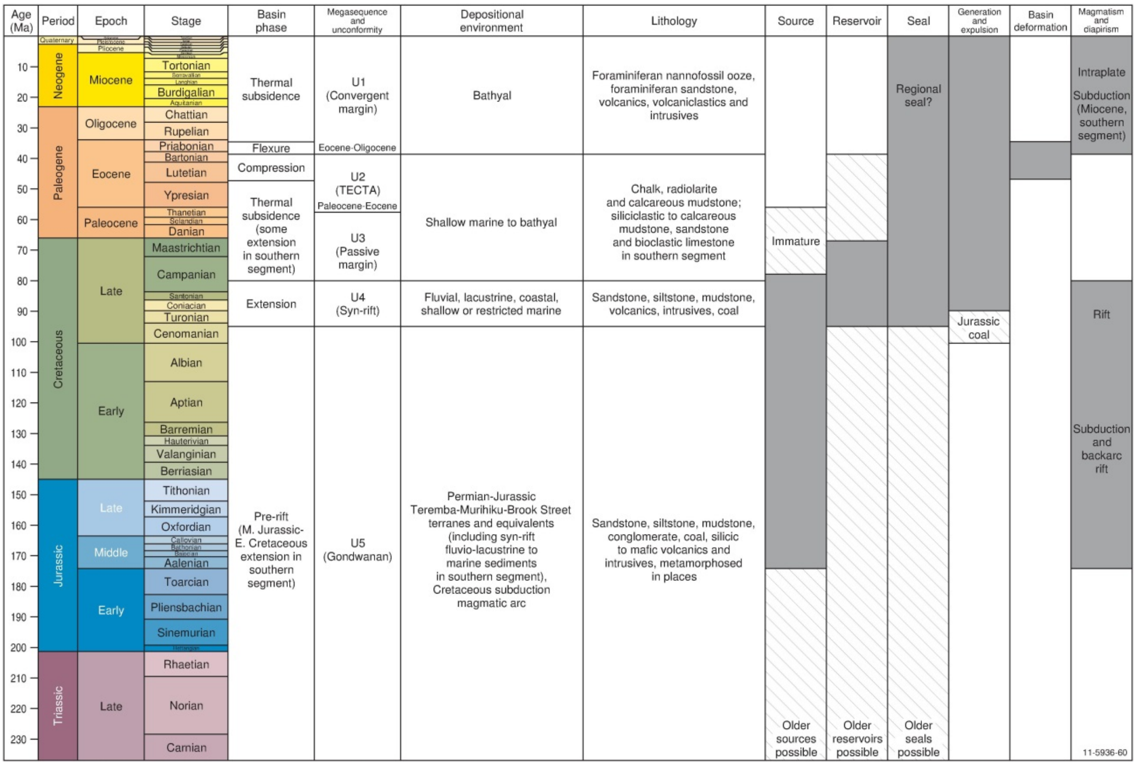
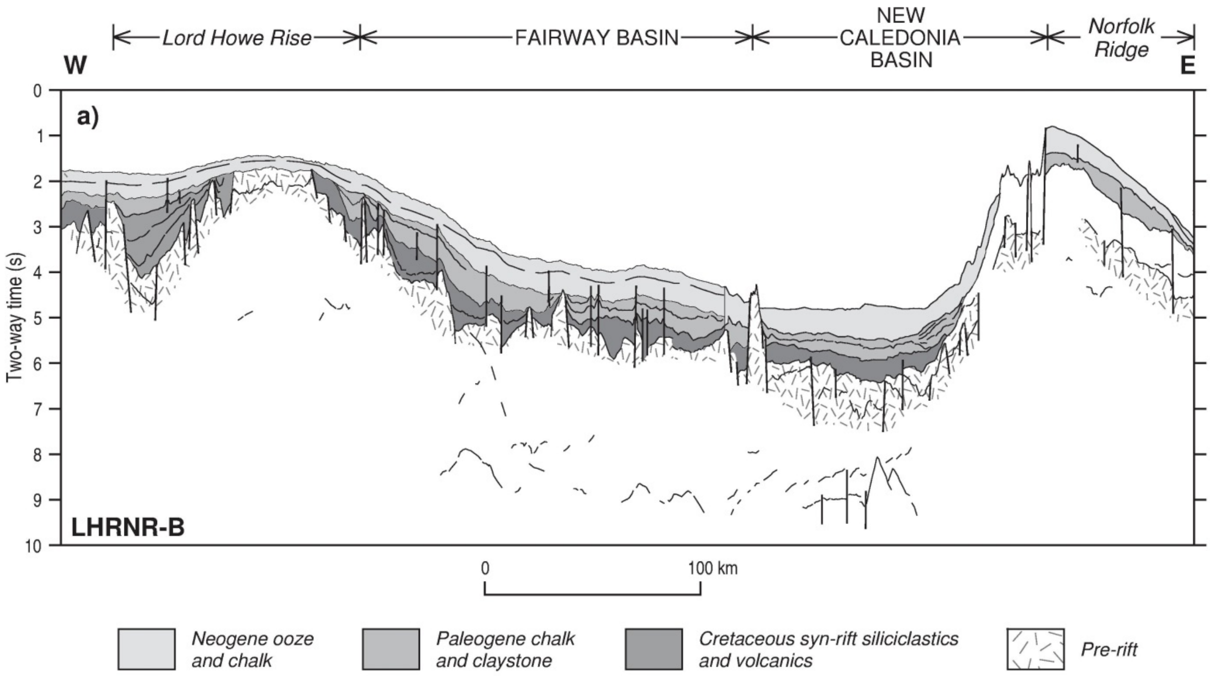


Figure 5.33: Stratigraphy of the New Caledonia Basin based on Exon et al. (2004), Lafoy et al. (2005), Collot et al. (2008, 2009), Norvick et al. (2008), Uruski (2008, 2010) and Uruski & Warburton (2010). Megasequence nomenclature after Collot et al. (2012) and predicted petroleum generation and expulsion after Vially et al. (2003), Stagpoole et al. (2007) and Uruski & Warburton (2010).



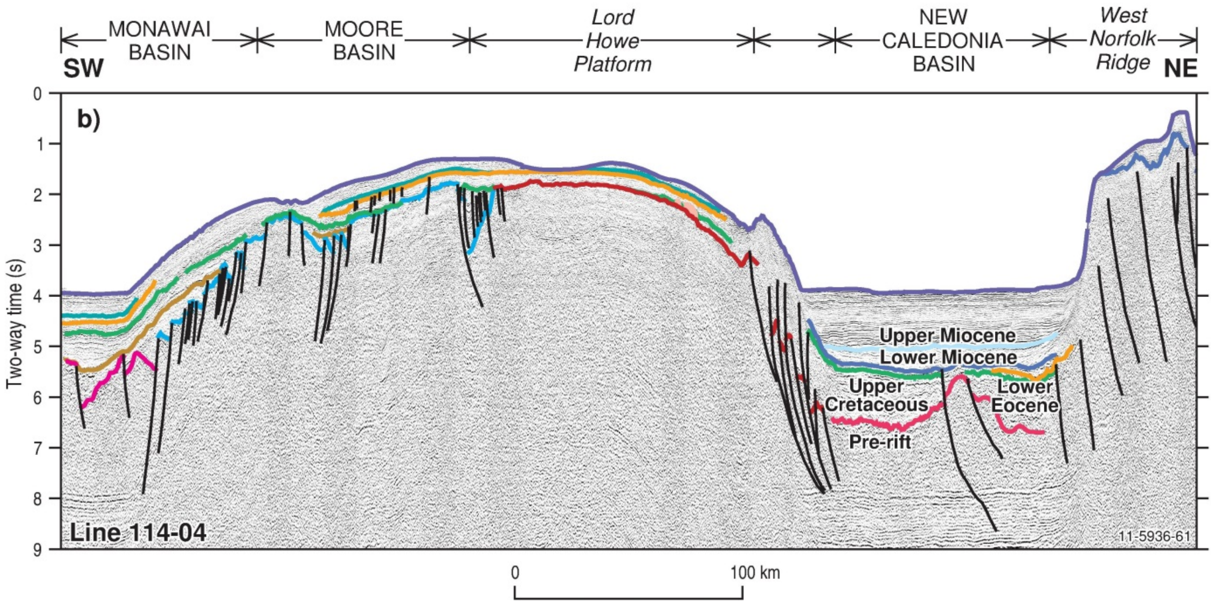


Figure 5.34: a) Geological cross-section of the northern Fairway and New Caledonia basins along regional seismic reflection line AGSO 177 LHRNR-B (after Exon et al., 2004); b) Details of seismic reflection line AGSO 114-04 showing structural and stratigraphic relationships (after Stagg et al., 2002).

5.7.3 Petroleum systems

No known petroleum systems occur in the central New Caledonia Basin. However, the presence of potential petroleum system elements has been confirmed in the southern segment of the basin, via direct seismic correlation with the shallow-water areas of the Taranaki Basin where petroleum production is well established.

5.7.3.1 Source rocks

Based on regional correlations, it is possible that potential source rocks are present within the Late Cretaceous succession in the central part of the basin (Figure 5.33). Seismic reflection data indicate widespread presence of coal-rich rocks in the New Caledonia, Deepwater Taranaki and Reinga basins and over the West Norfolk Ridge that correlate with the Upper Cretaceous Rakopi Formation, the principal source of oil in the shallow-water Taranaki Basin (Uruski, 2008, 2010). Cenomanian coal measures have been sampled from the West Norfolk Ridge (Herzer et al., 1997, 1999) and Upper Cretaceous coal is also known from onshore New Caledonia (Paris & Lille, 1977; Paris, 1981). Deposition within fault-bounded depocentres may also have resulted in restricted marine potential source rocks within the Upper Cretaceous syn-rift succession (Exon et al., 2007; Uruski, 2008; Uruski & Warburton, 2010).

5.7.3.2 Generation and expulsion

The thin sedimentary succession present in the central New Caledonia Basin makes generation and expulsion problematic in this part of the New Caledonia Basin (Vially et al., 2003). This contrasts with the northern and southern segments of the New Caledonia Basin where sediment thickness is generally sufficient for oil and gas generation, if viable source rocks are present (Vially et al., 2003; Stagpoole et al., 2007). Basin modelling indicates that in the southern part of the basin, Upper Cretaceous (and older) coaly source rocks would be capable of generation and expulsion from the Late Cretaceous to the present, although burial if any post-Cretaceous source rocks would generally be too shallow for significant generation in most areas (Vially et al., 2003; Stagpoole et al., 2007; Uruski & Warburton, 2010).

5.7.3.3 Reservoirs

Potential reservoir formations within the New Caledonia Basin include Cretaceous to Paleogene fluvial, deltaic and marine sandstones deposited during the transition from syn-rift to post-rift phases (Figure 5.33).

5.7.3.4 Seals

Regional seal may be provided by the extensive and thick Oligocene–Recent chalk and ooze, although seal integrity may be compromised in places by fluid migration, small-scale faulting and magmatism (Figure 5.33).

5.7.3.5 Play types

Likely play types in the New Caledonia Basin include horsts, tilted fault blocks and associated drapes within the Cretaceous–Paleogene section, and anticlines associated with the Eocene–Oligocene tectonism. Stratigraphic traps may be present in coastal plain, shelf wedge, and turbidite systems.

5.7.3.6 Critical risks

The presence of viable source, reservoir and seal facies are key uncertainties in this area. Direct correlation of seismic reflection data indicates that the southern part of the basin is likely to host petroleum system elements equivalent to those within the adjacent producing Taranaki Basin. The similarity of seismic stratigraphy and character also suggests that these petroleum system elements are distributed in the more northerly parts of the basin. The difficulty in extending those correlations to the central segment of the basin suggests that this region may be less prospective. Ongoing work by led by the New Caledonian Government and GNS Science may lead to an improvement in our understanding of the geology and petroleum prospectivity of the basin through analysis of existing data and further data acquisition surveys.

5.7.3.7 Overall prospectivity classification

Low

5.7.4 Exploration status

The New Caledonia Basin is an exploration frontier. Most of the basin has only experienced reconnaissance exploration by industry that resulted in several regional seismic surveys, e.g. surveys by Shell International, Mobil, Australian Gulf Oil Corporation and Elf, and the AUSTRADEC I and II. Data coverage over the basin has improved since the 1990s through a series of marine data acquisition surveys funded by the governments of France, New Caledonia, Australia and New Zealand. Programmes such as the ZoNéCo, NOUCAPLAC, FAUST and several Australian–New Zealand collaborative surveys were aimed at assessing offshore natural resources, and supporting maritime territorial claims under the United Nations Convention on the Law of the Sea (UNCLOS). During the 2000s, the Australian and New Zealand governments have funded initiatives to attract petroleum exploration activity to frontier basins within the region, resulting in further data acquisition in the areas surrounding the New Caledonia Basin, e.g. the Geoscience Australia GA 302 Capel-Faust Basins seismic reflection survey, and Crown Minerals REI09 Reinga Basin seismic reflection survey. Currently petroleum exploration activity is restricted to the southernmost part of the basin—the Deepwater Taranaki Basin in New Zealand waters.

5.7.5 Data

Data coverage over the Australian portion of the New Caledonia Basin is sparse. Key data sets for region are listed in Table 5.30–Table 5.31 and their locations shown in Figure 5.35 and Figure 5.36. Stratigraphic control for the Cenozoic succession is provided by the DSDP 206 site in the northernmost part of the southern New Caledonia Basin (The Shipboard Scientific Party, 1973). Long regional seismic ties to exploration wells in the shallow-water Taranaki and Northland basins provide stratigraphic control for the Mesozoic section (Milne & Quick, 1999). DSDP sites 589 to 591, located northwest of DSDP 206, provide information on the Miocene–Holocene section only (The Shipboard Scientific Party, 1986a, b, c).

The seismic reflection data coverage over most of the New Caledonia Basin comprises sparse regional 2D lines of variable quality. Data from pre-1990 surveys are generally of poor to moderate quality. Good quality data sets in the northern and central segments are derived from the FAUST and ZoNéCo surveys. In particular, the FAUST 3/GA 232 survey acquired a total of 2795 line-km of 24-channel seismic reflection data, of which approximately 1400 km are over the central New Caledonia Basin (Exon et al., 2004). The ZoNéCo 11 survey acquired approximately 1100 line-km of data over the northern New Caledonia Basin, together with seismic refraction data. In addition, parts of the NOUCAPLAC 2 and AGSO 177 surveys traverse the area. The key seismic reflection data sets over the main part of the southern New Caledonia Basin are the AGSO 114 and AGSO 177 surveys. The line TL-01 within the AGSO 177 survey, which follows the axis of the southern New Caledonia Basin, is regionally significant as it provides direct ties with exploration wells in the shallow-water Taranaki and Northland basins and with the DSDP 206 drill hole.

Seismic velocity data of relevance to the northern and central New Caledonia Basin include a two-ship seismic refraction survey of the southwest Pacific, with two transects across the Fairway and New Caledonia basins (Shor et al., 1971), and the ocean-bottom seismometer (OBS) survey along two transects during the ZoNéCo 11 survey (Klingelhoefer et al., 2007). In the southern segment, velocity data were collected during the 1972 Mobil survey in the southern New Caledonia Basin and the nearby Lord Howe Rise and Challenger Plateau, and along the line TL-01 during acquisition of the AGSO 177 survey.

Potential field and bathymetry data coverage over the New Caledonia Basin includes regional compilations derived from satellite, airborne and marine data (Sandwell & Smith, 1997; Andersen et al., 2010; Maus et al., 2007, 2009; Whiteway, 2009). In addition, shipboard gravity, magnetic and bathymetry data were acquired during the ZoNéCo, AGSO/GA, FAUST and NOUCAPLAC surveys.

Heat flow has been calculated from measurements at the DSDP 206 site in the southern New Caledonia Basin (von Herzen, 1973), and for five sites from the French–Australian MD-153 AUSFAIR–ZoNéCo 12 survey over the Fairway Basin and Ridge adjacent to the northern New Caledonia Basin (Colwell et al., 2006; Harmegnies & Foucher, 2006). The results indicate a range of values between 48 and 75 mW/m^2, suggesting normal to above average heat flow for a rifted margin setting. Geological sampling carried out to date within the New Caledonia Basin has mostly recovered Neogene sediments. Conglomerate, sandstone, and alkali intermediate–acid volcanic rocks recovered from the central New Caledonia Basin during the MD-153 AUSFAIR–ZoNéCo 12 survey (Colwell et al., 2006) are the only rocks sampled from the basin. Alkali volcanic rocks were also recovered during the survey from the nearby Lord Howe Platform (Colwell et al., 2006) and have been dated at 96.9 +/- 0.7 Ma (Cenomanian) and 74.1 +/- 0.7 Ma (Campanian; Higgins et al., 2011). The Lord Howe Platform rocks are similar to clasts within the conglomerate sample from the central New Caledonia Basin, which also contains mollusc fossils. Assuming that the clasts are of similar age to the dated volcanic rocks, the samples in combination provide a constraint on the timing of initial marine deposition in the region. On the flanks of the southern New Caledonia Basin, Upper Cretaceous coal measures and carbonaceous mudstone were dredged from the West Norfolk Ridge (Launay et al., 1977; Herzer et al., 1997, 1999). In addition, several Paleogene–Neogene sedimentary and volcanic rocks have been recovered from the seafloor in the areas flanking the central and southern New Caledonia Basin. A complete list of sampling surveys is provided in Table 5.33.

5.7.5.1 Confidence rating

Low

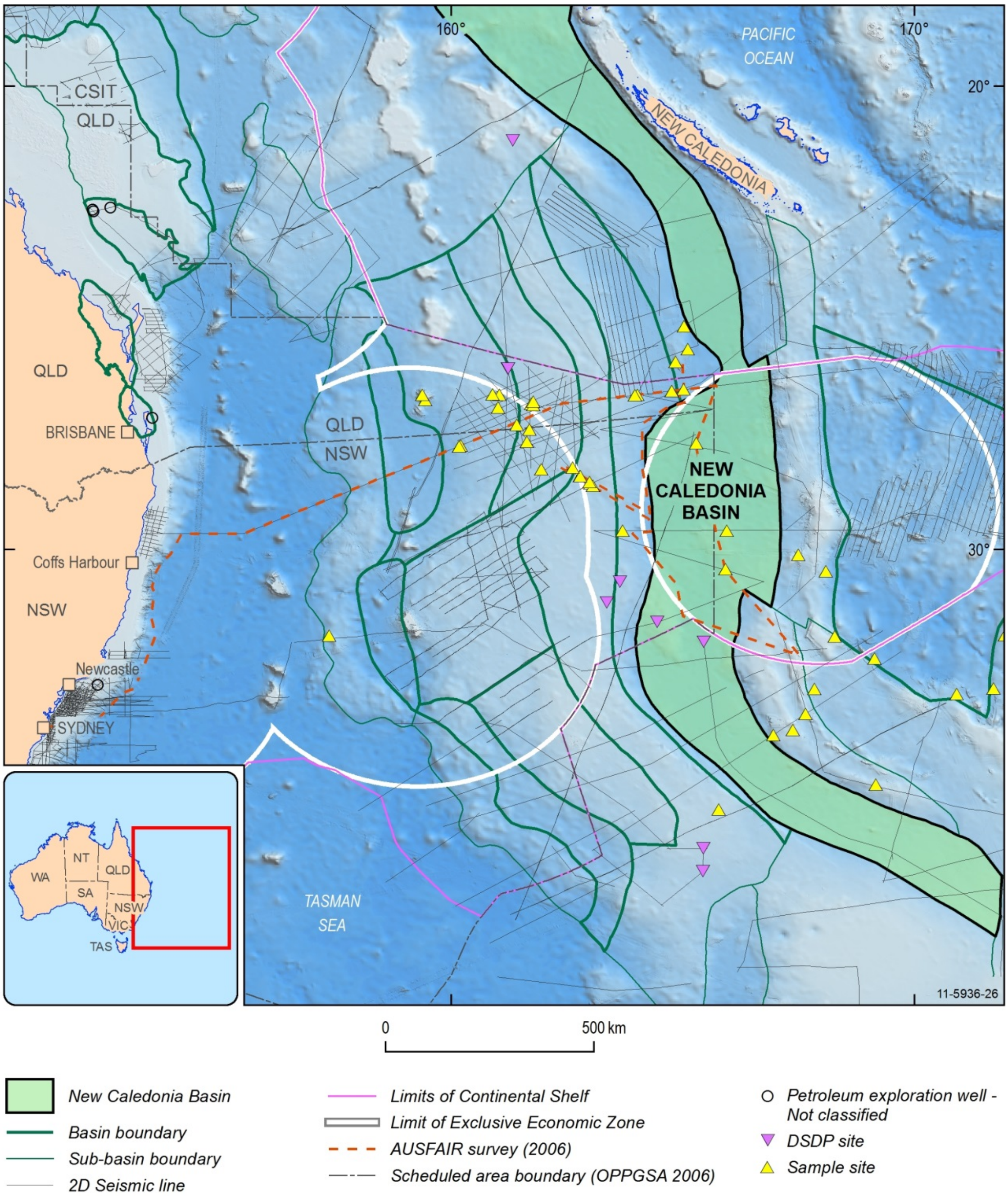


Figure 5.35: Seismic, well and sample distribution.

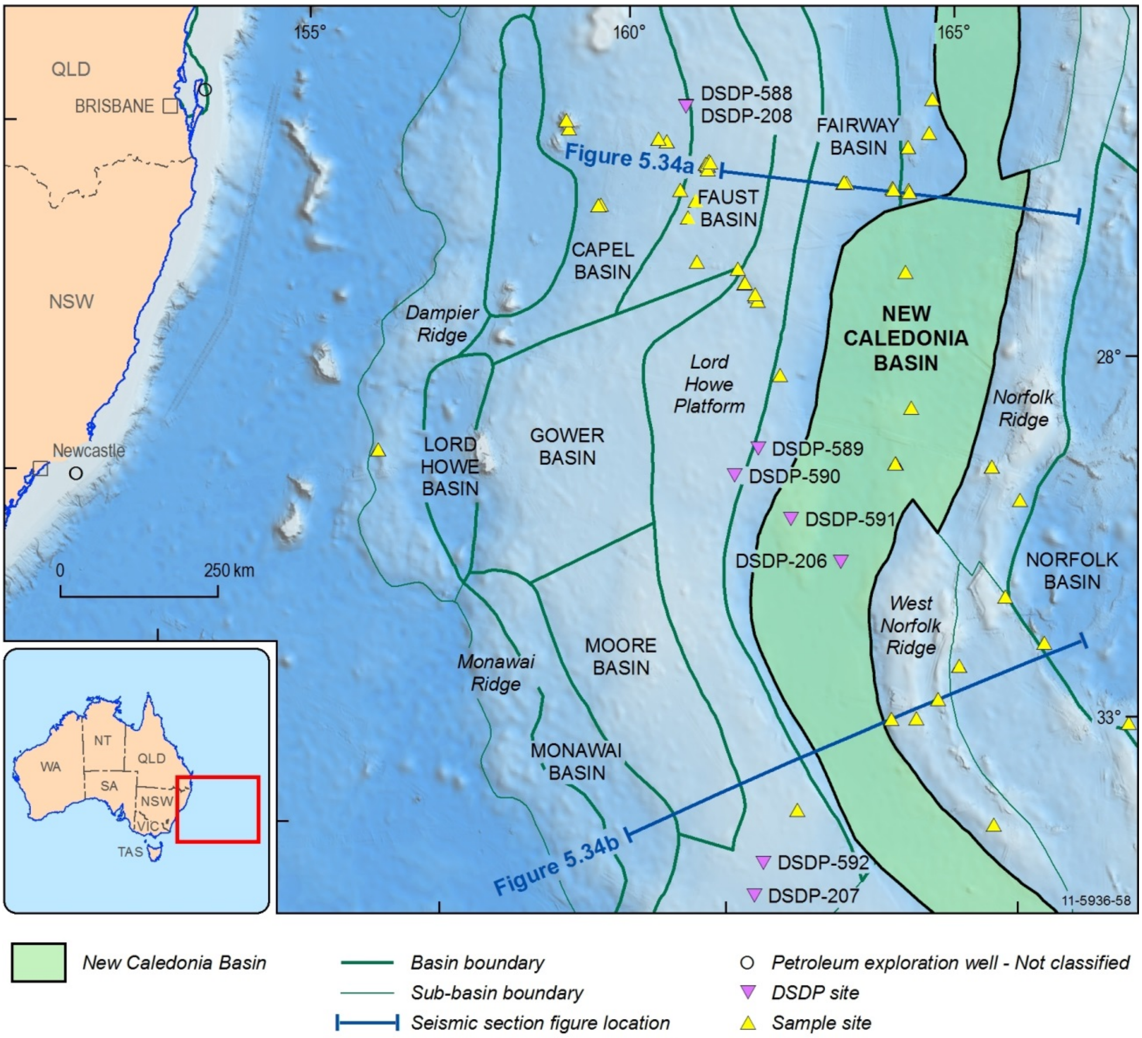


Figure 5.36: Location of DSDP holes and seismic lines shown in Figure 5.34.

5.7.6 Issues and remaining questions

Although proximity to the intensively explored shallow-water Taranaki Basin has contributed to a relatively advanced understanding of the geology and petroleum prospectivity of the southern New Caledonia Basin, most of the New Caledonia Basin remains a deepwater frontier with very sparse data coverage. The lack of data on the composition and age of the basin succession and basement, or evidence for the existence of source, reservoir, seal and active petroleum systems, remain major obstacles to improving the understanding of the petroleum prospectivity in the central and northern New Caledonia Basin. There, seismic imaging remains insufficient to determine with confidence whether pre-Upper Cretaceous syn-rift successions are present.

At an even more fundamental level, the tectonic mechanisms that led to the formation of the New Caledonia Basin remain enigmatic, especially in light of the anomalously rapid post-Eocene subsidence. Work on this subject by GNS Science, the New Caledonian Government, and other research organisations is in progress.

Further challenges to exploration in the Australian portion of the New Caledonia Basin are posed by the remoteness from existing petroleum production infrastructure and the considerable water depth (commonly over 3000 m). Recent exploration activity in the southernmost New Caledonia Basin demonstrates that the industry perception of that part of the basin's prospectivity is favourable. However, given the present understanding of the basin architecture, the areas of highest prospectivity are likely to lie mostly outside the Australian maritime jurisdiction.

5.7.6.1 Recommendations

Stratigraphic drilling that is sufficiently deep to penetrate at least the syn-rift (and preferably deeper into the pre-rift) section would address the lack of knowledge of the central New Caledonia Basin succession. High-density 2D or 3D reflection seismic surveys would be necessary to provide a better understanding of the distribution, size, stratigraphy and structure of depocentres and to identify potential drilling targets.

5.7.7 References

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5.7.8 Data Tables

Table 5.30: List of wells located in or close to central New Caledonia Basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
1971	DSDP 206	Scientific	Deep Sea Drilling Project	734	Middle Paleocene	Nil	The Shipboard Scientific Party, 1973
1982	DSDP 589	Scientific	Deep Sea Drilling Project	36.1	Latest Pliocene	Nil	The Shipboard Scientific Party, 1986a
1982	DSDP 590	Scientific	Deep Sea Drilling Project	26.2	Early Quaternary	Nil	The Shipboard Scientific Party, 1986b
1982	DSDP 590A	Scientific	Deep Sea Drilling Project	280.8	Middle Late Miocene	Nil	The Shipboard Scientific Party, 1986b
1982	DSDP 590B	Scientific	Deep Sea Drilling Project	499.1	Earliest Miocene	Nil	The Shipboard Scientific Party, 1986b
1982	DSDP 591	Scientific	Deep Sea Drilling Project	283.1	Early Late Miocene	Nil	The Shipboard Scientific Party, 1986c
1982	DSDP 591A	Scientific	Deep Sea Drilling Project	284.6	Early Late Miocene	Nil	The Shipboard Scientific Party, 1986c
1982	DSDP 591B	Scientific	Deep Sea Drilling Project	500.4	Latest Early Miocene	Nil	The Shipboard Scientific Party, 1986c

Table 5.31: Key 2D seismic surveys relevant to the central New Caledonia Basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1971	MV Petrel Roving	Shell International	320	van de Beuque et al., 2003; Sutherland et al., 2012
1972	Mobil 1972	Mobil	1460	Stagg et al., 2002; Sutherland et al., 2012
1972	Gulfrex	Australian Gulf Oil Corporation	390	Brodien et al., 2003; Sutherland et al., 2012
1972	AUSTRADEC 1	Comité d’Etudes Petrolières Marines (CEPM)	850	Brodien et al., 2003; Sutherland et al., 2012
1973	AUSTRADEC 2	Comité d’Etudes Petrolières Marines (CEPM)	890	Brodien et al., 2003; Sutherland et al., 2012
1981	WNC80	Elf	20	Brodien et al., 2003; Sutherland et al., 2012
1989	CH89	Department of Scientific and Industrial Research (New Zealand)	820	Wood, 1991
1992	AGSO 114	Australian Geological Survey Organisation	270	Marshall et al., 1994
1994	AGSO 125 *Tasmante*	Australian Geological Survey Organisation	145	Exon et al., 1994

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1996	AGSO 177	Australian Geological Survey Organisation	1220	Ramsay et al., 1997
1998	FAUST 1/AGSO 206 (FAUST 1)	Ifremer, Australian Geological Survey Organisation	550	Bernardel et al., 1999
2001	DTB01 *Astrolabe*	TGS-NOPEC, GNS Science	520	TGS-NOPEC, 2001
2001	FAUST 3/GA-232	Ifremer, Geoscience Australia	1400	Exon et al., 2004
2004	ZoNéCo 11	Ifremer, Agence de developpement économique de la Nouvelle-Calédonie	1080	Lafoy et al., 2004; Klingelhoefer et al., 2007
2004	NOUCAPLAC 2	Ifremer	220	Sutherland et al., 2012
2009	REI09	Crown Minerals, CGG-Veritas	75 (public data)	Stagpoole et al., 2009

Table 5.32: Refraction seismic and velocity surveys covering the central New Caledonia Basin and adjacent areas.

Year	Survey	Operator	Location	Reference
1967	Scripps Institution of Oceanography two-ship refraction seismic survey	Scripps Institution of Oceanography	23 profiles over Southwest Pacific	Shor et al., 1971
1972	Mobil 1972	Mobil	Three stations in southern New Caledonia Basin, one station in the Moore Basin, four stations without positioning data	Bentz, 1974; Stagg et al., 2002
1996	AGSO 177	Australian Geological Survey Organisation	Southern New Caledonia Basin along line TL-01	Ramsay et al., 1997
2004	ZoNéCo 11 OBS survey	Ifremer, Agence de Développement Economique de la Nouvelle Calédonie (ADECAL)	42 sites in French (New Caledonian) parts of Capel, Faust, Fairway and New Caledonia basins	Klingelhoefer et al., 2007

Table 5.33: List of key surveys involving geological sampling relevant to the central New Caledonia Basin.

Year	Survey	Operator	Region	Type	Rock types	Reference
1975	GEORSTOM III Sud	Office de la recherche scientifique et technique outre-mer (ORSTOM)	Norfolk Ridge, Reinga Basin and Lord Howe Platform	Dredge	Mudstone, limestone, organic shale, basalt, gabbro, hyaloclastic breccia	Launay et al., 1977; Herzer et al., 1997, 1999

Year	Survey	Operator	Region	Type	Rock types	Reference
1985	RV *Sonne* 36	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)	Lord Howe Platform	Dredge	Pebbly conglomerate, sandstone, calcarenite	Röser & Shipboard Party, 1985
1987	CH8701	Department of Scientific and Industrial Research (DSIR)	Challenger Plateau	Dredge	Granite	Tulloch et al., 1991
1993	RE9302	Institute of Geological and Nuclear Sciences (IGNS)	Norfolk, West Norfolk, Wanganella and Three Kings ridges,	Dredge	Carbonaceous sandstone and mudstone, bryozoal/foraminiferal limestone, calcareous volcaniclastic sandstone, lapilli tuff	Herzer et al., 1997, 1999
2001	FAUST 3/GA-232	Ifremer, Geoscience Australia	Fairway and New Caledonia basins, Fairway Ridge, Lord Howe Platform	Dredge, gravity core	Quaternary foraminiferal nannofossil ooze, foraminiferal sand, Miocene basalt, Eocene chalk/radiolarite,	Exon et al., 2004
2006	AUSFAIR MD-153 (RV Marion Dufresne)	Geoscience Australia, Ifremer	Capel, Faust and New Caledonia basins, Lord Howe Platform, Fairway Ridge	Dredge, giant piston core	Trachyte, latite, quartz–feldspathic conglomerate and sandstone, some with molluscan fossils, calcareous ooze, ferromanganese nodules and crust	Colwell et al., 2006; Higgins et al., 2011

Table 5.34: Swath bathymetry data sets relevant to the central New Caledonia Basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
2001	Australian continental margin levelled gravity, magnetic and bathymetry	Geoscience Australia, Intrepid Geophysics		Petkovic et al., 2001
2009	Bathymetry and Topography Grid of Australia AUSBATH09 (2009)	Geoscience Australia		Whiteway, 2009

5.8 Offshore Clarence-Moreton Basin

5.8.1 Summary

State(s)		NSW
Area (km^2)	**Offshore**	>10,000
	Onshore	26,000
Water Depth (m)		~0–90
Maximum sediment thickness (m)		~2500
Age range		Late Triassic–Late Jurassic/earliest Cretaceous
Basin	**Overlies**	New England Orogen; possibly overlies or is equivalent to the Ipswich Basin and/or Esk Trough/Nymboida Basin
	Underlies	Cenozoic siliciclastic to carbonate sediments
	Adjacent basins	Tasman (Sea) Basin; onshore Clarence-Moreton Basin
Basin type		Transtensional, sag, passive margin
Depositional setting, rock types		Fluvial, paludal and lacustrine siliciclastic rocks and coal; volcanic and intrusive igneous rocks
Petroleum prospectivity		Low
Confidence		*Low*

5.8.2 Geology

Seismic reflection surveys over the northern New South Wales section of the eastern Australian continental margin have confirmed the presence of a basin succession that may represent the offshore continuation of the Clarence-Moreton Basin. The full extent of the offshore depocentre is uncertain.

The onshore Clarence-Moreton Basin exhibits a general north-northeast structural trend. It extends from northern New South Wales into Queensland and adjoins the Surat Basin to the west (Figure 5.37). The onshore basin contains at least 3000 m of Upper Triassic to Upper Jurassic or Lower Cretaceous dominantly fluvio-lacustrine sedimentary rocks (Figure 5.38). It overlies Triassic sedimentary and volcanic rocks of the Esk Trough/Nymboida Basin, and the Ipswich and Tarong basins, and Paleozoic metasedimentary, volcanic and intrusive rocks of the New England Orogen (Figure 5.39).

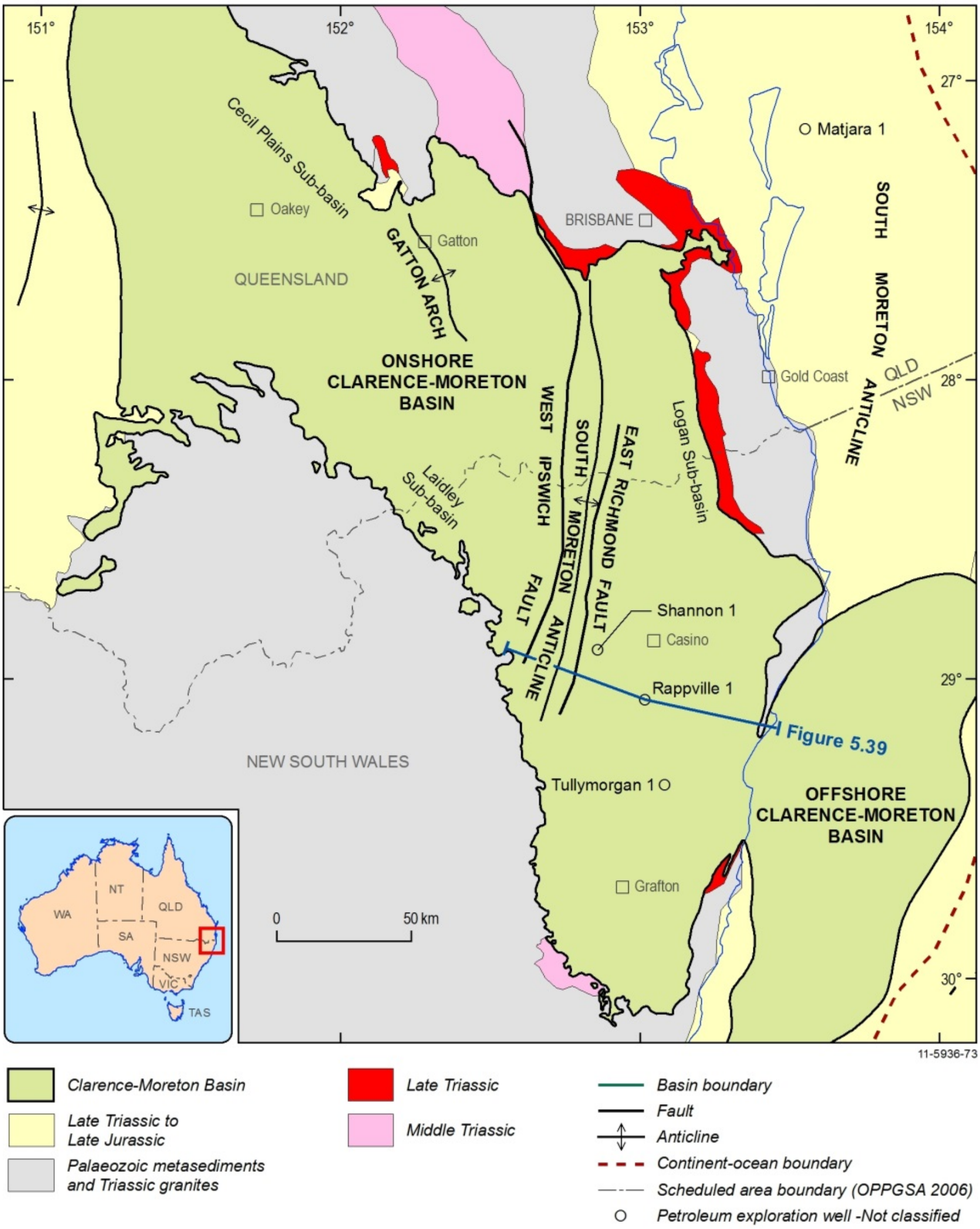

Figure 5.37: Structural elements, onshore and offshore Clarence-Moreton Basin (after Stephenson & Burch, 2004; O'Brien et al., 1994a).

The age of offshore basin is unknown. It is possible that the succession correlates with the Ipswich or Nymboida Basin, or the Early to Late Cretaceous Tasman Sea rift-related succession, rather than the Clarence-Moreton Basin (Alder, 2001). The onshore Clarence-Moreton Basin is prospective for conventional oil and gas, and coal seam gas. The basin has recorded a number of hydrocarbon shows, including several gas discoveries. In addition, the basin is currently being developed for its coal seam gas reserves. However, due to very sparse data coverage, the petroleum prospectivity of the offshore basin is virtually unknown.

5.8.2.1 Structural geology

The onshore Clarence-Moreton Basin comprises a series of generally north-northeast-trending en echelon depocentres: the Cecil Plains, Laidley and Logan sub-basins (O'Brien et al., 1994a). The sub-basins contain up to 4000 m of sediment and are underlain by fault-bounded, transtensional graben largely filled with the Triassic sediments and volcanics of the Esk Trough and the Nymboida, Ipswich and Tarong basins. The sub-basins of the Clarence-Moreton Basin are separated from each other by prominent structural highs, including the Gatton Arch and the South Moreton Anticline (Figure 5.37). The South Moreton Anticline is a prominent basement high, bounded by the West Ipswich and East Richmond faults, over which the Clarence-Moreton Basin succession abruptly thins, and against which the underlying successions of the Ipswich and Nymboida basins and the Esk Trough are truncated. Ongoing strike-slip faulting until the Cretaceous, then extensional and compressive tectonism into the Cenozoic, resulted in deformation of the basin sediments and the formation of positive flower structures and hanging wall anticlines (O'Brien et al., 1994a; Stewart & Alder, 1995). The margins of the Clarence-Moreton Basin and the underlying Ipswich and Nymboida basins generally exhibit onlap relationships, although parts of the eastern margin are steeply dipping and controlled by major faults e.g. the Coast Range Fault (Stewart & Alder, 1995).

The structure of the offshore Clarence-Moreton Basin is poorly known. Initial interpretation of seismic reflection data identified a northeast-trending depocentre, the Yamba Trough, which was believed to represent an offshore continuation of the Logan Sub-basin (O'Brien et al., 1994a). Subsequent reprocessing of seismic reflection data revealed that the basin extends beyond the confines of the Yamba Trough (Alder, 2001). However, the fault-controlled geometry of the depocentres imaged by seismic data suggests that the sedimentary succession could be a correlative of the Triassic basins, or Cretaceous syn-rift sediments associated with continental breakup, rather than the Clarence-Moreton Basin.

5.8.2.2 Basin evolution and depositional history

During the late Permian to Early Triassic, transtension along strike-slip faults led to development of the Esk Trough (Korsch et al., 1989). In the Middle Triassic, continued transtension resulted in the formation of the Ipswich and Tarong basins. In the Esk Trough and Nymboida Basin, post-rift subsidence led to the deposition of non-marine clastics, volcaniclastics, volcanics and coal (O'Brien et al., 1994a; Willis, 1994). Accumulation of coal measures continued in the early Late Triassic in the Ipswich Basin (Korsch et al., 1989; Willis, 1994; Ingram & Robinson, 1996). Late-stage deformation of the New England Orogen during the middle Late Triassic led to folding and faulting of the Ipswich Basin succession, followed by erosion that produced the basal unconformity of the overlying Clarence-Moreton Basin succession (Wells & O'Brien, 1994).

The Clarence-Moreton Basin was initiated in the Late Triassic through continued thermal subsidence following the end of deposition in the Ipswich Basin (Korsch et al., 1989; O'Brien et al., 1994a). Uplift of basin margins supplied quartzose to quartz-lithic sediments to the basin and the accumulation of alluvial fan and fluvial deposits. By the Early Jurassic, the maximum extent of the basin was established.

In the Middle Jurassic, widespread fluvio-lacustrine and paludal conditions led to the deposition of the Walloon Coal Measures, which attain a maximum thickness of approximately 600 m. The coal measures mainly comprise claystones, coal and lithic sandstones, but are sandstone dominated in parts of the basin (Stewart & Alder, 1995). The Walloon Coal Measures are overlain by a dominantly fluvial Upper Jurassic–Lower Cretaceous succession (Willis, 1994; Stephenson & Burch, 2004).

Ongoing strike-slip movements along the major basement-involved faults, e.g. West Ipswich Fault, resulted in transpressional deformation of the Clarence-Moreton Basin sediments through the Jurassic until the Early to mid-Cretaceous (O'Brien et al., 1994a).

Regional uplift resulted in widespread erosion across the onshore basin during the Cretaceous, although it is possible that localised deposition took place in rift depocentres in the offshore basin during this period. Vitrinite reflectance profiles suggest that up to 3000 m of sediment was eroded from the onshore basin (Russell, 1994). Apatite fission track data indicates that most of the uplift was completed by the end of Paleocene (Gleadow & O'Brien, 1994). Continental breakup and the opening of the Tasman (Sea) Basin between the Late Cretaceous and early Eocene (Hayes & Ringis, 1973; Gaina et al., 1998; Sdrolias et al., 2001) defined the eastern limit of the basin as it is known today, and a Cenozoic shelf wedge sequence (the marginal facies of the Tasman Basin succession) was deposited over the offshore basin. Intraplate magmatism during the late Oligocene to Miocene resulted in the widespread emplacement of mafic to acid volcanic and intrusive rocks within the basin.

5.8.2.3 Level of knowledge

The geology of the onshore Clarence-Moreton Basin is well documented, having been the focus of government studies and petroleum exploration since the late 1800s. By contrast, the offshore Clarence-Moreton Basin is a frontier with no exploration drill holes. The extent of the offshore basin is yet to be defined, and there is no direct information on the age or the composition of the sedimentary succession imaged by reflection seismic data.

AGE	Straphigraphic unit				Thickness (metres)	Lithology	Facies	Depositional environment
?Createaceous				Grafton Formation	150-250 m	Sandstone, clayey silstone minor clatstone, coal	Sandy channel-fill, overbank/flood plain daposits	Low-energy, mixed load meandering fluvial system, poss. terrestrial lakes
Late Jurassic				Kangaroo Creek Sandstone	200-?500 m	Quartose, cross bedded sandstone	Sandy channel-fill	Bed load fluvial system (braided stream)
Middle Jurassic			Walloon Coal measures	Maclean Sandstone member	10-50 m	Feldspathic sandstone	Sandy channel-fill, lesser overbank deposits	Bed load meandering fluvial system
			Walloon Coal measures		30-400 m	Interbedded sandstone, siltstone claystone, coal ironstone nodules	Sandy channel-fill,with overbank and flood plain deposits, some backswamp facies	Mixed load meandering fluvial system
Early Jurassic	Bundamba Group	Mauburg Subgroup	Koukandowie Formation		?50-400 m	Interbedded sandstone, siltstone claystone, coal	Overbank/flood plain deposits, sandy splays channel fill	Mixed load meandering fluvial system
				Heifer Creek Sandstone member	10-50 m	Course quartz sandstone granite conglomerate	Channel fill	Bed load meandering fluvial system
				Ma Ma Creek member	10-50 m	Interbedded sandstone, mudstone	Overbank/flood plain facies	Mixed fluvial, lacustrine system
				Towallum Basalt	10-50 m	Vesicular basalt, volcaniclastics	Lavas, epiclastics	? Terrestrial-lacustrine
			Gatton Sandstone		200-600 m	Sandstone, conglomerate , minor fossil wood	Channel fill	Bed load to mixed load fluvial system
				Koreelah Cgl	5-50 m	Pebble-cobble conglomerate, sandstone	Alluvial fan, channel fill	Alluvial fan to bed load fluvial system
				Calamia Member	5-500 m	Siltstone, claystone, sandstone	Flood plain/overbank facies	Mixed load fluvial, system
Late Triassic		Woogaroo Subgroup	Ripley Road Sandstone		100-150 m	Quartz sandstone granule conglomerate	Channel fill	Bed load, braided fluvial system
			Raceview Formation		0-250 m	Interbedded sandstone, siltstone, claystone	Overbank/flood plain with crevasse splays	Mixed load fluvial system
			Laytons Range Conglmerate		0-80 m	Conglomerate, minor sandstone	Alluvial fan	Alluvial fan system
Early Late Triassic	Ipswich Coal Measures		Redcliff Coal Measures		?>100 m	Lithic conglomerate and breccia, sandstone, siltstone, coal	Alluvial fan, overbank/flood plain deposits, interfan marshes	Alluvial fan-mixed load fluvial system
			Evans Head Coal Measures		?>50 m	Sandstone, siltstone, conglomerate, very minor coal	Channel fill, overbank/flood plain deposits,	Bed load to mixed load fluvial system
Middle Triassic				Nymboida Coal Measures	>1000 m	Sandstone, conglomerate, silstone, claystone, coal, colcanics	Varied	Varied

11-5936-70

Figure 5.38: Stratigraphy of the Nymboida, Ipswich and onshore Clarence-Moreton basins (after Willis, 1994).

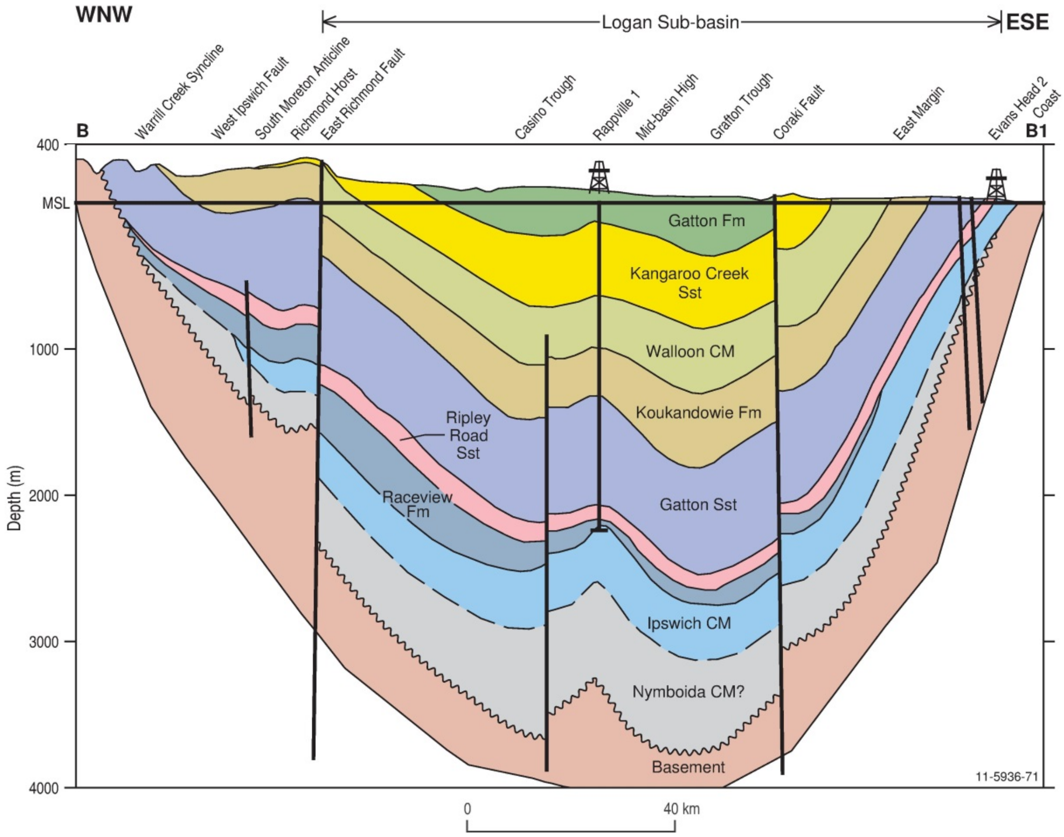

Figure 5.39: Geological cross-section of the Nymboida, Ipswich and Clarence-Moreton basins (after Ingram & Robinson, 1996).

5.8.3 Petroleum systems

The onshore Clarence-Moreton Basin, together with the underlying Ipswich Basin, has a long history of petroleum exploration dating back to 1897, when gas flow was recorded from a coal borehole near Grafton. Despite the numerous gas and minor oil shows, the basin has remained lightly explored for conventional petroleum, with approximately 30 exploration holes drilled in the New South Wales part. Much of the onshore basin has been under permit since the 2000s, and exploration activity is increasingly targeting coal seam gas. Seismic reflection data coverage over the onshore basin is sparse, although surveys since the 1980s have significantly improved the quality of imaging.

The lack of direct stratigraphic sampling in the offshore Clarence-Moreton Basin means that the likely presence of petroleum systems can only be inferred from the onshore basin. Moreover, it is uncertain whether the sedimentary succession in the offshore basin is a correlative of the Clarence-Moreton, Ipswich or Nymboida basins, or a Cretaceous syn-rift succession associated with the opening of the Tasman Sea.

5.8.3.1 Source rocks

Potential source rocks are present in the Nymboida and Ipswich basins underlying the onshore Clarence-Moreton Basin where Triassic coal measures are generally mature for gas (Willis, 1985).

In the onshore Clarence-Moreton Basin, the Middle Jurassic Walloon Coal Measures have the best source potential. The high organic matter content, a significant sapropelic component, and hydrogen index values exceeding 400, make the coal measures a potentially rich, oil-prone source rock (Powell et al., 1993; O’Brien et al., 1994b). The Upper Triassic to Lower Jurassic Bundamba Group is gas or oil mature in the central part of the onshore Clarence-Moreton Basin but generally has a low source potential due to the low organic matter content (Willis, 1985; Powell et al., 1993; O’Brien et al., 1994b). An exception is the Koukandowie Formation, which contains relatively high disseminated organic matter in places dominated by type II/III kerogen and hydrogen index values of 300 or more (Powell et al., 1993; O’Brien et al., 1994b).

If the offshore sedimentary succession is a correlative of Nymboida or Ipswich Basin, rather than the offshore extension of the Clarence-Moreton Basin, the main potential source rock in the offshore basin may be Triassic coals. Alternatively if the offshore basin is an Early to Late Cretaceous rift depocentre associated with opening of the Tasman Sea, the basin could contain coaly potential source rocks; seismic data from the Lord Howe Rise and New Caledonia Basin regions to the east suggest widespread syn-rift deposition of coal-rich sediments during this interval (e.g. Willcox & Sayers, 2002, Stagg et al., 2002; van de Beuque et al., 2003; Collot et al., 2009; Colwell et al., 2010).

5.8.3.2 Generation and expulsion

The Walloon Coal Measures and Koukandowie Formation are oil mature in the central part of the onshore Clarence-Moreton Basin, but become rapidly overmature toward the eastern basin boundary (Powell et al., 1993; O’Brien et al., 1994b). Potential source rocks within the Clarence-Moreton Basin succession were generating hydrocarbons during the Late Cretaceous (100–80 Ma), at the time of maximum burial and heat flow (Powell et al., 1993), and after most major structures were in place (O’Brien et al., 1994a). Triassic potential source rocks within the underlying Ipswich and Nymboida basins are currently gas mature. Modelling indicates that the Ipswich Coal Measures would have commenced oil generation during the Early Jurassic, and all in situ oil would have been cracked to gas by the mid-Cretaceous (Russell, 1994).

Seismic interpretation indicates that the maximum thickness of the sedimentary succession offshore is approximately 2500 m, which suggests that the potential for petroleum generation is low (Alder, 2001). However, elevated heat flow associated with the Late Cretaceous to Eocene opening of the Tasman Sea (Gleadow & O'Brien, 1994; Russell, 1994)—indicated by the rapid increase in thermal maturity along the eastern boundary of the onshore basin—could have mitigated the effect of shallow burial on hydrocarbon generation. It is also possible that, due to the shallow depth of burial, Triassic to Jurassic potential source rocks, which are gas-mature to overmature onshore, may have only attained oil maturity in parts of the offshore basin.

5.8.3.3 Reservoirs

Sandstones in the Nymboida and Ipswich basins probably have limited reservoir potential due to diagenesis, and a high lithic, volcaniclastic or mud content (Cranfield & Schwarzbock, 1976). In the onshore Clarence-Moreton Basin, the best reservoir potential is within the Ripley Road Sandstone of the Bundamba Group; this unit is extensive, has excellent porosity and permeability, and is associated with hydrocarbon shows (O'Brien et al., 1994b). The Heifer Creek Sandstone Member of the Koukandowie Formation has good porosity and permeability where it comprises coarse sandstones and granule conglomerates, and hosts a number of gas shows (O'Brien & Wells, 1994b). Other potential reservoirs include the sheet-like Kangaroo Creek Sandstone, and the quartzose sandstone intervals within the Gatton Sandstone and Raceview Formation of the Bundamba Group (O'Brien & Wells, 1994; O'Brien et al., 1994b). The sandstones of the Walloon Coal Measures are generally volcanogenic and have poor porosity, but locally contain reservoir-quality intervals (O'Brien et al., 1994b).

The reservoir potential within the offshore succession is unknown. If the succession is a direct correlative of the onshore Clarence-Moreton Basin, this would imply good reservoir potential. However, if the succession is more akin to the Nymboida or Ipswich basins, the potential may be lower. The Late Cretaceous to Cenozoic marine incursion following the opening of the Tasman Sea may have resulted in the deposition of shoreline and shelf sands, which may have good reservoir potential depending on their degree of sorting by marine processes.

5.8.3.4 Seals

In the onshore Clarence-Moreton Basin, the Ma Ma Creek Member of the Koukandowie Formation and the Calamia Member of the Gatton Sandstone may act as potential regional seals to the underlying Gatton and Ripley Road sandstones, respectively (O'Brien et al., 1994b). Floodplain, lacustrine and paludal facies in other sections of the Bundamba Group may act as local, intraformational seals.

These potential seal formations may also be present in the offshore basin. Additional seal potential may be offered by the fine-grained paralic and shelf facies within the Cenozoic succession overlying the pre-Tasman Sea sediments.

5.8.3.5 Play types

The main types of structural traps in the onshore Clarence-Moreton Basin are: drapes over pre-Clarence-Moreton topography; hanging wall anticlines associated with minor thrusts; Late Triassic anticlines and fault traps within the Ipswich and Nymboida basins successions; pinchouts against pre-Clarence-Moreton structural highs, and; stratigraphic traps, typically as channel sand bodies of low interconnectivity encased by floodplain facies (O'Brien et al., 1994a, b; Stewart & Alder, 1995).

In the offshore basin potential plays include stratigraphic plays within the Cenozoic succession or sub-unconformity plays top-sealed by the Cenozoic sediments. Fault block and associated drape plays may also be associated with the Cretaceous rifting leading to the opening of the Tasman Sea.

5.8.3.6 Critical risks

There is no direct geological data or any evidence of an active petroleum system in the offshore Clarence-Moreton Basin. The age and composition of the pre-Tasman Sea sediments are difficult to infer, despite extensive geological knowledge of the onshore basin. If the offshore sedimentary succession is a correlative of the Clarence-Moreton Basin proper, there is some potential for the presence of a petroleum system. A thickness of only 2500 m for the succession indicates a risk with source rock maturity, but this may be countered by the high heat flow experienced during the opening of the Tasman Sea. The timing of structuring relative to hydrocarbon generation would only be a major issue with any oil derived from the Triassic sources. However, gas generation from the Triassic section may have had a negative impact on the accumulation of oil generated from the Clarence-Moreton basin source rocks given the geometry of the source kitchens and traps (Stephenson & Burch, 2004). In the offshore basin, the timing of seal formation relative to hydrocarbon generation would be a major issue, if the trapping mechanism relies on a Cenozoic seal.

5.8.3.7 Overall prospectivity classification

Low

5.8.4 Exploration status

The offshore Clarence-Moreton Basin is a petroleum exploration frontier. Despite a long history of exploration and numerous hydrocarbon shows in the onshore part of the basin, little is known of the geology and petroleum prospectivity offshore. The only exploration activity of note has been by Murphy Oil, who acquired 2D reflection seismic data in 1969. Several other reconnaissance surveys have been completed by the Bureau of Mineral Resources (BMR) and the Australian Geological Survey Organisation (AGSO), some in collaboration with the New South Wales Department of Mineral Resources.

5.8.5 Data

There are no wells in the offshore Clarence-Moreton Basin and geophysical data coverage is very sparse. Key data sets are listed in Table 5.35 and Table 5.36 and their locations shown on Figure 5.40. The main seismic data set is the Yamba–Evans Head 2D reflection survey, completed in 1969. The data was reprocessed by the New South Wales Department of Mineral Resources, resulting in the imaging of at least 2.5 km thickness of the sedimentary succession. During 1971, BMR acquired a limited seismic data set in the area during Continental Margin surveys 12, 14 and 15; however the data quality is poor. One line from AGSO survey 206 traverses a 55 km section of the offshore basin. The data quality is good, enabling the imaging of fault-bounded depocentres underlying the Cenozoic shelf wedge.

Shipboard gravity, magnetic and bathymetry data have been acquired over the offshore Clarence-Moreton Basin during seismic and other marine data acquisition surveys traversing the region. In 1996, AGSO completed the Clarence-Richmond Airborne Geophysical Survey. A total of 48,401 line-km of magnetic and radiometric data were acquired, part of which cover the offshore Clarence-

Moreton Basin (Mitchell & Minty, 1998). Potential field and bathymetry data coverage over the offshore Clarence-Moreton Basin includes regional compilations derived from satellite, airborne and marine data (Sandwell & Smith, 1997; Andersen et al., 2010; Maus et al., 2007, 2009; Whiteway, 2009). Additionally, shipboard gravity and magnetic data were levelled in 2001 by Geoscience Australia (Petkovic et al., 2001).

5.8.5.1 Confidence rating

Low

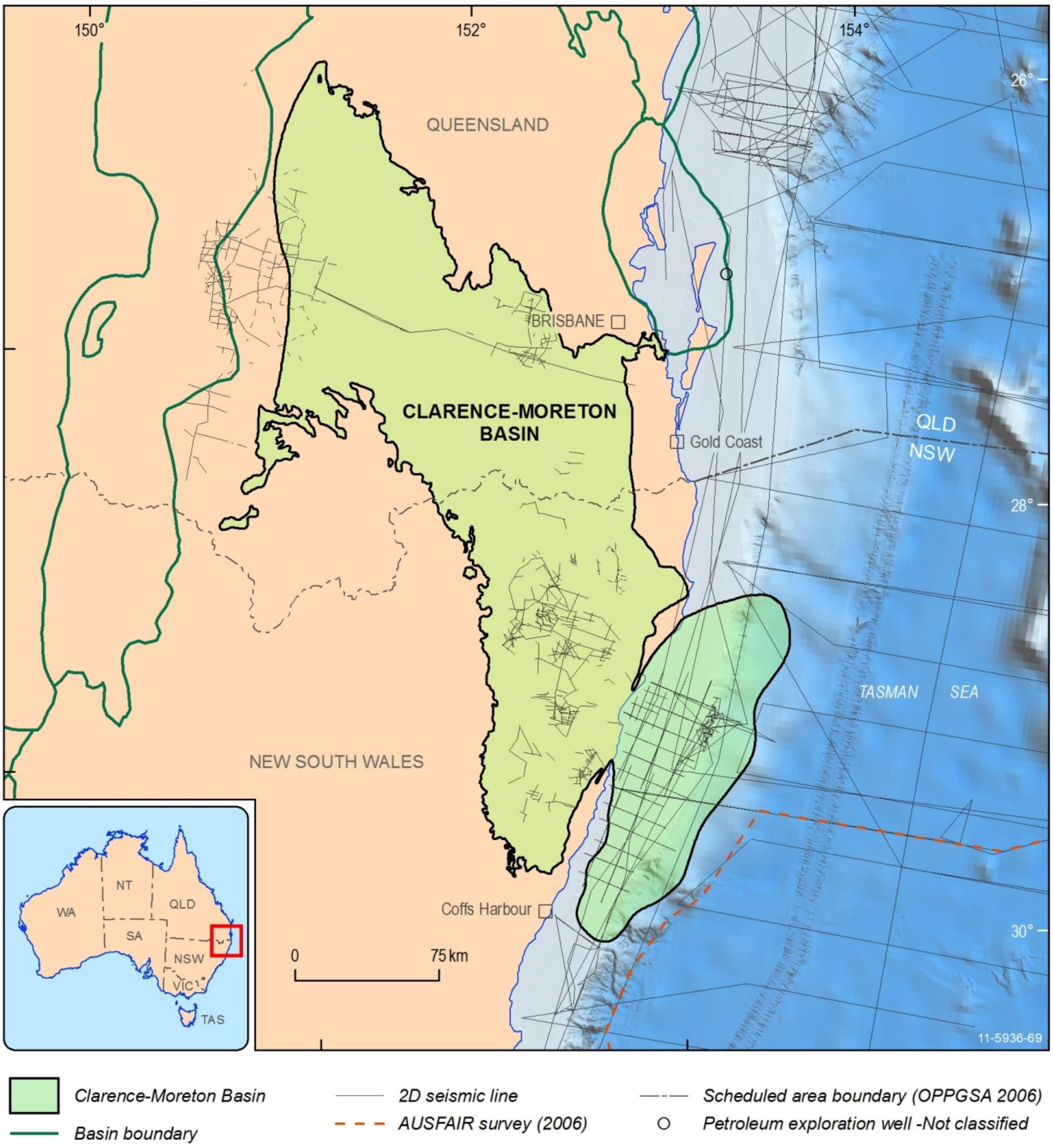

Figure 5.40: Seismic data coverage over the Clarence-Moreton Basin.

5.8.6 Issues and remaining questions

The petroleum prospectivity of the offshore Clarence-Moreton Basin remains practically unknown, due to the very sparse geophysical data coverage and absence of drilling data. There is great uncertainty regarding the age and composition of the pre-Cenozoic (i.e. pre-Tasman Sea) succession. Possibilities range widely from a Triassic succession equivalent to Nymboida or Ipswich basins onshore, through a dominantly Jurassic extension of the onshore Clarence-Moreton Basin, to a Cretaceous Tasman Sea rift-related succession. The burial and thermal history of the offshore basin cannot be easily extrapolated from the onshore areas, due to the effects of Tasman Sea rifting and passive margin evolution. Moreover, the reservoir and seal potential of the Cenozoic shelf succession is completely untested along this sector of the eastern Australian continental margin. As a consequence, the level of prospectivity cannot be inferred with any degree of confidence.

The offshore Clarence-Moreton Basin has a favourable geographic location relative to energy markets, especially the major urban centres of southeastern Queensland. In combination with the high prospectivity of the adjacent onshore basin and the shallow water depth, the offshore Clarence-Moreton Basin is well placed to attract future industry interest. Potential environmental sensitivities may be associated with the southern part of the basin adjacent to the Solitary Islands Marine Park and Commonwealth Marine Reserve, annual whale migration through the area, and settlements and tourist activity along the coast.

5.8.6.1 Recommendations

The fundamental geological questions that relate to the offshore Clarence-Moreton Basin should be addressed through the acquisition of reconnaissance-level 2D seismic data. If a depocentre can be identified that is sufficiently thick for hydrocarbon generation, acquisition of higher resolution, closely spaced 2D seismic data may be warranted.

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5.8.8 Data Tables

Table 5.35: 2D seismic surveys, offshore Clarence-Moreton Basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1969	Yamba–Evans Head 2D	Murphy Oil	870	Alder, 2001
1971	Continental Margin Survey 12	Bureau of Mineral Resources (BMR)	40	Stagg et al., 2002
1971	Continental Margin Survey 14	Bureau of Mineral Resources (BMR)	120	Stagg et al., 2002
1971	Continental Margin Survey 15	Bureau of Mineral Resources (BMR)	40	Stagg et al., 2002
1998	AGSO 206 (FAUST 1)	Australian Geological Survey Organisation	55	Bernardel et al., 1999

Table 5.36: Swath bathymetry data sets relevant to the offshore Clarence-Moreton Basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1987	NSW Phosphorites Survey 71 (bathymetry)	Bureau of Mineral Resources	New South Wales north coast, mostly over offshore Clarence-Moreton Basin	Mowat & Kossatz, 1989
2001	Australian continental margin levelled gravity, magnetic and bathymetry	Geoscience Australia, Intrepid Geophysics		Petkovic et al., 2001
2009	Bathymetry and Topography Grid of Australia AUSBATH09 (2009)	Geoscience Australia		Whiteway, 2009

5.9 Offshore Sydney Basin

5.9.1 Summary

State(s)		NSW
Area (km^2)	**Offshore**	28,000
	Onshore	36,000
Water Depth (m)		0–4000
Maximum sediment thickness (m)		>6000
Age range		Permian–Triassic
Basin	**Overlies**	Lachlan and New England orogens
	Underlies	Localised Jurassic–Cenozoic intrusive rocks; Cenozoic siliciclastic to carbonate sediments
	Adjacent basins	Tasman (Sea) Basin
Basin type		Extensional, foreland, passive margin
Depositional setting, rock types		Fluvial, paralic and marine siliciclastic sediments; coal; mafic to acid volcanic and intrusive rocks
Petroleum prospectivity		Moderate-low
Confidence		*Medium–low*

5.9.2 Geology

The Sydney Basin is located on the central part of the New South Wales coast (Figure 5.41). The basin covers an area of approximately 64,000 km^2, of which 28,000 km^2 lies offshore on the eastern Australian continental margin (Cadman et al., 1998). The onshore Sydney Basin occupies a trapezoidal area elongated in a north-northwest to northwest direction and is contiguous with the Gunnedah Basin to the northwest across the Liverpool Range. The northeastern boundary of the onshore basin is defined by the north-northwest to northwest-trending Hunter–Mooki Thrust (Figure 5.41). Offshore, it is truncated by the edge of the eastern Australian continental shelf along its southeastern boundary. The Sydney Basin contains at least 6000 m of Permian to Triassic non-marine and marine sedimentary rocks (Figure 5.42). A Jurassic to Cretaceous succession is also believed to have been deposited, but is now completely eroded onshore (Mayne et al., 1974; Sullivan et al., 1996; Alder et al., 1998). Maximum sediment thickness in the offshore part exceeds 5000 m and is overlain by Cenozoic paralic, shelfal and bathyal sediments deposited since the final breakup of eastern Gondwana and the opening of the Tasman Sea Basin (Maung et al., 1997; Alder et al., 1998). The Sydney Basin is part of a superbasin that extends southward from the Bowen Basin that collectively contains the largest reserves of Permian coal in Australia (Stephenson & Burch, 2004). The onshore parts of the Sydney, Gunnedah and Bowen basins also are prospective for coal seam gas and oil shale, and have several recorded conventional hydrocarbon discoveries. However, the petroleum prospectivity of the offshore Sydney Basin is poorly known and there has only been one unsuccessful exploration well drilled to date.

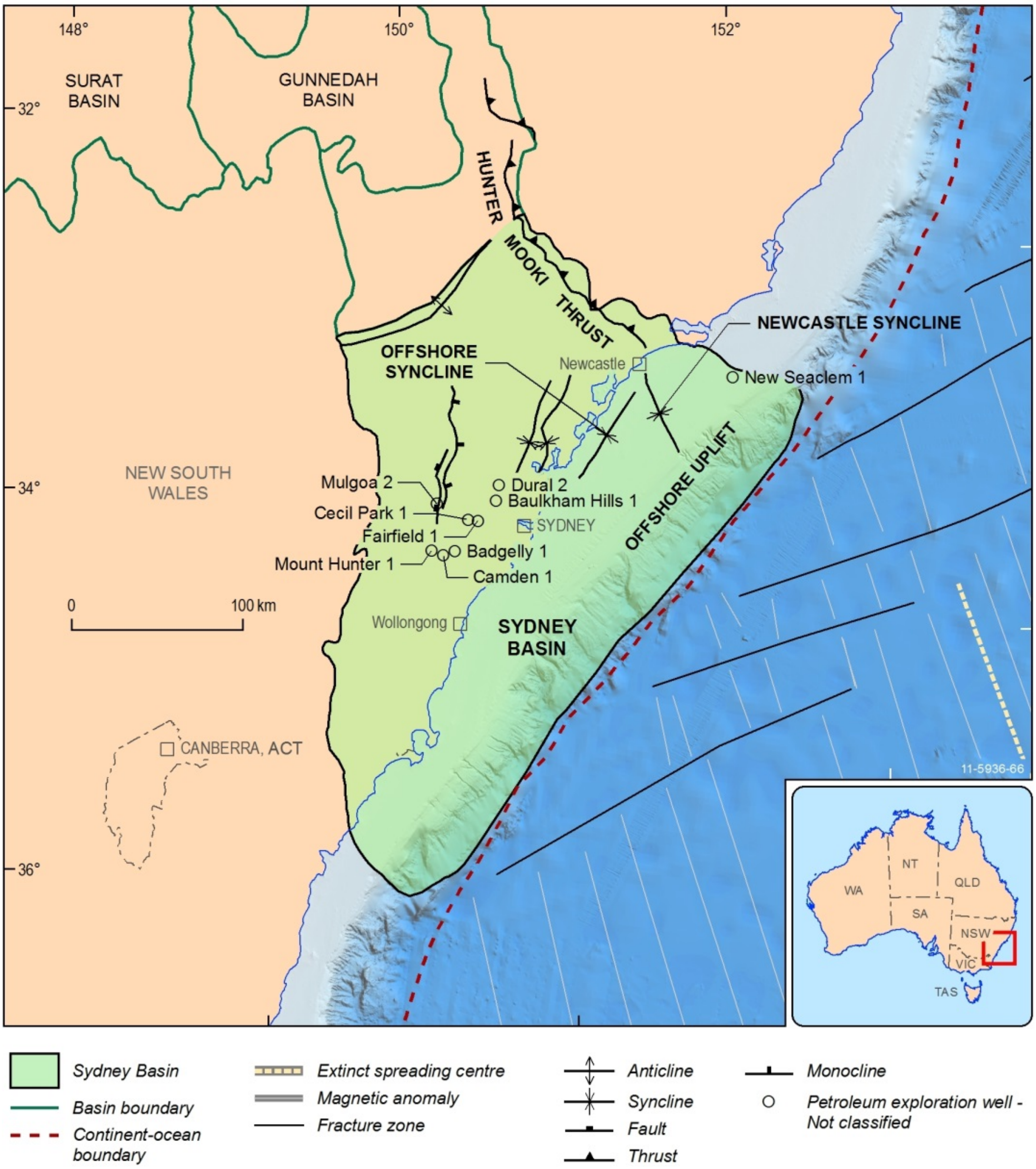

Figure 5.41: Structural elements, Sydney Basin (after Maung et al., 1997).

5.9.2.1 Structural geology

The Sydney Basin generally deepens to the north-northeast toward the Hunter–Mooki Thrust, along which the basin succession is overlain by the thrust sheets of the Paleozoic New England Orogen (Figure 5.43). Along the western boundary, the basin sediments generally onlap the Paleozoic rocks of the Lachlan Orogen. The axes of folds within the basin predominantly trend north-northeast (Figure 5.41). The main structural features of the offshore basin are the Offshore and Newcastle synclines and the Offshore Uplift. The Offshore Uplift and Syncline trend north-northeast, however, the Newcastle Syncline trends north-northwest. The Offshore Uplift originated as a late Carboniferous to Permian volcanic arch that controlled Permian deposition within the offshore part of the basin (Stewart & Alder, 1995; Alder et al., 1998). The boundary between the Offshore Uplift and the Offshore Syncline is an extensional fault zone that was subsequently reversed in the northern part (Stewart & Alder, 1995).

5.9.2.2 Basin evolution and depositional history

The Sydney Basin evolved predominantly as a foreland basin associated with the deformation of the New England Orogen, driven by the long-lived Paleozoic to Mesozoic plate convergence along the eastern Gondwana margin. The basin was initiated as a volcanic arc-related rift during the late Carboniferous to early Permian along the boundary between the Lachlan and New England orogens (Scheibner, 1993; Veevers & Powell, 1994; Maung et al., 1997; Korsch et al., 2009). An easterly shift in the locus of subduction resulted in the conversion of the rift into a foreland basin during the early Permian, and west- to southwest-directed overthrusting of the New England Orogen (Veevers & Powell, 1994). Deposition accompanying the foreland loading phase was marine-dominated during the early Permian, when the shoreline and shelf sandstones and marine siltstones of the Shoalhaven and Dalwood groups were formed (Gostin & Herbert, 1973; Tye et al., 1996). During the middle to late Permian, the nearby uplift of the New England Orogen (the Hunter–Bowen Orogeny) resulted in transgressive–regressive cycles of non-marine and marine deposition. The Tomago, Newcastle, Wittingham and Illawarra coal measures, dominated by fluvio-deltaic to shelf sandstones, siltstones and coal, were formed at this time (Herbert, 1980, 1995). Sediment sources to the basin alternated between periods of active uplift of the New England Orogen, when arc-derived volcaniclastic sediments were supplied from the northeast, and periods of tectonic quiescence when quartz-rich cratonic sediments were supplied from the Lachlan Orogen to the west. Deposition of the coal measures filled much of the accommodation within the basin, and the Offshore Uplift, a persistent structural high in the eastern part of the basin, became onlapped by sediments by the late Permian.

Extensive uplift and activity along the Hunter–Mooki Thrust from the end of the Permian into the Early Triassic resulted in the influx of sediment from the New England Orogen and the deposition of the Narrabeen Group deltaic, estuarine and fluvial siltstones, sandstones and claystones (Ward, 1972). The northern Sydney Basin experienced deformation through foreland thrust faulting and folding (Glen & Beckett, 1997). Waning uplift along the thrust during the Middle Triassic caused an influx of quartzose sediments from the Lachlan Orogen (Conaghan et al., 1982). The resultant Hawkesbury Sandstone was deposited in braided fluvial to tidal embayment environments (Mayne et al., 1974; Conaghan & Jones, 1975; Miall & Jones, 2003). Sediment supply diminished during the Middle Triassic, leading to the deposition of fluvial to shallow marine shales, siltstones and sandstones of the Wianamatta Group.

Thermal maturity data from eastern Australia suggest that 1 to 4 km of Jurassic to Cretaceous sediments were deposited in the Sydney Basin (Korsch & Totterdell, 1996; Sullivan et al., 1996). However, this succession has been completely eroded during uplift associated with rifting that led to the opening of the Tasman Sea during the Campanian to early Eocene. Late Mesozoic syn-rift sediments associated with the margin breakup have previously been identified from the edge of the continental shelf in the offshore Sydney Basin (AGSO, 1993). It is likely that the correlatives of the Sydney Basin succession are distributed over parts of the central Lord Howe Rise and Dampier Ridge i.e. the conjugate margin to the offshore Sydney Basin (Willcox & Sayers, 2002; Norvick et al., 2008).

After continental breakup, up to 700 m of predominantly Eocene–Oligocene to Holocene siliciclastic to carbonate shelf wedge succession has been deposited over the offshore Sydney Basin (Maung et al., 1997). Ongoing compressional tectonics, associated with the distal convergence of the Australian and Pacific plates, have resulted in mild structural reactivation and deformation within the basin during the Cenozoic.

5.9.2.3 Level of knowledge

Despite the long history of petroleum exploration in the onshore Sydney Basin, and proximity to the largest population centre in Australia, the offshore Sydney Basin remains a frontier. Several reflection seismic and geophysical surveys have been completed over the offshore basin since the mid-1960s, resulting in a moderate coverage of geophysical data. Only one exploration well has been drilled, which has provided stratigraphic control for the Cenozoic succession. The underlying Sydney Basin succession remains undrilled. Ongoing work within PEP11 is expected to result in further drilling and analyses, which will no doubt improve the current state of knowledge.

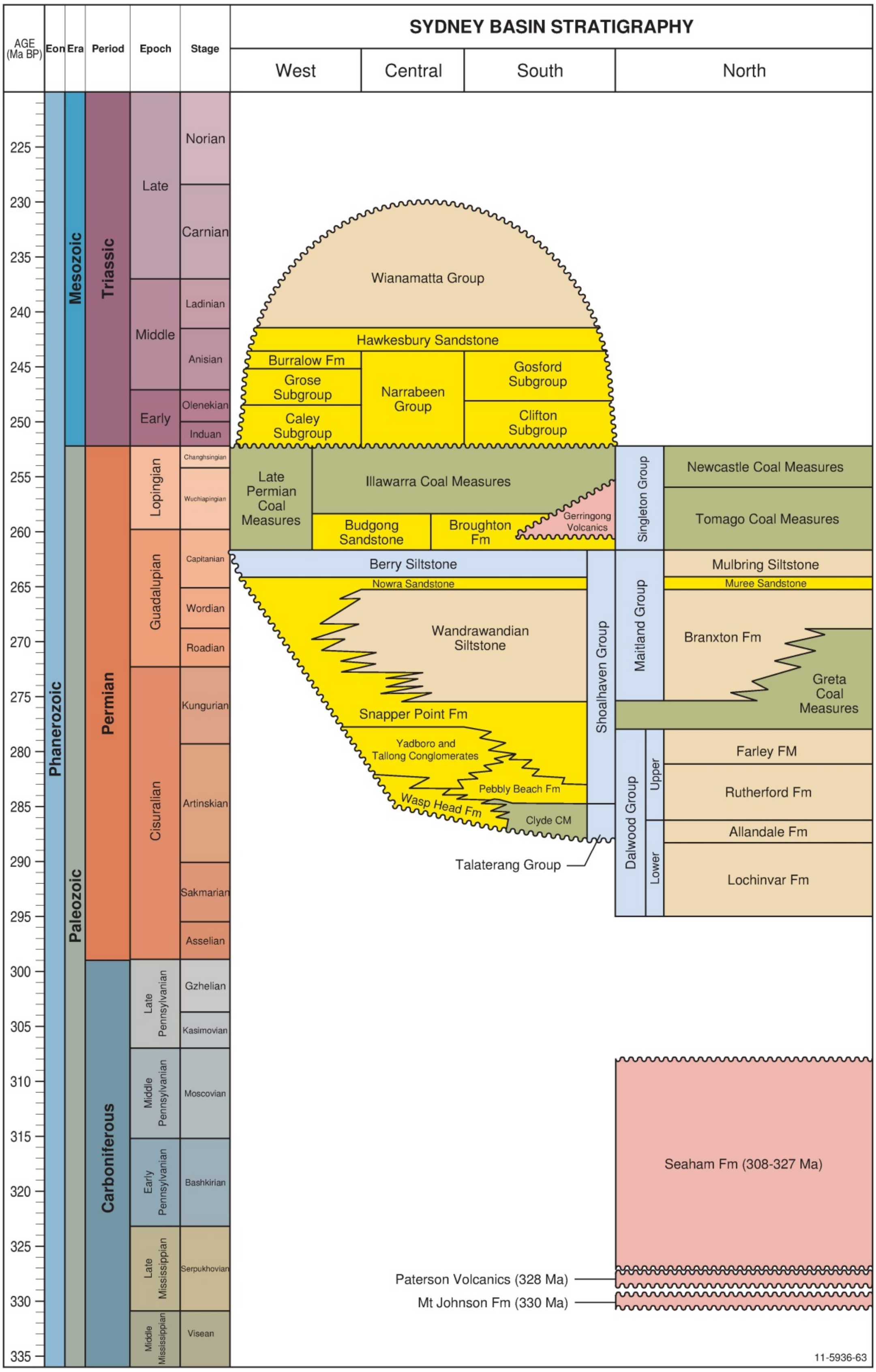

Figure 5.42: Stratigraphy of the Sydney Basin (Stephenson & Burch, 2004, after Maung et al., 1997).

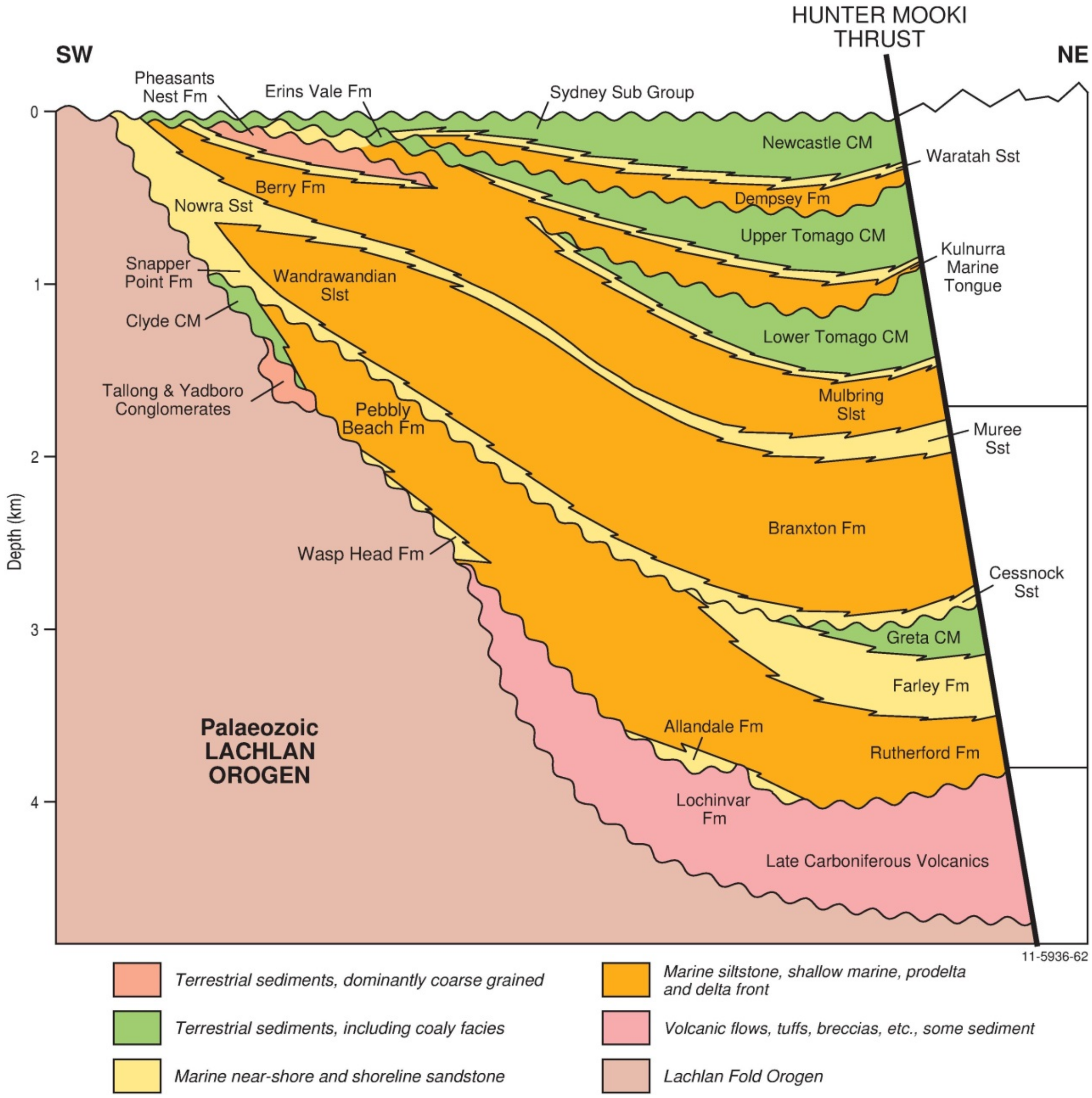

Figure 5.43: Schematic geological cross-section of the Sydney Basin showing the stratigraphy of the Permian succession (Stephenson & Burch, 2004, after Maung et al., 1997).

5.9.3 Petroleum systems

Recent work by Advent Energy in PEP11 has identified several features that may indicate an active petroleum system within the offshore Sydney Basin. These include: interpreted sea-surface hydrocarbon slicks in satellite-derived synthetic aperture radar (SAR) imagery; potential fluid migration chimneys, hydrocarbon-related diagenetic zones (HRDZs), anomalous amplitude-versus-offset (AVO) and flat spots observed on reflection seismic data; and megapockmarks and hardgrounds on the seafloor (Advent Energy, 2012). In addition, several structures, interpreted to be capable of containing large gas accumulations, have been identified (Advent Energy, 2012). The first exploration well in the offshore Sydney Basin, New Seaclem 1, was drilled in 2011 but was unsuccessful (Figure 5.41).

The lack of stratigraphic data for the pre-Cenozoic section means that the presence of potential petroleum system elements in the offshore Sydney Basin can only be inferred from the extensive geological knowledge of the onshore part of the basin.

5.9.3.1 Source rocks

Stewart & Alder (1995) reported that potential source rocks in the onshore Sydney Basin are generally dominated by type III kerogen and high in dispersed organic matter. Potential source rocks in the offshore Sydney Basin may include equivalents of the early Permian Greta Coal Measures in the northern Sydney Basin and marine and deltaic sediments within the Shoalhaven and Dalwood groups. The high exinite content of the Greta Coal Measures, in particular, suggests a high potential for oil (Stewart & Alder, 1995; Cadman et al., 1998).

Further source rock potential is likely within the upper Permian Tomago, Newcastle, Wittingham and Illawarra coal measures. The coals themselves are likely to be mainly gas-prone, although the high liptinite content and onshore oil seeps indicate that they also have significant oil potential (Maung et al., 1997). The marine and deltaic siltstones within or underlying the upper Permian coal measures (Denman and Dempsey formations, Kulnura Marine Tongue, Mulbring Siltstone and Branxton Formation), are likely to have good oil and gas potential (Stewart & Alder, 1995; Maung et al., 1997; Stephenson & Burch, 2004). Petroleum prospectivity may be enhanced in the offshore part of the Sydney Basin by the greater thickness of the upper Permian coal measures.

It is also possible that potential source rocks were deposited during the Jurassic to Early Cretaceous, in restricted rift depocentres prior to the opening of the Tasman Sea. Seismic data from the Lord Howe Rise and New Caledonia Basin regions to the east suggest widespread syn-rift deposition of coal-rich sediments during this interval (e.g. Willcox & Sayers, 2002, Stagg et al., 2002; van de Beuque et al., 2003; Collot et al., 2009; Colwell et al., 2010). Late Mesozoic rift depocentres are known to exist along the edge of the continental shelf in the offshore Sydney Basin. However, no data is available to substantiate the source rock potential of this succession.

5.9.3.2 Generation and expulsion

Thermal maturity studies in the onshore Sydney Basin, mainly based on vitrinite reflectance data, suggest that the upper Permian coal measures are mature for gas in the central and southern parts of the basin, and oil mature in the remainder of the basin (Stewart & Alder, 1995; Maung et al., 1997). The lower Permian potential source rocks are marginally mature to oil mature in the southern and western parts of the basin, but are expected to be more mature in the central part (Stewart & Alder, 1995). Generation from the lower Permian source rocks is likely to have taken place from the Triassic onward, while the upper Permian sources commenced generation between the Middle Jurassic to Late Cretaceous (Grybowski, 1992; Bai et al., 1993; Stephenson & Burch, 2004). Uncertainties surrounding the thickness of the Jurassic–Cretaceous succession, timing of maximum burial, amount of missing section removed by erosion during the Cretaceous and Cenozoic makes the burial history modelling of Sydney Basin challenging. Moreover, an episode of elevated heat flow during the Early Cretaceous to Campanian is thought to have preceded uplift and erosion, but the extent and magnitude of this thermal event is difficult to constrain (Maung et al., 1997).

Extrapolation of onshore vitrinite reflectance gradients suggests that the lower Permian source rocks would be gas mature in the offshore Sydney Basin (Shibaoka et al., 1973). The offshore basin is more likely than the onshore part to have experienced elevated heat flow and magmatism during the Cretaceous rifting leading to the opening of the Tasman Sea. This may have enhanced the maturation of potential source rocks, such that the upper Permian coal measures may also have attained the gas window. Onshore data suggests that the southern parts of the basin experienced higher heat flow, which may implies that the northern areas of the offshore basin could be more prospective for light oil or wet gas (Stewart & Alder, 1995).

5.9.3.3 Reservoirs

Potential reservoir rocks in the Sydney Basin include the lower to upper Permian nearshore, shelf and wave-dominated deltaic sandstones of the Shoalhaven and Maitland groups, sandstones associated with marine incursions within the upper Permian coal measures, and Triassic fluvial sandstones of the Narrabeen Group and the Hawkesbury Sandstone (Stewart & Alder, 1995; Maung et al., 1997). Triassic sandstones have been identified as a reservoir target (Stewart & Alder, 1995), however interpretation of seismic data suggests that they are absent in much of the offshore basin (Arditto, 2003). In addition, Arditto (2003) argued that upper Permian coal measures in the offshore basin are likely to contain reservoir quality quartz-rich sands, although early hydrocarbon charge would be necessary to preserve porosity. However, Blevin et al (2007) reported that in wells in onshore areas adjacent to the offshore depocentre, reservoir quality is generally poor, with porosity values low (1–10%) and permeability poor to non-existent (<10 mD to near-zero). It is considered that reduction in primary porosity and permeability as a result of diagenesis is a major risk to reservoir quality in the offshore basin. A possible mitigating factor is that deposition in the offshore part of the basin is likely to have had a stronger marine influence, which may have improved the sorting (and thus the primary porosity and permeability) of marine and shoreline sandstones.

Advent Energy (2011) reports that Cenozoic sandstones with up to 30% porosity were encountered during the drilling of New Seaclem 1 in PEP11. The reservoir potential of the post-Triassic successions in the offshore Sydney Basin is otherwise untested.

5.9.3.4 Seals

Potential seal formations identified in the onshore Sydney Basin include the lower Permian marine siltstones within the Shoalhaven and Maitland groups, which may act as regional seals to the underlying sandstone reservoir units. The fine-grained delta plain, interdistributary bay, prodelta and marine facies within the lower and upper Permian coal measures are obvious potential seals to the fluvio-deltaic sandstone reservoirs within the coal measures. Claystones within the Narrabeen Group and the Wianamatta Group as a whole may provide potential seals to the Triassic sandstones.

5.9.3.5 Play types

In the offshore Sydney Basin, the main expected play types are associated with the Offshore Uplift and the Offshore and Newcastle synclines (Maung et al., 1997). Inversion anticlines, overthrust and sub-thrust traps are associated with thrust faulting along the flanks of the Offshore Uplift. North-northeast-trending transpressional structures occur within the synclines, which appear to have been modified by faulting associated with the opening of the Tasman Sea. Extensional fault block plays occur on the eastern flanks of the Offshore Uplift leading down to the Tasman Sea Basin. The main time of trap formation is inferred to be during the Permian and, for extensional structures, during the Cretaceous.

In addition, there is abundant potential for stratigraphic trapping. Examples include fluvio-deltaic channel, mouth bar, crevasse splay and shoreface sandbodies within the lower to upper Permian successions.

5.9.3.6 Critical risks

Arditto (2003) proposed that the critical risks for the offshore Sydney Basin are the timing of structuring relative to migration and preservation of accumulations. Seismic data shows significant structuring post-dating peak hydrocarbon generation from upper Permian source rocks, which is considered to have commenced around the Middle Triassic and terminated during mid-Cretaceous uplift associated with breakup (Arditto, 2003).

The other key risk relates to reservoir quality. While the potential exists for good quality sands to have been deposited within the upper Permian coal measures, widespread diagenesis, the presence of volcaniclastic material in some sandstones, and uplift and thermal effects related to Tasman Sea rifting may have had a negative impact on the reservoir quality.

5.9.3.7 Overall prospectivity classification

Moderate–low

5.9.4 Exploration status

In contrast to the adjacent onshore basin, the offshore Sydney Basin is a frontier in terms of petroleum exploration. Initial exploration took place in the mid-1960s, and has continued intermittently to the present, resulting in a moderate density of seismic reflection, gravity, magnetic and bathymetry data (Figure 5.44). The current phase of exploration started in 1989, with the awarding of PEP10 to Santos, who acquired over 6000 line-km of 2D seismic data and identified multiple major structural targets. However, the permit was relinquished and a revival in exploration did not occur until the 2000s, with the awarding of PEP 11 to Bounty Oil and Gas. Advent Energy has been the operator of the permit since 2008, and drilled the first exploration well in the offshore Sydney Basin, New Seaclem 1, in 2011. The well reached a total depth of 755 m below seafloor in Cenozoic sediments, but failed to penetrate the underlying succession or encounter any hydrocarbons (Advent Energy, 2011).

5.9.5 Data

Key data sets for the offshore Sydney Basin are listed in Table 5.37–Table 5.39. 2D reflection seismic surveys acquired by industry, and by the Bureau of Mineral Resources (BMR) and its successor, the Australian Geological Survey Organisation (AGSO), provide the main data set for the offshore Sydney Basin. No 3D seismic reflection data have been collected, although the upcoming work programme within PEP11 may result in the first-ever 3D survey over the basin, as well as further drilling (Advent Energy, 2012).

Shipboard gravity, magnetic and bathymetry data have also been collected as part of industry and government data acquisition programmes, including the New South Wales Department of Minerals and Energy Sydney 1:250,000 aeromagnetic survey, part of which covers the offshore Sydney Basin (Stephenson & Burch, 2004). . Potential field and bathymetry data coverage over the offshore Sydney Basin includes regional compilations derived from satellite, airborne and marine data (Sandwell & Smith, 1997; Andersen et al., 2010; Maus et al., 2007, 2009; Whiteway, 2009). In addition, shipboard gravity and magnetic data were levelled in 2001 by Geoscience Australia (Petkovic et al., 2001).

5.9.5.1 Confidence rating

Medium–low

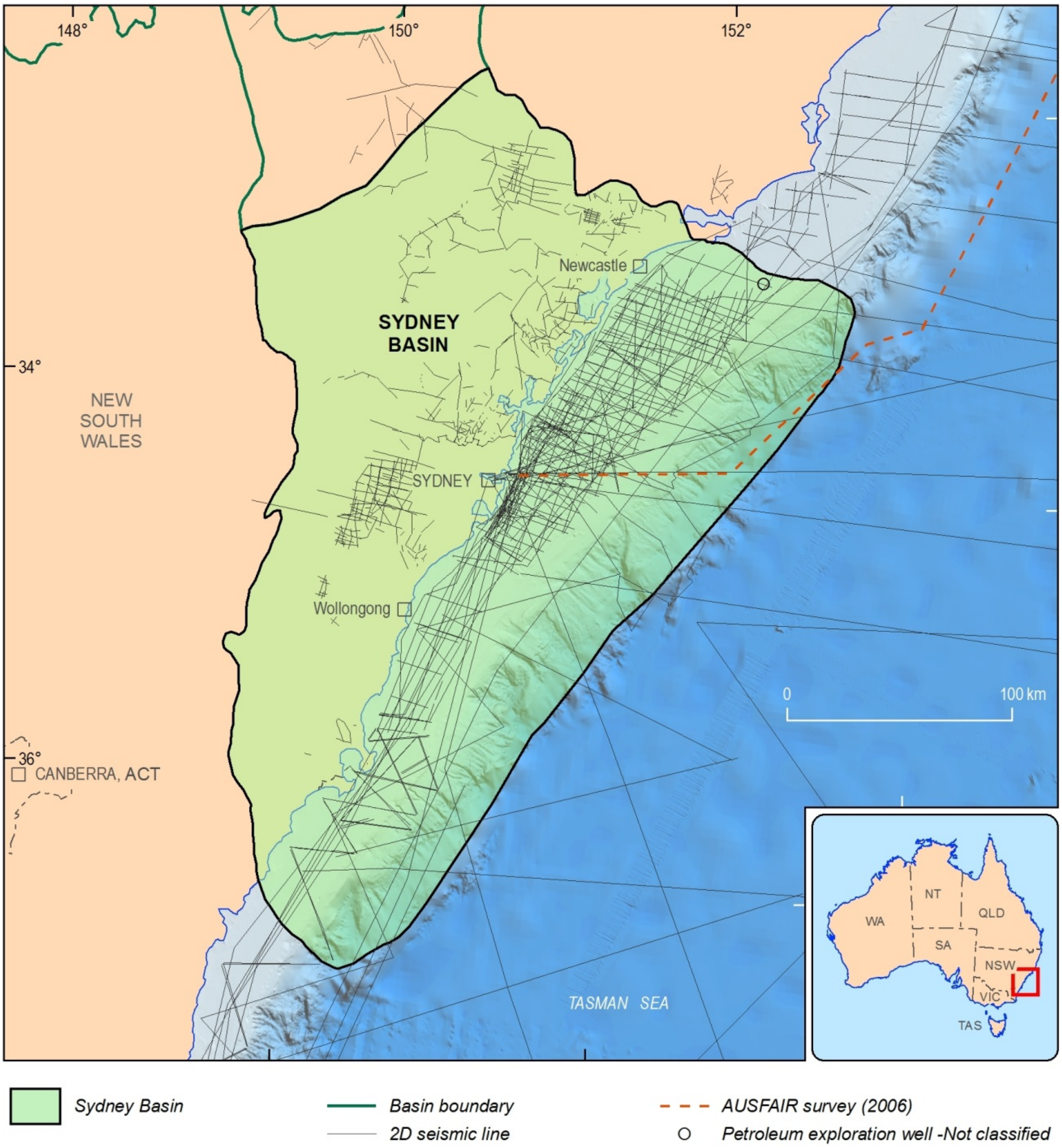

Figure 5.44: Seismic and well distribution.

5.9.6 Issues and remaining questions

The lack of direct evidence for a working petroleum system raises several questions about the fundamental prospectivity of the offshore Sydney Basin. The offshore basin is likely to contain good source and seal units, however, the potential for good quality reservoirs is less certain. Improving our understanding of the timing of generation, expulsion, trap formation and structuring, which probably differs significantly from the onshore areas due to proximity to the effects of the opening of the Tasman Sea Basin, is also a critical issue in the offshore basin.

Proximity to the largest population centre in Australia, and the eastern energy market, favourably positions the offshore Sydney Basin for future development of its hydrocarbon resources. A small portion of the southern offshore Sydney Basin is covered by the Jervis Commonwealth Marine Reserve, within which resource exploration activities are permitted.

5.9.6.1 Recommendations

Further exploration drilling that is sufficiently deep to penetrate the pre-Cenozoic section is essential in order to address some of these uncertainties. The depositional environments of the potential source, reservoir and seal formations are undoubtedly different from those in the onshore Sydney Basin, and direct sampling by drilling is required to constrain facies variability.

High-density 2D or 3D seismic data is also required in order to better understand stratigraphy and facies, the nature and timing of structuring, and to improve definition of potential trapping structures.

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5.9.8 Data Tables

Table 5.37: List of wells, offshore Sydney Basin.

Year	Well	Type	Operator	TD (m)	Age at TD	Shows	Reference
2011	New Seaclem 1	Exploration	Asset Energy Pty Ltd (Advent Energy Ltd)	755	Cenozoic	Dry hole	Advent Energy, 2011

Table 5.38: 2D seismic surveys, offshore Sydney Basin.

Year	Survey	Operator	Line-km/	Reference
1964	Offshore Sydney Basin	Shell Company of AustraliaLtd	1497	Stephenson & Burch, 2004
1967	Offshore Sydney	Shell Development (Australia) Pty Ltd	113	Stephenson & Burch, 2004
1969	Broken Bay	Longreach Oil Ltd	1400	Stephenson & Burch, 2004
1969	NSW Marine	Murphy Oil		Stephenson & Burch, 2004
1970	Teledyne Scientific	Teledyne Inc		Stephenson & Burch, 2004
1970	South Sydney Basin	Magellan Petroleum	64	Stephenson & Burch, 2004
1970	South Broken Bay	Longreach Oil Ltd	92	Stephenson & Burch, 2004
1971	Continental Margins Survey 12	Bureau of Mineral Resources (BMR)	23,924	Stagg et al., 2002
1971	Sealion	Longreach Oil Ltd	407	Stephenson & Burch, 2004
1972	Continental Margins Survey 15	Bureau of Mineral Resources (BMR)		Stagg et al., 2002
1981	Offshore Sydney Basin	ESP Exploration (Sydney Oil)	1742	Stephenson & Burch, 2004
1987	Survey 68	Bureau of Mineral Resources (BMR)		Stephenson & Burch, 2004
1991	Seaspray	Santos Ltd	603	Stephenson & Burch, 2004
2004	PEP 11 Biggus	Bounty Oil and Gas	1500	Stephenson & Burch, 2004

Table 5.39: Swath bathymetry data sets relevant to the offshore Sydney Basin.

Year	Survey	Operator	Line-km/Area (km^2)	Reference
1971	Continental Margins Survey 12 gravity	Bureau of Mineral Resources (BMR)	23,924 line-km	Stagg et al., 2002
1972	Continental Margins Survey 15 gravity	Bureau of Mineral Resources (BMR)		Stagg et al., 2002
1987	Survey 68 gravity	Bureau of Mineral Resources (BMR)		Stephenson & Burch, 2004
2001	Australian continental margin levelled gravity, magnetic and bathymetry	Geoscience Australia, Intrepid Geophysics		Petkovic et al., 2001
2006	AUSFAIR MD-153 (RV *Marion Dufresne*) bathymetry	Geoscience Australia, Ifremer	65 line-km within offshore Sydney Basin	Colwell et al., 2006
2009	Bathymetry and Topography Grid of Australia AUSBATH09 (2009)	Geoscience Australia		Whiteway, 2009

6 Summary and Conclusions

6.1 Prospectivity

Australia's offshore frontier basins are diverse in terms of geology, prospectivity and accessibility. They range from old (e.g. Proterozoic–Paleozoic Arafura Basin) to young (e.g. Mesozoic–Cenozoic Barcoo Sub-basin), from areas widely acknowledged to be highly prospective (e.g. Ceduna Sub-basin) to those where the prospectivity is more difficult to assess (e.g. Sorell Basin), and from the nearshore (e.g. offshore Sydney Basin) to the remote (e.g. New Caledonia Basin).

Figure 6.1 summarises the prospectivity assessments presented in this Inventory, with Australia's offshore frontier basins classified in terms of both their perceived prospectivity, and the confidence of this rating based on the amount (and quality) of data available.

The assessment illustrated in Figure 6.1 provides a snapshot of our current understanding and knowledge, and is subject to change. The prospectivity–confidence matrix illustrates clearly that there are many basins where acquisition of new data could fundamentally change perceptions of prospectivity, for the better or worse. Of particular interest for Geoscience Australia are those basins considered to have moderate or better levels of prospectivity but where data availability is such that the confidence of that rating is medium or low. Pre-competitive data acquisition programs and/or geoscientific studies in these basins would be a priority for GA's forward program. Prioritisation of work programs will consider the:

- critical geological, exploration and data issues within these basins
- potential for making a material difference to our understanding of prospectivity
- potential impact of any such advances in data/knowledge in terms of energy security and the identification of resources, e.g., what is the likelihood of significant discoveries, and is distance from/access to infrastructure and markets likely to impact exploration?

Of course, for all frontier basins drilling results are critical. Over the next few years, this will be no better illustrated than in the Ceduna and Rowley sub-basins. In the Ceduna Sub-basin—the basin ranked highest in terms of prospectivity and confidence—primary term exploration activities will double the number of wells in the entire Bight Basin and provide almost blanket 3D seismic coverage across the northern and southern parts of the basin. In a similar way, an eight well drilling campaign will be carried out in the Rowley Sub-basin, a basin that currently has only two wells. In five years' time, our understanding of these two, for now, frontier areas will be transformed.

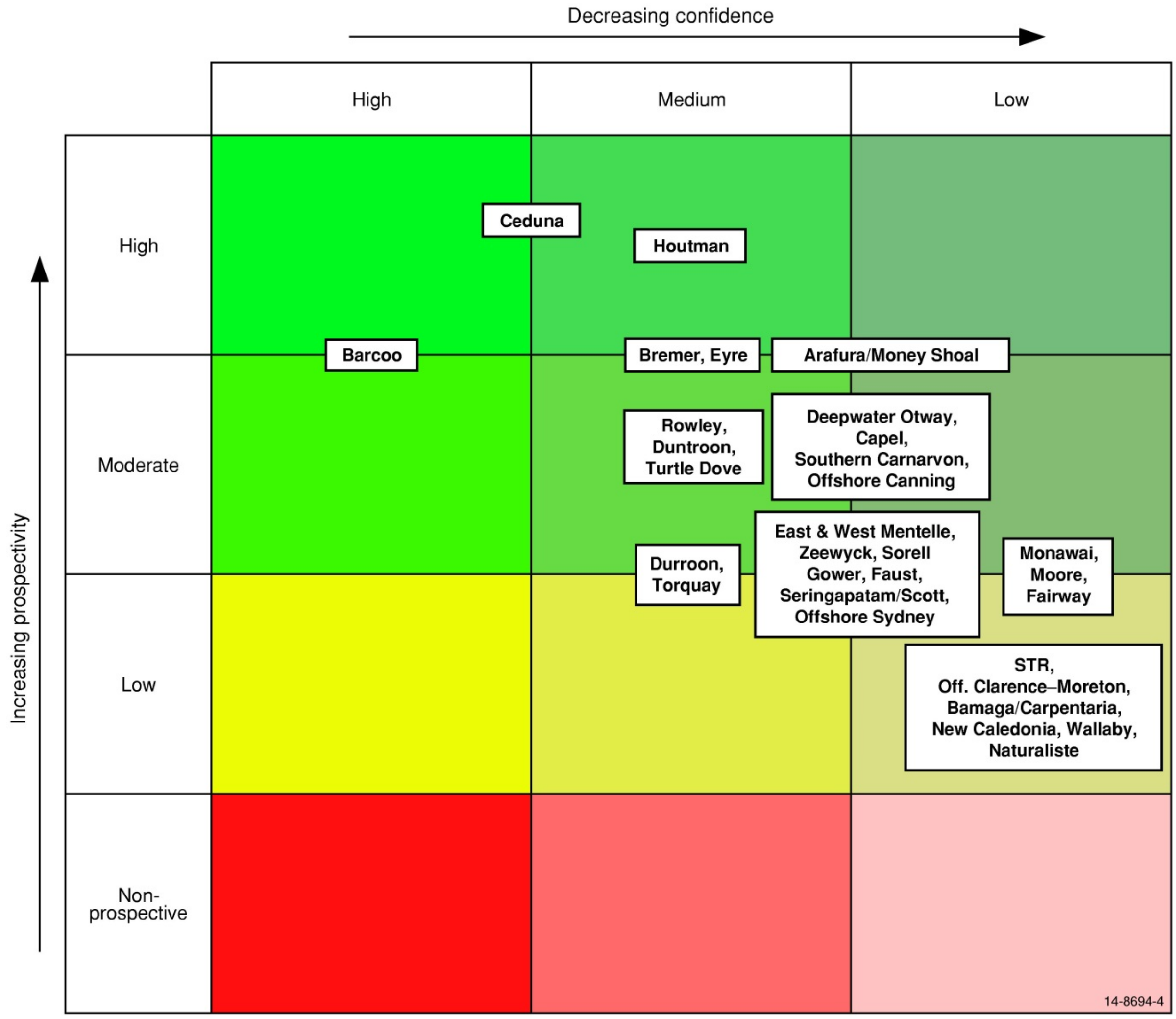

Figure 6.1: Prospectivity-confidence matrix for Australia's offshore frontier basins

6.2 Southern margin summary

The frontier basins of the southern margin can be grouped into three categories:

- Middle Jurassic–Late Cretaceous and Early Cretaceous–Cenozoic passive margin basins. These contain Middle Jurassic–Lower Cretaceous, non-marine, Austral 1 and 2 potential source rocks overlain by thick progradational Upper Cretaceous successions that potentially contain marine or marine-influenced Austral 3 source rocks (Ceduna Sub-basin, deepwater Otway Basin, northern Sorell Basin);
- Middle Jurassic–Early Cretaceous half graben. These potentially contain lacustrine or coaly Austral 1 and 2 source rocks and are variably affected by mid- or Late Cretaceous uplift and erosion events that may have compromised the preservation of hydrocarbons (Bremer, Eyre, Duntroon, Torquay and Durroon sub-basins);
- Poorly known and remote Late Cretaceous extensional depocentres (southern Sorell Basin, South Tasman Rise)

6.2.1 Middle Jurassic–Late Cretaceous and Early Cretaceous–Cenozoic basins

The Middle Jurassic–Late Cretaceous or Early Cretaceous–Cenozoic passive margin basins hold the greatest promise for exploration success on the southern margin. Of these, the Ceduna Sub-basin is considered to be the most prospective (Figure 6.1). The >15 km thick Ceduna Sub-basin succession is interpreted to contain a suite of potential source rocks, from Upper Jurassic lacustrine rocks to Upper Cretaceous oil-prone marine shales, such as the Cenomanian–Turonian organic-rich shales retrieved by dredging from the up-dip northwestern margin of the Ceduna Sub-basin. Confidence in the prospectivity of the Ceduna Sub-basin is supported by the number of permits taken up in the basin since 2011 and the scope of proposed exploration programs, particularly those of BP/Statoil and Chevron, whose guaranteed exploration programs include the drilling of eight wells. Upgrading of the geological knowledge base in the Ceduna Sub-basin is already in progress, with the acquisition by BP of approximately 12,000 km^2 of 3D seismic data.

The deepwater Otway and northern Sorell basins are considered to be moderately prospective. However, water depths and source rock maturity issues in the deepwater Otway and uncertainty about the petroleum potential of a relatively thin section in the southern Sorell represent exploration challenges. These challenges in turn provide opportunities for targeted and specific data acquisition programs, such as margin scale seismic refraction data and closely spaced 2D seismic. A key question for these basins is the distribution of potential Albian–Upper Cretaceous marine, oil-prone potential source rocks. While the presence of such rocks in the Ceduna Sub-basin has been demonstrated in part, the extent of marine influence farther east into the deepwater Otway and Sorell basins during this time is unclear. To address this and other stratigraphic and petroleum systems questions, acquisition of seismic data of sufficient density and quality to support detailed sequence stratigraphic and structural analysis of the Cretaceous succession is required. Such data would allow the building of stratigraphic and depositional models that could be used to predict the distribution of source, reservoir and seal facies, particularly within the Upper Cretaceous succession.

6.2.2 Middle Jurassic–Early Cretaceous basins

The Middle Jurassic–Early Cretaceous depocentres are located in the relatively shallow, proximal parts of the southern rifted margin. Due to a seismic data coverage of variable quantity and quality and limited drilling (nine wells) in these basins, a lack of geological constraint is a common issue. Structurally, the depocentres are characterised by half graben; as a result, early deposition was likely to have been confined to relatively isolated depocentres, with deposition becoming more extensive and connected later in basin development. Given such compartmentalisation and the data issues, a clear understanding of the variations and distribution of potential source, reservoir and seal facies is often lacking. Of particular interest in the Early Cretaceous rift basins is the presence (confirmed or interpreted) of lacustrine oil-prone potential Austral 1 source rocks; a better-constrained understanding of the timing of generation and migration from these source rocks versus trap formation and any later structural events is essential. To address these questions, detailed spatial and temporal analysis of the distribution of facies and timing of structuring in the Early Cretaceous rift basins is required. Such analysis would improve both our ability to predict the distribution of petroleum systems elements, and our understanding of the likelihood of preservation of accumulations. While some of these basins have good 2D seismic coverage (e.g. Bremer), most areas would require acquisition of closely spaced 2D or 3D data before such analysis could be undertaken. At a more regional-scale, palaeogeographic mapping and uplift, exhumation and provenance studies could improve understanding of the nature and distribution of facies, while source rock characterisation and kinetics studies of potential Austral 1 and 2 source rocks from well-explored areas of the Otway Basin may help constrain petroleum systems modelling in these frontier basins.

Particular areas may require more specialised studies, e.g. the Bremer Sub-basin, where seafloor dredging and/or piston coring could help test the salt model for the basin.

6.2.3 Late Cretaceous–Cenozoic remote frontiers

At present the third category, the remote frontiers, would appear to hold little interest for explorers due to the paucity of data, lack of evidence for active petroleum systems and distance from infrastructure and markets. The challenge in these basins is to acquire fundamental seismic data sets of sufficient quality and density to improve our understanding of the location, distribution and character of depocentres, and encourage industry interest.

6.3 Southwestern margin summary

The frontier basins of the southwestern margin comprise:

- Jurassic to Cenozoic depocentres, strongly influenced by development close to rifted or sheared margins (Houtman and Zeewyck sub-basins, Turtle Dove Ridge, Western Mentelle Basin)
- Paleozoic or Paleozoic–Early Mesozoic extensional depocentres underlying thin Mesozoic post-breakup successions on inboard parts of the margins (eastern Mentelle Basin, Southern Carnarvon Basin)
- poorly known and remote marginal plateaus of mixed continental–igneous origin (Naturaliste and Wallaby plateaus).

6.3.1 Jurassic–Cenozoic passive margin basins

The frontier basins of the northern Perth Basin (Houtman and Zeewyck sub-basins, Turtle Dove Ridge) contain a sedimentary section that records the evolution of the southwestern margin from an intracratonic Permian rift system to breakup in the early Cretaceous and the subsequent establishment of a passive margin. The basins contain several potential source rocks of Permian–Jurassic age including the Hovea Member of the Kockatea Shale, the source of hydrocarbon accumulations in the adjacent Abrolhos Sub-basin. Mapping of this sequence into the Houtman Sub-basin and the nearby exploration success underpins the high prospectivity ranking of the Houtman Sub-basin. The structural development and thermal history of these basins has been influenced by their location adjacent to a long transform segment of the rifted margin. This provides a range of exploration challenges for the area, including understanding the controls on distribution of potential source rocks and their thermal history, and the preservation of accumulations. Data coverage in these basins is variable, with significant data gaps in the Zeewyck and northern Houtman sub-basins. Drilling and seismic data acquisition and drilling in recently awarded Abrolhos and southern Houtman sub-basin permits will begin to address some of these issues. In addition, Geoscience Australia has prioritized the northern Houtman Basin as an area for future data acquisition.

To the south, the western Mentelle Basin also developed close to the rifted margin. This un-drilled deepwater province contains a thick ?Jurassic–Cretaceous succession. However, the relatively poor seismic data coverage, which limits understanding of the basin fill and the size of likely traps, and deep water remain deterrents for exploration in this area. The release of a large exploration area there in 2010 was unsuccessful. The poor perceptions of prospectivity and current data gaps could be addressed by future precompetitive data acquisition programs and, potentially, stratigraphic drilling.

6.3.2 Inboard Paleozoic and Paleozoic–Mesozoic basins

The Eastern Mentelle and offshore Southern Carnarvon basins contain early extensional depocentres (?Permo-Triassic to Jurassic and ?Ordovician–Carboniferous respectively) overlain by thin Cretaceous–Holocene passive margin successions. Data coverage in the offshore Southern Carnarvon is variable, and is particularly sparse over much of the Bernier Platform. The combination of Siluro-Devonian potential source rocks of limited distribution, and complex, poorly constrained burial, thermal and erosional histories adversely affects perceptions of prospectivity in this area. There is no direct age control on the Eastern Mentelle Basin, but the thickness of known depocentres and the structural history suggests both maturation and/or preservation are critical issues in this area. In this basin, the acquisition of both closely spaced 2D seismic data and drilling is required to improve understanding of potential petroleum systems.

6.3.3 Marginal plateaus

The marginal Naturaliste and Wallaby plateaus are poorly known rank frontiers. Although small ?Jurassic half graben have been identified on the Naturaliste Plateau, the prospectivity of these depocentres and the overall region is considered to be low due to their small size and remote location. The geology of the Wallaby Plateau is even less understood. Although sedimentary rocks have been dredged from the margin of the plateau, seismic data suggests that the identified depocentres contain a largely volcanic succession, and therefore prospectivity is considered to be low.

6.4 Northern and northwestern margins summary

The frontier basins of the northern and northwestern margins can be grouped into three categories:

- Paleozoic to Cenozoic depocentres adjacent to proven hydrocarbon provinces (Barcoo and Rowley sub-basins)
- outboard provinces strongly affected by volcanism and/or igneous intrusion (Seringapatam Sub-basin, Scott Plateau)
- Proterozoic–Paleozoic and Paleozoic extensional basins underlying thin Mesozoic post-breakup successions on inboard parts of the margins (offshore Canning Basin, Arafura/Money Shoal and Bamaga/Carpentaria basins).

6.4.1 Paleozoic–Cenozoic adjacent frontiers

The Barcoo and Rowley sub-basins are located adjacent to two of Australia’s most important hydrocarbon provinces—the Caswell Sub-basin of the Browse Basin and the Northern Carnarvon Basin. The Barcoo and Rowley sub-basins contain thick Paleozoic–Jurassic successions that are likely to contain a range of potential source rocks as well as potential reservoirs, seals and traps; their prospectivity is therefore perceived to be moderate–high (Barcoo) or moderate (Rowley). The frontier status of these basins may be due in part to the perception that in these basins the Upper Jurassic–Lower Cretaceous source rocks that underpin the successful petroleum systems in the Caswell Sub-basin and Northern Carnarvon Basin are either poorly developed or not mature. Successful exploration is therefore likely to depend on plays involving Lower–Middle Jurassic or Triassic source rocks. Both areas are currently the focus of renewed industry interest, with Woodside/Shell due to commence an eight-well drilling campaign in the Rowley Sub-basin that will focus on Triassic plays.

Due to the paucity of drilling, both areas may benefit from a basin- to regional-scale approach, incorporating data from adjacent basins to help assess potential source rocks, understand the structural evolution of the basins, the nature of depositional systems and the distribution of facies. In addition, the faulted nature of the outer margin of the Rowley Sub-basin provides opportunities for targeted dredge sampling of the Triassic–Jurassic succession that could provide additional information about potential source, reservoir and seal units.

6.4.2 Outboard volcanic provinces

The Scott Plateau and Seringapatam Sub-basin are rank frontier areas of the outer Browse Basin; data coverage is poor and the geology poorly constrained. Both areas have been strongly affected by volcanism and igneous intrusion, particularly the Scott Plateau. The distribution of depocentres is poorly known because of the poor seismic data coverage on the Scott Plateau. Current industry activity in the area is focused on the transition between the Caswell and Seringapatam sub-basins and the identification of prospects to extend the outer Browse gas play. However, the abundant Jurassic volcanic and intrusive rocks within the section provide a significant exploration challenge. These areas would benefit from studies incorporating both potential field (gravity and aeromagnetic) and seismic data to better understand the distribution of igneous rocks and the timing and degree of lithospheric thinning, and their impact on maturation history.

6.4.3 Inboard Proterozoic–Paleozoic basins

The prospectivity of the older inboard basins—the Arafura and Bamaga basins on the northern margin, and the offshore Canning Basin on the northwestern margin—varies considerably. The Arafura Basin is the most prospective, based on oil shows in the Goulburn Graben and the presence of large simple structures in the northern Arafura Basin; however significant data quality issues preclude a comprehensive analysis of the basin's prospectivity. Recent exploration successes in the onshore Canning Basin would appear to enhance the prospectivity of the offshore Canning Basin; however, widespread igneous intrusions and multiple periods of uplift and deformation may negatively affect its petroleum potential. The poorly known Bamaga Basin (underlying the Carpentaria Basin) is a rank frontier; it may represent an equivalent of the northern Arafura Basin succession, but a lack of good quality seismic data and an apparent absence of any large structures contribute to its low ranking. The critical geological and exploration issues in these areas are specific to those basins and are listed in the relevant basin assessments.

6.5 Remote eastern and southeastern margins summary

The frontier basins of the remote eastern and southeastern margins can be grouped as follows:

- Cretaceous to Cenozoic extensional depocentres on the Lord Howe Rise characterised by graben and half graben (Capel, Faust, Gower, Moore, Monawai basins)
- Late Cretaceous to Cenozoic sag depocentres located on the highly extended crust on the margins of the Lord Howe Rise (Fairway and New Caledonia basins)
- offshore extensions of large onshore basins (offshore Sydney and Clarence-Moreton basins).

6.5.1 Lord Howe Rise extensional depocentres

The Late Cretaceous extensional basins of the Lord Howe Rise are remote and drilling information is sparse (DSDP/ODP holes only). Regional-scale 2D seismic data has demonstrated the presence of graben and half graben, and seismic interpretations based on regional knowledge suggest that some have the potential to host petroleum systems. Perceived prospectivity ranges from moderate (Capel) to moderate–low (Gower, Faust, Moore and Monawai), but Figure 6.1 shows that data confidence for all areas is at best medium–low. While the basins of the Lord Howe Rise would all benefit from the acquisition of both additional regional-scale 2D and more closely-spaced 2D or 3D seismic data, the geology and petroleum prospectivity of these depocentres can only truly be tested by drilling (stratigraphic or exploration) that penetrates the full section.

6.5.2 Remote Late Cretaceous to Cenozoic sag basins

Only the central portions of the extensive Fairway and New Caledonia basins are within the limits of Australia's Continental Shelf; the central portion of the New Caledonia Basin is considered to be the least prospective part of the basin. These basins overlie highly extended continental crust and are interpreted to contain an Upper Cretaceous–Cenozoic succession. Data coverage is generally poor. Good quality seismic data and drilling that could verify the age and nature of the basin fill is required to better understand the petroleum potential of these basins. However, in view of their remoteness and relatively thin sedimentary succession, they are unlikely to be a priority area for data acquisition in the near future.

6.5.3 Southeastern margin basins

Offshore extensions of the Permian–Triassic Sydney Basin and Triassic–Jurassic Clarence-Moreton basin occur on the narrow southeastern continental margin. Data coverage is low–medium and the geology of these offshore depocentres is poorly understood. The reservoir quality issues that have prevented exploration success in the onshore Sydney Basin are also likely to be present in the offshore region, where the heating and diagenetic effects of Tasman Sea breakup are also likely to impact potential reservoirs. Little is known about the depocentre that lies offshore from the Clarence-Moreton Basin, including its age. Both basins would benefit from acquisition of high-quality seismic data and ultimately, drilling. Some of the critical questions for the offshore Sydney Basin may be answered in the next few years as the area is currently under permit, and the exploration program includes drilling.

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Corrigenda

- References to the well Thistle 1, previously wrongly located, have been removed and the number of wells in the deepwater Otway Basin corrected; pages 78, 82, 86, 91 and 93.
- Revisions made to the following figures:
  - Figure 2.1 (p. 6)
  - Figure 2.24 (p. 75)
  - Figure 2.35 (p. 112)
  - Figure 3.1 (p. 155)
  - Figure 4.1 (p. 269)
  - Figure 6.1 (p. 513)