



Regional Geology of the Otway Basin

The Otway Basin is a broadly northwest to southeast striking rift basin that extends for approximately 500 km along the onshore and offshore parts of southeastern Australia (**Figure 1**). Approximately 80% of the basin is located offshore and 20% onshore. In total, the basin covers an area of approximately 155 000 km²; 45% of the basin is located in Victoria, 35% in South Australia and the remaining 20% within Tasmanian jurisdiction.

The Otway Basin is an important gas-producing region with discoveries onshore and in shallow water areas offshore approximately 170–220 km west-southwest of Melbourne, the State Capital of Victoria, delivering gas to the southeastern Australian energy market (**Figure 2**). Natural gas from Victoria, transported via the Port Campbell–Adelaide pipeline and the South East South Australia Pipeline, powers the 80 MW Ladbroke Grove power station adjacent to the Katnook facility. This gas also supplies markets serviced by the South East Pipeline System, replacing declining supply from the local onshore fields (**Figure 3**). The greater Melbourne region represents a large domestic gas market and is supported by two major petroleum refineries in Geelong and Altona. Portland, on the western Victorian coast, is a deep-water port suited to offshore operations and is serviced by an excellent road and rail network.

Basin outline

In the Otway Basin, several distinct depocentres developed in response to two major phases of extensional tectonism; the first in the Late Jurassic–Early Cretaceous and the second in the Late Cretaceous. These include the Robe, Colac, Gellibrand and Penola troughs in the onshore part of the basin. The Tartwaup-Mussel Fault Zone became the principal basin-margin fault zone when rifting progressively propagated southward along the western margin of Tasmania. In the offshore Otway Basin, rifting created the basin's principal structural elements, including the Voluta Trough, Mussel Platform, Prawn Platform and Shipwreck Trough (**Figure 4**). Further offshore are the Upper Cretaceous depocentres of the Morum, Nelson and Hunter sub-basins, and the Discovery Bay High (Totterdell et al, 2014). The Torquay Sub-basin, a largely offshore depocentre, is situated in the northeastern part of the basin and contains a Lower Cretaceous succession similar to that elsewhere in the basin. This interval is overlain by a thin, post-rift Upper Cretaceous succession that has affinities with the Upper Cretaceous sediments in the Bass Basin (Trupp et al, 1994; Blevin and Cathro, 2008; Totterdell et al, 2014).

Basin evolution and stratigraphy

With the onset of the major rifting phase in the Late Jurassic, several east-northeast-trending extensional depocentres were generated, which developed into the Robe, Colac and Gellibrand troughs in the onshore part of the basin. Older parts of the Portland Trough and the Torquay Sub-Basin may also be related to this extensional phase (Trupp et al, 1994; Perincek and Cockshell, 1995). The Penola Trough and most of the Portland Trough were formed by southeasterly transtension between the original rifts, as extension continued. The easternmost portion of the offshore Voluta Trough may represent a continuation of these structures (**Figure 4**). Final break-up in the Otway Basin probably occurred in Victoria in the Maastrichtian at about 67 Ma (Lavin, 1997).

For detailed descriptions of the sedimentary history and stratigraphy of the Otway Basin, the reader is referred to publications by Parker (1995), Lavin (1997), Geary and Reid (1998), Boyd and Gallagher (2001), Constantine (2001), Partridge (2001) and Krassay et al (2004).

Early Rifting (Late Jurassic-Early Cretaceous)

During the Late Jurassic, as extension progressed into the Early Cretaceous and subsidence continued, the various, initially distinct rift basins expanded substantially. In excess of 5000 m of non-marine fluvio-lacustrine Otway Group (**Figure 5**) sediments filled these depocentres. The Robe and Penola troughs provide the record of Early Cretaceous sedimentation (**Figure 5** and **Figure 6**). The lacustrine sediments and interbedded flow basalts of the Casterton Formation are overlain by the predominantly fluvial sediments of the Pretty Hill Formation, which are, in turn overlain by lower energy fluvial and lacustrine sediments of the Laira Formation. The overlying Katnook Sandstone represents the return to higher energy fluvial deposition.

Rift to Sag Transition (Aptian-Albian)

The influence of the main extensional faults that controlled the Late Jurassic to Early Cretaceous rifting waned in the early Aptian across most of the Otway Basin. Previously elevated footwall blocks disappeared as widespread thermal subsidence occurred across the basin. In excess of 4000 m of Aptian to Albian sediments belonging to the Eumeralla Formation were deposited southward of the Mussel-Tartwaup-Fault-Zone in a progressively widening, regional sag basin. In the western Otway Basin, the Morum Sub-basin became the focus of deposition, and up to 3100 m of non-marine sediments (Eumeralla Formation) were deposited (Jensen-Schmidt et al, 2001). Separated from the Morum Sub-basin by the Discovery Bay High, the Nelson Sub-basin (**Figure 4**) developed into the major depocentre of the eastern Otway Basin. Sediments accumulated in a variety of non-marine depositional environments including fluvial, flood plain, coal swamp and lacustrine. These sediments are characterised by a large amount of volcanoclastic detritus, derived from local intra-rift sources (Duddy, 2003) and, to a lesser extent, from volcanic complexes located to the east of the Gippsland Basin (Bryan et al, 1997).

The Morum Sub-basin contains at least 5 s TWT (~8 km) of Cretaceous sediments overlain by a thin Cenozoic succession. The sub-basin is characterised by intense faulting that affects the entire Cretaceous succession (Moore et al, 2000). The faults are typically high-angle, particularly in the inboard fault zone that underlies the upper continental slope. Lower-angle listric faults are common farther basinward (**Figure 7**).

Compression, Uplift and the Otway Unconformity (mid-Cretaceous)

Rifting ceased in the late Albian as the Otway Basin was subjected to significant compression giving rise to the basin-wide, angular Otway Unconformity (Partridge, 2001). Several areas including the Otway Ranges and the Cape Otway-King Island High underwent several kilometres of inversion. However, structuring was not uniform across the basin, with many areas experiencing only mild uplift. Studies of apatite fission track (AFT) data and vitrinite reflectance (VR) data from wells in the basin, suggest that it experienced regionally elevated temperature gradients (50-60°C/km) in the Early Cretaceous (Foster and Gleadow, 1992; Duddy, 1994; O'Brien et al, 1994; Cooper and Hill, 1997; Mitchell, 1997). Driven by uplift and erosion, the heat-flow and associated geothermal gradient decreased sharply in the early Late Cretaceous.

Renewed Rifting (Late Cretaceous)

A renewed phase of extension and rift-related subsidence began in the Turonian. Rifting continued to control basin development through much of the Late Cretaceous until the latest Maastrichtian when final continental breakup took place (Lavin and Naim, 1995; Lavin, 1997). Syn-rift sedimentation during that period is recorded by the partially marine Sherbrook Group (**Figure 8**).

The second rifting phase was driven by a change in crustal extension direction to northeast-southwest, from the earlier north-south direction. This created a structural style distinctly different from that developed by the earlier rifting. In the offshore, where the Late Cretaceous rifting was concentrated, the resulting structures overprinted those of the initial rift phase. Most of the major structural features, including the Voluta Trough (the major rift-induced depocentre), Mussel Platform, Prawn Platform, Tartwaup-Mussel Fault System, Shipwreck Trough and Sorell Fault Complex (**Figure 4**), were formed by the Late Cretaceous rifting. In some areas such as the Shipwreck Trough and Mussel Platform in the eastern part of the basin, sinistral strike-slip motion resulted in the development of transpressional structures with both extensional and compressional components. These are tightly folded, north-trending anticlinal structures, which are particularly well developed in the Shipwreck Trough.

Continental Break-up (late Maastrichtian)

Moderate structuring and regional uplift which accompanied the late Maastrichtian continental break-up along this part of the margin, resulted in development of the Late Maastrichtian Unconformity, which separates pre-rift from post-rift strata. Post-rift (latest Maastrichtian to Holocene) sediments were deposited along the continental shelf in a divergent, passive margin setting, as Antarctica separated and drifted further away from Australia with concomitant opening of the Southern Ocean. The post-rift succession is made up of three distinct supersequences (Krassay et al, 2004) separated by major unconformities that represent different stages of passive margin development. This succession is subdivided into three groups: the Wangerrip, Nirranda and Heytesbury groups (**Figure 5**).

Thermal Subsidence and Marine Transgression (Paleocene-early Eocene)

The peneplain represented by the Late Maastrichtian Unconformity was flooded during the first major transgression of the incipient Southern Ocean towards the end of the Maastrichtian, initially depositing the Massacre Shale (**Figure 8**) which accumulated in a distal offshore environment of uncertain water depth (Partridge, 1999). This was followed by the creation of shallow marine to coastal depositional environments in which the Pebble Point Formation accumulated. This sequence is succeeded by strongly progradational Paleocene to early Eocene sediments belonging to the Pember Mudstone. This sequence was deposited in shelfal to shallow marine environments on a southwesterly building marine shelf that trended approximately parallel to the present day coastline (Arditto, 1995). The Pember Mudstone is partly equivalent to, and partly succeeded by the Dilwyn Formation (represented by topset beds) deposited in coastal plain and deltaic environments. All three formations are time equivalent to terrestrial sediments of the lower Eastern View Coal Measures that are restricted to the Torquay Sub-basin (**Figure 9**) and the Colac Trough.

Seafloor Spreading in Southern Ocean (middle Eocene-early Oligocene)

The Middle Eocene Unconformity separates the Wangerrip Group from the overlying Nirranda Group. This unconformity, which is widespread on the southern Australian margin, is correlated with minor tectonism produced by a significant increase in the rate of seafloor spreading in the Southern Ocean south of Australia (Yu, 1988). The erosional surface, which in some parts of the Otway Basin is incised by steep channels and exhibits considerable relief, is infilled and draped by sediments of the middle Eocene to lower Oligocene Nirranda Group. The Nirranda Group comprises prograding nearshore to offshore marine clastics of the basal Mepunga Formation that grade upwards into increasingly open marine carbonates of the Narrawaturk Marl. Both formations are time equivalent to the proximal Demons Bluff Formation and Eastern View Coal Measures recognised onshore in the northeastern part of the Otway Basin and Torquay Sub-basin (Abele et al, 1976; Blake, 1980; Tickell, 1991). In South Australia, Cenozoic strata of the Wangerrip, Nirranda and Heytesbury Groups are classified as belonging to the Gambier Basin, known previously as the Gambier Embayment of the Otway Basin (Smith et al, 1995) the stratigraphy of which extends into the Voluta Trough (**Figure 10**).

Exploration history

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 part of the Otway Basin at Kingston. Early drilling was based on the theory that coorongite (subsequently found to be a surface algal deposit) originated from underground oil seepages. Commercial CO₂ was discovered in Caroline 1 in 1968, but it was not until 1987 that the first commercial gas discovery was made at Katnook. This was followed by the discovery of the Ladbroke Grove Field in 1989. In 2007, the appraisal of the Jacaranda Ridge Field significantly upgraded the northern part of the Penola Trough as a wet gas–condensate play. The lack of early success may be attributed to poor quality seismic data prior to the early 1980s, and a poor understanding of structural and stratigraphic relationships in the Robe and Penola troughs. Good quality modern seismic coverage now exists over the offshore and most of the onshore parts of the basin and stratigraphic relationships are better understood.

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). These wells were relatively shallow (<500 m) and only penetrated Cenozoic sediments. 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 (118 931 m³/d) from Waarre Formation sandstones.

In 1966, Esso and Shell farmed into the Otway Basin and, with Frome-Broken Hill, drilled 22 wells in both Victoria and South Australia. Hoping to find an analogue for the Gippsland Basin, their efforts were largely unrewarded as only minor gas shows were initially recorded in Pecten 1A—the first well drilled on the Mussel Platform in the eastern part of the Otway Basin. The major companies had abandoned the Otway Basin by 1976, discouraged by the lack of commercial oil or gas discoveries.

After a period of limited drilling and seismic acquisition in the region, Beach Petroleum discovered gas in Waarre Formation sandstones in North Paaratte 1, located only 3 km northeast of Port Campbell 1. Encouraged by this gas discovery onshore, offshore release areas were offered and petroleum exploration permits were awarded to Esso, Phillips and Ultramar, though no new discoveries were made. In contrast, Beach Petroleum made additional small onshore gas discoveries within the Upper Cretaceous Waarre Formation in 1981 at Grumby 1 and Wallaby Creek 1.

In 1987, gas fields in the Port Campbell area went into production, supplying the regional centres of Portland and Warrnambool. In the early 1990s, BHP Petroleum Pty Ltd (BHP) discovered gas in two wells drilled on the Mussel Platform on the flanks of the Shipwreck Trough—Minerva 1 (1993) and La Bella 1 (1993)—as well as drilling two dry holes. After drilling an additional three wells that only encountered minor gas shows, BHP relinquished its exploration permits in 1997, but obtained retention leases over the Minerva and La Bella fields.

Only three wells have been drilled in the deep water 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 by Somerset 1 in 2009; all wells were dry. The oldest unit penetrated in the deep water Otway Basin is the Turonian Waarre Formation, which was reached in Morum 1 (Esso Australia, 1975). All of these wells are located on the edge of the continental shelf. The continental slope and deep-water areas remain relatively unexplored.

Similarly, the Torquay Sub-basin has seen only moderate levels of exploration activity, and only three wells have been drilled in the offshore parts of the sub-basin (**Figure 1**). The best quality seismic data is available over the Snail Terrace. Exploration in the sub-basin commenced in the 1960s, when Shell drilled the Nerita 1 well (Shell Development, 1967). In the early 1970s, Hematite acquired seismic data and drilled the Snail 1 well (Hodgson and Mellins, 1973). The Bureau of Mineral Resources (BMR; now Geoscience Australia) also acquired several regional seismic lines in 1982. During the late 1980s to early 1990s, Shell undertook an exploration campaign in the basin that included the acquisition of gravity, magnetic and seismic data, and culminated in the drilling of Wild Dog 1 (Trupp et al, 1993). Permit VIC/P62 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 to the east of Wild Dog 1. The joint venture partners have identified numerous leads that include an untested structural play in the Lower Cretaceous Pretty Hill Formation (Rogers, 2013). The permit was renewed in 2014 and full ownership was transferred to Loyz Energy in 2016. However, after conducting a series of feasibility studies, Loyz Energy has decided to relinquish the permit (Loyz Energy, 2017).

There was a strong resurgence in exploration activity in the Otway Basin from 1999 to 2005, which was driven by a combination of factors, including changes in the gas market and technological advances. A major exploration program by a Woodside Energy Ltd joint venture, utilising state-of-the-art 3D seismic technology, resulted in the large (approximately 1.3 Tcf [36.8 Gm³] GIP combined) Geographe and Thylacine gas discoveries. In the onshore, a Santos Limited joint venture exploration program, again using state-of-the-art 3D seismic acquisition technology, resulted in the discovery of three new gas fields. In 2002, another commercial offshore gas discovery was made by Strike Oil with the Casino 1 well, drilled by Santos Limited approximately 20 km southwest of the Minerva field on the western flank of the Shipwreck Trough. According to Offshore Technology (2018,) the Casino gas field holds an estimated recoverable reserve of 290 Bcf (7.9 km³)—the field was brought into production in 2006. In 2004 and 2005, Santos Limited made an offshore gas discovery during the drilling of Martha 1 and Henry 1. Also in 2005, Woodside discovered the Halladale and Blackwatch gas fields about 4 km offshore in the Shipwreck Trough, with Origin Energy subsequently acquiring Woodside's interest in these fields as part of their development strategy. In 2008, gas shows were encountered at Netherby 1 and Pecten East 1, but there has been limited exploration success since that time. In 2012, Thistle 1 was drilled by Origin Energy to the north of the Thylacine/Geographe gas fields but no hydrocarbons were encountered. Onshore, three exploration wells were drilled in South Australia in 2013–2014—one targeting a conventional petroleum play (Sawpit 2), and two targeting unconventional plays (Jolly 1 and Bungaloo 1).

During the last decade, drilling has largely focused on the appraisal and development of known accumulations. Origin Energy appraised the Halladale field with the drilling of Halladale 2 ST1 in 2014 (Origin Energy Limited, 2015). Origin Energy also drilled the Speculant 1 exploration well in the Victorian part of the inner Otway Basin, which resulted in a gas discovery (Origin Energy Limited, 2014). This was followed with the Speculant 2 appraisal well in 2015 (Origin Energy Limited, 2015).

In 2017, a new entrant to the Otway Basin, Adelaide-based Cooper Energy, was awarded operatorship of VIC/P44 with a 50% title interest, the other 50% being shared with Peedamullah Petroleum Pty Ltd and Mitsui E&P Australia Pty Ltd. The transferred work program from original title holder Santos Ltd included the drilling of one exploration well. In September 2019, Cooper Energy announced the discovery of a new gas accumulation at Annie 1, the first in a decade for the Otway Basin. The well successfully tested the Waarre Formation and intersected a gross gas column of 70 m within the Waarre C reservoir section. According to Cooper Energy, the discovery has a net pay thickness of 62 m and is earmarked to commence production via the existing Minerva Gas Plant in late 2021, provided that development drilling can proceed in a suitable timeframe (Cooper Energy, 2019).

Most recently, gas was discovered in license VIC/P43 held by Beach Energy Ltd (60%) and O.G. Energy (40%). Exploration well Artisan 1, drilled in early 2021, intersected 69.5 m of gas (gross, 62.9 m net pay) in the Upper Waarre Formation and a further 20.9 m of gas (gross, 4.6 m net pay) in the Flaxman Formation, a secondary target. The well has been cased and suspended as a future producer with potential to supply the Otway Gas Plant by tie into existing pipelines (Beach Energy, 2021).

Several offshore seismic surveys were acquired in the last decade, including Origin Energy's Astrolabe 3D and WHL Energy's La Bella 3D, carried out in 2013. These were followed by Origin Energy's Enterprise 3D and 3D Oil's Flanagan 3D, both completed 2014.

In December 2019, 3D Oil announced the successful farm-out of 75% of its interest in T/49P to ConocoPhillips. Under the new arrangement, a 3D seismic survey is scheduled to begin in August 2021. Following the completion of the acquisition, processing and interpretation of the 3D seismic survey a decision regarding the drilling of an exploration well will be made.

The latest seismic data acquisition in the basin was carried out by Schlumberger in early 2020. The Otway Basin 2D Multiclient Marine Seismic Survey (Otway Basin 2DMC MSS; NOPSEMA, 2019) acquired 7000 line kilometres across the underexplored deep-water part of the basin. The new data will improve imaging of the sedimentary section, enabling a reassessment of the basins prospectivity. It is anticipated that the processed data, including the new acquisition and reprocessed legacy data, will become open file in 2021. This survey is part of a major regional petroleum geological review of the Otway Basin, being carried out by Geoscience Australia. Parts of the review will focus on the distribution of petroleum systems elements in the Early and Late Cretaceous sequences. Of special interest is the recognition of possible marginal marine environments in the deep-water area, which might be an analogue to the Late Cretaceous section in the Bight Basin. On completion of the study, the results and related data sets will be made publicly available. Additionally, an open file Petroleum Systems model of the deep-water Otway will be released in 2021.

Production and development

Production from the Minerva gas field commenced in 2004, via two subsea wells drilled in shallow waters tied back to an onshore gas plant. By the year ending December 2018, total petroleum production from the Minerva field was 2.33 MMboe (EnergyQuest, 2019). Production from the Minerva field ceased in early September 2019 (EnergyQuest, 2020). The Minerva gas plant, subsequently acquired by Cooper Energy and Mitsui and renamed Athena, is undergoing upgrades and modifications to replace processing at the Iona gas plant and potential to further develop the Henry field and develop the Annie 1 discovery (EnergyQuest, 2021).

In 2007, the Otway Gas Project commenced production of gas, condensate and LPG from the Thylacine field in Tasmanian waters. In 2013, the Geographe field, 15 km north of Thylacine (**Figure 1**, **Figure 2**), also commenced production (Origin Energy Limited, 2013). The project was expanded in 2018 when Beach Energy acquired the Lattice Energy (Origin Energy's gas upstream arm) operated Halladale/Speculant gas project which came online in August 2016. The project involved a new 33 km pipeline connecting the Halladale and Speculant well sites to the Otway Gas Plant (Beach Energy, 2019). Beach Energy is now operating the natural gas production at Speculant/Halladale delivering up to 80 TJ/day to the SE-Australian gas market. Total gas production from the Otway Gas Project was 34.2 PJ for the 12 month period ending March 2020 (EnergyQuest, 2020). Drilling of the Black Watch 1 well was successfully completed on 19 April 2020 and is planned to be tied into the Otway Gas Plant later in 2020 (Beach Energy, 2020).

The Casino gas project, now operated by Cooper Energy, went into production in 2006 with an estimated recoverable reserve of 280 Bcf (7.9 Gm³). The success of the Casino Gas project facilitated development of the Henry, Martha and Pecten discoveries, allowing production of gas from these fields via the existing Casino infrastructure to the onshore Iona production facility. Total gas production from the Casino hub was 11.6 PJ for the 12 month period ending March 2020 (EnergyQuest, 2020). Production from the Netherby 1 DW1 and Henry 2 wells in the Henry gas field commenced in 2010. The gas from Pecten will also be linked to the Henry gas field infrastructure for future production

Australia's southeastern gas market is currently undergoing major supply challenges which are partly driven by LNG exports to Asian markets from Gladstone, Queensland, but also by an existing moratorium on shale gas development in NSW and a total ban on oil and gas exploration and production in onshore Victoria. In June 2020, the Victorian Parliament passed the *Petroleum Legislation Amendment Act 2020*, which will strengthen community safeguards in the regulatory framework and provide for the implementation of an orderly restart of the onshore conventional gas industry from 1 July 2021 (Victorian State Government, 2021). The permanent ban on unconventional gas remains, which prevents hydraulic fracturing or exploring and mining of coal-seam gas. In this context, the newly released acreage in the offshore Otway Basin provide excellent opportunities to make additional gas discoveries that can be monetised rapidly by taking advantage of the existing infrastructure (**Figure 2**).

At the end of 2019 a total of 1,866 PJ (1.66 Tcf) of gas had been produced from the Otway and Bass basins (Geoscience Australia, 2021). Remaining gas reserves (2P) are estimated at 1.065 PJ (0.95 Tcf) and contingent resources (2C) at 721 PJ (0.64 Tcf).

A map showing the current main operators, active exploration permits, retention leases and production licences is provided in **Figure 11**.

Regional petroleum systems

Hydrocarbon discoveries on the Australian southern margin are assigned to the Austral Petroleum Supersystem (Bradshaw, 1993; Edwards et al, 1999; Summons et al, 2002), in which three subsystems are recognised:

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

O'Brien et al (2009) mapped the peak hydrocarbon generation fairways for the three petroleum systems in the Otway Basin (**Figure 12**) and concluded that the principal control on the distribution of significant hydrocarbon accumulations in the basin is proximity to actively generating source kitchens. This is related to poor fault seal in the basin, so that development of hydrocarbon accumulations is reliant on the charge rate exceeding the leakage rate, complicated by relatively complex and tortuous migration pathways.

While many discoveries have been made in the inboard basin, only six petroleum exploration wells have been drilled in the remainder of the offshore parts of the basin—three in the deep water sub-basins (Morum 1, Amrit 1 and Somerset 1) and three in the offshore Torquay Sub-basin (Nerita 1, Snail 1 and Wild Dog 1). All of these wells were plugged and abandoned as dry holes. Austral 2 source rocks are modelled as being overmature across much of the Late Cretaceous depocentre in the deep water parts of the basin (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 support for the concept that active petroleum systems are present in the deep water parts of the basin.

Petroleum Systems Elements

Sources	<ul style="list-style-type: none"> Upper Cretaceous–lowest Paleogene fluvial-deltaic Sherbrook Group (Turonian Waarre Formation and Coniacian–Santonian Belfast Mudstone) and marginal marine basal Wangerrip Group (Austral 3 unproven) Aptian–Albian lower coastal plain and peat swamp Eumeralla Formation shale and coal (Austral 2) Upper Jurassic to Lower Cretaceous fluvial-lacustrine shales of the Casterton Formation and Crayfish Subgroup (Austral 1)
Reservoirs	<ul style="list-style-type: none"> Paleocene Pebble Point Formation Upper Cretaceous Paaratte Formation and Timboon Sandstone Upper Cretaceous Thylacine Member, Belfast Mudstone Upper Cretaceous Waarre and Flaxman formations Lower Cretaceous Eumeralla Formation Lower Cretaceous Pretty Hill Formation
Seals	<p><i>Regional seals</i></p> <ul style="list-style-type: none"> Upper Cretaceous Belfast Mudstone Lower Cretaceous Laira Formation <p><i>Intraformational seals</i></p> <ul style="list-style-type: none"> Eocene Mepunga Formation Paleocene–Eocene Pember Mudstone and Dilwyn Formation Uppermost Cretaceous/Paleocene Massacre Shale Intraformational mudstones within Upper Cretaceous Paaratte Formation and Timboon Sandstone Upper Cretaceous Flaxman Formation Lower Cretaceous Eumeralla Formation
Traps	<ul style="list-style-type: none"> Faulted anticlines, tilted fault blocks with cross-fault seal

Source Rocks

In the Otway Basin, the source rocks of the Austral 1 Petroleum System consist of non-marine, Upper Jurassic to Lower Cretaceous fluvial-lacustrine shales deposited in half graben (Casterton Formation and Crayfish Subgroup). Edwards et al (1999) grouped liquid hydrocarbons sourced by Austral 1 source rocks into four oil families, based on isotopic and biomarker signatures, and interpreted the depositional environments of the source rocks. The Austral 1 Petroleum System is recognised primarily in the Penola and Robe troughs as the source for: oil and bitumen in Crayfish 1A and Zema 1 (Family 1); condensates and oil in Wynn 1 and Sawpit 1, respectively (Family 2); condensates in Haselgrove 1, 2 and Haselgrove South 1, 2 (Family 3); and, gas and minor condensate in Troas 1 (Family 4).

With the exception of the Penola and Robe troughs, the vast majority of hydrocarbon discoveries in the Otway Basin belong to the Austral 2 Petroleum System, which consists of Lower Cretaceous (Albian–Aptian) source rocks charging the overlying basal Upper Cretaceous Waarre siliciclastic reservoir unit (Edwards et al, 1999; Boreham et al, 2004; O'Brien et al., 2009). These include the onshore fields in the Port Campbell Embayment and all offshore gas fields in the greater Shipwreck Trough area (Mehin and Link, 1994; Foster and Hodgson, 1995; Luxton et al, 1995; Boreham et al, 2004). Source intervals comprise coals and carbonaceous shales within two coal measure sequences in the Eumeralla Formation, one of Aptian age near the base of the unit and the other of early Albian age.

The Sherbrook and basal Wangerrip group potential source rocks of the Austral 3 Petroleum System have not been definitively linked to any hydrocarbons in the Otway Basin (Totterdell et al, 2014), but most of the wells drilled in the basin have been located either on inner shelfal areas or onshore where the Sherbrook Group has not reached sufficient thermal maturity for significant hydrocarbon generation to have occurred. 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 provides the sole hydrocarbon charge. Migration of Austral 3-sourced wet gas from the deep-water basin up the Tartwaup–Mussel Fault Zone was suggested by O'Brien et al (2009) as a possible mechanism to explain this difference. The only oil thought to be attributed to the Austral 3 Petroleum System is derived from the Pebble Point Formation in Wilson 1, located in the Victorian onshore part of the basin (Lavin, 1998). However, the Wilson 1 oil stain has since been reinterpreted as a drilling contaminant rather than in-place or migrated hydrocarbons (Boreham et al, 2004; O'Brien et al, 2009; Goldie-Divko, 2015). The Turonian Waarre Formation contains both marginal marine and coastal plain sediments that can be regarded as viable source rocks, provided they are sufficiently deeply buried. Farther basinward, these units are likely to comprise prodelta and open marine facies, which may have greater potential for containing high-quality source rocks, especially as studies by O'Brien et al (2009) suggest that the Turonian section in the deeper offshore would lie within the hydrocarbon maturity window. 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 deep water 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 interpretation that the basal parts of the Sherbrook Group became increasingly rich in organic matter basinward, as marine conditions became more prevalent in the Late Cretaceous.

The nature of potential source rocks basinward of the Tartwaup–Mussel Fault Zone in the Otway Basin is not well understood; however interpretation of seismic data indicates that the Lower and Upper Cretaceous depositional sequences that contain Austral 2 and Austral 3 source rocks elsewhere in the basin (Boreham et al, 2004), are also likely to be present in the deep water Otway Basin (Totterdell et al, 2014). Seismic interpretations indicate that Lower Cretaceous sequences thin basinward into the deep water Otway Basin; conversely, the Upper Cretaceous Shipwreck and Sherbrook supersequences thicken considerably basinward of the controlling Late Cretaceous faults systems (**Figure 13**).

Given the thickness of the Upper Cretaceous succession, potential Austral 2 source rocks (coaly sediments of the Eumeralla Supersequence) are modelled to be overmature across much of the deep water basin (Reid et al, 2001; O'Brien et al, 2009). Consequently, exploration success in the deep-water basin is likely to be dependent on the presence of Turonian or younger (Austral 3) source rocks in the Shipwreck and Sherbrook supersequences (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 source potential (Duddy et al, 2003). In this region, the basinward-thickening Upper Cretaceous succession 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 Torquay Sub-basin, the best potential source rocks are the Upper Jurassic to lowest Cretaceous Casterton Formation and Crayfish Supersequence (Austral 1; Edwards et al, 1999; Boreham et al, 2004) and the Lower Cretaceous Crayfish and Eumeralla supersequences (Austral 2; Edwards et al, 1999; Boreham et al, 2004). Although the Eastern View Formation provides 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.

Reservoirs and seals

The Pretty Hill Formation (part of the Crayfish Subgroup) is the major play fairway in the South Australian part of the Otway Basin and is the producing unit in the Katnook, Ladbroke Grove, Haselgrove and Haselgrove South gas fields. In Victoria, the Pretty Hill Formation has good reservoir characteristics at shallow to moderate depths of burial (1000–2300 m), with measured porosity of 13.2–32.0% (average 20.7%), and permeability of 390 mD (Mehin and Constantine, 1999). The reservoir potential of the unit at depths greater than approximately 2300 m is uncertain due to a lack of well penetrations. However, reservoir data from gas fields in the Penola Trough, onshore South Australia, suggest that porosity and permeability within the Pretty Hill Formation may be quite high, given that the gas zones in these fields (between 2500 m and 2800 m) have effective average core porosity of 10–18% and permeability of 0.6–549 mD (Parker, 1992).

Vertical and cross-fault sealing of the Penola Trough gas reservoirs in South Australia is provided by the Laira Formation (Parker, 1992; Lovibond et al, 1995). In Victoria, by contrast, the sealing unit is likely to be the Eumeralla Formation, since the Laira Formation is absent, except in a few wells located near the Victorian–South Australian border (Mehin and Constantine, 1999).

The Turonian Waarre Formation (**Figure 5**) is the major regional reservoir unit in the Victorian part of the Otway Basin. Producing gas has been encountered in sixteen onshore fields in the Port Campbell area. In the offshore Shipwreck Trough, the Waarre Formation hosts gas accumulations at Minerva, La Bella, Geographe and Thylacine. 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. In the Shipwreck Trough, marine sandstones in the basal part of the Flaxman Formation contain gas and constitute part of the total gas reservoir section for the Minerva and La Bella fields (Geary and Reid, 1998).

In the shelfal areas of the Otway Basin, including at the Port Campbell and Shipwreck Trough gas fields, the most widely distributed sealing facies is the marine claystone Belfast Mudstone, which provides a reliable regional top seal for reservoirs within the Waarre and Flaxman formations. In addition, shales within the Flaxman Formation may act as intraformational seals. Both units are regionally developed and are thickest in the offshore part of the basin.

The Campanian–Maastrichtian Paaratte Formation has been intersected by many wells in South Australia and is known to contain good quality reservoir intervals. The Paaratte Formation and Timboon Sandstone are also characterised by intraformational mudstones that have good sealing capacity, and the Paleocene Pebble Point Formation is sealed by the seaward-thickening Pember Mudstone. Potential sealing units within the Wangarrup Group include the basal Massacre Shale, basal mudstone units of the Dilwyn Formation, and mudstones in the Mepunga Formation.

Although the Sherbrook Group remains untested in terms of mature source rocks, all other petroleum systems elements appear to be present. However, the extent to which these reservoir facies are developed in the deep-water Otway Basin is not known. In this part of the 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. Only ongoing exploration, especially in the deeper parts of the basin, will shed light on the viability of this petroleum system. Two wells drilled in the vicinity of the shelf break (Amrit 1 and Hill 1) targeted the Paaratte Formation and verified the presence of good quality reservoir facies. An overlying seal facies in mudstones coeval with the more proximal Timboon Sandstone was also found in Amrit 1 (Subramanian, 2004, 2005). Petrophysical analyses of samples from Amrit 1 indicated 42.5 m of net sand with an average porosity of 16.2% was present (Subramanian, 2005).

In the Torquay Sub-basin, the reservoir properties of the Eocene Boonah Formation and the Upper Cretaceous–Eocene Eastern View Formation were found to be fair to excellent, while two deeper Cretaceous units (the Pretty Hill Formation in the Crayfish Supersequence and the Eumeralla Supersequence) is also predicted to have reservoir potential (Bernecker et al, 2004). All these potential reservoir units are 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.

Timing of generation

Burial history modelling indicates the Eumeralla Formation has a two-stage hydrocarbon generation history consisting of an initial Early Cretaceous phase of hydrocarbon expulsion followed by a lesser Cenozoic expulsion phase (Duddy, 1994, 1997; Mehin and Link, 1997b). Early Cretaceous expulsion was associated with the initial rifting event, when the geothermal gradient was approximately 50–70°C/km (Mehin and Link, 1997a; Mitchell, 1997). This event would have resulted in significant hydrocarbon generation from the Casterton Formation, Crayfish Subgroup and basal Eumeralla Formation, peaking at the end of the Early Cretaceous.

During the Late Cretaceous, hydrocarbon expulsion from the Casterton Formation (Crayfish Subgroup) and base Eumeralla Formation ceased after the regional geothermal gradient dropped from 50–70°C/km to 30°C/km (Duddy, 1997; Mitchell, 1997). Further hydrocarbon generation did not recommence until the Eumeralla Formation experienced burial temperatures greater than those attained at the end of the Early Cretaceous. Duddy (1997), and Mehin and Link (1997b) believe this occurred in the Paleogene with peak generation occurring in areas where the Eumeralla Formation is overlain by about 2000 m of Upper Cretaceous sediments and 1000–2000 m of Paleogene sediments.

Significant sediment loading took place in the deep water Otway Basin during the Late Cretaceous (Shipwreck and Sherbrook supersequences). O'Brien et al (2009) suggest 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. 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 succession is not as thick, much of the Sherbrook Group is currently at peak maturity, which enhances the petroleum 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.

In the Torquay Sub-basin, Trupp et al (1994) suggested 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, timing of generation (101 Ma) relative to the Cenomanian deformation event (95–90 Ma) would not 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.

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. All of the producing fields and a majority of the discoveries are from the Waarre reservoir. The principal structural traps involve closure associated with faulted anticlines and tilted fault blocks. Regional seal is provided by the Belfast Mudstone while the Flaxman Formation exhibits local sealing capability. The Eumeralla Formation is expected to be gas generative across most of the region. The potential for oil generation from lower Sherbrook Group source rocks is inferred to be the highest in the Voluta and Portland troughs. Recent petroleum geochemical studies suggest that in the offshore, mature Turonian source rocks may be capable of generating liquid hydrocarbons, if it can be demonstrated that these shales are marine in origin (O'Brien et al, 2009).

In the western Otway Basin, Turonian–Santonian slope fan sediments provide a valid exploration target in addition to the Waarre/Flaxman play. Rapid deepening and steepening of the shelf to the southwest of the Tartwaup Hinge Zone, combined with high eustatic sea levels, created a deep-water depositional environment over much of the Otway Basin. Post break-up uplift in the hinterland provided large volumes of clastic material that bypassed the relatively stable platform of the Tartwaup Hinge Zone to the northeast. Lower delta plain and marginal marine conditions suitable for the formation of oil-prone source rocks within the Waarre and Flaxman formations are most likely to be found in rapidly subsiding troughs, such as those located southwest of the Tartwaup Hinge Zone. Slope-fan deposits, overlying a thick, coal-bearing sequence of the Waarre Formation, have been identified on seismic data in the South Australian part of the basin.

Another regionally well developed play type is associated with tilted fault blocks that contain Paaratte Formation sediments. These fault blocks rely on both intraformational and cross-fault seal for trap integrity. In proximal locations, trap seal is the main exploration risk associated with this play. In more distal areas, where the unit interfingers with the Belfast Mudstone, the risk of seal failure is reduced. Rollovers associated with faulted anticlines developed on the hanging wall of listric faults may provide independent four-way dip closures. The generally coarsening-upwards quartz sandstones display excellent reservoir characteristics. Although this play has yet to be validated by a hydrocarbon discovery, only one offshore well (Discovery Bay 1) has targeted this play. Downthrown fault blocks, with juxtaposition of Paaratte Formation reservoirs against shaly sequences from the same unit, or Belfast Formation mudstones, may also constitute valid traps. The potential for fault seal is expected to increase in a basinward direction.

While there is potential for plays charged by early-generated, Austral 2-sourced hydrocarbons in the inboard parts of the deep water Otway Basin, preservation of such accumulations is considered 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 east–west strike, rather than northwest–southeast.

In the deep-water 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 deep-water Otway Basin are likely to be reliant on charge from unproven Austral 3 source rocks (Geary and 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 deep water 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), significant occurrences of hydrocarbons were not encountered and the play remains unproven. Minor hydrocarbon indications 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 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.

Play types within the Torquay Sub-basin consist of: Miocene anticlines, similar to those in the Gippsland Basin, with an Eocene reservoir seal. Throughout the exploration history of the offshore Otway Basin, poor fault-seal integrity has often been cited as the main reason for well failure (e.g. at Loch Ard 1 and Eric the Red 1). However, geochemical studies indicate the distribution of the present day peak generation window for the respective petroleum systems is the primary determinant of prospectivity within the basin (O'Brien et al, 2009). Maturity modelling suggests that the inner shelf, inboard of the Tartwaup–Mussel Fault Zone, lies well within the area of mature Eumeralla source rocks and carefully mapping of appropriate structures on 3D seismic will be required. In these inboard areas, it is also very important to understand lateral facies distribution that range from fully terrestrial lower coastal plain to open shelf depositional environments. Champion 1 and Nautilus A1 failed due to a lack of reservoir, and risk in the area is associated with recognising the extent of good quality reservoir facies that are kept intact either by fault-seal mechanisms or by the presence of intraformational and regional sealing lithologies. In the palaeo-nearshore zone, such facies changes occur abruptly and reservoir compartmentalisation is a common feature.

In the eastern part of the offshore Otway Basin, the Waarre/Flaxman play was tested by Whelk 1 and, although encountering good reservoir sandstones, failed to record any hydrocarbons because of an interpreted facies change in the Belfast Mudstone equivalent. As shown **Figure 14**, the Cretaceous succession thickens considerably basinwards from the King Island High. Recent petroleum systems modelling indicates reservoir facies within the Upper Cretaceous Waarre Sandstone are likely to be in the gas window in that part of the basin. Structural configuration suggests that fault-blocks represent feasible exploration plays; however, the sealing capacity of mudstones in the Sherbrook Group remains unknown.

Geoscience Australia products and data

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

Data discovery tools

- The [National Offshore Petroleum Information Management System \(NOPIMS\)](#) provides access to wells and survey data acquired primarily in Commonwealth waters and submitted under legislation, currently the Offshore Petroleum and Greenhouse Gas Storage Act 2006. This data can be downloaded or packaged on request. NOPIMS has been upgraded to provide access to over 50 years of data submission of well and survey information. It represents more than 1 million records and includes an [interactive mapping tool](#) for data discovery.
- [Geoscience Australia's Data Discovery Portal](#) provides full access to Geoscience Australia data and other publically available data sources as well as a suite of analytical and multi-criteria assessment tools. This includes the [Acreage Release](#) and [Energy](#) personas that allow access to a wide range of geological and geospatial data. Themes include source rock geochemistry, petroleum wells, stratigraphic information, province and basin geology, geophysical survey data coverage and other fundamental geospatial and administrative datasets.
- The [National Petroleum Wells Database](#) application provides access to Geoscience Australia's Oracle petroleum wells databases. Data themes include header data, biostratigraphy, organic geochemistry, reservoir and facies, stratigraphy, velocity and directional surveys. Data is included for offshore and onshore regions, however scientific data entry is generally limited to offshore wells and is dependent on Geoscience Australia's project activities.

Marine and environment information

The following section contains information about the existing marine parks, their special habitat zones and physiographic features within the Otway Basin (**Figure 15**). The information is provided in support of business decisions with respect to planned exploration and development activities. Potential hazards of note include storms and swell generated by the Southern Ocean, and shallow reefs which pose a hazard for navigation.

Marine Parks

Australian Marine Parks (Commonwealth reserves proclaimed under the EPBC Act in 2007 and 2013) are located in Commonwealth waters that start at the outer edge of state and territory waters, generally 3 nautical miles (nm) (5.6 km) from the shore, and extend to the outer boundary of Australia's Exclusive Economic Zone, 200 nm (370.4 km) from the shore. Marine parks have also been established by the state and territory governments in their respective waters. The marine parks operate under management plans that provide a balance between protection of the marine environment, and sustainable use of the area. Links to these management plans are provided for each marine park or marine park network in the Otway Basin region.

Australian Marine Parks: South-east Marine Parks Network

The South-east Marine Reserves Network comprises 14 Commonwealth marine reserves, together representing examples of the ecosystems of the South-east Marine Region. The network is located within the South-east Marine Region, which incorporates Commonwealth waters extending from near the far south coast of New South Wales, around Tasmania and as far west as Kangaroo Island in South Australia. It includes the Commonwealth waters of Bass Strait and those surrounding Macquarie Island in the Southern Ocean. The Commonwealth marine area starts at the outer edge of state waters, 3 nm (5.6 km) from the shore (territorial sea baseline), and extends to the outer boundary of Australia's exclusive economic zone, 200 nm (370.4 km) from the territorial sea baseline. State and territory jurisdictions extend from the shoreline to 3 nm (5.6 km) offshore.

The South-east Marine Region is recognised as a major marine biogeographic region. When compared to most of the world's marine environments, those of temperate Australia display an enormous diversity of plant and animal species and are believed to have the most diverse marine floral assemblage in the world. High diversity in terms of the number of species is a feature common to many plant and animal communities in the Region. In addition to high diversity, the Region has large numbers of endemic species, that is, species found nowhere else in the world.

Significant variation in water depth and sea-floor features found throughout the South-east Marine Region are contributing factors to the high level of species diversity in the Region. Sections of the continental shelf, including Bass Strait, have a mosaic of rocky reefs and soft sediments. The shelf habitats support a diverse range of species from a broad range of taxonomic groups. The shelf break, which includes the edges of the continental shelf and the upper slope, serves to intensify currents, eddies and upwellings, creating a rich and productive area for biodiversity, including species that are fished commercially and recreationally.

Sea-floor canyons along the continental margin are identified as important ecological features in the Region. Canyons can have steep or rugged topography that provide habitat for sessile invertebrates, such as corals, which in turn attract other organisms including higher order species. Depending on their size and shape, canyons can intensify local currents and the concentration of nutrients to enhance productivity and biodiversity.

One marine park within the South-east Marine Parks Network overlies the Otway Basin—Apollo Marine Park.

Management plans for the South-east Marine Parks Network are in place, and can be viewed at: <https://parksaustralia.gov.au/marine/pub/plans/se-network-management-plan2013-23.pdf>

Apollo Commonwealth Marine Reserve

The [Apollo Commonwealth Marine Reserve](#) is in Bass Strait south of Cape Otway and Apollo Bay in southwestern Victoria, and northwest of King Island. The reserve represents the continental shelf that extends from South Australia to the west of Tasmania. The cool waters of the reserve are less than 50 m deep near Cape Otway. The reserve includes the Otway Depression, a 100 m deep undersea valley joining the Bass Basin to the deeper ocean. This valley was an outlet channel for the ancient Bass Lake and mainland river systems, during the last ice age.

The waters of the park are exposed to large swell waves generated from the southwest, as well as strong tidal flows. The sea floor has many rocky reef patches interspersed with areas of sediment and, in places, has rich, benthic fauna dominated by sponges.

Statement of significance

- Seabirds, dolphins and seals forage in the reserve.
- Ecosystems, habitats and communities associated with the Western Bass Strait Shelf and the Bass Strait Shelf Province
- Associated with the following seafloor features: deep/hole/valley; shelf
- Important migration area for Blue, Fin, Sei, and Humpback whales
- Important foraging area for Black-Browed and Shy albatrosses, Australasian Gannet, Short-Tailed Shearwater, Crested Tern and White Shark.

Cultural and Heritage site: Wreck of the MV City of Rayville

The park is zoned Multiple Use Zone IUCN Category VI. Mining operations, including exploration, are allowed.

Victorian Marine Protected Areas

Discovery Bay Marine National Park

The [Discovery Bay Marine National Park](#) (2770 ha) is located 20 km west of Portland, and protects part of the largest coastal basalt formation in western Victoria. The park is adjacent to Cape Bridgewater along the coast from Blacks Beach to Whites Beach and offshore to 3 nm (5.6 km). Between Whites Beach and Cape Duquesne the park boundary commences 500 m from the coastline.

The park comprises several habitats—intertidal rocky shores, subtidal rocky reef, subtidal soft sediment, and the water column—that provide for a range of significant marine fauna including mammals, birds and invertebrates. The park encompasses a section of the Bonney Coast, which is a productive area because of a nutrient-rich cold water upwelling. This high productivity provides an important feeding ground for seabirds, fur seals and whales, and supports commercially important fishery species and significant recreational fishing in the area. The park provides feeding and roosting habitat for fifteen threatened bird species, and feeding area for ten internationally significant migratory bird species.

Point Addis Marine National Park

The [Point Addis Marine National Park](#) (4600 ha) is located about 25 km southwest of Geelong. It extends offshore from the high water mark along 10 km of coastline east of Anglesea, around Point Addis to the eastern end of Bells Beach, and offshore approximately 3 nm (5.6 km) to the limit of Victorian waters. The park includes all waters within these boundaries and extends 200 m beneath the seabed.

The park protects representative examples of subtidal soft sediments, subtidal rocky reef, rhodolith (benthic marine red algae) beds, and intertidal rocky reef habitats. These substrates provide habitat for a range of invertebrates, fish, algae, birds and other wildlife. The park also has cultural importance based on evidence of a long history of Indigenous use, and contains surf breaks that are culturally important to many people associated with surfing. The park is zoned a National Park IUCN Category II. Category II areas are managed primarily for ecosystem protection and recreation.

Port Phillip Heads Marine National Park

The [Port Phillip Heads Marine National Park](#) (3580 ha) is located at the southern end of Port Phillip, about 60 km southwest of Melbourne, and stretches along 40 km of coastline. The park comprises six sections: Swan Bay, Mud Islands, Point Lonsdale, Point Nepean, Popes Eye and Portsea Hole.

The park supports a great diversity of marine species, due to the presence of diverse habitats ranging from mudflats and seagrass to deep and shallow reefs, rocky shores, and pelagic waters. The area marks the end of range for some animals that prefer the cold waters of western Victoria, whilst also supporting warm-water species from eastern Australia. The waters of Port Phillip also provide shipping access to one of Australia's busiest seaports, and contain heritage-listed shipwrecks. The park is zoned a National Park IUCN Category II. Category II areas are managed primarily for ecosystem protection and recreation.

Twelve Apostles Marine National Park

The [Twelve Apostles Marine National Park](#) (7500 ha) is southeast of Port Campbell between Broken Head and Pebble Point, and extends offshore 3 nm (5.6 km) to the limit of Victorian waters.

The park protects unique limestone rock formations—including the iconic cliffs and pillars of the Twelve Apostles—and a range of marine habitats representative of the Otway marine bioregion. The park also protects Indigenous culture based on a spiritual connection to sea country and a history of marine resource use, as well as the wreck of the clipper Loch Ard.

Arches, canyons, fissures, gutters and deep sloping reefs support kelp forests, sponge gardens, habitat for seabirds, seals, lobsters, reef fish and sea spiders. Marine mammals visit the area and Little Penguins nest in the caves below the Twelve Apostles. The park is zoned a National Park IUCN Category II. Category II areas are managed primarily for ecosystem protection and recreation. All forms of extraction are prohibited in the park (Parks Victoria, 2006).

The Arches Marine Sanctuary

The [Arches Marine Sanctuary](#) (45 ha) is approximately 600 m offshore from Port Campbell. The sanctuary is in the vicinity of the Twelve Apostles Marine Park, and the two areas are covered by the same management plan.

The sanctuary protects important features including underwater limestone formations of arches and canyons, a diverse range of encrusting invertebrates, and Indigenous culture based on a spiritual connection to sea country, as well as spectacular scuba diving areas. Waters of the sanctuary are characterised by high-energy waves and cool waters. There is a diverse array of life including gorgonians, sponges, bryozoans and hydroids. The upper side of limestone structures are covered in the thick, brown kelp *Ecklonia radiata* with an understory of delicate red algae. These habitats support schools of reef fish, seals and a range of invertebrates such as lobster, abalone and sea urchin.

Lady Julia Percy Island Wildlife Reserve

The Lady Julia Percy Island Wildlife Reserve spans Lady Julia Percy Island, which is located approximately 6 km offshore from the Barwon South West region of Victoria. The island is a low, flat, basaltic volcanic island, rising to around 30-40 m above sea level (Edwards et al., 2004).

The island supports a seal breeding colony. Boats are not permitted to approach within 100 m of a seal during the breeding season, which runs from 1 November to 28 February, or within 50 m at other times (Victorian State Government, 2018).

Biologically important areas

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

- The Antipodean, Black-browed, Buller's, Campbell, Indian Yellow-Nosed, Shy, and Wandering albatross forage in the region
- The Common Diving-Petrel forages in the region year-round, and also breeds on islands in the region from July until January
- Australian Sea Lions forage in the waters over the northern area of the basin

The basin overlaps the migratory corridor of the Pygmy Blue Whale, and the region is also a known important foraging area, with seasonally high density. Southern Right Whales also occur in the region from May to November

The basin overlaps the White Shark distribution area, also used as a breeding nursery and opportunistic feeding area in autumn, winter, and spring. White Sharks generally occur in water depths between 120 m and 1000 m.

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

Heritage

Maritime Heritage

Australia protects its shipwrecks and associated relics that are older than 75 years through the [Historic Shipwrecks Act 1976](#).

There is one [historic shipwreck protected zone](#) in the Otway Basin region: the screw steamer SS Alert. The SS Alert is located to the west of Cape Schank, where it sank in bad weather in December 1893, whilst on a voyage from Lakes Entrance to Melbourne via Port Albert. The SS Alert is historically significant as one of the worst maritime wrecks in Victorian history and archaeologically significant as no official salvage has taken place such that the wreck still contains the crew and passengers' personal effects. The SS Alert is therefore a rare example of an iron coastal trading vessel that has not been officially salvaged, scuttled or looted, and is representative of the iron vessels engaged in coastal trade around the southern coast of Australia in the late 1800s. The protected zone extends in all directions from the shipwreck, with a radius of 500 m.

There are several additional shipwrecks within the Gippsland Basin that are not associated with a defined protected zone. These can be identified using the [Australian National Shipwreck Database](#) map search tool.

Cultural Heritage

The Kirrae Wurrung, Gunditj Mara, and Gadabanud—collectively known as Maar (the people)—are the first peoples of southwest Victoria. The Australian Government recognises the responsibilities and interest of Indigenous peoples in ocean environments Indigenous cultural heritage, including protection of Sea Country, is discussed in the [Kooyang Sea Country Plan](#). Kirrae Wurrung Country encompasses the region west of the Gellibrand River (Framlingham Aboriginal Trust and Winda Mara Aboriginal Corporation, 2004).

Fisheries

Fishing effort varies spatiotemporally in the region based on fishing restrictions, stock status and environmental conditions (Larcombe et al, 2001). The following [Commonwealth fisheries](#) are within the Otway Basin area:

The Bass Strait Central Zone Scallop Fishery operates in the Bass Strait north of Tasmania and extends from the Victoria/New South Wales border around to the Victoria/South Australian border. The fishery is between the Victorian and Tasmanian scallop fisheries that lie within 20 nm (37.0 km) of their respective coasts. The default period for the fishing season is 1 April to 31 December, although the 2018 season opened on 19 July and closed 31 December.

The Victorian Scallop Fishery extends out to 20 nm (37.0 km) from the high tide mark, excluding bays and inlets. Continued low levels of scallop abundance have resulted in a low Total Allowable Commercial Catch of 135 tonnes since 2015/2016.

The Eastern Tuna and Billfish Fishery extends from Cape York in Queensland to the South Australian/Victoria border. Fishing occurs both in the Australian Fishing Zone (generally between 3 nm and 200 nm [5.6-370.4 km] from the coast) and adjacent high seas. The fishing season generally runs for 12 months, starting on 1 March. However, the 2018 season ran for 10 months from 1 March to 31 December.

The Small Pelagic Fishery extends from the Queensland/New South Wales border, typically outside 3 nm (5.6 km), around southern Australia to a line at latitude 31°S (near Lancelin, north of Perth). The Gippsland Basin intersects the western sub-area of this fishery. The fishing season runs for 12 months, starting on 1 May.

The Southern and Eastern Scalefish and Shark Fishery stretches south from Fraser Island in southern Queensland, around Tasmania, to Cape Leeuwin in southern Western Australia. The fishery comprises major sectors, of which three overlap the Gippsland Basin: the Commonwealth South East Trawl Sector, the Scalefish Hook Sector, and the Shark Hook and Shark Gillnet Sector. The fishing season runs for 12 months, starting on 1 May.

The Southern Bluefin Tuna Fishery covers the entire sea area around Australia, out to 200 nm (370.4 km) from the coast. The fishing season runs for 12 months, starting on 1 December.

The Southern Squid Jig Fishery is located off New South Wales, Victoria, Tasmania and South Australia, and in a small area of oceanic water off southern Queensland. The fishing season runs for 12 months, starting on 1 January.

The following [Victorian commercial fisheries](#) are within the Otway Basin area:

The [Abalone Fishery](#) operates along the majority of the Victorian coastline, in depths to 30 m. The fishing season runs for 12 months, starting on 1 April.

The western zone of the [Rock Lobster Fishery](#) extends from Apollo Bay westward to the border with South Australia. Southern Rock Lobsters are found to depths of 150 m, with most of the catch coming from depths of less than 100 m. Closed seasons are 1 Jun to 15 November for female lobsters, and 15 September to 15 November for male lobsters.

The [Giant Crab Fishery](#) is a small, limited entry fishery with the same boundaries as the western zone of the Rock Lobster fishery. Closed seasons are 1 June to 15 November for female crabs, and 15 September to 15 November for male crabs. The fishery is closely linked to the Rock Lobster fishery.

The [Victorian Wrasse \(Ocean\) Fishery](#) extends along the entire length of the Victorian coastline and out to 20 nm (37.0 km) offshore, except for marine reserves.

Climate of the region

The region is characterised by a cool temperate climate. Precipitation is delivered throughout the year, and there are few temperature extremes. At the closest onshore weather station (Cape Otway Lighthouse), mean minimum and maximum temperatures were 7.5°C and 21.5°C respectively for the period 1864–2019 (Bureau of Meteorology, 2019). Mean annual rainfall over a 151 year period at Cape Otway Lighthouse is 894.8 mm. The region is at the edge of a known climate change hotspot (Oliver et al, 2013; Hobday and Hartog, 2016).

Oceanic regime

The shelf in the Otway region is a swell- and storm-dominated open cool-water carbonate platform (Boreen et al 1993; Li et al., 2003). The region has cool temperate waters with complex oceanography due to subpolar influences from the south, subtropical influences from the Leeuwin Current along the Western Australian Coast, and the Great Australian Bight (Commonwealth of Australia, 2015), as well as the influence of Bass Strait immediately to the east. Cool, nutrient-rich water—the ‘Bonney Upwelling’—upwells along the shelf and to the west of the Otway Basin region (between Robe and Portland) between November and April (Integrated Marine and Coastal Regionalisation of Australia, 2006; Butler et al, 2002). The Bonney Upwelling may also be linked to strong storm events throughout the year (Blackman et al, 1987). Mean surface-water temperatures range between 14°C and 18°C. Water temperatures are 2–3°C lower than adjacent bioregions due to the cooling effect of upwelling (Integrated Marine and Coastal Regionalisation of Australia, 2006; Parks Victoria, 2006). The Otway coast is a high wave-energy coastline, consistently impacted by southwesterly swells generated in the Southern Ocean (Barton et al, 2012). Mean annual wave heights of 2.7 m recorded on the coastline cause significant erosion of sea cliffs and pillars (Bird, 1993). The tidal regime is microtidal (0.8 m to 1.2 m) (Parks Victoria, 2003).

Seabed environments: regional overview

The Otway continental shelf has sediment and sedimentary rock primarily of Palaeogene and Neogene age, with textures and compositions broadly similar to modern sediment. Coastal sediment sources include recent basaltic rock and carbonate sediment; both lithologies are present below sea level, both on the shallow shelf and as reefs. Unconsolidated seabed sediments are generally carbonate sands (Barton et al, 2012; Murray-Wallace and Woodroffe, 2014; see also the Geoscience Australia [Marine Sediments Database](#)). The shelf environment has approximately shelf-edge parallel distribution of surficial sediment facies, with two main facies present. The inner shelf is dominated by hard substrate and palimpsest quartz, bivalve and bryozoan gravels. Unconsolidated sediment cover in this zone is fairly thin or absent (James and Bone, 2011; James et al., 1992). The mid-shelf is dominated by bryozoan sand (Boreen et al, 1993; Harris et al, 2000).

Ecology

The Otway Basin is part of the Southeast Marine Bioregion which extends from the far south coast of New South Wales to Kangaroo Island. This region hosts high levels of biodiversity and endemism, particularly of macroalgae (Womersley, 1990), and possibly represents one of the most diverse marine floral assemblages in the world (Commonwealth of Australia, 2015). At a regional scale, habitats include kelp forests, temperate seagrass meadows, and rocky reefs, as well as extensive soft sediment ecosystems. These marine habitats support a diverse range of temperate marine plants, invertebrates, fishes, and larger marine animals such as whales, dolphins and seals. Humpback Whales, seabirds and other threatened animals migrate through this region on their way to breeding grounds, and other species such as Blue Whales use this region as a feeding ground (Gill et al, 2011).

At the smaller regional scale of provincial bioregions (cf. Integrated Marine and Coastal Regionalisation of Australia, 2006), the Otway Basin is included in the Western Bass Strait Shelf Transition, which is an area of overlap (i.e. it does not have fauna, flora or ocean conditions distinct from adjacent areas; Commonwealth of Australia, 2015).

Quaternary geological history

The morphology of the Otway Shelf has been shaped by tectonic uplift, nearshore processes and eustatic changes in sea-level. These processes have resulted in tall cliffs and prominent sea-stacks (the ‘Twelve Apostles’), which are composed of mid-Cenozoic limestones (Bird, 1993).

At present, the cliffed coasts of the Otway Shelf are predominantly under destructive stresses from ocean swell waves produced during Southern Ocean storms, providing sediment to the shelf (Porter-Smith et al, 2004). The documented Quaternary sedimentary record and geomorphology of the Otway Shelf are similar to that of a tropical carbonate platform with Holocene and relict sediment overlying Cenozoic and older carbonate sedimentary rocks. However, the Quaternary record on the Otway Shelf is essentially palimpsest, with little recent sedimentation taking place.

Offshore reef patches, remnants of shore platforms, are common on the inner to mid-shelf (Bird, 1993) and extend beyond the limits of coastal waters (Holmes et al, 2007). Remnants of drowned relict Cenozoic limestone stacks, 6 km offshore in 50 m water depths have recently been mapped (Brezore et al, 2016).

National seabed mapping data and information

Geoscience Australia provides acoustic datasets including bathymetry, backscatter, sidescan sonar and sub-bottom profiles to assist in understanding the shape and composition of the sea floor. Geoscience Australia also maintains the Marine Sediment database ([MARS](#)), comprising information (e.g. percentage mud/sand/gravel, mean grain size, sediment texture) from seabed sediment samples collected during marine surveys between 1905 and 2017.

These data are discoverable and accessible through the AusSeabed [Marine Data Discovery Portal](#). AusSeabed is an innovative national seabed mapping initiative designed to coordinate data collection efforts in Australian waters and provide open access to quality-controlled seabed data. AusSeabed is currently focussed on enabling accessibility of bathymetry data in Australian waters; however, the long-term goal is to establish a comprehensive online platform containing data and information, including tools, to support data collectors and users in connecting with the broader seabed mapping community. This platform will also include derived data products such as morphological and geomorphological maps of the sea floor.

Other online information resources

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

- [Bureau of Meteorology: climate statistics](#)
- [National Conservation Values Atlas](#)
- Australian Marine Parks: [South-east Marine Parks Network](#)
- [Parks Victoria Marine protected areas](#)
- [Commonwealth Fisheries](#)
- [Victorian Fisheries Authority—Commercial Fisheries](#)
- [Historic shipwrecks](#)
- [Protected Matters Search Tool](#)

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Figure Captions

Figure 1: Map of the Otway Basin showing bathymetry, petroleum well distribution and oil and gas fields.

Figure 2: Map showing the pipeline network in south-eastern Australia

Figure 3: Map showing petroleum exploration permits, gas fields and petroleum production facilities in the Otway Basin.

Figure 4: Tectonic elements map of the Otway Basin showing bathymetry, petroleum well distribution and gas fields.

Figure 5: Stratigraphic chart for the Otway Basin showing hydrocarbon occurrences (after Kelman et al, 2015; Geologic Time Scale after Gradstein et al, 2020).

Figure 6: Stratigraphic chart for the Robe Trough and Penola Trough showing well intersections of hydrocarbons (after Kelman et al, 2015; Geologic Time Scale after Gradstein et al, 2020).

Figure 7: Seismic section (line p137/03) across the Crayfish Platform and Morum Sub-basin highlighting the intense faulting and thickness variations of the Cretaceous supersequences.

Figure 8: Stratigraphic chart for the Port Campbell Embayment and Shipwreck Trough showing well intersections of hydrocarbons (after Kelman et al, 2015; Geologic Time Scale after Gradstein et al, 2020).

Figure 9: Stratigraphic chart for the offshore Torquay Sub-basin (after Kelman et al, 2015; Geologic Time Scale after Gradstein et al, 2020).

Figure 10: Stratigraphic chart for the Gambier Embayment and Voluta Trough (after Kelman et al, 2015; Geologic Time Scale after Gradstein et al, 2020).

Figure 11: Map showing the current main operators, active exploration permits, retention leases and production licences.

Figure 12: Peak prospectivity zones for the Austral 1, 2 and 3 petroleum systems in the Otway Basin (modified from O'Brien et al, 2009).

Figure 13: Seismic section (line p137/09) across the inner shelf to the Nelson Sub-basin highlighting the basinward thickening of the Upper Cretaceous supersequence.

Figure 14: Geological interpretation of Otway sequences along seismic line DS01-126 (a) and modelled present-day maturity for same section (b).

Figure 15: Map showing marine reserves, marine parks, multiple use zones and ecological features in the Otway Basin.