Regional Geology of the Otway Basin

Basin Outline

The Otway Basin is a northwest-striking passive margin rift basin that extends from southeastern South Australia to the northwestern coast of Tasmania (**Figure 1** and **Figure 2**). It belongs to a series of basins, including the Bight (comprising the Ceduna, Duntroon, Eyre, Bremer, Recherche and Denmark sub-basins), Polda, Otway, Sorell, Bass and Gippsland basins, that were formed during Gondwana break-up and the Antarctic-Australian separation (Willcox and Stagg, 1990). The Otway Basin is filled with Late Jurassic to Recent sediments and covers an area of 150,000 km^2, 80% of which lies offshore. The basin's western, northern and eastern boundaries are defined by the preserved limits of the latest Jurassic-Early Cretaceous Otway Group sediments, whilst its southern boundary is delimited by the southernmost extent of Cenozoic sediments in the Hunter Sub-basin.

According to Norvick and Smith (2001), rifting along the southern Australian margin was initiated during the Oxfordian (about 158 Ma) and, progressing from west to east, had affected the Otway, Bass and Gippsland provinces by Tithonian times (about 150 Ma). However, when underlying basement rocks are considered, the southern Australian break-up rift system may have an older history that is recorded in the Polda Basin which hosts Neoproterozoic rift basalts in the Kilroo Formation (Rankin, 1993). In Western Australia, the break-up can be correlated with the northernmost extent of Neoproterozoic terrigenous clastic sediments of the Stirling and Mount Barren groups that are exposed north of the 1200 Ma Albany Fold Belt (Nelson et al, 1995).

Basin Evolution and Tectonic Development

The basin's tectonic elements which are recognised today were initially controlled by the distribution of basement rocks (Moore, 2002; Bernecker and Moore, 2003). These belong to three broad tectono-stratigraphic provinces:

- the late Early Cambrian to Furongian Delamerian Fold Belt (in South Australia and Victoria).
- the Lachlan Fold Belt (Victoria), cratonised during the early Silurian to Middle Devonian and bounded by the Moyston and Bambra faults,
- the Neoproterozoic to Cambrian Selwyn Block (Victoria and Tasmania) that represents the northern extension of Tasmania into Victoria (VandenBerg et al, 2000; Cayley et al, 2002). Onshore, this is largely covered by Lachlan Fold Belt rocks, but the underlying Neoproterozoic fabric seems to have controlled the Otway Basin architecture.

With the onset of the major rifting phase in the Late Jurassic, several east-northeast-trending extensional depressions were generated, which developed into the Robe, Colac and Gellibrand troughs in the onshore. Older parts of the Portland Trough and the Torquay Sub-Basin may also be related to this extensional trend (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 rifting continued. The easternmost portion of the offshore Voluta Trough may represent a continuation of these structures (**Figure 2** and **Figure 3**). Moreover, this early extension has been recorded as far south as the South Tasman Rise (O'Brien et al, 1994; Royer and Rollet, 1997). Final break-up in the Otway Basin probably occurred in Victoria in the Maastrichtian at about 67 Ma (Lavin, 1997) but seems to have been as late as the Eocene-Oligocene boundary on the South Tasman Rise (Hill et al, 2001).

The basin fill was initially dominated by fluvial and lacustrine sediments during Early Cretaceous rifting, represented by the Otway Group (**Figure 4**). Following uplift of the Otway Ranges, broad delta plain and marginal marine environments developed during the Late Cretaceous. The corresponding sediments are represented by the Sherbrook Group and include the Waarre Formation, the main exploration focus. Deltaic and nearshore marine processes dominated until Late Eocene times (Wangerrip and Nirranda groups), after which more open marine conditions were established and cool water carbonates began to accumulate. For detailed descriptions of the sedimentary and stratigraphic evolution of the Otway Basin, the reader is referred to publications by Parker (1995), Lavin (1997), Geary and Read (1998), Boyd and Gallagher (2001), Constantine (2001), Partridge (2001) and Krassay et al (2004).

Early Rifting (Late Jurassic-Early Cretaceous)

The Otway Basin rift system was initiated in the Late Jurassic when north-south extension produced a series of east-west to northwest-southeast asymmetric half-graben across the proto-rift (Williamson et al, 1990; Cooper and Hill, 1997). The major controlling extensional faults dip relatively steeply towards the north (Hill and Durrand, 1993). This regional structural style compares well with oblique-rift analogue models (Cooper and Hill, 1997), confirming that the extensional history of the region was strongly controlled by the prevailing basement fabric.

The incipient Jurassic half-graben were of limited lateral extent, but as extension progressed into the Early Cretaceous and subsidence continued, the rift basins expanded substantially. In excess of 5000 m of non-marine fluvio-lacustrine Otway Group sediments filled these growing half-graben. Initial lacustrine sedimentation (interbedded with flow basalts) of the Casterton Formation gave way to dominantly fluviatile sedimentation of the Pretty Hill Formation. Lower energy fluvial and lacustrine deposits characterise the Laira Formation while the overlying Katnook Sandstone represents the return to higher energy fluvial deposition.

Rift to Sag Transition (Aptian-Albian)

The main extensional faults that controlled the Late Jurassic to Early Cretaceous rifting lost their geological influence 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 in a progressively widening, regional sag basin. Sediments accumulated in a variety of non-marine depositional environments including fluvial, flood plain, coal swamp and lacustrine. These sediments are characterised by the large amount of volcaniclastic detritus they contain, 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).

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 a basin-wide angular unconformity - the Otway Unconformity (Partridge, 2001). Several areas including the Otway Ranges, King Island High and the Stawell Basement Block 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 palaeotemperatures (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). Palaeo-temperatures fell sharply in the early Late Cretaceous, driven by uplift and erosion associated with a declining geothermal gradient.

Renewed Rifting (Late Cretaceous)

After a 6.5 Ma hiatus (Partridge, 1997), 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 4** and **Figure 5**).

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 distinctly different structural style compared to 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 System, were formed by the Late Cretaceous rifting (**Figure 2**). 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.

Most of the space created by Late Cretaceous extensional rifting was accommodated by prominent displacement along northwest-striking and southwest-dipping normal listric faults including the Tartwaup, Mussel and Codrington fault zones that form the northern margin of the Voluta Trough (**Figure 2** and **Figure 3**). Rift-related faulting resulted in the development of large and deep depocentres, including the Voluta Trough, along the outboard part of the Otway Basin. Late Cretaceous syn-rift deposition of the Sherbrook Group was initiated by a major sea level rise that occurred close to the Cenomanian/Turonian boundary. It is the first major marine incursion into the Otway Basin. Deposition throughout the Late Cretaceous was dominated by deltaic sedimentation, as large deltas prograded southwards across the marginal platforms into the Voluta Trough, where the Sherbrook Group section attains a thickness in excess of 5000 m. While sedimentation was influenced by eustasy, overall development of the Sherbrook Group was controlled by syndepositional rift-related tectonism. A three-fold stratigraphic subdivision is recognised in the Sherbrook Group: the basal Waarre Formation; the Flaxman Formation; and an overlying sequence comprising the Belfast Mudstone, Nullawarre Sandstone, Paaratte Formation and Timboon Sandstone that represent facies equivalents of major, prograding delta complexes.

Continental Break-up (Late Maastrichtian)

Moderate structuring and regional uplift which accompanied the late Maastrichtian continental break-up of Antarctica from Australia , resulted in development of the Late Maastrichtian Unconformity that 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 megasequences separated by major unconformities that represent different stages of passive margin development and are subdivided into three groups: the Wangerrip, Nirranda and Heytesbury groups.

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. This created 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 equivalent in part and 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 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. It is recognised in all basins along the southern Australian margin and 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 early 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).

Regional Hydrocarbon Potential

Hydrocarbons sourced from basins along the southern margin of Australia have been assigned to the Austral Petroleum Supersystem by Bradshaw (1993) and Summons et al (1998). Within this Supersystem, three petroleum sub-systems related to the Otway Basin have been recognised (Edwards et al, 1999). Each sub-system comprises geochemically distinct oil families and related source rock facies; the differences between the families are primarily related to differences in the depositional environments of the source rocks.

The three sub-systems are:

> Austral l - Late Jurassic to earliest Cretaceous fluvio-lacustrine shales

> Austral 2 - Early Cretaceous fluvial and coaly facies

> Austral 3 - Late Cretaceous to earliest Paleogene fluvio-deltaic facies

Hydrocarbon Families and Source Rocks

In the Otway Basin, the source rocks of the Austral 1 petroleum sub-system consist of non-marine, Upper Jurassic to Lower Cretaceous fluvio-lacustrine and lacustrine shales deposited in rifted 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 sub-system is recognised as the source for oil recovered from a Repeat Formation Test (RFT) in Troas 1 and a Drill Stem Test (DST) in Nunga Mia 1. Both wells are located in South Australia.

The Casterton Formation is widely recognised as an excellent source rock (Lovibond et al, 1995; Lavin and Muscatello, 1997). In Victoria, the Casterton Formation has an average TOC content of 2.6% (range 0.4-8.9%) and consists largely of Type II-III kerogens, which suggests it is generative for both oil and gas (Mehin and Constantine, 1999). Geochemical studies (Padley et al, 1995; Edwards et al, 1999) have also identified the Casterton Formation and/or Crayfish Subgroup as the most likely source for oil and gas in the Pretty Hill Formation in South Australia. The source rocks correspond via their geochemistry to four depositional environments, namely saline lacustrine, freshwater lacustrine, fluvio-lacustrine/peat swamp and marginal marine (Edwards et al, 1999). The interpretation of a marginal marine depositional environment is, however, difficult to reconcile with the published palaeogeographic and tectonic reconstructions (Norvick and Smith, 2001). The hydrocarbons in the Katnook and Ladbroke Grove accumulations are thought to be derived principally from a fluvio-lacustrine/peat swamp source.

The Crayfish Subgroup in Victoria consists of two units, the Pretty Hill and Laira formations, the latter of which is restricted in its distribution to the far west of Victoria, near the South Australian border, where it conformably overlies the Pretty Hill Formation. Geochemical analysis suggests that the Pretty Hill Formation has fair source rock potential, with an average TOC content of 1.7% (range 0.4-13.8%) (Mehin and Constantine, 1999). Type III kerogens predominate, with some Type II and IV also present, which suggests the unit is generative for both oil and gas (Mehin and Constantine, 1999). Maturation studies by Hill (1995) show that the Crayfish Subgroup is approaching peak maturity for oil generation within the Robe Trough in South Australia.

With the exception of the Penola Trough, the Early Cretaceous Austral 2 petroleum sub-system is widely recognised as the source for the majority of gas and oil discoveries in the Otway Basin (Edwards et al, 1999).

Geochemical studies have identified the Eumeralla Formation as the primary source interval for the gas in the Port Campbell and Shipwreck Trough area (Mehin and Link, 1994; Foster and Hodgson, 1995; Luxton et al, 1995). Gas shows reported at Triton 1 in the Victorian offshore (Luxton et al, 1995) and gas accumulations at Troas 1 and Breaksea Reef 1 in the South Australian offshore have also been ascribed to the Austral 2 petroleum sub-system. The gas is believed to have been derived from two coaly horizons in the Eumeralla Formation, one of Aptian age (*P. notensis* biozone) near the base of the unit and the other of Lower Albian age (*C. striatus* biozone). The coal-bearing sequences are about 200 m thick and consist of multiple, 2 to 3 m thick seams with interbedded mudstones that are rich in disseminated organic matter. Well control and seismic data indicate that these sequences extend across the basin (BHP Petroleum, 1992; Tupper et al, 1993) and have excellent potential for the generation of gas and light oil (Preston, 1992a-e; Geary and Reid, 1998).

Although there appears to be significant potential for the generation of liquids, exploration results in the offshore areas actually indicate that the source rocks are predominantly gas-prone, with only minor quantities of condensate. However, the oil potential within this petroleum sub-system cannot be ruled out, as the medium-gravity, waxy oils recovered from the onshore Victoria wells Flaxmans I, Windermere 1, 2 and Port Campbell 4 demonstrate. Whole-oil gas chromatograms indicate that the oils are derived from terrestrial, land-plant material (Kopsen and Scholefield, 1990; McKirdy et al, 1994). The Lindon 1 and 2 oils also belong to this petroleum sub-system, but have been extensively altered by microbial activity and water washing (McKirdy 1987; Tabassi and Davey, 1986).

Austral 3 source rocks in the Otway Basin, the Sherbrook and basal Wangeripp groups, have not yielded any commercial quantities of hydrocarbons. The only oil recovered from this interval was derived from the Pebble Point Formation in Wilson 1 (Lavin, 1998). This apparent lack of offshore success does not necessarily mean that mature, generative and oil-prone Austral 3 petroleum sub-system source rocks are not developed in the Otway Basin. Most of the wells drilled in the basin have been located either onshore or on platform areas offshore, where the Sherbrook Group has not reached sufficient thermal maturity for hydrocarbon generation and expulsion. Where wells have been drilled in basinal areas, such as in Breaksea Reef 1 (Hill, 1995) and Normanby 1 (Lavin, 1998), hydrocarbons that may have been sourced from Late Cretaceous source rocks have not been analysed geochemically.

A possible source rock interval is the Belfast Mudstone, which was interpreted geochemically to be a moderately good source in Breaksea Reef 1 (Hill, 1995). This well is located in the Voluta Trough, a major Late Cretaceous depocentre in the west-central part of the basin. The underlying Cenomanian-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. Given that the Cenomanian-Turonian is a well documented time of global anoxia and source rock accumulation, it may be that the Waarre Formation has good source rock potential in more basinal parts of the Otway Basin, on what is now the continental slope. Until further exploration is undertaken, especially in the deeper water areas, the ability of the Austral 3 petroleum sub-system in the Otway Basin to generate substantial volumes of hydrocarbons, especially liquid hydrocarbons, remains largely unknown. However, recent studies by O'Brien et al (in prep) suggest that the Turonian section in the deeper offshore would lie within the maturity window (see Release Area Geology of the Central Otway Basin).

Regional Petroleum Systems

As yet, there have been no commercial petroleum discoveries sourced by the Austral 1 petroleum sub-system in the Victorian part of the Otway Basin. However, oil shows have been observed in several wells, including Garvoc 1, Woolsthorpe 1 and Hawkesdale 1 (Kopsen and Scholefield, 1990). It is possible that source rocks in the Victorian Otway Basin may be over-mature and hence no longer oil-generative. Maturation and hydrocarbon expulsion from these units may have occurred before the traps were formed in the Late Cretaceous to Neogene. This is especially likely in the offshore parts of the basin, where thick Late Cretaceous sequences have greatly increased the maturity of the basal Cretaceous intervals.

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. The Katnook Field contains 40.5 Bcf gas-in-place (GIP) (<0.05% CO_2), with the discovery well, Katnook 2, flowing 16.3 MMcf/d of gas on production testing, plus 119 bbl/d of 52° API condensate (Morton and Sansome, 1995). The Ladbroke Grove Field, in comparison, contains 17.4 Bcf GIP (54% CO_2), with the discovery well, Ladbroke Grove 1, flowing 4.6 MMcf/d on production testing, plus a small amount of 37.8° API condensate (Morton and Sansome, 1995). The Pretty Hill Formation in Victoria has good reservoir characteristics at shallow to moderate depths of burial (1000-2300 m), with measured porosities and permeabilities ranging from 13.2-32.0% (average 20.7%), and 390 mD respectively (Mehin and Constantine, 1999). In the Victoria part of the Otway Basin, the reservoir potential below depths of about 2300 m is uncertain due to a lack of well penetrations. Reservoir data from gas fields in the Penola Trough, onshore South Australia, however, suggest that the porosity and permeability may be quite high, given that the gas zones in these fields (between 2500 and 2800 m) have effective average core porosities and permeabilities of 10-18% and 0.6-550 mD respectively (Parker, 1992).

Vertical and cross-fault sealing of the Penola Trough gas reservoirs is provided by the Laira Formation (Parker, 1992; Lovibond et al, 1995). In Victoria, in contrast, the sealing unit would probably be the Eumeralla Formation, since the Laira Formation is essentially absent, except in a few wells located near the Victoria-South Australia border (Mehin and Constantine, 1999). Trap types in the Penola Trough are represented by either east-striking, faulted anticlines, with closure at the producing Pretty Hill Formation level (e.g. Katnook Field), or by tilted fault blocks with footwall closure (e.g. Ladbroke Grove Field) (Parker, 1992).

The thermal maturity of the Casterton Formation in Victoria is poorly understood because only wells drilled along the northern basin margin intersected the interval at relatively shallow levels (< 2100 m). In these wells, the Casterton Formation is presently mature for oil (VR 0.7-1.0%), and probably increases in maturity to the southwest, towards the basin centre (Mehin and Constantine, 1999).

Most of the wells that intersect the Pretty Hill Formation in Victoria are also located along the northern, onshore margin of the basin. In these wells, the top of the unit is presently early mature for oil (VR 0.5-0.7%), reaching mid-level maturity (VR 0.7-1.0%) towards the coast (Mehin and Constantine, 1999).

Burial history modelling (Lovibond et al, 1995; Duddy, 1997) indicates that hydrocarbons were generated towards the end of the Early Cretaceous in the Penola Trough. The hydrocarbons may have migrated into the traps principally by vertical migration (Lovibond et al, 1995) as a condensate phase and were perhaps generated from source rocks at maturity levels of VR 0.7-1.0% (Tupper et al, 1993).

The Austral 2 petroleum subsystem is the most prolific in the entire Otway Basin and very much related to the majority of gas discoveries within the Waarre Formation, the major regional reservoir interval in the Victorian part of the basin. Producible gas has been encountered in 16 onshore fields in the Port Campbell area ranging in size from Skull Creek (2.2 Bcf GIP) to Iona (40.3 Bcf GIP). In the offshore Shipwreck Trough, the Waarre Formation hosts the gas accumulations at Minerva, La Bella, Geographe and Thylacine, all of which, except La Bella, are currently being considered for development. Gas in Thyalcine is estimated at 1300 Bcf GIP and in Geographe 465 Bcf GIP. Minerva contains 425 Bcf GIP, primarily methane with some CO_2, whereas the La Bella field has about 210 Bcf GIP (Luxton et al, 1995).

The sealing units for the Port Campbell and Shipwreck Trough gas fields are marine claystones of the overlying Flaxman Formation and Belfast Mudstone. Both units are regionally extensive and thickest in the offshore part of the basin. 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 gas fields (Geary and Reid, 1998).

The gas accumulations in the Port Campbell-Shipwreck Trough are trapped in faulted anticlines and tilted fault blocks of Late Cretaceous age (**Figure 6**) which were slightly modified by Late Tertiary compression (Foster and Hodgson, 1995; Geary and Reid, 1998).

Vitrinite reflectance data indicates that the Eumeralla Formation west of the Moyston Fault Zone increases in maturity in a southwesterly direction (Mehin and Constantine, 1999). The top of the unit is presently immature for oil (V_{R0} < 0.50%) along the northern, onshore margin of the basin (Mehin and Link, 1996), but becomes increasingly mature (V_{R0} 1.0 - 1.3%) offshore (Geary and Reid, 1998). The base of the unit, in comparison, is early mature for oil (V_{R0} 0.5-0.7%) along the northern, onshore margin of the basin and increases to gas mature (V_{R0} 1.3 - 2.6%) near the coast.

Burial history modelling indicates the Eumeralla Formation in this area has a two-stage hydrocarbon generation history consisting of an initial Early Cretaceous phase of hydrocarbon expulsion followed by a smaller Cenozoic expulsion phase (Duddy, 1994, 1997; Mehin and Link, 1997b). Early Cretaceous expulsion was associated with the initial rift event when the geothermal gradient was about 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 part of the 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 Late Cretaceous sediments and 1000-2000 m of Paleogene sediments.

Hydrocarbons from the Eumeralla Formation are thought to have reached the Waarre Formation via vertical migration along faults. Sandstones in the formation are unlikely conduits because pervasive chlorite cementation has occluded most pore spaces (Geary and Reid, 1998).

The Austral 3 petroleum sub-system is currently not known to be a significant contributor to the hydrocarbon inventory of the Otway Basin. The delineation of reservoir and seal lithologies in the Late Cretaceous appears less problematic than the identification of potential source rocks. The Paaratte Formation and Timboon Sandstones are characterised by intra-formational mudstones which have good sealing capacity, whereas the Paleocene Pebble Point Formation is sealed by the seaward-thickening Pember Mudstone. Although the Sherbrook Group remains untested in terms of mature source rocks, all other Austral 3 petroleum sub-system elements appear to be present. Only continued exploration, especially in the deeper parts of the basin, coupled with supportive geoscientific studies such as those currently carried out by Victoria's DPI (O'Brien et al, in prep), will shed light on the viability of this petroleum sub-system.

Exploration History

Petroleum exploration interest in the Otway Basin predates that in the Gippsland Basin. Sightings of coastal bitumen strandings led to the drilling of an exploration well at Kingston, South Australia in 1892. 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 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, with only minor gas shows in Pecten 1A, located 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 with only 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 Late 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. Offshore petroleum exploration permits VIC/P30 and VIC/P31 were awarded to BHP Petroleum Pty Ltd (BHP). In the early 1990s; BHP discovered gas in 2 wells drilled on the Mussel Platform - Minerva 1 (1993) and La Bella 1 (1994) - as well as drilling two dry holes. After drilling an additional 3 wells which only encountered minor gas shows, BHP relinquished the permits in 1997, though Retention Leases were awarded over the Minerva and La Bella fields.

Since 1999, there has been a strong resurgence in exploration activity in the Otway Basin, which has been driven by a combination of factors, including changes in the gas market and technological advances. A major exploration program by the Woodside Energy Ltd joint venture, utilising state-of-the-art 3D seismic technology, resulted in the large (approx. combined 1.3 Tcf GIP) Geographe and Thylacine gas discoveries. In the onshore, the Santos Limited joint venture exploration program, again using state-of-the-art 3D seismic acquisition technologies, resulted in the discovery of 3 new gas fields. 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 (**Figure 2**). Elsewhere in the basin, a high level of exploration activity continues, with other exploration groups currently at various stages of their respective exploration programs. Recently, Santos Limited made an offshore gas discovery during the drilling of Henry 1, which once again highlights the prospectivity of this region. The increasing demand for gas as a cleaner energy source appears likely to result in sustained investment in petroleum exploration in the Otway Basin.

Hydrocarbon Reserves

A current hydrocarbon reserves listing for the Otway Basin is publicly unavailable. The Designated Authority, Victoria's Department of Primary Industries (DPI) monitors production levels and reserve estimates, but these records remain confidential. Some older estimates may be on open file and further information can be obtained from **www.dpi.vic.gov.au/minpet/**

Figures

Figure 1:	Location map
Figure 2:	Regional map, showing tectonic elements
Figure 3:	Gravity image Otway Basin, highlighting hinge zones and main basement faults
Figure 4:	Stratigraphic chart for Otway Basin (complete column)
Figure 5:	Stratigraphic chart for Otway Basin (Cretaceous section)
Figure 6:	Generalised and representative regional seismic line across basin (N-S)

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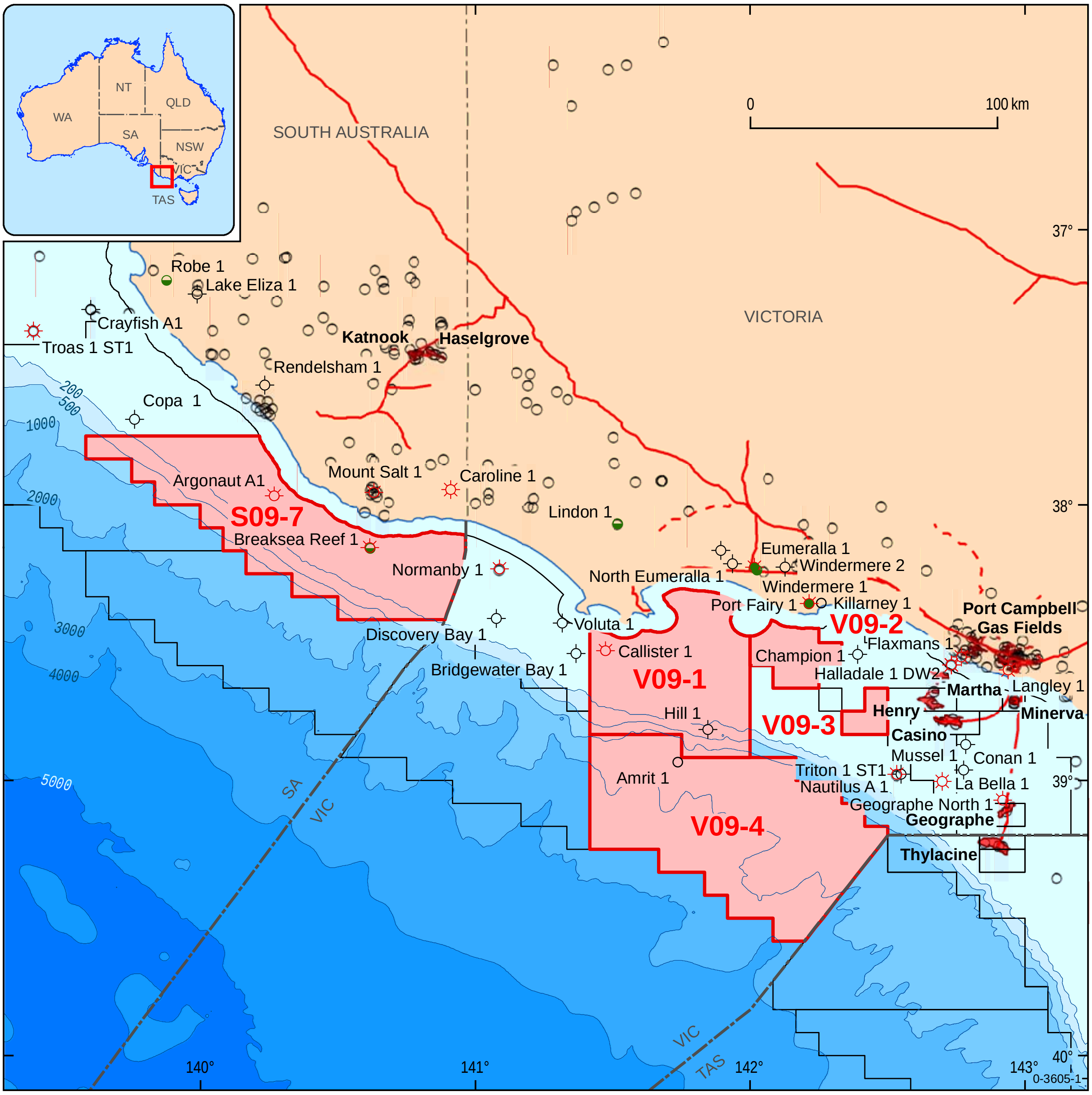

Where well symbol information is sourced from publicly available "open file" data, it has been provided by Geoscience Australia from Well Completion Reports. These symbols were generated from open file data as at 31 March 2009. Where well symbol information is not publicly available from titleholders'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

- *2009 Offshore Petroleum Acreage Release Area*
- *Existing petroleum title*
- *Gas field*
- *Gas pipeline*
- *Gas pipeline (proposed)*
- *Scheduled area boundary (OPGGSA 2006)*
- *200 Bathymetry contour (depth in metres)*
- *Petroleum exploration well - Not classified*
- *Petroleum exploration well - Dry hole*
- *Petroleum exploration well - Gas show*
- *Petroleum exploration well - Gas discovery*
- *Petroleum exploration well - Oil and gas show*
- *Petroleum exploration well - Oil discovery and Gas show*
- *Petroleum exploration well - Oil show*

Figure 1. Location map, showing 2009 Release Areas in offshore Otway Basin.

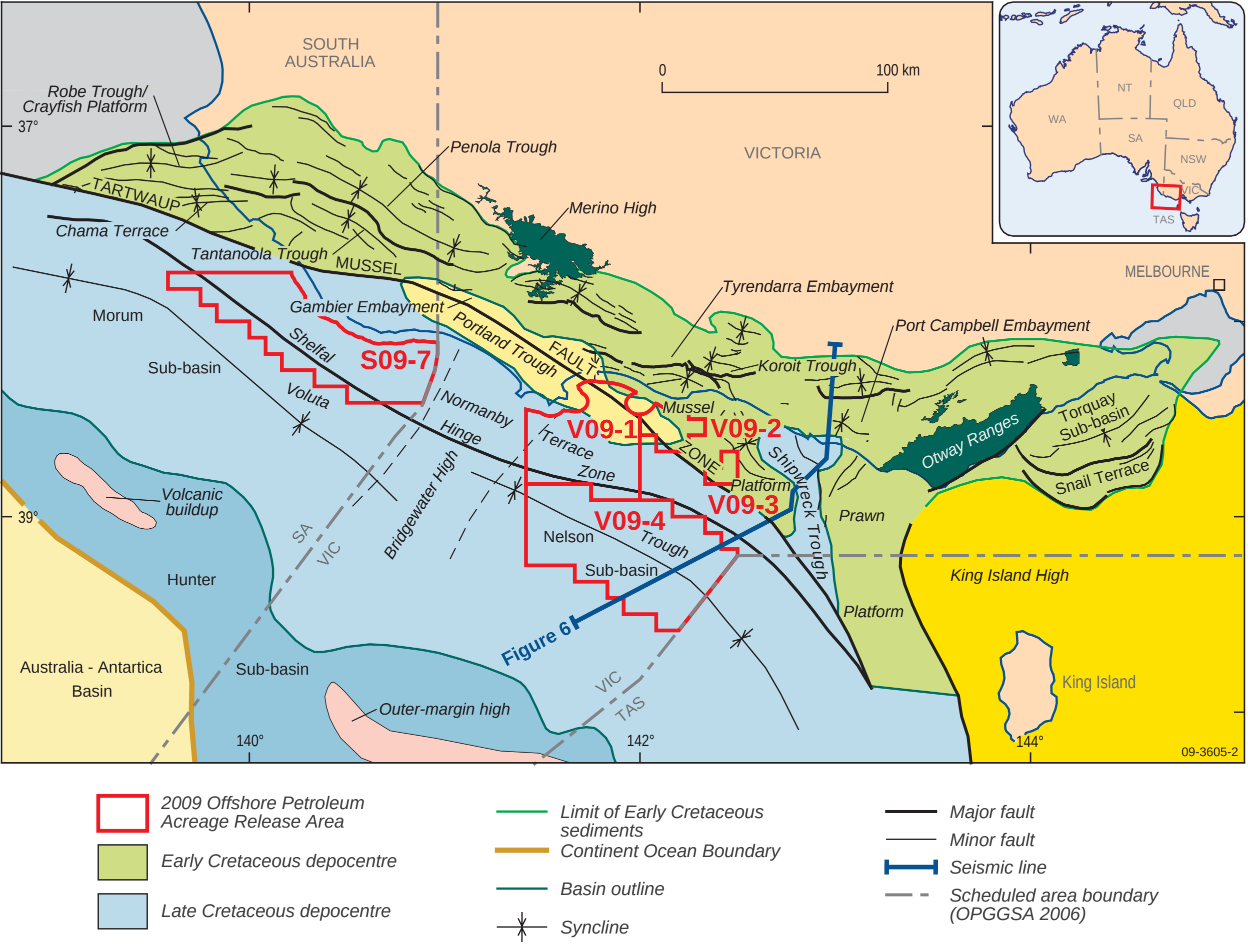

Figure 2. Regional tectonic elements map, Otway Basin.

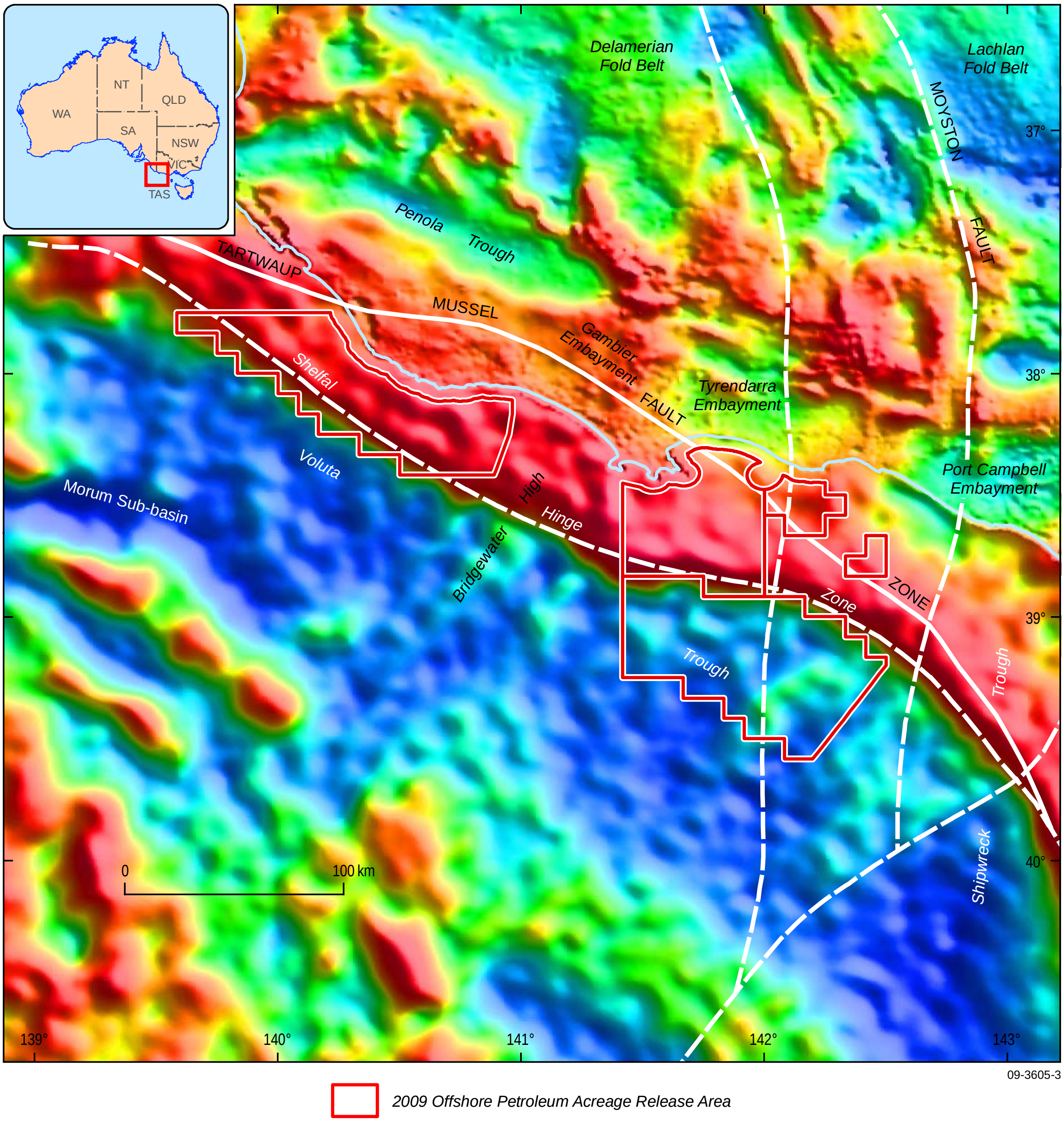

Figure 3. Gravity image Otway Basin, highlighting hinge zones and main basement faults.

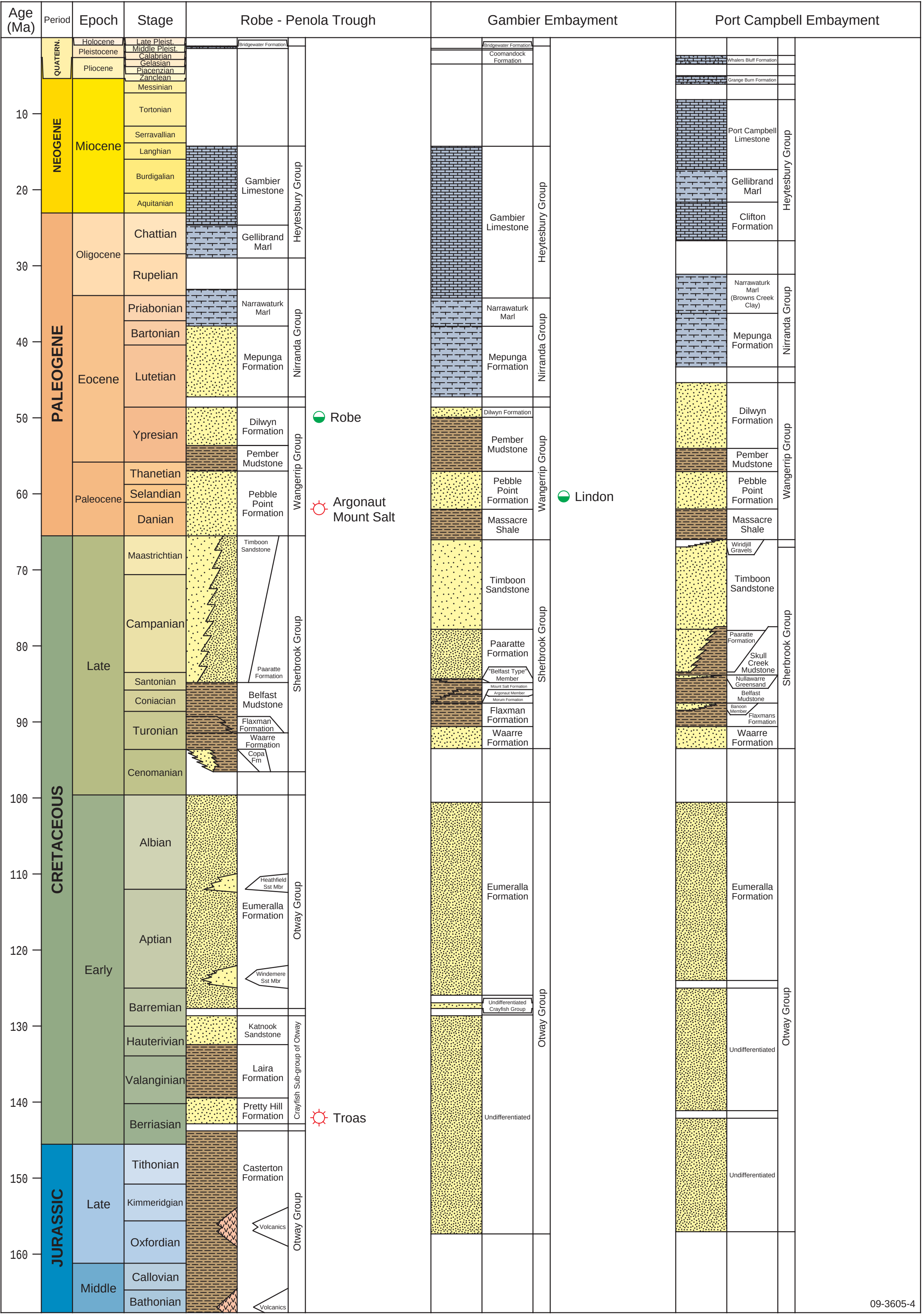

Figure 4. Stratigraphic chart for Otway Basin (Jurassic-Quaternary).

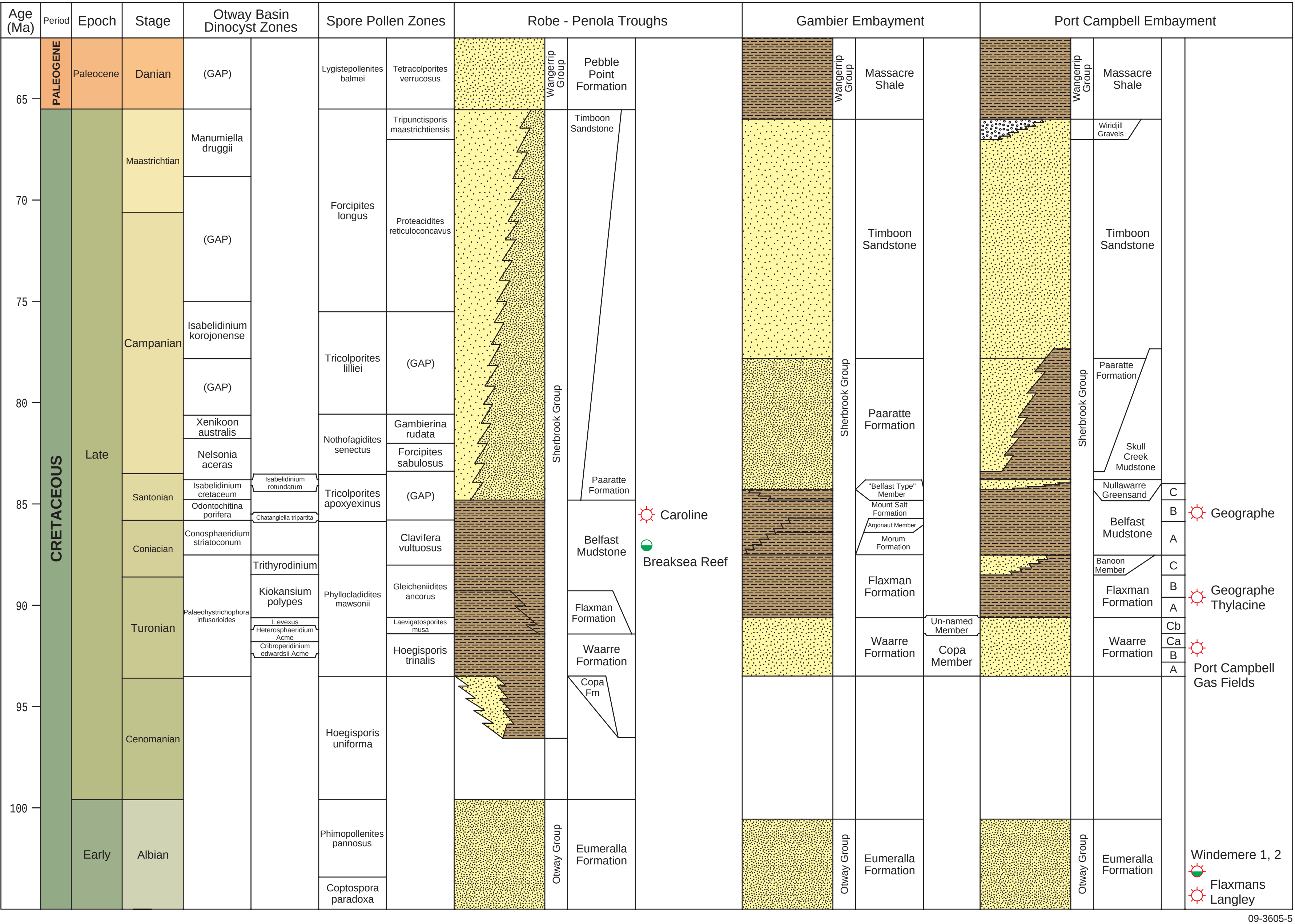

Figure 5. Stratigraphic chart for Otway Basin (Aptian-Danian).

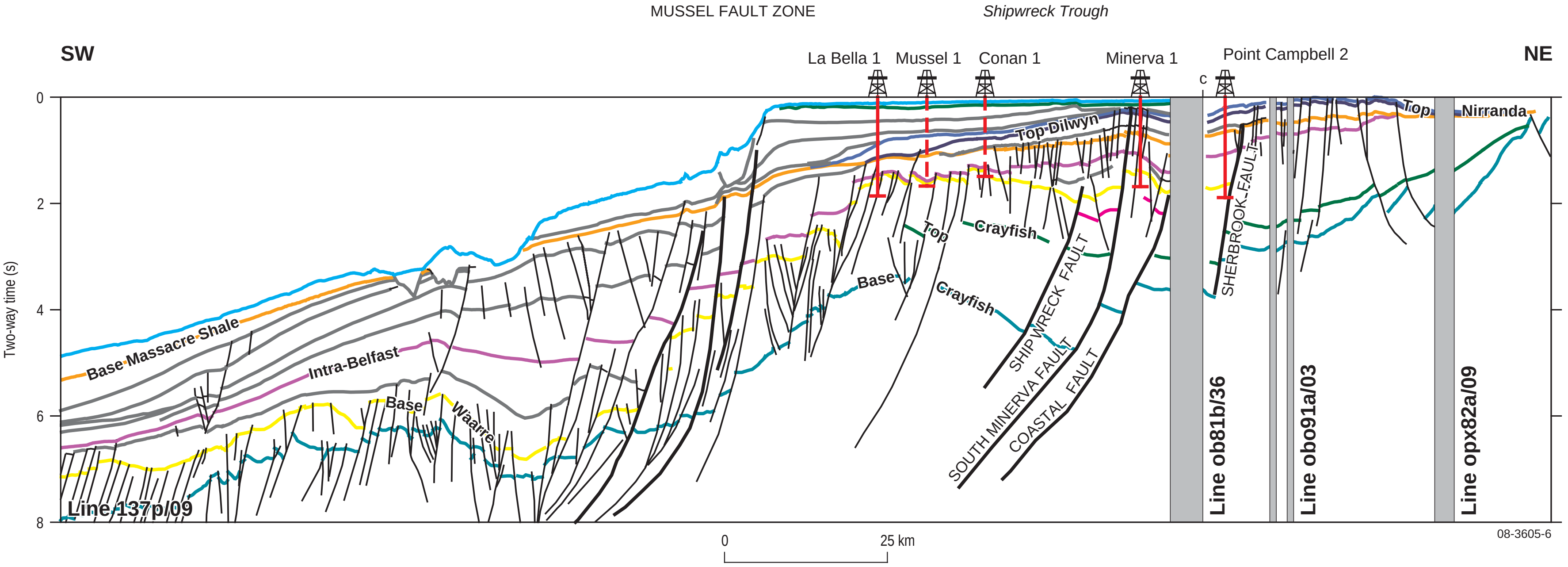

Figure 6. Generalised and representative regional NE-SW oriented seismic section across basin.