Out of Gondwana

This is the story of how the island continent of Australia emerged from the supercontinent of Gondwana, and the far-reaching impacts of this history on Australian resources, economy and society. We owe our energy resources of coal, oil and gas to Gondwana and its breakup, and hence an Australian economy dependent on fossil fuels. The isolation imposed by the breakup has been fundamental to how life developed in Australia and has shaped Australian society in response to the tyranny (or opportunity) of distance. This chapter focuses on how Gondwana broke up, why the fossil fuels are where they are, why their discovery and exploitation have followed the pattern that they have, and why all that is important to Australians.
Figure 4.1: Age of ocean floor around Australia. Note the rapid spreading in the Southern Ocean after about 40 Ma. Named features include: CAP–Cuvier Abyssal Plain, GAP–Gascoyne Abyssal Plain, PAP–Perth Abyssal Plain, GAB–Great Australian Bight, OT–Otway Basin, BS–Bass Basin, LHR–Lord Howe Rise, PNG–Papua New Guinea, AAD–Australia Antarctic Discordance, MTJ–Macquarie Triple Junction, SEIR–South East Indian Ridge (Source: modified from Muller et al., 2011).
Gifts of Gondwana

The coal, oil and gas resources of Australia are the ‘gifts of Gondwana’. The quality, quantity and distribution of these fossil fuels were determined by the geological evolution of Australia as it emerged from the supercontinent. First we will chart this dramatic history from the Early Paleozoic tropical seaways to the Late Paleozoic glaciation, through Permian coal-forming forests to the breakup of Gondwana and the creation of the island continent with its hydrocarbon-rich marginal basins, now on its journey north. In the second section of the chapter, we will examine the history of Australia’s search for oil using three case studies. Combined, these form a story about why the fossil fuels are where they are, why their discovery and exploitation have followed a particular pattern, and why they are important to Australians today and in the future.

Australia’s journey out of Gondwana is recorded in the patterns of seafloor spreading in the surrounding oceans (Figure 4.1) and the sediments that were deposited in the onshore and offshore basins of the continent (Figure 4.2). The Mesozoic marginal basins created as Gondwana broke apart contain around 90% or more of Australia’s conventional oil and gas. The majority of the known gas accumulations are on the North West Shelf, and most of the oil was originally in the Gippsland Basin (Figure 4.2), but it has now been largely produced. Australia has sufficient gas resources to support growing domestic and export demands for liquefied natural gas (LNG) over many decades, especially when unconventional resources such as coal-seam gas (CSG) are also considered (Chapter 9); but finding a future oil supply is more of a challenge.

Early energy self-sufficiency with wood and coal in the age of steam was replaced by dependency on imported oil once the internal combustion engine became crucial to keeping Australians moving...
across the vast distances by the early 1920s. Energy self-sufficiency returned in the 1960s with the discovery of giant oil fields in the offshore Gippsland Basin and more oil finds on the North West Shelf. These fields supplied most of Australia’s crude oil needs for 30 years, with production peaking in 2000. Since then, crude oil production has declined and, by 2030, imports are expected to supply three-quarters of our oil demand. There still remains the chance that a major new oil province awaits discovery in the deepwater frontier basins around Australia’s margin, formed as Gondwana broke apart.

Hydrocarbon exploration is guided by a concept known as the petroleum system, which brings together all the essential elements for oil and gas accumulations to occur. Let us look at what this system entails.

**Petroleum systems and hydrocarbon resources**

Petroleum is formed by the thermal and chemical alteration of organic matter buried in sedimentary basins. Time and temperature act on organic matter, generating buoyant gas and oil. As they are lighter than water, they move upwards, following permeable migration pathways through the sedimentary sequence until trapped by a permeability barrier. For petroleum accumulations to form and be preserved, a complex series of processes occurring over millions of years is needed. The crucial elements of a petroleum system are:

- the depocentre—a basin container influenced by the underlying basement architecture
- the source—an organic-rich rock, such as a coal or oil shale
- the reservoir—porous and permeable rock, such as sandstone
- the seal—an impermeable rock such as a shale
- the trap—a subsurface structure that contains the accumulation, such as a fault block or anticline
- the overburden—overlying sediments that are required to bury the source rock to depths hot enough for thermal maturation to occur
- the migration pathways—to link the matured source to the trap (Figure 4.3).

In addition to these static elements, the actual processes involved—trap formation, hydrocarbon generation, expulsion, migration, accumulation and preservation—must occur, and in the correct
order, for the petroleum system to operate successfully and for oil and gas accumulations to be formed and preserved. A mineral system is a similar conceptual process (Chapter 8), but with a critical difference. In a mineral system, the fluids are not trapped but are fluxed through a ‘throttle’ or smaller rock mass where metals in the fluid are deposited and the residue fluid is expelled.

Unconventional oil and gas resources are those that are more difficult and costly to extract than conventional accumulations. In a conventional field, the hydrocarbons generated from organic-rich source rocks have migrated into a reservoir from which they can be fairly readily produced. Unconventional oil and gas are often hosted within the source rock (shale oil, shale gas and coal-seam gas), in a poor-quality reservoir (tight gas), or is of poor quality (tar sands). Oil shale is an example, where a thermally immature source rock has not generated and expelled hydrocarbons (e.g. Early Cretaceous Toolebuc Formation in the Eromanga Basin; Did you know? 4.1). Oil or tar sands occur where conventional crude oil has failed to be trapped at depth and has migrated near to the surface and become degraded by evaporation, biodegradation and water washing to produce a viscous, heavy, oil residue. In the case of coal-seam gas, the gas molecules are still within the coal source rock, absorbed onto the surface of the coal. Coal-seam gas can only flow to the surface once the confining pressure has been decreased by dewatering the coal seam (Chapter 9).

Another key difference is that conventional oil and gas resources occur in discrete accumulations within structural closures, whereas many unconventional hydrocarbon resources are described as ‘continuous’. Examples include basin-centred gas, which occupies large areas in a basin axis, contained in tight gas sands, shale and/or coaly source rocks; and coal-seam gas that is throughout a coal formation, often covering hundreds of square kilometres (Figure 4.3).

The petroleum resource pyramid (Figure 4.4) describes how a smaller volume of easily extracted conventional gas and oil is underpinned by larger volumes of unconventional gas and oil, which are more difficult and more costly to extract. For the unconventional hydrocarbon resources, additional technology, energy and capital have to be applied to extract the oil or gas, replacing the natural action of the geological processes of the petroleum system. Technological developments and commodity price rises can make the lower parts of the resource pyramid accessible and economic to produce. The recent development of oil sands in Canada, and of shale gas in the United States, are examples where rising energy prices and technological development have facilitated the exploitation of large unconventional hydrocarbon resources lower in the pyramid.

With an understanding of a petroleum system and the nature of these hydrocarbon resources, let us now look briefly at how Australia has evolved in the Paleozoic and, in particular, how the continent came out of Gondwana.

**Australian petroleum supersystems**

The dramatic shifts in climate and tectonic regime experienced as Australia evolved within and then separated from, Gondwana have produced
a great variety of individual petroleum systems with widely differing characteristics. Source rocks range in age from the Mesoproterozoic to the Cenozoic, and, along with the reservoir and seal facies, almost every sort of depositional environment is represented, from desert salt lakes and tropical reefs to glacial outwash plains and deep-sea fans. However, a pattern emerges among this extreme diversity when continent-wide studies of palaeogeography, hydrocarbon habitat and oil and gas geochemistry are considered.

The individual systems have been classified into a number of large groupings or petroleum supersystems with shared geological characteristics (Appendix 4.1.1). These are the McArthur, Urupungan, Centralian, Larapintine, Gondwanan, Westralian, Austral, Capricorn and Murta supersystems (Figures 4.5 and 4.6). The spatial pattern of these supersystems is reflected and validated in the geochemistry of Australian oil and gas, which again fall into a number of distinct oil families. Oil families match petroleum supersystems because oil and gas composition is controlled by the depositional environment of the source-rock facies and the biological evolution of the algae, bacteria, plants and animals, all of which contribute the initial organic matter. The oil families in Australia can be geographically represented in a dendrogram based on a cluster analysis, showing the relationship between them. For example, oils from the Papuan, Bonaparte (Vulcan and Sahul), Browse and Carnarvon (Dampier, Barrow and Exmouth) basins cluster together as they are derived from Late Jurassic marine shales. This Westralian oil family shares more chemical affinity with Perth Basin oils sourced from Triassic marine rocks than with oils derived from land plants found in the Gippsland, Otway and Eromanga basins (Figure 4.6).

Most of Australia’s conventional oil and gas resources are within the Larapintine, Gondwanan, Westralian and Austral supersystems (Figure 4.5), although there is the potential for significant

Figure 4.4: Petroleum resource pyramid, showing how resource quality varies with permeability. The pores in a conventional sandstone reservoir (a) are several orders of magnitude larger than those in a shale gas reservoir (b). (1.3 mm horizontal field of view in both thin section photomicrographs) (Sources: Geoscience Australia; photomicrographs SE Phillips, Phillips-Gerrard Petrology Consultants)
unconventional shale gas resources in the Proterozoic McArthur Supersystem, as well as oil shale deposits in the younger Murta and Capricorn supersystems.

Gondwana to island continent

The fragments of continental crust that are now Australia have undergone several amalgamation and fragmentation supercontinent cycles (Chapter 2). However, the heritage of Gondwana has remained indelible in the landscape, in the flora and fauna, and in the distribution of fossil fuel resources, and so has shaped the Australian economy and society. The formation of the continent's margins gave the island nation of Australia its shape, *girt by sea*, and the boundary conditions within which the coastal realm developed. This is where most Australians live (Chapter 1).

Tectonics and climate are the big drivers that play out in the supercontinent cycles. Driven by the processes of plate tectonics, the continental
blocks wander over Earth’s surface, changing latitude; landmasses group together and break apart, altering climate and sea-level as the world shifts from greenhouse to icehouse and back again (Box 2.5). During the Permian, the climate was paramount, Earth being under the ‘bulldozer’ of ice, followed by the greening thaw. In the Jurassic and Cretaceous, tectonic processes dominated during the breakup. Mostly there is an intricate interaction between tectonics and climate. These forces are also identified as the big drivers in landscape evolution (Chapter 5).

The prelude to this tale begins in the Ordovician, when Australia was located in tropical latitudes in the Northern Hemisphere and locked into the recently formed jigsaw of Gondwana. Antarctica lay to the south, Greater India to the west and various Asian continental blocks to the north and west (Figure B4.1a). Sea-level was high, Australia was criss-crossed by shallow seas and a series of volcanic arcs formed the eastern seaboard of the continent. Oil source rocks were deposited in the seaways, and some of the gold endowment of eastern Australia was created by this tectonic activity (Chapter 8).

By the Late Devonian, Australia, within Gondwana, had shifted southwards and lay in the Southern Hemisphere. Tropical conditions still held sway across the north, with reef-fringed marine embayments on the western margin (Carnarvon, Canning and Bonaparte basins), and on the eastern margin (Broken River, Adavale basins). The Ordovician Larapintine Seaway (Chapter 2) was severed, and central Australia, as today, was under desert sands. North China and other Asian
Over the past half a billion years, dramatic changes have shaped the Australian continent as it travelled from the tropics to the pole and back again. Australia commenced this journey within Gondwana, then emerged as the island continent and is now in collision on its northern margin with Asia. This history can be unravelled from the record preserved in the sedimentary basins, the evidence cut and etched into the landscape, and the patterns of seafloor spreading in the surrounding oceans (Figure 4.1).

The detailed stratigraphy of basins such as the Canning (Appendix 4.3.7) captures this epic story—the Ordovician Larapinta seaway retreats, as limestones are replaced with salt and desert sands, which in turn are overlain by Permian glacial sediments. Then these are capped by the mud and sand of the Early Cretaceous inland sea.

In the Kalbarri cliffs (left), Ordovician sandstones deposited in fluvial to coastal environments when Australia was in the tropics are overlain by the Cretaceous sediments of the rising seas, deposited when the continent was in polar latitudes.

Using such information from outcrop and well data from across the whole continent, a series of palaeogeographic maps from the Cambrian to the Quaternary were produced for Australia (BMR Palaeogeographic Group, 1992). The 70 time-slice maps show how the pattern of environments shifted across the continent through the Phanerozoic (Appendix 2.3.5). The more recent products of the Earthbyte Group at the University of Sydney are needed to see Australia in its plate tectonic context (Appendix 4.4.1). (Sources: BMR Palaeogeographic Group, 1992; www.earthbyte.org)
Figure B4.1a: Middle Ordovician (ca 470 Ma) global plate reconstruction, showing Australia (highlighted in white) within Gondwana with Antarctica, India and other Asian fragments. The palaeo-equator (marked in red) bisected Australia. Shallow tropical marine environments extended from the North China Block to eastern Australia, with the Larapintine Seaway linking the Canning and Amadeus basins to the deepwater convergent margin. (Source: modified from PALEOMAP Project, 2008)

Figure B4.1b: Late Devonian (ca 360 Ma) global plate reconstruction, showing Australia within Gondwana. Note that Australia has shifted south but still edges into the tropics. The seas have retreated from the interior as Gondwana begins to collide with Laurentia. A large marine embayment occupies the Canning Basin, with a fringing coral reef developed along its northern margin. A deep marine seaway has opened as North China and Tarim separate from Gondwana. (Source: modified from PALEOMAP Project, 2008)

Figure B4.1c: Early Permian (ca 280 Ma) global plate reconstruction. Australia has continued its southward journey within Gondwana and now lies partially within the polar circle. Most of the continent is covered by an icecap, like modern-day Antarctica. The Asian continental fragments have parted company with Gondwana and are heading north, while Antarctica, India, southern Africa and South America remain in the cold south with Australia. (Source: modified from PALEOMAP Project, 2008)

Figure B4.1d: Late Jurassic (ca 160 Ma) plate reconstruction for the Australian region, showing the continent still within southerly latitudes. The northwest margin is facing onto the Tethys Ocean, and organic-rich sediments accumulate in restricted marine rifts. The Australian–Antarctic rift valley remains non-marine at this time. Lush forests in eastern Australia were the site of coal deposition, some of these coals are now the source of coal-seam gas. (Source: modified from PALEOMAP Project, 2008)

Figure B4.1e: Late Cretaceous (ca 70 Ma) plate reconstruction for the Australian region, showing a developing marine gulf between Australia and Antarctica. The Lord Howe Rise is also separating from the eastern margin as the Tasman Sea is formed. The southwest margin is fully marine, and India has left Gondwana and is moving north towards its rendezvous with Asia. The Tasman Sea has begun to open. (Source: modified from PALEOMAP Project, 2008)

Figure B4.1f: Late Eocene (ca 34 Ma) plate reconstruction for the Australian region, showing Australia starting its journey back to the north. Australia is now the island continent, having recently separated from Antarctica along the Tasman Fracture Zone. The opening of this seaway, together with that between South America and Antarctica, allowed the circumpolar current to flow. (Source: modified from PALEOMAP Project, 2008)

Aerial view of a modern-day tropical sea, the Bahamas, Caribbean Sea. Similar shallow-water carbonate environments are interpreted to have occurred in the Ordovician Larapintine Seaway.

Aerial view of the modern-day Great Barrier Reef, Australia. In the Late Devonian, similar reef environments occurred in the Canning and Bonaparte basins.

Modern-day icefield. Large areas of Gondwana were similarly mantled with ice in the Early Permian.

Modern-day fluvial environment in high latitudes. Similar environments are interpreted to have occurred along the Australian–Antarctic rift valley in the Late Jurassic.

Coastline at western end of the Great Australian Bight, near Esperance, Western Australia, where a broad seaway was established between Australia and Antarctica by the Cretaceous.

Aerial view of the Nullarbor Plain and cliffs, Great Australian Bight. Neogene limestones are exposed along this southern edge of the island continent.
blocks rifted from the northwest margin of the supercontinent at this time, and their geological history began to diverge from that of Australia, which continued a southward journey with its partners in Gondwana (Figure B4.1b).

**Gondwana’s heritage**

The distinctive Permo-Carboniferous Gondwana facies was deposited as basal glacial sediments overlain by coal measures across Australia, Antarctica, India, Arabia, Madagascar, Africa and South America. This shared stratigraphy was an important part of the early evidence pointing to continental drift and hence plate tectonics (Box 4.2). In Australia, sediments record the history of the Late Paleozoic ice age, followed by coal deposition in foreland basins along the convergent eastern Gondwanan margin, creating a legacy of major Permian coal resources that underpin Southern Hemisphere fossil energy supplies (Chapter 9). In contrast, the main episode of Northern Hemisphere coal deposition was in the appropriately named, and preceding, Carboniferous period.

**Gondwana glaciation**

Australia, within Gondwana, continued on a journey south during the Carboniferous, shifting rapidly through about 40° of latitude from the tropics to the polar regions. As Pangaea came together in the mid- to Late Carboniferous, there were continuing collisions between parts of Gondwana and Euramerica, causing the Variscan or Hercynian Orogeny in Europe, and the Orogeny Alleghenian in North America. At the same time in central and eastern Australia, the Alice Springs and Kanimblan orogenies (Chapter 2) formed vast uplands, where seasonal snow cover had a better chance of becoming permanent ice than at lower altitudes. Once established, the ice sheets reflected more heat back into space. Compounding the cooling effect was the enhanced removal of CO₂ from the atmosphere due to accelerated erosion and weathering induced by this episode of mountain building. In this way, the increase in elevation and the meridional arrangement of landmasses helped move Earth into an icehouse regime, and glaciation took hold across the Gondwanan continents arrayed around the South Pole (Figure B4.1c). The ice sheets appear to have been centred in what are now the Gambertsev and Transantarctic mountains in Antarctica, and glaciers radiated out into southern Australia and the other conjugate Gondwana continents (Figure 2.35).

There were three main episodes of glaciation from the Carboniferous through to the Permian, which ranged across Gondwana from South America to Australia. The third episode, in the Late Carboniferous to Early Permian, was the most extensive and the one that deposited glacial sediments in many Australian basins (Figure 2.35). Hundreds of metres to several kilometres of diamictite and other glacially influenced sediments were dumped into the Carnarvon, Canning, Officer and Cooper basins around the edges of three ice sheets that may have joined together to cover half of Australia at the glacial maximum. The clean and wind-winnowed sandstones deposited at the edge of the ice are reservoirs for oil, gas and groundwater in the Cooper and Canning basins.
The name ‘Gondwana’ is derived from the Sanskrit gondavana, meaning the forest of the Gonds, an ancient indigenous people of India. The term Gondwana series was used by the Geological Survey of India from the 1870s to denote plant-bearing sedimentary sequences with characteristic *Glossopteris* flora. By the 1900s, Gondwanaland had entered the global literature as the term for the southern supercontinent, fragments of which, although now dispersed by continental drift, still preserve glacial sediments deposited when the fragments were united around the South Pole. Southern Hemisphere geologists (Alex Du Toit and Lester King in South Africa and Sam Carey in Australia), surrounded by this evidence, championed the idea, although it was not until the plate tectonics revolution of the late 1960s that the mechanism of continent dispersal by seafloor spreading was understood (Chapter 2).

Today Gondwana has passed into the general consciousness, especially in Australia where it is found in literature, in song and in company names for clothing lines and tourist ventures. The name conjures up remnants of something ancient and original. Even the origin of the name, from one of the earliest Indo-European languages, seems apt as an echo of a lost world.

Examples of temperate rainforest. (a) Oparara, West Coast, South Island, New Zealand. (b) Barrington Tops National Park, New South Wales, which is part of the Gondwana Rainforests of Australia World Heritage Area.

*Glossopteris*, the iconic fossil of Gondwana.
In eastern Australia, mountain glaciers scoured the highlands along the convergent margin of Gondwana where the ice was established earlier and lingered longer.

The *Glossopteris* forests of Gondwana: the origins of Australia’s energy base

When the ice sheets melted, sea-level rose, and marine to brackish water embayments extended into Gondwana, which was now re-mantled by thick vegetation, including *Glossopteris* forests (Chapter 3). These forests may have resembled the high-latitude peat-swamp forests of today’s taiga in Siberia. Thick coal measures accumulated on all the Gondwanan continents in areas of basin subsidence. In eastern Australia, the Sydney–Gunnedah–Bowen basin system formed as a foreland depocentre behind the convergent margin (Chapter 2).

Black coal, conventional gas and coal-seam gas are the major resources that were formed while Australia was part of Gondwana during the Permian. The organic matter that accumulated in Gondwanan swamps now powers Australia. Coal has been mined for more than 200 years and forms the cornerstone of Australia’s domestic economy; it is our largest energy resource, has a low cost of extraction and is located close to population centres. High-quality Australian black coal is also a major contributor to the trade balance, with Australia being the world’s largest coal exporter (Chapter 9).

In addition to the traditional mineable coal, the Permian basins also host major coal-seam gas and conventional oil and gas resources. Conventional gas from the Cooper and Bowen basins has supplied the domestic gas needs of much of eastern Australia for more than 40 years. These resources are the products of the widespread Gondwanan petroleum supersystem that is characterised by clastic terrestrial facies and coaly source rocks (Figure 4.5).

Production from conventional fields is now being supplemented by the new coal-seam gas industry. This resource is now considered large enough to rival the giant conventional gas fields on the North West Shelf. In Queensland, several coal-seam gas to LNG projects are progressing to development, although not all stakeholders are happy with the potential intrusion into agricultural land. The development of unconventional hydrocarbon resources does bring environmental and other challenges, including understanding the impact on groundwater and competing land uses (Chapters 7 and 11). The economic benefits, however, may outweigh environmental concerns.

Challenges also lie ahead in a carbon-constrained world for an Australia dependent on coal for power generation and export income; late 2011 saw the Australian Parliament pass a new law to tax carbon emissions. Gas-fired electricity is less carbon intensive, and carbon capture and storage offers a low-emission way to continue to reap the benefits from Gondwanan coal and gas. The eastern Australian coal basins are being actively studied for possible CO$_2$ storage sites (Chapter 11). Coal-to-liquids and gas-to-liquids are other technologies that may form part of the future energy mix, again using the gifts of Gondwana to power Australia.
Pangaea at its zenith

With the coalescence of most landmasses into the one huge supercontinent of Pangaea, the remaining building blocks of Gondwana were placed mostly south of the equator. Australia, attached to Antarctica as East Gondwana, was moving southwards in the farthest southern latitudes. The new configuration allowed land flora and fauna to achieve rapid and vast distributions. Throughout the Late Permian, the forests were laying down coal widely across Australia, from the Laura Basin in Cape York to Tasmania in the south and across to the Perth Basin (Figure 4.2). Following the end-Permian global extinction event (Chapter 3), the sedimentary record preserves a very different world, often referred to as the ‘coal gap’. The supercontinent Pangaea reached its maximum size in the Triassic, altering the global climate to one dominated by semi-arid conditions and a Pangaean monsoonal circulation pattern. Triassic red beds overlie Permian coal-bearing sediments in many locations across Gondwana (southern Africa, Antarctica, India and Australia), as well as in north China.

In eastern Australia, Permian coal measures are overlain by Early Triassic red beds and fluviatile sandstones; marine deposits are rare. In contrast, along the western margin, thick marine shales mark a major Early Triassic inundation (Figure 4.5) The Blina Shale crops in the Canning Basin, and the Locker Shale is a distinctive bland seismic package in the offshore Carnarvon Basin. The Mount Goodwin Shale in the Bonaparte Basin is the seal facies for gas accumulations contained in Late Permian sandstones (Petrel gas field); in the Perth Basin, the Kockatea Shale is both a seal and an oil-rich source rock for oil and gas accumulations (Figure 4.7).

From the Permian and into the Triassic, eastern Australia was part of the active Gondwana convergent plate margin. Triassic igneous activity occurred along this margin from South America through Antarctica, New Zealand and eastern Australia (New England Orogen, Chapter 2) to Papua New Guinea. A fragmentary sedimentary record for onshore Australia in the Triassic reflects deformation and erosion related to major tectonic events, including the Hunter–Bowen Orogeny in the east and the Fitzroy Movement in the west (Chapter 2). Widely scattered coal deposition had returned by the Late Triassic—in narrow rift basins in Queensland and northern New South Wales, and in small fluviolacustrine basins in South Australia and Tasmania.

Figure 4.7: Seismic sections of Triassic features. (a) Perth Basin, showing the distinctive Kockatea Shale with a bland texture in the seismic data on-lapping older units. (b) Carnarvon Basin—Triassic fault blocks with high amplitudes circled, indicating possible gas sands. (c) Exmouth Plateau—seismic image and a schematic diagram of a Late Triassic carbonate pinnacle reef. (Sources: Geoscience Australia; Woodside, 2010)
In the Middle Triassic through to the Early Jurassic, major deltas up to 5 km thick were built along a stretch of more than 3000 km on the northwest margin, in the Carnarvon, Roebuck, Browse and Bonaparte basins. Contributions to this vast sediment pile were delivered by rivers that rose in the central Australian highlands, and from the south, from the Pinjarra Orogen and perhaps from elsewhere in Gondwana (Antarctica and Greater India). The coaly sediments and fluvial sandstones that accumulated on these delta plains form the source rocks and reservoirs, respectively, for many of the giant gas fields on the North West Shelf (Figures 4.2 and 4.5). They provide the lion’s share of Australia’s conventional gas resources and support a major export LNG industry (Chapter 9).

The petroleum systems of the Carnarvon Basin will be one of the case studies discussed later in the chapter, where we will look in detail at the Triassic delta of the Mungaroo Formation.

Although the sandstone gas reservoirs on the North West Shelf are a key part of Australia’s energy-security future, other Triassic sandstones also occupy a place in our consciousness. The earliest convict settlements were hewed from the Hawkesbury Sandstone in Sydney and the Ross Sandstone in Hobart. Both building stones are Early to Middle Triassic quartzite deposited from a major river system that flowed from Antarctica. The rugged sandstone escarpment of the Blue Mountains was a barrier to the early explorers (Chapter 5) and is now a scenic escape from Sydney. Before the convicts laboured in ‘The Rocks’ or expressways were sliced through, Aboriginal people carved their stories into the sandstone. The clean, quartz sands were well winnowed in their journey down transcontinental rivers, to be reworked and deposited in the tidal delta environments of the Hawkesbury Sandstone. Later diagenesis has produced a well-cemented quartzite that provides strong foundations for Sydney’s skyscrapers and preserves Aboriginal rock art.

**What was beyond the shore?**

As we have seen, Australia in the Triassic was largely high and dry; except for the Early Triassic transgression along the western margin, non-marine to deltaic sedimentation dominated. But beyond the delta fronts, at the continent edges, the fine-grained materials carried by the giant rivers of Gondwana were deposited as marine silts and muds. Further out on the northwest margin, there were carbonate facies, including pinnacle reefs lapped by the tropical waters of the Tethys Ocean (Figure 4.7c). On nearby Timor, thick Triassic marine shales and limestones, deposited as the distal edge of the North West Shelf sequence, have been caught up in the Cenozoic collision between Asia and Australia.

We can only speculate on the fate of the finer grained sediments that were shed by Gondwana’s rivers and deltas. On the eastern margin, did the Hawkesbury Sandstone delta deposit fine-grained sandstones on the Lord Howe Rise? Are the muds of the Mungaroo delta now somewhere in South-East Asia?

Now, let’s move into the Jurassic and see how these depositional systems were dismembered as Gondwana broke apart and the continental fragments were dispersed.
Gondwana breakup

By the Middle Jurassic, Gondwana had started to break up. The Gondwana series in India, Argentina, South Africa and Tasmania were capped with dolerites in response to mantle upwelling associated with the breakup (Figure 4.8). The spectacular landscapes of Tasmania record the rending of Gondwana as doleritic magma was intruded into the Permo-Triassic sediments (Did you know? 4.2). Although Tasmania did not break away, elsewhere around Australia the process went to completion with the formation of new seafloor. Deep-blue sea (4 km and deeper) encircles Australia on three sides—to the west, south and east—floored by oceanic crust (Figure 4.1). These are the divergent passive margins of the continent. To the north, the margin is currently actively convergent (although it too was divergent and passive in the Mesozoic).

The pattern of seafloor ages (Figure 4.1) indicates that new oceanic crust was formed progressively off the northwest, followed by the southwest, south, southeast and northeast margins, as Australia unzipped from the ‘jacket’ of Gondwana. The last clasp opened as Tasmania, which remained with mainland Australia, slid past Antarctica in the latest Eocene. Rapid seafloor spreading since the Middle Eocene then shifted Australia back towards the tropics and into collision with Asia and the Pacific Plate (Chapter 2). Ongoing seafloor spreading from the South East Indian Ridge continues to move Australia northward.

Each of the Australian margins differs in character, reflecting varying histories and controlling factors. The nature of the margin (rifted or sheared), the amount of volcanism, the influence of ancient
basement structures on the pattern of breakup, and post-breakup modifications (later convergence, growth of deltas or carbonate build-ups) are all-important criteria differentiating the various margins of Australia:

- The ragged northwest margin of submerged plateaus and failed rifts is the product of the successive continental slivers launched towards Tethys and Asia over hundreds of millions of years from the Early Paleozoic to the Cretaceous (Figures 4.9a and 4.9b).

- The southwest margin is dominated by the Wallaby–Zenith Fracture Zone and records the impact of the Kerguelen Large Igneous Province it shared with India. This margin had a dextral transtensional sense of opening.

- The southern margin marks the break from Antarctica along Proterozoic and Paleozoic lines of weakness, with its shape modified by progradation of the Late Cretaceous Ceduna delta (Figures 4.9c and 4.9d).

- The eastern margin is the complex Tasman borderland, which has evolved out of the Paleozoic convergent margin of Gondwana.

- The northern margin is now in collision, forming the highlands of New Guinea and the swirl of the islands through the Banda Arc in eastern Indonesia and Timor.

The continent’s breakup history from Gondwana has had a fundamental control on the distribution of Australia’s major hydrocarbon resources. The identified petroleum resources are dominated by widely distributed natural gas, but the major known accumulations of crude oil are restricted to the Gippsland Basin and five ‘oily’ sub-basins along the northwest margin (Figure 4.10). This distribution is controlled by the occurrence of deep, narrow troughs containing mature oil source rocks. In the case studies at the end of this chapter, the operation of the proven petroleum systems of the Gippsland and Carnarvon basins are discussed, along with the potential in the Great Australian Bight. But before we delve into the oil kitchens and how they have influenced the Australian economy, let’s paint a bit more of the broader context by looking at each margin in turn, since they delimit the edges of Australia and reveal the inheritance of Gondwanan breakup.

**Australia’s elusive conjugate margins**

The neat fit of Africa to South America demonstrates that they are conjugate passive margins now separated by seafloor spreading from the Mid Atlantic Ridge. In contrast, Australia’s conjugate margins are far less obvious, as many are ‘hidden’ continental fragments. The strongest evidence for Argo Land—which separated from Australia in the Late Jurassic when the Argo Abyssal Plain formed (Figure 4.1)—is the requirement for another side of the rifted northwest and southwest margins of Australia. West Burma, Sumatra and other destinations in South-East Asia have all been proposed for Argo Land. Greater India, which once lay to the west of the Perth Basin, is now considered to be hidden beneath the Himalaya. The Wallaby–Zenith Fracture Zone marks the northern limit of Greater India (Figure 4.11). The Gascoyne Terrane is postulated to be a separate

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Figure 4.9: Map and seismic profiles from the Australian region. (a) Combined topographic/bathymetric image of the southern Australian region, showing the sub-marine terrace in the Great Australian Bight built by the Late Cretaceous Ceduna delta and the large submerged continental fragment of the Lord Howe Rise lying between New Zealand and New Caledonia.
Figure 4.9 continued: (b) Seismic section across the wide and complex volcanic western margin of the Exmouth Plateau, showing seamounts on the Gascoyne Abyssal Plain. (c) Seismic section across the narrow sheared southern margin of the plateau along the Cape Range Fracture Zone stepping down to the ocean floor of the Cuvier Abyssal Plain. The block-faulted Triassic sediments of the Exmouth Plateau host giant gas fields and are overlain by a drape of younger sediments. (d) and (e) Seismic section across the Bight Basin rifted margin, showing the perched Jurassic rift of the Eyre Sub-basin and the highly extended continental crust beneath the Bight Basin sediments, extending out to the continent-ocean boundary (COB). (Sources: modified from Alcock et al., 2006; Symonds et al., 2000; Totterdell et al., 2000; Stagg et al., 2004)
block between Greater India and Argo Land. The terrane broke away in the Early Cretaceous, with the formation of the Gascoyne and Cuvier abyssal plains. The submerged Lord Howe Rise and other continental fragments in the Tasman and Coral seas are the poorly known conjugates of the eastern Australian margin. Only on the southern margin do we have an obvious conjugate pair. This southern conjugate is found in Antarctica, although now it is mantled by kilometres of ice and Cenozoic glacial sediments.

Northwest margin

Looking to the northwest of the continent, we see the Argo Abyssal Plain, a deep-blue ‘window’ on the map in contrast to the complex collision zone to the north and east (Figure 4.9a). This plain contains the oldest seafloor around Australia and some of the oldest preserved seafloor on Earth (Figure 4.1). This is the area where Argo Land, perhaps now located in West Burma, parted company with the Australian continent at 156 Ma (Oxfordian) as eastern Gondwana fragmented. The record of Jurassic seafloor further to the northeast has been lost to subduction and collision in the Cenozoic convergent margin. Argo Land was one of a series of Asian continental blocks and slivers that were successively rifted from the Gondwanan northwest and northern margins and transported across Tethys to be accreted onto Eurasia since the Early Paleozoic (Chapter 2).

The embayed configuration of the northwest margin reflects the interplay of two structural trends: the dominant northeast–southwest Westralian trend established in the Permian and seen in the alignment of the margin and the offshore basin depocentres; and an older northwest–southeast grain, which controls the distribution and orientation of the Early Paleozoic basins and the northern margin of the Exmouth Plateau (Figure 4.10). These older basins may have been exploiting lines of weakness established in the Proterozoic along former collision zones such as the Paterson Orogen (Figure 2.10).

During Late Jurassic rifting, the Westralian trend controlled the pattern of deep-marine depocentres that now host the source of the major oil fields on the North West Shelf. The Exmouth, Barrow and Dampier sub-basins are failed rifts inboard of the Exmouth Plateau, and the Vulcan Sub-basin occupies a similar structural position inboard of the Ashmore Platform to the north. The oil-rich Nancar–Flamingo–Sahul area is where the Westralian trend intersects the older northwest–southeast grain of the Petrel Sub-basin, again creating a deep trough where organic-rich Upper Jurassic oil source rocks accumulated (Figure B4.1d).

Early Cretaceous seafloor spreading west and south of the Exmouth Plateau formed the Gascoyne and Cuvier abyssal plains (Figures 4.1 and 4.9b) and further broke apart Gondwana. The rifted conjugate continental fragment may be the Gascoyne Terrane, now located in Southeast Asia, and considered to have docked in Burma some 20 Myr after Argo Land. The Barrow delta was the Gascoyne Terrane’s parting gift to Australia. This terrane was the conduit and one of the sources of sediment to the north-flowing fluvial system that built the Barrow Group as a series of delta lobes out across the southern half of the Exmouth Plateau and the inboard rifts in the earliest Cretaceous. Locally, the delta provided enough sediment load to push the underlying Late Jurassic organic-rich marine shales in the Exmouth and Barrow sub-basins into the hydrocarbon-generating window, as well as clean reservoir sands to host the expelled oil and gas.

The Barrow delta was severed from its hinterland when the Gascoyne Terrane broke away, sliding along the transform margin of the southern edge of the Exmouth Plateau as the Cuvier Abyssal Plain was formed. Comparison of the western and southern edges of the Exmouth Plateau provides insight into the processes of continental breakup (Figure 4.9). The volcanic rifted western edge contrasts with the sheared southern margin that follows the old northwest–southeast trend, which is picked up again in the Wallaby–Zenith Fracture Zone further to the south and was crucial in shaping the southwest margin. The seismic profile in Figure 4.9c depicts the steep and linear southern transform margin along the underlying Cape Range Fracture Zone. There is an abrupt change from a thick sedimentary pile over the Exmouth Plateau to ocean-floor basalts. The transition zone is a narrow intruded and uplifted rim that forms a steep slope mantled with basaltic

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Figure 4.10: Structural elements map of the North West Shelf region, showing the thick Mesozoic depocentres trending northeast–southwest and the Paleozoic basins extending from onshore along a northwest–southeast trend.

OPGGSA = Offshore Petroleum and Greenhouse Gas Storage Act 2006 (Cwlth)

Field outlines are provided by Encom GPin, a Pitney Bowes Software (PBS) Pty Ltd product. While all care is taken in the compilation of the field outlines by PBS, no warranty is provided regarding the accuracy or completeness of the information, and it is the responsibility of the reader to ensure, by independent means, that these parts of the information used by them are correct before any reliance is placed on them.
During the breakup, not all the action was on Australia’s developing margins; there were also important depositional events under way in the interior, as vast seaways once again invaded deep into the continent. Twice in the Early Cretaceous, marine environments held sway from the Gulf of Carpentaria through the Eromanga Basin to the Great Australian Bight and from the Canning Basin in the west to the Maryborough Basin in the east. The first Cretaceous marine transgression occurred in the Valanginian (from ca 135 Ma) at the same time as the breakup between Greater India and Australia’s southwestern margin, and was probably caused by widespread cooling following the onset of seafloor spreading.

The second marine flooding event occurred later in the Early Cretaceous, during the Aptian and Albian. The last time the continent was under such extensive marine conditions was about 400 Myr previously in the Ordovician (see Chapter 2). As then, fine-grained sediments, some rich in organic matter, were widely deposited. These Early Cretaceous marine shales are now crucial seal facies in petroleum and groundwater systems. In onshore basins, they have not been buried deeply enough to have generated hydrocarbons (see Did you know? 4.1). However, Cretaceous marine shales of the inland sea remain important as the confining beds for the Great Artesian Basin (Chapter 7) and as major elements in the landscape (Chapter 5). Some of Australia’s most exciting fossils are giant marine reptiles and sharks from the Cretaceous inland sea (Chapter 3).

The high sea-level phases of the Cretaceous are associated with global oceanic anoxic events, and at least one of these is recognised in Australia—the late Albian (ca 100 Ma), coinciding with the widespread deposition of the oil shales of the Toolebuc Formation in the Eromanga Basin (Figure B4.3). The organic-rich shale is finely interlaminated with shell beds containing *Inoceramus sutherlandi*, filter-feeding bivalves that were tolerant of oxygen-poor bottom water conditions in the inland sea.

Elsewhere, there was also major inundation of the continents in the Cretaceous and deposition of oil source rocks—in North and South America, north Africa and the Middle East. But looking more closely at the global palaeography for the Early and Late Cretaceous, we see that Australia is out of step; the Turonian (93 Ma) is the highest sea-level globally but, for Australia, highstand occurs nearly 30 Myr earlier in the Aptian. Why?

The global eustatic signal of high sea-level in the Late Cretaceous reflects the low volumetric capacity of the young ocean basins, formed as Gondwana breaks apart. The flooding of Australia in the Early Cretaceous has a more local tectonic cause. As Australia moved eastward, it passed over the sinking subducted slabs on the convergent Gondwana margin, and this higher density material in the mantle induced widespread subsidence and, consequently, the inland sea. By the Turonian, the interior of the continent had passed over the slab and rebounded to be high and dry—an example of dynamic topography.
flows (Figure 4.9c). In contrast, the western volcanic rifted margin of the Exmouth Plateau steps down across a rugged and broad slope to the Gascoyne Abyssal Plain (Figure 4.9b). A complex pattern of volcanic ridges, flows and buildups, seaward-dipping reflector sequences and igneous intrusions was created during the breakup as the Cuvier spreading centre cleared the southwestern corner of the plateau and overprinted the earliest formed Gascoyne oceanic crust.

Following continental breakup and seafloor spreading ca 135 Ma (Valanginian or Hauterivian), there was a major marine transgression as the northwest margin subsided in response to thermal collapse or cooling of the stretched lithospheric mantle from Perth to New Guinea. This transgression was followed by a period of condensed, deepwater sedimentation, which lasted from the Valanginian to the Barremian. Fine-grained marine sediments accumulated in deepwater environments, forming a regional shale blanket, the Muderong Shale and its equivalents, which is the seal facies to most of the North West Shelf’s oil and gas resources (Figure 4.5). By the Late Aptian, deposition of radiolarian-rich claystones records the establishment of open ocean circulation. Contemporaneous flooding occurred on much of onshore Australia, making the Early Cretaceous inland seas (Box 4.3).

On the northwest margin, marine shales and siltstones gave way to carbonate sediments by the Late Cretaceous. The initial deposits were pelagic marls and chalks that graded into coarser calcarenites as the carbonate pile built up into shallower water and prograded seaward, eventually

Figure 4.11: Southwest margin map, showing its sedimentary basins and surrounding ocean floor, hydrocarbon fields and pipelines. The Wallaby and Naturaliste plateaus are largely volcanic features, underpinned by extended continental crust and formed during the final stages of the breakup between Greater India and Australia. The Perth Basin has several small oil and gas fields that are part of the Gondwanan petroleum supersystem. The deepwater frontier Mentelle Basin is still to be tested. (Source: modified from Bradshaw et al., 2003)

Well symbol information is sourced either from ‘open file’ data from titleholders (where it is publicly available as at 1 December 2011) or from other public sources. Field outlines are provided by Encorm GPInf, a Pitney Bowes Software (PBS) Pty Ltd product. While all care is taken in the compilation of the field outlines by PBS, no warranty is provided regarding the accuracy or completeness of the information, and it is the responsibility of the reader to ensure, by independent means, that those parts of the information used by them are correct before any reliance is placed on them.
creating the modern bathymetric North West Shelf. From the mid-Miocene, coral reefs were common, and they continue to flourish, reflecting Australia’s journey north back into tropical waters (Chapter 6). The prograding Cenozoic carbonate wedge can be up to 3 km thick and, in several areas, (e.g. Dampier Sub-basin, Carnarvon Basin, Vulcan Sub-basin, Bonaparte Basin) provides the crucial sedimentary load to push the underlying Jurassic source rocks into the oil window.

In the later Miocene, the architecture of the passive margin was modified by a major regional compressive event as the Australian and Eurasian plates collided (Chapter 2). Pre-existing normal faults were reactivated and inverted, new reverse-fault trends created and anticlines formed; some of these structures now trap hydrocarbons. In the Carnarvon Basin case study, we will see that this is only the last in a long sequence of events required for the oil and gas fields to form on the North West Shelf.

Southwest margin

In contrast to the petroleum-rich northwest, the southwest margin contains only one small oil field offshore and a scattering of modest oil and gas accumulations onshore in the Perth Basin (Figure 4.11). In fact, the major gas supply for the city of Perth is piped more than 1000 km from the giant North West Shelf fields. Why is this contrast so stark? Let’s consider the story of this pivotal point within Gondwana to see if we can find an answer.

The southwest margin formed during the breakup as oceanic crust was created in the Perth Abyssal Plain from ca 135 Ma (Valanginian) onwards;
the Wallaby Plateau may be a fragment of the Gascoyne Terrane left behind along the transform margin. Greater India slid out along the transform margin of the Wallaby–Zenith Fracture Zone, following the same ancient northwest–southeast trend that controlled the southern and northern edges of the Exmouth Plateau (Figure 4.10); control probably came from the Proterozoic and Archean shear zones that cut the adjacent Yilgarn Craton. However, the structural trend of the Permo–Carboniferous Perth Basin is north–south, reflecting its origin as part of the Gondwanan rift system (Figures 4.8 and 4.11) and the underlying grain of the Neoproterozoic basement (Pinjarra Orogen, Figure 2.10). The dispersal of Gondwana was aided by a mantle plume that was located close to the triple junction between Australia, Antarctica and India, producing large igneous provinces of the Kerguelen Plateau (ca 115 Ma), Broken Ridge (ca 95 Ma) and Naturaliste Plateau, as well as extensive volcanism in the Mentelle Basin (Figure 4.11).

The Perth Basin contains Permian coal measures, which are mined at Collie (Chapter 9; Figure 4.11) and are a source for some of the gas accumulations (e.g. Whicher Range, in the Bunbury Trough). However, the main source rock for the small oil and gas fields (Cliff Head, Dongara, Mt Horner) is the Early Triassic Kockatea Shale, deposited in restricted marine environments (Figure 4.7) as the sea flooded a landscape created by earlier Permian rifting. The remainder of the Triassic and much of the Jurassic is dominated by sandstones, including red beds with only minor marine and lacustrine shales and coal measures. The coarse sands are good groundwater aquifers (Chapter 7), but are lean in the organic matter needed to source hydrocarbons. There is no sign of the thick pods of Late Jurassic marine shales that are oil sources along the North West Shelf. The time-equivalent strata in the Perth Basin are the coarse fluvial sandstones of the Yarragadee Formation, which were probably derived from Antarctica to the south. There may be a different story in the offshore frontier Houtman Sub-basin and the yet-to-be-drilled Mentelle Basin, which in part is a failed rift between the Australian mainland and the Naturaliste Plateau (Figures 4.11 and 4.12). Very little is known about these two remote deepwater regions.

As with the northwest margin, after the breakup the southwest subsided, and marine shales followed by carbonates were deposited as the passive margin sequence. In their early post-rift history, the Wallaby and Naturaliste plateaus and western Mentelle Basin were affected by extensive volcanism, triggered by the proximity of the Kerguelen Large Igneous Province. Several hundred metres of igneous and volcaniclastic rocks were emplaced and deposited, masking the original geometries, including any pre-existing depocentres. This volcanic episode, which continued for at least 10 Myr after the breakup, adversely impacted their hydrocarbon potential in comparison with the
Southern margin

Australia’s break with Antarctica created the southern margin, the longest south-facing coastline in the world, stretching more than 3500 km from the Naturaliste Plateau to the South Tasman Rise (Chapter 6). At its eastern end are the hydrocarbon-producing basins of Bass Strait. But from Kangaroo Island to the west is a large region with only around 12 exploration wells, making this area very much a frontier province (Figure 4.12).

Antarctica has been Australia’s longest partner in Gondwana, for close to a billion years (Chapter 2), and the process of separation between the two continents took more than 100 Myr to complete (Figure 4.13). The apparent clean break of the current coastline belies the complex story that commenced with a Middle Jurassic to Early Cretaceous rift valley (Did you know? 4.3). The crust thinned along the rift, which contained a system of lakes, rivers and high-latitude forests that stretched from the Naturaliste Plateau to the Gippsland Basin. The eastern highlands uplifted in the late Albian (ca 100 Ma), with reorganisation of the drainage networks to flow southwest and the beginning of the growth of the Ceduna delta, which was well established by 95 Ma (Cenomanian).

The margin evolved through repeated episodes of extension and thermal subsidence leading up to, and following, the commencement of seafloor spreading between Australia and Antarctica. Breakup progressed from west to east, with a well-established initial age of seafloor spreading of 83 Ma (Santonian) for the central Bight Basin, although perhaps starting as early as

Figure 4.12: Map of the southern Australian margin, showing sedimentary basins, oil and gas fields, exploration wells and pipelines. Note the extensive drilling and infrastructure in the Gippsland, Bass and Otway basins in contrast to the west of Kangaroo Island or on the South Tasman Rise.

Well symbol information is sourced either from ‘open file’ data from titleholders (where it is publicly available as at 1 December 2011) or from other public sources. Field outlines are provided by Encom GPinfo, a Pitney Bowes Software (PBS) Pty Ltd product. While all care is taken in the compilation of the field outlines by PBS, no warranty is provided re the accuracy or completeness of the information, and it is the responsibility of the reader to ensure, by independent means, that those parts of the information used by them are correct before any reliance is placed on them.
ca 90 Ma in the Bremer Sub-basin. Propagating to the east, seafloor spreading off the Otway Basin commenced at ca 55 Ma, and off the Sorell Basin at ca 47 Ma (Figure 4.1). In general, breakup was not accompanied by significant magmatism, and the margin is classified as a magma-poor (or ‘non-volcanic’) rifted margin in contrast to those on the Exmouth Plateau. As in the northwest, however, there are both rifted and transform components (Figures 4.9c and d).

Initial northwest–southeast ultra-slow to slow seafloor spreading (latest Santonian to mid-Eocene, 83–45 Ma) was followed by north–south fast spreading. This history, and the pre-existing basement architecture, has resulted in segmentation into:

- an oblique to normally rifted margin that extends from the westernmost Bight Basin to the central Otway Basin
- a transform continental margin in the east (western Tasmania – South Tasman Rise) along the Tasman Fracture Zone
- a transitional zone between those end-members (southern Otway–Sorell basins) (Figures 4.9, 4.12 and 4.13).

Seafloor spreading thus was slow in the Late Cretaceous, but by the mid-Eocene (45 Ma), a widening seaway had appeared between Australia and Antarctica as seafloor spreading accelerated. Tasmania stayed with the mainland, and both separated from Antarctica along the Tasman Fracture Zone. The final break came in the Late Eocene at ca 34 Ma (Figure 4.13).

Figure 4.13: Schematic structural evolution of the southern margin with reconstructions from the Late Jurassic (Early Tithonian, 145 Ma) to the latest Oligocene (25 Ma). In the west, the rift valley marks the site of the future break (probably along the southern edge of the Naturaliste Plateau), whereas, in the east, Bass Strait overlies the area where the rifting failed to go to seafloor spreading. The Oligocene reconstruction shows the final configuration with the sharp edge of the South Tasman Rise. (Sources: modified from Norvick & Smith, 2001; Norvick, 2005)
The oblique- to normally-rifted margin is characterised by a broad zone of crustal thinning and thick extensional basin development. In the Bight and Otway basins, a well-developed distal ocean–continent transition zone includes basement highs interpreted as exhumed subcontinental lithospheric mantle (Figure 4.9e). In the eastern part of the margin, where transcurrent stresses controlled deformation, lithospheric thinning is not as marked, and the continent–ocean boundary is probably a combination of rift and transform elements. In the southern Sorell Basin and the South Tasman Rise, the Tasman Fracture Zone forms a transcurrent continent–ocean boundary (Figures 4.1, 4.9a and 4.12).

Basement terranes such as the Mesoproterozoic Albany–Fraser Orogen, Mesoarchean–Proterozoic Gawler Craton and Lower Paleozoic Delamerian Orogen influenced the breakup of the southern margin (Figure 4.14; Chapters 2 and 8). The Shipwreck Trough off western Tasmania marks an abrupt change in Early Cretaceous rift basin geometry from northwest–southeast to dominantly north–south- or northeast-trending structures. This switch is also evident onshore and coincides with the west-dipping, crustal-scale Paleozoic Avoca Fault, a structure that forms the western boundary of a poorly exposed Proterozoic basement terrane in central Victoria, the Selwyn Block (Figure 4.14), and continues southward into the Sorell Fault and the Tasman Fracture Zone. Crustal weaknesses inherited from the underlying basement rocks (Chapters 2 and 8) evidently persisted into Mesozoic times, when they were reactivated under extension during the Australia–Antarctica separation.

The characteristic sedimentary sequence in the southern margin basins is Late Jurassic to Early Cretaceous fluvio-lacustrine facies with a pervasive volcaniclastic component, overlain by Late Cretaceous to Paleogene deltaic and marine sediments with a cap of Cenozoic carbonates (Figure 4.5). This sequence records the progression from the rift valley deep within Gondwana to a passive margin facing the ever-widening sea between Australia and Antarctica. The mid-Cretaceous uplift of the eastern highlands was a prelude to the breakup of that margin. The Ceduna delta was so large that it modified the bathymetry of the margin (Figures 4.14 and 5.14) as it built out an apron of sediment more than 5 km thick over an area of more than 100 000 km². Which raises the question of why such an enormous delta was deposited when the river that fed it is no longer seen.

The accommodation space provided by the eustatic high sea-levels of the Late Cretaceous (Box 4.3) and the subsidence of the underlying highly extended continental crust (Figure 4.9d) may have allowed the sediments gleaned from half a continent to prograde out into the narrow seaway between Australia and Antarctica. A dramatic reduction in sediment supply at the end of the Cretaceous, and perhaps switching of the principal river system feeding it, may have caused the abrupt abandonment of deltaic deposition. Regional uplift resulted in some erosion, but, as the delta sank with Early Cenozoic thermal subsidence, it was preserved as a deepwater terrace. We will return to consider the Ceduna delta and its hydrocarbon potential in the frontier petroleum system case study. After Australia and Antarctica severed their
last connection along the Tasman Fracture Zone and the circum-Antarctic current was established at the end of the Eocene, cool-water carbonate deposition became dominant.

Australia’s southern continental margin is home to both rich hydrocarbon resources and huge potential. Most of Australia’s oil has come from one small basin located at the eastern end of the Australia–Antarctic rift system—the Gippsland Basin. Here, all the elements and processes of the petroleum system have converged to produce Australia’s only billion-barrel oil fields. Non-marine coaly sediments are source rocks for the oil and gas in the Otway, Bass and Gippsland basins; deltaic to shallow marine sandstones are the reservoirs; and marine mudstones and marls provide sealing facies.

Eastern margin

Eastern Australia is the ancient convergent margin of Gondwana (Chapter 2) and, in the mid-Cretaceous, the plate boundary with the palaeo-Pacific Ocean shifted eastwards. Pre-existing crustal weaknesses along possible former terrane boundaries were exploited as the breakup process opened the Tasman Sea as a backarc basin and created the narrow shelf along the New South Wales coast (Figure 4.14). Here, the Late Cretaceous seafloor of the deep Tasman Sea lies a few tens of kilometres from the shore. On the other side of the spreading ridge, the continental fragment of Lord Howe Rise now lies many hundreds of kilometres to the east and is linked to New Caledonia and New Zealand, also former parts of Gondwana (Box 4.4). Initial seafloor spreading began in the south between New Zealand and Tasmania in the Santonian (ca 85 Ma) and propagated irregularly northwards, finishing in the Coral Sea in the Early Eocene (ca 52 Ma). A number of sedimentary basins without drillhole evidence are of probable Jurassic to Cretaceous age, and these occur on the Lord Howe Rise; some may be prospective for petroleum, as are the once-neighbouring Gippsland Basin and Taranaki Basin (New Zealand).

North from the apex of the Tasman Sea, the Queensland margin opens out into a broad and complex borderland (Figure 4.9a). Again, as in the northwest, thick sedimentary basins (Capricorn...
The Lord Howe Rise is a major submerged plateau (1000–3000 m of water depth) located east of the Australian continent. The Lord Howe Rise extends almost 2000 km from southwest of New Caledonia to the Challenger Plateau, west of New Zealand, and has an area of about 1.5 M km². The central portion of the Lord Howe Rise lies within the Australian marine jurisdiction as defined by the United Nations Convention on the Law of the Sea (Chapter 1). Australia now shares political boundaries with France–New Caledonia and New Zealand.

The rise is surrounded by a complex of continental fragments, ocean basins, volcanic arcs and accretionary prisms, as far as the Tonga and Kermadec trenches and New Zealand, where the present-day active plate margin now lies (Chapter 2). The deepwater region off eastern Australia formed during the Cretaceous to Recent, by continental rifting, magmatic arc formation, subduction rollback and backarc spreading. The resulting continental crust is therefore a rheologically weak collage of accreted Paleozoic to Early Cretaceous arc and related material, which broke up into numerous irregular pieces.

The Lord Howe Rise may have originally consisted of at least two separate continental pieces that rifted from eastern Australia during the Cretaceous breakup of the East Gondwana margin and the Tasman Sea opening (85–52 Ma). Rock samples and tectonic reconstructions suggest that the Lord Howe Rise is underlain by offshore continuations of the Paleozoic New England and Lachlan orogens (Chapter 2) and Mesozoic basins of eastern Australia (Clarence–Moreton and Maryborough basins), New Zealand and New Caledonia.

Subparallel geological provinces that extend along its length dominate the basin framework on the rise: the Lord Howe Platform, the Central Rift Province, the Western Rift Province and the Western Ridge System. Depocentres on the Lord Howe Rise have the potential to generate and accumulate petroleum, comparable with other East Gondwanan Cretaceous rift basins, such as the Taranaki, Gippsland and Clarence–Moreton basins. Evidence for Cenozoic post-rift igneous activity is widespread throughout the Lord Howe Rise region. The most prominent are the north–south seamount hotspot chains, the Tasmanid and Lord Howe seamount chains (Figure 4.9a; Chapter 2). They developed to the west of the rise from the Miocene to Recent.

The Lord Howe Rise is a unique, isolated and large continental fragment with volcanic islands and exceptional wildlife. Lord Howe Island was officially inscribed on the UNESCO World Heritage List on 14 December 1982 because of the outstanding universal values of its terrestrial and marine species and ecosystems. The island is covered in beautiful banyan, pandanus and Australian rainforest species and fringed by the world’s southernmost coral reef (Chapter 6). Although this tiny World Heritage speck is only 11 km long and 3 km wide, it is home to numerous endangered endemic species. Some species endangered in other places (for example, masked owls in Tasmania) now thrive in densities unheard of elsewhere following their introduction to Lord Howe Island. In the Pleistocene, it was also a refuge for species such as the giant horned turtle, *Meiolania* (Chapter 3).
Out of Gondwana

Basin, Townsville and Queensland troughs) and submerged marginal plateaus (Marion and Queensland) formed as the rifted margin developed, leading to the opening of the Coral Sea in the Paleogene (Figure 4.1). The Marion and Queensland plateaus now support coral reefs, and, to landward, the Great Barrier Reef has grown during the Quaternary (Chapter 6). Despite early exploration, the environmental value of this region precluded the development of the petroleum potential in these basins. Seafloor spreading between about 60 Ma and 52 Ma created the Coral Sea, the last new ocean basin to open around the Australian margin as it emerged from Gondwana.

The next act in the drama is the formation of the convergent northern margin, as the island continent proceeds on its journey north.

**Northern margin**

Between the Argo Abyssal Plain in the northwest and the Coral Sea in the northeast are the island chains of eastern Indonesia and Timor, the island of New Guinea and the shallow Arafura Sea and Gulf of Carpentaria (Figures 4.1 and 4.9a). This collage of geomorphological and geological elements is home to active volcanoes, equatorial jungle swamps and towering mountains capped by a glacier.

Travelling rapidly north in the Eocene, Australia collided with the Pacific and Eurasian plates, forming the tectonically active northern margin. The structural impact of this collision, which has lasted for about 30 Myr, has been profound on the buckled and sheared northern margin of the plate, but has also had an influence far into the continent and continues to do so today (Chapter 2). There is an enrichment of the flora and fauna as the old Gondwana meets Asia across the Wallace and other biogeographical lines (Chapters 1 and 3). Many of Australia’s oil and gas fields are in traps formed or reactivated by the Neogene collision.

The complex northern margin can be considered in two parts: the New Guinea fold belt, running from the Aure Trough to the Bird’s Head, and the outer Banda Arc, running from Seram around to Timor and Sumba (Figure 4.9a). The island of New Guinea, extending northwards to the fold belt, is geologically contiguous with Australia. This region reflects a similar east–west contrast between a Late Paleozoic active magmatic margin in the east and a region of extension with Gondwana breakup to the west. Strong Mesoproterozoic crust and lithosphere and thick Neoproterozoic to Paleozoic sedimentary rocks occur in the southwest (West Papua), an extension of the North Australian Element and the overlying Arafura and Bonaparte basins. To the east of the (projected) Tasman Line in New Guinea, the oldest basement is formed by Permian metasediments intruded by Triassic granites. Triassic and Jurassic rifting created a Cretaceous passive margin, with promontories of extended continental crust and embayments of oceanic crust similar to those preserved on the northwest margin. Although similar stratigraphy and shared oil geochemistry show the affinity of the Papuan Basin to the North West Shelf, the original New Guinea passive margin has been severely modified by terrane accretion and strike-slip faulting.

West of New Guinea is the horseshoe-shaped Banda Arc, part of a wide and complex suture zone in eastern Indonesia. There is an outer non-volcanic arc (Timor, Seram) where deformed Mesozoic sediments, which are distal equivalents of the North West Shelf sequences, crop out. There is also a younger, inner volcanic arc, which has been active for the past 10 Myr. The Banda Arc formed where an embayment of oceanic crust within the northward-moving Australian Plate reached the subduction zone around 12 Ma. The old, cold and dense Jurassic ocean lithosphere fell away rapidly, causing the Banda subduction hinge to roll back to the south and east, forming the arc, opening the Banda Sea and, by about 3 Ma, bringing into collision the inner volcanic arc with the Australian continent in the region of Timor.

**The island continent**

The last episode in the story of Australia’s release from Gondwana began with the final clearance of Tasmania from Antarctica in the latest Eocene. Australia was for the first time the island continent on its northward path into Asia. This final separation changed ocean currents and global climate, including the start of glaciation in Antarctica. With changing latitude, cold-climate rainforests were eventually replaced by deserts. However, along the northeastern monsoonal margin of Australia, new Asian rainforest floral elements began to invade this part of the continent. The Gondwanan flora and fauna then evolved through millions of years, mostly in isolation (Chapter 3). Aridity and deserts developed as Australia moved up into the mid-latitudes in the Late Miocene.
We will see in Chapter 5 how the impact of this change to aridity affected the Australian landscape and people.

The search for Australia’s petroleum

The pattern of hydrocarbon discovery in Australia has followed a path from onshore to offshore, and from Bass Strait to the North West Shelf (Figure 4.15; Appendix 4.1.2). Today, with the development of coal-seam gas and other unconventional hydrocarbons, the activity is shifting back onshore. The main drivers of this exploration activity have been market demand, perceived prospectivity, technological change, government behaviour and geological endowment, along with the strong positive market feedback of significant discoveries encouraging further exploration. In recent years, there has been a fundamental shift in the market for gas in the Asia–Pacific region, with the industrialisation of China and India, and this is pushing along the current boom in gas exploration and development (Chapter 9).

Petroleum exploration began in Australia in the 1860s after there were shows of gas and oil in different places. Activity was initially low, with only a handful of wells drilled from 1900 to 1950, and exploration technology was rudimentary by today’s standards. Initially, the wrong clues were followed—the obvious surface oil seeps that directed early exploration efforts elsewhere were rare in Australia. False guides, such as beach stranding of bitumen and algal mats in coastal lagoons, inspired the first wells. The great depth of 9 m was reached at Salt Creek in the Coorong in 1866, targeting the source of ‘Coorongite’, now known to be the remains of modern algal blooms and dead fish. The first ‘offshore’ well was drilled
Out of Gondwana

in Albany Harbour in 1907 (Figure 4.15a), looking in the Mesoproterozoic Albany–Fraser Orogen basement terrane for the source of the bitumen strandings common along the southern margin. But, as we shall see, these strandings may in the end lead us to a major new oil province.

Gas and oil shows in water bores (Appendix 4.1.2) prompted a low and sporadic level of drilling through the first half of the 20th century. Most activity was concentrated around Roma in the Surat Basin, where gas was eventually found (Figure 4.15b). Drilling was restricted to onshore areas and consequently was largely dependent on viable Paleozoic source rocks for success. The technology was not available to access the more prospective and younger offshore basins. Prospectivity was perceived by overseas experts to be low, as the Australian continent was considered too old to have preserved major oil accumulations.

Despite this predominance of negative factors, some minor and sporadic production of hydrocarbons had been achieved from the Gippsland and Surat basins by the 1940s.

After nearly a hundred years of largely unrewarded effort, the first flow of oil to the surface in Australia occurred in 1953, with the discovery of a small oil accumulation at Rough Range 1 in the onshore Carnarvon Basin. In 1957, the Australian Government introduced a 50% subsidy scheme for exploration drilling, and in 1959, the fledgling industry body APEA (the Australian Petroleum Exploration Association) was formed to counteract ‘waning public, government and even professional interest in the Australian oil search’. By the early 1960s, the momentum of exploration had built and, with increased drilling, discoveries came. First was onshore in the Surat, Cooper, Adavale, Amadeus and Perth basins, and on Barrow Island in the Carnarvon Basin, followed by offshore in the Gippsland Basin (Figure 4.15a; Appendix 4.1.2). The giant Gippsland oil discoveries in Bass Strait encouraged more exploration and further discoveries, with the result that, by 1972, all the major basins and petroleum systems that are today producing hydrocarbons had been found (Figure 4.15a).

Australian oil production from the 1960s to the 1990s was dominated by the three giant fields in the offshore Gippsland Basin and the Barrow Island field that produced at a steady but much lower rate (Figure 4.16). As production from the Gippsland fields peaked in the late 1980s, dozens of smaller fields on the North West Shelf (Carnarvon and Bonaparte basins) progressively came on stream to make up the shortfall and maintain Australian self-sufficiency in oil (Figure 4.16). Today, production is in decline and the oil search continues, now
moving into deeper offshore Australian waters, further exploring for ‘gifts of Gondwana’ in the basins formed by its breakup.

Gippsland Basin, Victoria

The Gippsland Basin is Australia’s prolific, world-class oil province. It has provided most of Australia’s oil and has underpinned the economy (Figure 4.16). It is the most heavily explored basin and one of the best-known petroleum systems in Australia. Lake Bunga No. 1, drilled in 1924 near Lakes Entrance (Figure 4.17), is considered our first oil discovery. The Latrobe Valley brown coal deposits are another major energy resource (Chapter 9) in this relatively small basin of 46,000 km², nestled between the Paleozoic basement terranes of the Lachlan Orogen and the Cretaceous seafloor of the Tasman Sea (Figure 4.14).

Discovery and development

As happened elsewhere in onshore Australia, traces of oil and gas were found in a flow of artesian water from the first well sunk onshore near the town of Lakes Entrance. At 370 m, the bore intersected a 13 m interval of oil-saturated Oligocene glauconitic conglomerates. The oil was very viscous and would not flow to the surface; it was ‘heavy oil’ that had been biodegraded and water-washed. The shallow and cool oil reservoir with its intrusion of freshwater was an ideal environment for bacteria to grow, consuming the shorter chain hydrocarbons and leaving behind a heavier, sticky oil. More than 60 other wells were drilled in following decades, which delineated an extent of around 20 km² for the shallow oil sands. Although the oil would not flow to the surface under its own buoyancy, it was shallow enough to be pumped or bailed up out of the reservoir, and around 3000 barrels of oil was produced in this fashion by 1941.

During World War II, amid concerns about security of oil supply via shipments from overseas, the Australian Government initiated the ‘Lakes Entrance Oil Shaft Project’. A 3 m-wide shaft...
was sunk down some 365 m, and then, from an expanded work chamber at the bottom, horizontal wells were drilled into the oil-bearing sandstones. The oil that collected at the bottom of the shaft was then hauled to the surface in buckets. Close to another 5000 barrels of oil were produced, a negligible addition to the fuel supply in a time of petrol rationing. It is ironic that such desperate measures were employed, when the giant oil fields nearby in the offshore were eventually found to have excellent production characteristics, with light oil flowing at a rate of tens of thousands of barrels per day. But their discovery and development had to wait until the 1960s.

The Australian oil search was in full swing in the 1960s, encouraged by finds from Western Australia to Queensland and government subsidies for exploration. On the advice of Lewis Weeks, retired chief geologist of the Standard Oil Company of New Jersey (forerunner of Esso–Exxon), BHP Ltd acquired a number of leases in 1960, including some offshore in Bass Strait, where they focused their search on the thick, young sediments adjacent to onshore oil indications. Initial seismic surveys were conducted in 1962 by BHP Ltd, which then formed a joint venture with Esso Australia Pty Ltd in 1964 over the offshore Gippsland Basin. The seismic surveys revealed the Central Deep and six large anticlinal closures. The first two wells, Barracouta 1 (1964–65) and Marlin 1 (1965–66), were large gas-condensate discoveries, but the third, Kingfish 1 (drilled 1967), struck Australia’s largest oil field (1.2 B barrels recoverable), and Australia was at last on the world oil map (Figure 4.17; Did you know? 4.4).

By the beginning of the 1970s, the first five of 11 newly discovered fields were on production, with gas and oil pipelines connected to onshore processing facilities (Figure 4.17). The hydrocarbons were reservoired in the coarse-grained clastics at the top of the Latrobe Group (Figure 4.18). Many more, but smaller, discoveries were to follow, and exploration added new play types such as the Kipper gas field, the first significant intra-Latrobe find in 1986 (Figure 4.18). In 1990, the oil province was extended into deep water, with the Blackback discovery in 400 m of water, off the shelf edge (Figure 4.17). Since the late 1990s, high oil and gas prices, combined with the application of 3D seismic technology, have continued to drive exploration efforts in the Gippsland Basin. More than 300 exploration wells have now been drilled, and there is a dense grid of 2D and 3D seismic coverage with an inventory of more than 30 fields.

Bass Strait oil discovery: among the most pivotal events in Australia’s history?
The discovery of a giant oil field in one of the first offshore exploration wells drilled in Australian waters revolutionised our energy security by removing the vulnerability clearly demonstrated during World War II. Important economic benefits flowed from the next decades of oil self-sufficiency following the Gippsland Basin discoveries. The development of Australia’s oil and gas industry improved the balance of trade and helped underpin the nation’s economic prosperity and growth. The discoveries were the crucial kick-start for the $28 B/year ($25.6 B in 2010–11) oil and gas industry, which, in 2008, contributed 58% of Australia’s primary energy, 2.5% of Australia’s

Did you know?

4.4: Australia’s largest oil field was nearly missed when first drilled

The sedimentary sequences in the offshore Gippsland Basin have been cut by large submarine channels and canyons, particularly in the Neogene carbonates (Figure 4.18). Less consolidated channel fill and areas of dolomitite cementation create abrupt lateral changes in density and thus in seismic response, as seismic data record the travel time of soundwaves through the sediments, with a faster and shorter travel time through denser material. The resulting complex velocity variations in the upper section can mask underlying structures. Such a velocity anomaly from channelling in the Seaspray Group occurs over the top of the Kingfish field. The conversion from travel time to depth, based on the 1960s vintage seismic data, was so misleading that the billion-barrel oil field was almost missed by the drill. Today’s explorers have the advantage of 3D seismic data and visualisation technology.
The Bass Strait finds have been assessed as one of the 10 most important events in recent Australian history. The training of a generation of Australian petroleum industry professionals was an additional benefit, as infrastructure and industries grew with the development of the rich hydrocarbon resources close to the major population centres in southeastern Australia. The Bass Strait finds showed that there was significant oil in Australia and so sustained the search into the other offshore basins formed during the breakup of Gondwana, such as the Carnarvon Basin on the North West Shelf.

Petroleum systems

**Why so much oil in this one small basin?**

As we have shown in the story of Gondwanan breakup, the Gippsland Basin is in a special tectonic position. Sitting at the eastern end of the Early Cretaceous rift between Australia and Antarctica, the basin is also on the rifted eastern margin that developed between Australia, the Lord Howe Rise and New Zealand.

As part of the great southern rift zone (Figures 4.13 and 4.14), the Gippsland Basin began as a series of Early Cretaceous northeast–southwest-trending half-grabens. In the Late Cretaceous, as the Tasman Sea opened, continued extension generated a broader rift in what is now the offshore part of the basin, flanked by fault-bounded platforms and terraces to the north and south (Figures 4.17 and 4.18). This Central Deep became the main depocentre, which filled with large volumes of material eroded from the uplifted basin margins. The thick succession included organic-rich rocks of lacustrine, coastal plain and marine facies (Figure 4.19), and thus the Central Deep became the main hydrocarbon kitchen when pushed into the oil window by the overburden load of more than 3 km of Cenozoic sediments.

The relatively thick Cenozoic section is another feature that distinguishes the Gippsland from other Australian basins. The section thickness...
Figure 4.18: Gippsland Basin stratigraphic chart, showing sedimentary units, petroleum system elements and tectonic events. (Source: modified from Bernecker et al., 2006)
reflects ongoing clastic supply from the rugged and well-watered hinterland (Chapter 5) and the Neogene accumulation of cool-water carbonate sediments in the offshore. The large anticlinal traps that now contain the giant oil fields are the product of compression and partial basin inversion from Eocene to Quaternary as the Australian Plate moved into a convergent regime. The late loading and generation means that only traps formed in this most recent episode of the 'out of Gondwana' story can be filled with hydrocarbons. There is also less time for trap breach, leakage, gas displacement and biodegradation to affect oil accumulations, although, as we will see in the analysis of the petroleum system, some of these destructive processes are under way.

The thick 10 km sedimentary succession in the Gippsland Basin records the last 100 Myr of the 'out of Gondwana' story in southeastern Australia (Figure 4.18). The Early Cretaceous volcaniclastic and coaly Strzelecki Group was deposited during initial Australia–Antarctica rifting. Renewed crustal extension occurred during the Late Cretaceous in an abandoned rift branch or aulacogen, associated with the opening of the Tasman Sea. The Central Deep was established, infilling with copious material eroded from the uplifted basin margins (Latrobe Group). A series of large, deep lakes developed, which were rapidly filled by the lacustrine Kipper Shale in the Turonian.

Figure 4.19: (a) Block diagram of the sedimentary packages in the Gippsland Basin. (b) Modern sedimentary environments, Lakes Entrance, Victoria. (Sources: modified from Johnstone et al., 2001; Bernecker et al., 2006)
The first marine incursion into the Gippsland Basin occurred in the Late Santonian (Anemone Formation, Golden Beach Subgroup) in the eastern part of the basin. Rift-related extension and sagging continued until the Early Eocene, with a sequence of alluvial–fluvial, deltaic and marine sediments deposited across the basin (Halibut Subgroup).

By the Middle Eocene, seafloor spreading had ceased in the Tasman Sea, and there was a period of basin sag, during which the lower coastalplain, coal-rich Burong Formation was deposited, followed by the transgressive shallow to open marine and partly condensed Gurnard Formation (Cobia Subgroup). Marine deposition expanded from the Early Oligocene, with the deposition of the Lakes Entrance Formation (Seaspray Group). These onlapping, marly sediments provide the principal sealing unit across the basin (Figures 4.18 and 4.19). At the same time in the onshore part of the basin, the major brown coal resource (Latrobe Valley Coal Measures) was deposited during the Oligocene and Miocene (Chapter 9).

The Neogene deposition of the thick Gippsland Limestone, particularly during the Late Miocene and Pliocene, provided the critical overburden load for late generation of hydrocarbons from source rocks in the deeper Latrobe and Strzelecki groups (just as Neogene carbonates play a similar role in the operation of the petroleum systems on the North West Shelf). The major anticlines hosting the large oil and gas accumulations (Barracouta, Tuna, Kingfish, Snapper and Halibut) were formed by compression and basin inversion, starting in the Early Eocene and finishing by the end-Eocene.

A younger onshore inversion event formed the anticlines that constitute the Strzelecki Ranges, which are Late Miocene to Recent in age.

Most of the hydrocarbons in the Gippsland Basin are located offshore in the Central Deep, with gas in the north and big oil fields in the southeast, although there are some smaller fields on the terraces and onshore (Figure 4.18). Stratigraphically, most of the oil and gas is at the top of the Latrobe Group, trapped under the complex Latrobe Unconformity (Figure 4.18), which ranges in age from latest Cretaceous to Eocene and younger. In addition to giant anticlinal traps in the top Latrobe Group, there are also hydrocarbon accumulations within the group, sealed by local shales and, in some cases, by volcanic rocks. Erosion and fill of ancient submarine channels in the Eocene has created trap geometries; again, the modern environment of the Gippsland Basin reflects the past (see the Bass Canyon in Figure 4.17).

The hydrocarbon fields in the Gippsland Basin are classified as part of the Austral Petroleum Supersystem (Figure 4.6; Appendix 4.1). There are several source units, including a gas source. These are mainly in the onshore in the Early Cretaceous (Austral 2), which provides geochemical evidence of a contribution from marine source rocks in the Late Cretaceous (Anemone Formation). The dominant and most prolific source, however, is the coals and carbonaceous shales within the Latrobe Group (Austral 3). There were several episodes of generation and expulsion, but the first major hydrocarbon charge was probably oil in the Late Miocene, which was partially displaced.
Figure 4.20: Gippsland Basin schematic cross-section, showing hydrocarbon leakage and seepage through the seal during (a) Miocene peak oil charge, (b) Pliocene peak gas charge and (c) present day. (d) Gippsland Basin, showing the postulated distribution of hydrocarbon accumulations and migration pathways in the Miocene. (e) Present-day Gippsland Basin, showing the postulated distribution of hydrocarbon accumulations and migration pathways. (Sources: modified from O’Brien et al., 2008; Tingate et al., 2011)
Analysis and modelling of the Gippsland Basin petroleum system have revealed a complex history of hydrocarbon generation, expulsion, migration and accumulation, followed by gas flushing and leakage (Figure 4.20).

Why is there an anomalous distribution of oil and gas in the Gippsland Basin?

Most petroleum systems operate so that oil fields are located towards the basin edges; gas fields tend to be in the centre of the basin, overlying the highest temperature regions of the hydrocarbon kitchen (Figure 4.3). This is because the early-generated oil migrates to the basin margin, driven by gas in the Pliocene in the northern fields. Along by the later generated gas, which fills the traps in the middle of the basin. The distribution of oil and gas in the Gippsland Basin is anomalous, in that the gas is on the northern basin margin and the oil towards the centre (Figure 4.17). A buoyancy-driven migration model explains this distribution of hydrocarbon fields. Two main migration pathways or fill-spill chains link the hydrocarbon kitchen of the Central Deep to the oil and gas fields (Figure 4.20). In the Miocene, the traps were mostly filled by oil, but, as generation continued, further burial moved the area of the Central Deep between Kingfish and Barracouta into the gas window. Gas moving along the northern fill-spill chain displaced oil,
which leaked away at the basin margins where the seal facies is thin and sandier. Some of this oil was trapped onshore as oil sands in Cenozoic sediments (Lakes Entrance Formation—hence the World War II Lakes Entrance Oil Shaft Project). Today, the southern fill-spill chain continues to receive oil generated from the more recently buried southeastern part of the basin.

**Carnarvon Basin, Western Australia**

**Discovery and development**

The first flow of oil to the surface in Australia was from Rough Range No. 1, drilled in 1953 onshore near Exmouth Gulf. This, the first petroleum exploration well drilled in Australia after World War II, targeted a surface anticline at the margin of the Carnarvon Basin. Oil flowed at 500 barrels per day from the Lower Cretaceous Birdrong Sandstone, but it proved to be a very small accumulation, and further drilling on the same anticline within a few hundred metres of the first well failed to replicate the initial success. As with the Gippsland Basin, the real hydrocarbon potential was in the offshore part of the basin.

Decades earlier, émigré geologist Curt Teichert had inferred that the limited outcrop of marine Jurassic sediments was the feather-edge of a large Mesozoic basin offshore. This proved to be correct when oil exploration ventured offshore with an island drilling campaign by West Australian Petroleum (WAPET). In 1964, the giant Barrow Island oil field was discovered in a surface anticline. More than a billion barrels of oil are in place in multiple reservoirs, and more than 300 M barrels have been produced, providing a sustained base level of oil production for Australia over many decades (Figure 4.16). Also, both Curt Teichert and later Woodside chief geologist Nicholas Boutakoff suggested that the bathymetry of the North West Shelf might reflect a series of anticlinal ridges propagated from Timor and viewed this as prospective because of Timor oil seeps. In 1963, on Boutakoff’s advice, Woodside Petroleum Ltd leased almost all of the rest of Western Australia’s offshore areas north of WAPET’s existing permits. One of the earliest offshore wells, Legendre 1, drilled in 1968 by Woodside, discovered oil in the Dampier Sub-basin. Several giant gas discoveries were later made along the Rankin Platform in the 1970s and early 1980s—North Rankin, Goodwyn and Gorgon, a gas field with a significant CO₂ content (Figure 4.22). In 1984, the North West Shelf Venture, led by Woodside, commenced domestic gas production from the North Rankin field and, in 1989, the first LNG cargo was shipped to Japan. Since then, the project has contributed $70 B to Australia’s GDP (Chapter 9).

In the period 1979–80, Australian exploration took the brave step out into the deepwater Exmouth Plateau to test the large structures imaged on seismic surveys (Figure 4.9b). These initial exploration programs, operated by Esso Standard Oil Co. and Phillips Australian Oil Co., began when no proven technology existed to develop a deepwater oil field. Disappointingly in one way, rather than the hoped-for oil charge, only gas was found in the 11 deepwater wells drilled in 740–1375 m water depths, but this did include the giant Scarborough field. In the 1980s,

### 4.5: The colourful history of Barrow Island

Whereas man-made destruction prevented West Australian Petroleum (Wapet) from exploring Barrow Island in the 1950s to 1960s, it was nature’s destructive forces that delayed the spudding of its first well on the island. Britain used the Monte Bello Islands, located 20 km north of Barrow Island, as an atomic testing site between 1952 and 1956. Not until May 1963 did the Australian Government lift its ban on access to Barrow Island, which Wapet field parties had earlier recognised to be a very broad anticline. In April 1964, while Wapet was preparing to move the rig onto the island for the first well, a late-season cyclone wiped out the newly constructed airstrip and beach landing. Barrow Island-1 was eventually spudded on 7 May.

Barrow Island will soon be home to the Gorgon LNG facility and the site of a carbon-capture and storage project, to demonstrate the technology and to mitigate the problems of the high CO₂ content of the gas (Chapter 11).
such ‘stranded’ gas fields littered the North West Shelf (Figure 4.15), awaiting a change in the global energy market to make their development commercially viable (Chapter 9).

Exploration in the offshore Carnarvon Basin then shifted inboard, back to the ‘oily’ sub-basins and away from the home of the gas giants. From the early 1980s to the mid-1990s, a number of significant, mostly medium-sized oil (and gas) discoveries were made in the Barrow and Dampier sub-basins, as a result of the application of dense 2D seismic surveys. More recently 3D seismic and amplitude vs offset (AVO) technology has contributed to an improvement in the success rates. In 1999, the Enfield discovery was made in the Exmouth Sub-basin. A string of nearby oil finds followed, which were brought into production from 2006.

Growing demand for LNG has stimulated exploration along the Rankin Platform and a return to the deepwater Exmouth Plateau in recent years, and dozens of major gas discoveries have resulted. Accompanying exploration success has been a series of new, large-scale development projects and associated investment in infrastructure (Did you know? 4.5).

**Petroleum systems**

Major hydrocarbon fields occur all along the North West Shelf, from the Exmouth Sub-basin in the southwest, to the Malita Graben and Sahul Platform in the northeast (Figure 4.10). Most of these fields are part of the Westralian Supersystem (Appendix 4.1.1). The offshore Carnarvon Basin, however, led the way in discovery and

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**Figure 4.22**: Carnarvon Basin map, showing major fields and discoveries, with the age of the reservoir indicated by colour.

Field outlines are provided by Encom GPInfo, a Pitney Bowes Software (PBS) Pty Ltd product. While all care is taken in the compilation of the field outlines by PBS, no warranty is provided regarding the accuracy or completeness of the information, and it is the responsibility of the reader to ensure, by independent means, that those parts of the information used by them are correct before any reliance is placed on them.
Out of Gondwana development and currently contains the largest resources (Figure 4.21). There are major oil fields in the failed rift marked by the Exmouth, Barrow and Dampier sub-basins, and giant gas fields on the western rim of the rift (the Rankin Platform) and all the way out across the Exmouth Plateau (Figures 4.10 and 4.11).

The offshore Carnarvon Basin, at 535 000 km², is more than 10 times the size of the Gippsland Basin. The basin is also more complex and relies on older Mesozoic petroleum systems—a product of Pangaea and Gondwana breakup. The key elements are:

- sources—Triassic and Early Jurassic coaly gas-prone rocks (Westralian 1) and restricted marine Late Jurassic oil kitchens (Westralian) in the failed rift
- reservoirs—Triassic fluvial reservoirs in the Early Cretaceous Barrow delta and also marine sands in the Jurassic, Cretaceous and Paleocene (Figure 4.22)
- regional seal—Early Cretaceous deep-marine shale
- overburden—prograding Cenozoic carbonate wedge to bury the underlying elements, providing thermal maturation (Figure 4.23).

The geological history of the offshore Carnarvon Basin means that oil-prone source rocks are restricted to the Late Jurassic failed rifts, but a very extensive gas-prone source system stretches for more than 500 km across the Exmouth Plateau—even to Alaric 1, a recent large gas find close to its western edge (Figure 4.22). The major source of all this gas is the deeply buried coals and carbonaceous claystones of the Triassic Mungaroo Formation. These are the delta plain deposits of transcontinental rivers that prograded across the plateau when Australia was still locked into the Pangaea–Gondwana supercontinent. The thick, clean sands of the fluvial channels provide the reservoir facies, and the typical hydrocarbon trap is a fault block formed in the Late Triassic–Early Jurassic and sealed by Early Cretaceous or older shales (Figure 4.23). Some of the largest gas fields, however, are stratigraphically trapped in reservoirs of other ages. Two such fields are Io–Jansz in Late Jurassic shallow marine sands, reworked from the uplifted western rim of the failed rift, and Scarborough, an Early Cretaceous basin-floor fan deposited in deep water in front of the Barrow delta (Figures 4.22 and 4.23).
Jurassic and Cretaceous shallow marine to deltaic sands are the main oil reservoirs located within the inboard rifts overlying or close by the Dingo Claystone oil kitchens. Especially important are the various sands related to progradation and then reworking of the Barrow delta as sea-level rose with breakup and the creation of new seafloor in the Early Cretaceous (Figure 4.23). The first phase of oil generation was in the Early Cretaceous in the Exmouth Sub-basin and southern parts of the Barrow Sub-basin due to the loading of the Barrow delta. Oil accumulations formed at this time required preservation for about 100 Myr. Not all survived intact, and there are examples of biodegradation, trap destruction and displacement of oil by later gas migration. In the Dampier Sub-basin to the northeast, where the stratigraphic equivalent of the Barrow delta is a thin, distal marine shale, the main phase of hydrocarbon generation was in the Cenozoic when the progradation of the carbonate shelf provided sufficient burial to shift the Jurassic source rocks into the oil window (Figure 4.3). The same is true beyond the basin, with geochemically similar oils recognised in the Carnarvon, Bonaparte and Papuan basins, all derived from Late Jurassic marine source rocks. Compare how this successful petroleum system has evolved with that of the less successful Toolebuc Formation (Did you know? 4.1).

The majority of the hydrocarbons discovered to date in the offshore Carnarvon Basin are in highly porous sandstone reservoirs beneath the Early Cretaceous Muderong Shale. This thin but effective regional seal makes a major contribution to exploration success in the basin. One notable exception is in the Barrow Island oil field, where the oil-bearing Windalia Sandstone (top Muderong Shale) is top-sealed by the Aptian Windalia Radiolarite, an open-ocean siliceous unit deposited at the height of Australian inundation, when the inland sea stretched across the continent and the Carnarvon Basin was far from shore (Box 4.3). Another exception is the Maitland gas accumulation, in which a Paleocene sandstone is the reservoir (Figures 4.22 and 4.23).

The main trap styles in the basin are anticlines, horsts, fault roll-over structures and stratigraphic pinch-outs beneath the regional seal (Figure 4.23). Extensional faulting in the Triassic and Jurassic rift sequences set up the fundamental architecture of the basin and the geometries of many of the fault block traps. The Cenozoic collision at the northern plate boundary caused tilting, inversion and renewed faulting. This latter event destroyed some accumulations but also produced another suite of structural traps to capture late-generated hydrocarbons.

**Why is Australia gas rich and oil poor?**

Australia was located in the high southerly latitudes and largely emergent during the key global source-rock depositional episodes of the Permian, Jurassic and Cretaceous (Box 4.1). Many of the richest oil-prone source rocks—in the Middle East, northern South America and west Africa—formed in marine palaeotropical environments. These are regions of high algal productivity, where oil-prone organic matter is linked to the fundamental driver of high solar-energy input near the equator. In the marine
environment, the source rocks can also be deposited as basin-wide blankets. In contrast, depending on the vegetation, non-marine coaly source rocks, which dominate Australian petroleum systems, are often inherently gas prone. There are some ‘sweet spots’ in the delta systems where marine influence and bacterial reworking of terrestrial organic matter produced a more oil-prone source rock. This was the case in the Gippsland Basin.

In addition, the maturation history of many Australian basins has been less than ideal for generating and preserving oil charge. Oil accumulations sourced from Early Paleozoic tropical marine shales of the Larapintine petroleum supersystem (Appendix 4.1.1) had a high likelihood of being destroyed in the mid-Carboniferous Alice Springs Orogeny (Chapter 2). And as we have seen, the Toolebuc Formation oil shale has not been buried sufficiently to generate hydrocarbons (Did you know? 4.1). Also, the Toolebuc Formation was deposited far from the plate boundary. The general strength of the Australian continental lithosphere (Chapters 2 and 5) has meant that there are no inland (intraplate) areas that have subsided fast enough to receive a thick enough sedimentary overburden load in the Cenozoic, such as in the oil and gas-rich Gippsland Basin closer to the continental margin. Many Australian petroleum systems rely on preserving oil generated in the Cretaceous or early Cenozoic. Later gas flushing has spilled and displaced many accumulations.

There is a large Late Cretaceous delta in the Bight Basin and evidence of Cretaceous marine oil shales that may have been buried enough to generate hydrocarbons. Let us now look at this frontier basin.

The Bight Basin: Australia’s largely untested southern frontier

One of the largest unexplored frontier provinces in Australia occupies the deep water of the Great Australian Bight, including the Late Cretaceous Ceduna delta, which underpins part of the Bight Basin (Figures 4.12 and 4.14). Remarkably few wells have been drilled as yet, and these mostly lie on the shelf, in water depths less than 250 m. One exception is Jerboa 1, drilled in 761 m of water by Esso Ltd in 1980 to test the Eyre Sub-basin. It was drilled with the deepwater rig brought to Australia for the Exmouth Plateau campaign and provided a welcome break in that effort, allowing time to assimilate the initial results of finding gas rather than oil on the Exmouth Plateau.

The only well to investigate the ‘real prize’ in the Great Australian Bight—the delta you can see on the bathymetry—has been Gnarlyknots 1, drilled by Woodside and partners more than 20 years after Jerboa 1 in 2003 in 1313 m of water (Figures 4.12 and 4.24). This well was plagued by mechanical problems and was eventually abandoned due to bad weather before the target depth was reached and some 1500 m above the planned total depth. It was an expensive exercise with an inconclusive result, and exploration stalled. Evidence of a viable petroleum system would be needed to encourage another try.

How can we reveal the petroleum system in the Bight Basin?

Collecting seismic and other geophysical data, dredging samples from the seafloor and remote sensing are all ways to understand this deepwater
frontier. Geoscience Australia and its predecessors have a long history of research in the Bight Basin, conducting several gravity and magnetic surveys and acquiring more than 28 000 km of regional seismic data. The geochemistry of the bitumen washed ashore along the southern margin beaches was studied, as well as satellite data indicative of natural seepage of oil. Using all these data and the limited well information, a detailed analysis was undertaken. Models of the possible petroleum system and plays were produced. These studies informed a marine survey in 2007, which recovered potential source rocks of Late Cenomanian to Early Turonian age from the northwestern edge of the Ceduna Sub-basin. Exploration is now under way in the deepwater Bight Basin, with the awarding of new petroleum exploration permits in 2011. Drilling is planned in 2013 or 2014.

So, is Australia really oil poor? We can only answer once this, and other frontier basins, have been more fully tested.

Postscript

From the story of ‘Out of Gondwana’, we see that geology has directed the track of the past and constrains our future choices, a Phanerozoic story with modern consequences. How much of a role will oil and gas play in the future energy mix; how will the development of unconventional resources be balanced against environmental protection; will there be a new oil province in the Great Australian Bight?

In the distant future, Australia will once again join a supercontinent; this time it will be Amasia, linking Australia back with its Asian partners from Gondwana. A collision zone of Himalayan proportions will have destroyed the hydrocarbon fields of the North West Shelf. But new oil and gas accumulations will have formed, perhaps where the Toolebuc Formation has been buried deeply by sediments shed from the mountains. Will oil be of any relevance to whoever remains 50 Myr in the future? Perhaps oil will still be a convenient, energy-dense substance, capturing and concentrating as chemical energy the sunlight that warmed ancient seas.

We will now look at the journey Australia made out of Gondwana, but from the perspective of the old, flat and red landscape ...
Bibliography and further reading

Gifts of Gondwana


Ozimic S & Saxby JD 1983. Oil shale methodology: an examination of the Toolebuc Formation and the laterally contiguous time equivalent units, Eromanga and Carpentaria Basins, Bureau of Mineral Resources and CSIRO research project.


Pangaea at the zenith

Gondwana breakup

Northwest margin

Southwest margin

Southern margin
Northern margin


The Australian petroleum search


