Foundations of wealth—
Australia’s major mineral provinces

Since the 1850s, Australians have prospered not only from the wool off the sheep’s back but also from the mineral wealth bequeathed by Australia’s geological history. Our mining history has contributed significantly to our national identity. Much of the country was explored and settled because of its vast mineral wealth. Today, Australia’s economy is highly dependent upon minerals that provide most of our export income. Major mineral provinces in Australia—the Victorian goldfields, the Eastern Goldfields in Western Australia, Broken Hill, Mt Isa and Olympic Dam—although linked to different tectonic events, share many commonalities. These include a spatial association with major fault zones, a temporal association with major thermal events, an association with changes in tectonics, and a broad association with major crustal boundaries. This mineral wealth was created as a consequence of the large-scale tectonic processes that built Australia from its disparate elements.
Figure 8.1: Map showing the locations of deposits and localities discussed in the text. The greyed areas indicate subcropping or outcropping basement province and basins mentioned in the text.
Sources of wealth

Australia, considered by some as the 'Lucky Country', has vast agricultural lands, unique flora and fauna, a sunny climate, diverse people and, importantly, abundant mineral resources (Chapter 1). Early last century, Australia was, on a per-capita basis, one of the two or three wealthiest countries in the world. The country is still in the top 20, and in the top 10 'most liveable' by some reckonings. In the past, much of this wealth was based on agriculture (wool and wheat), although mining played a very important role, especially after the nation-changing discovery of gold (Au).

Today, the bulk commodities of iron ore, coal, hydrocarbons and bauxite are generating most of Australia's mineral wealth (Chapter 9), whereas the early mineral wealth was generated by metallic elements such as Au, copper (Cu), silver (Ag), lead (Pb) and zinc (Zn). The 1851 discovery of Au ushered in changes and events—mass immigration, early multiculturalism, the opening up of the outback (Figure 8.1), the Eureka Stockade, unionism—that still resonate today. Gold made many Australians, as well as the country, rich.

The benefits of Australia's mines go beyond wealth. The first mass migration of non-Anglo-Celtic people to Australia occurred in response to the discovery of Au. People came from all over the world, but one of the largest waves of immigrants came from China. Many of the early goldfields and mining districts were highly multicultural. Resentment shown towards the Chinese resulted in violence in several goldfields, and these sentiments eventually led in part to the development of the 'White Australia Policy', a contingency that selected Australian immigrants based upon race that was not abolished until the 1960s. Descendants of the Chinese miners still live in the Victorian (and other) goldfields, and the Chinese Spring Festival forms an integral part of Bendigo's annual Easter Fair.

Historically, mining also has had its downside, including environmental, societal and even economic effects (Chapter 9). For individual miners, the greatest downside is the hazardous nature of mining, with fire, collapses, large plant and machinery, and chronic disease being of particular importance. In the modern age, these...
hazards have been significantly reduced, largely due to improvements in worker training, health and safety regulations and mining methods.

Like virtually every other human activity, mining can have significant effects on the environment (Figures 8.2a and b). Modern mines generally have a much smaller impact on the environment than those in the past (Figure 8.2c). Today, modern rehabilitation programs can successfully restore the landscape and vegetation after mining. Although improvements have been made, one of the largest challenges to the mining industry is to minimise the future effects of its operations on the environment and maintain support in the public arena—its social licence to operate (Chapter 9).

In this chapter, we present an abbreviated history of Australian mining and its importance to shaping the Australian people. We introduce the concept of a mineral system and use this concept to describe four important metallogenic provinces: the Victorian goldfields, the Eastern Goldfields of Western Australia, the Proterozoic zinc belt in central Australia, and the Olympic Dam Iron-Oxide-Copper-Gold (IOCG) Province in South Australia. Each of these discoveries had, and continues to have, a shaping influence on the development of Australia. We bring these major metallogenic provinces together and show that they are not isolated phenomena; rather, their individual geneses (mineral systems) have much in common.

A short history of discovery and mining in Australia

Many social historians attribute wool as the main commercial factor that influenced the development of Australia. The equally great contribution of mining has been often overlooked. For example, from 1851 until the early 1870s, Au was the predominant Australian export. Through much of the rest of the 19th century, the mineral industry was very close to wool as the predominant export industry. Since the late 1940s and especially now into the 21st century, mining and related industries have accounted for the bulk of Australia's export earnings, eclipsing the agricultural sector many times over (Chapter 9).
Early mining in Australia

The history of Australian mining began with Aboriginal mining of various rocks and ochres for stone tools and pigments (Chapter 5). Trade of these commodities enabled members from different language groups to share aspects of ‘The Dreaming’. Specific cultural knowledge and practices were shared and reinforced during meetings. Trade occurred between tribes, with particularly valued commodities being distributed across the country (see Did you know? 8.1).

The utilisation of stone continued with the arrival of the First Fleet in 1788, when convicts were assigned to cut sandstone blocks from the shores of Port Jackson for the Governor’s residence, warehouses, military barracks, prisons and other buildings. Within 10 years of the arrival of the First Fleet, coal was discovered in 1791 by convicts near Newcastle (NSW) and later to the south and west of the settlement (Chapter 9). The find led to the establishment of the Coal River penal settlement in 1801. These areas provided fuel for heating and cooking, and later steam locomotion in the young colony of New South Wales. Australia’s first truly commercial mining venture was at Newcastle in 1799, when coal was exported to Bengal (India). From those humble beginnings, Newcastle has developed into a major metropolitan centre and is now the world’s largest coal export port.

The first metallic mine in Australia was the Glen Osmond Ag–Pb mine, which was opened near Adelaide in 1841. Mining saved the near-bankrupt economy of South Australia, with the discovery of Cu, first at Kapunda in 1843, followed by Burra in 1844. Up to the 1850s, Burra was the world’s richest Cu mine, and for the first 20 years of operation, it paid dividends of 300% per annum, making it a significant economic driver in the early days of the colony. More than 1000 miners were employed in the Burra Mine in 1849–50. Before these Cu finds, South Australia’s population in 1844 (Appendix 8.1.1) was around 17 000; it more than quadrupled in 10 years, to more than 85 000 people. By the 1870s, South Australia had replaced Cornwall as the largest Cu-producing region in the British Empire. Many of the skilled Cornish mine workers came to South Australia, both pulled by the allure of rich deposits and pushed by the potato blight and the declining mining industry in Cornwall.

Like Australia’s coal resources, close proximity to the sea was an important factor in the early discovery and mining of South Australian Cu. Ore was initially brought by bullock wagon to Wallaroo for shipment to the smelters of South Wales. Later, ports were used (Chapter 6), and coal was shipped from Newcastle to South Australian smelters, with some lower grade ore back-loaded for smelting at Newcastle. Funding for these early mining ventures and the development of the Victorian goldfields (see below) was sourced mainly from overseas (London), as the first Australian stock exchange did not open until 1861 in Melbourne.

Gold, silver, lead and copper rushes of the mid- to late 19th century

Really large mining-driven changes began with the gold rushes. The winter of 1851 saw the first gold rush at Ophir near Bathurst in New South
Wales. Although controversies remain about who first discovered Au, Edward Hargraves, using his California experiences, promoted the new field and started the rush. A further rush followed shortly after in Victoria. In response to these rushes, the New South Wales and Victorian colonial governments initiated a licensing system for prospecting, which was partly designed to encourage unsuccessful miners to return to their jobs in the cities and on farms. Development of this licensing system, which replaced the Crown's exclusive mineral rights, was one of two important drivers on the development of the mining industry in the 19th century. The other was economic depression, which drove city people to the bush and resulted in discoveries like Broken Hill (Zn–Pb) in New South Wales, and Coolgardie (Au) in Western Australia (Figure 8.1). The combination led to the first expression of 'revolution' and demonstration of the Australian spirit at the Eureka Stockade, where miners protested against licensing and raised their own flag, now preserved at the Ballarat Museum.

Other than the arrival of the First Fleet, the discovery of Au shaped the make-up of the Australian people more than any other event. The first people on the goldfields were from Sydney and Melbourne and the surrounding sheep properties. When news reached England, the mass influx of Au seekers from overseas began. Australia's population soared dramatically, trebling in 10 years, with, as noted above, the first large numbers of Asian immigrants. By 1861, there were more than 24 000 Chinese immigrants on the Victorian goldfields of Ararat, Ballarat, Beechworth, Bendigo, Castlemaine and Maryborough. There were more than 11 000 Chinese on the New South Wales goldfields. In the 1870s, there was an influx of Chinese miners to Queensland after the discovery of Au in the Palmer and Hodgkinson rivers and in Cooktown. Chinese miners worked not only Au but also other metals such as tin (Sn), tungsten and Cu. The influx of people from around the world captured the imagination of poet Henry Lawson.

The patterns of discovery were similar at many of the new goldfields. The alluvial resources ('placer' deposits) were usually the first to be discovered, but they were commonly depleted in a few years, with most diggers moving on to the next new find. Where deeper vein or hard-rock Au resources were discovered, fields lasted much longer (for more
than 120 years in some cases). These resources required capital and company structures, and provided employment for many of the original diggers. There was, however, a strong appeal in digging for yourself. Although many diggers made great fortunes, others lost everything, including their lives.

The gold rushes began in the southeast corner of the continent, and then worked their way anti-clockwise around Australia (Appendix 8.1.1). In the 1860s, the first big goldfields were found in Queensland, first at Gympie, and then at Charters Towers in the early 1870s. These Au discoveries saved the almost-bankrupt colony’s economy. Gold was then discovered at Pine Creek, south of Darwin, in the 1870s, and in the 1880s gold rushes reached the northwest of Western Australia with a rush to Halls Creek. By the end of the 1880s, prospectors were finding Au some 200 km east of Perth, and then, in 1893, at the richest of all Australian goldfields, the Golden Mile at Kalgoorlie. This period of Au prospecting also yielded tales of lost Au, the most famous being Lasseter’s reef. In 1897, an Australian-born prospector from the Victorian goldfields, Lewis ‘Harry’ Lasseter, supposedly found a rich vein of Au somewhere near the border between Western Australia and the Northern Territory. The myth persists to this day, and fortune hunters still roam the Australian outback in search of Lasseter’s and other lost Au reefs.

As prospectors went inland, most looking for Au, other commodities were found (Appendix 8.1.1). Sn was discovered at Mount Bishop in northwest Tasmania in the early 1870s, and in 1883 Ag and Pb were detected at Broken Hill. CU was discovered at Mount Lyell in western Tasmania and at Mount Morgan and Cloncurry in Queensland by the 1880s. At Mount Morgan, oxidised ores rich in Au graded downwards into Au–Cu ores at depth. By 1900, Australia had the beginnings of a diverse mining industry, with coal at Newcastle and Port Kembla, Au in virtually every part of Australia, Cu in many places, and Sn in western Tasmania. In the 1870s, Australia was probably the largest Sn producer in the world.

New expansion and contraction: 1900–39

Although Au mining had dominated the second half of the 19th century, by the beginning of the 20th century, prospectors had found most of the easily won sources. By about 1914, the prospectors had found virtually all the deposits that were payable using the technology at the time. The value of Au declined, the cost of mining increased, and
World War I began. The importance of Au as an economic and therefore social driver declined. Mining continued, but the wealth it generated did not rival the earlier influence. Rather, the only major finds of the first half of the 20th century were Pb, Zn and Cu deposits at Mt Isa in Queensland, but their full potential was not realised until the 1950s (see below).

The Great Depression of the late 1920s and 1930s had a mixed effect on the Australian mining industry. The industry was mostly depressed because of low commodity prices, but a rise in the price of Au and a government bonus led to a surge in Au prospecting and production. Consequently, Au mining in Western Australia had a boom, and a new goldfield was discovered at Tennant Creek in the Northern Territory. At the same time, Newcastle and other coal-producing areas had major strikes as that industry and its labour supply adjusted to economic depression.

**The post-war boom: 1945–75**

Aside from Au in the 1930s, the mining industry went into near hibernation until the late 1940s, when a boom began that was to last two decades. This boom differed from the earlier ones in that it involved a different mix of commodities and was driven in part by changes in government policies. The development of military ‘Cold War’ and then civilian nuclear programs, particularly in the United States and Great Britain, required uranium (U), a commodity that previously had no use. Other commodities that were found at this time included bauxite (an ore of aluminium–Al) at Gove and later Weipa and the Darling Range, and iron ore, firstly at Koolanooka and then in the Pilbara region (Chapter 9). Although this boom also saw the discovery of important base-metal deposits, Au exploration was virtually non-existent, only resuming in the 1980s after the Au price had been floated relative to the US dollar and technological innovation allowed mining of low-grade deposits (see below).

This mid-20th century mining boom also saw the development of a new style of discovery. Previously, all discoveries in Australia had been made by prospectors, semi- or self-educated men who roamed the outback looking for the telltale signs of mineralisation, Au nuggets in streams or veins, or the green bloom of malachite...
on surface outcrops. Exploration now became increasingly capital and technology dependent, and geoscientists—geologists, geochemists and, particularly, geophysicists—became important players in finding deposits. As the costs of exploration increased, mineral exploration was carried out by junior exploration companies and the exploration divisions of major mining houses. Many of these discoveries were made using newly developed geophysical techniques, giving geophysics the aura of a 'magic bullet' for success. Exploration was also facilitated by government surveys (Chapter 2). The Bureau of Mineral Resources, Geology and Geophysics, better known as BMR—now Geoscience Australia—was established in 1946, with the aim of mapping the continent to assist industry to uncover new mineral and energy resources.

Changes in government policy also drove this boom. As late as 1945, Australia was believed to be deficient in iron ore, and its export was banned. Removal of these bans resulted in the discovery of huge iron ore deposits in the Hamersley Basin of Western Australia in the 1960s, which has become one of the great iron ore provinces of the world (Appendix 8.1.1; Chapter 9). Decreases in shipping costs and the development of open-cut mining methods made these resources payable, and very profitable. Giant bauxite deposits and manganese (Mn) deposits at Gove in the Northern Territory were discovered at this time. The coupling of easily won coal using open-cut mining methods and high-quality alumina meant the synergistic development of Al refineries adjacent to some of Queensland’s ports (Chapter 9).

The nickel boom: 1960s to 1970s

While prospecting for Au in 1947, George Cowcill collected green-stained ferruginous rock specimens in the Kambalda area of Western Australia. Later, in 1954, thinking the samples might be U-bearing, he submitted them for chemical analysis, only to find that they contained nickel (Ni). A decade later, Western Mining Corporation geologists explored for Au and base metals in the same area, but, as happens commonly in exploration, they discovered something quite different, the great Kambalda Ni deposits (Appendix 8.1.1). Discovery of the Lunnon shoot (initial intersection of 8.3% Ni over 2.7 m) was announced in 1966, sparking a boom that continued until 1972. The host magnesium (Mg)-rich ultramafic rocks, called komatiites, were difficult to identify in the weathered rocks of the Yilgarn Craton. These komatiites hosted a style of Ni deposit previously unrecognised anywhere else in the world. In some places, the komatiites weather to silica-rich cap rocks, bearing little chemical relationship to their parent rock, and only preserving their characteristic spinifex rock texture (Chapter 2). Fortunately, these rocks are magnetic, so the use of aeromagnetic data rapidly assisted explorers in identifying prospective ground. The Ni boom was intense, with competition leading to the pegging of very speculative leases with a low prospect of discovery.

Nevertheless, more than 70% of the mined Ni deposits in Western Australia were discovered in these early years. In the late 1960s, demand for Ni soared to meet armament requirements for the Vietnam War and as a result of industrial relations problems at the Canadian company Inco, then the largest Ni producer in the world. Many new companies were listed, some without leases, let alone mines, to take advantage of the high prices.

Gold booms of the late 20th century

From the end of World War II, the US dollar had been pegged to the gold standard. By the early 1970s, Au had truly lost its lustre. Towns synonymous with the Australian gold rushes were nearly dead; Kalgoorlie, for instance, had only around 100 working miners in 1976. However, when the convertibility to Au by the US dollar was terminated in 1971, the price of Au began to rise steadily, peaking in 1980 at more than US$850 (or more than US$1800 per ounce in 2011 dollars). Opportunities materialised to acquire large shares of the most prospective ground at rock-bottom prices. From this, the Golden Mile was reborn, this time as a ‘super pit’ but with grades less than a fifth of those of the early mines.

Technology also played its part in the late-20th century Au resurgence. The development of the carbon-in-pulp process and refinements in open-cut mining methods in the 1980s permitted mining of the large low-grade halos of previously mined, high-grade deposits. By 1993, Kalgoorlie was once again Australia’s largest Au producer, a century after its founding; the Super Pit has a projected mine life to 2017. Other old fields have also been re-energised, including Kanowna, Kambalda and Coolgardie (WA), Charters Towers (Qld), and Stawell (Vic.).

Interest in Au continued apace, and by 1990, around 10% of all listed stocks on the Australian Stock Exchange were partly or wholly involved
in Au mining. Companies synonymous with other commodities also chased the allure of Au. For example, North Flinders Mines’ foray into the Granites–Tanami Province of the Northern Territory was a far cry from their original target of base metals in the Flinders Ranges of South Australia. Mineral fields not previously known for Au, such as the bauxite fields southeast of Perth, were also tested, leading to the discovery of the giant Boddington Cu–Au deposit.

**Boom time from 2005 onwards**

The latest boom began in about 2005 and continues, albeit with a short hiccup associated with the 2007–08 global financial crisis. This boom differs in important ways from previous ones in that it crosses virtually all commodity sectors—Au, Ni, base metals, U, iron ore, coal and bauxite—with major price increases in most commodities. In addition, there has been increasing interest in new commodities such as rare-earth elements, Mn and lithium (Li), which are important inputs into high-technology and other strategic industries (Appendix 8.1.1). Because the bulk commodities of coal, iron ore, natural gas and aluminium dominate the economics of this boom, they are discussed in more detail in Chapter 9.

**Mining busts of the late 20th century**

Busts have just as large an impact on the industry and society as the booms they follow (Figure 8.3). The mining industry is highly susceptible to economic downturns; as commodity prices fall, mines close, jobs are lost and mineral exploration declines. Since 1970, there have been four busts with periods ranging from four to eight years (Figure 8.3). The ‘deepest’ bust, which accompanied the mid-1970s oil crisis, involved a 65% decrease in real exploration expenditure relative to the peak of the Ni boom. The most recent bust, which started just before the turn of the 21st century, differed from those before in that many junior exploration companies did not go bankrupt but diversified into other business activities, including information technology ventures that collapsed later during the ‘dotcom’ bust of the early 2000s. Another important consequence of this bust was the consolidation of the industry, with the disappearance of virtually all mid-tier Australian producers (e.g. Mt Isa Mines Ltd, Western Mining Corporation Ltd) into large multinational conglomerates. This was accompanied by the dismantling of industry-based research groups, with the research niche taken up by consultants, academia and government.

**Australia’s giant mineral systems**

Australia is among the top five countries, in terms of both production and resources, for many commodities, including Au, Cu, U, Zn, Pb, Ag and others discussed in Chapters 4 and 9. Australia is a big country, with the full spectrum of geological time recorded, making this resource endowment widely distributed in time and space. Almost all Australian states and territories have world-class deposits containing at least one of these commodities, which are hosted by Archean, Proterozoic and Phanerozoic rocks (Figure 2.21).

It takes a lot of energy and a lot of fluid to make a giant mineral deposit. A mineral deposit is, however, only a symptom of a much larger
system—a mineral system (Figure 8.4). For a more complete explanation of this approach, see Appendix 8.3.1. In essence, a mineral system works like this:

1. Fluids from various sources with favourable physical and chemical properties dissolve metals from a large volume of dilute metal-rich source rock.

2. The metal-rich fluids follow pathways that focus and concentrate them through a much smaller volume of rock.

3. Most of the rock volume has very low permeability. For fluid flow to occur, the rocks must be fractured or faulted and linked with a connected architecture.

4. The architecture must also be able to throttle or focus the large volumes of metal-rich fluid through a smaller volume of rock.

5. In this smaller rock volume, the metal-rich fluid encounters a change in the physical and/or chemical conditions.

6. The properties of the metal-rich fluid at this critical time become unfavourable for holding the dissolved metals in solution.

7. The metals are deposited, and the remaining fluid is expelled and dispersed.

8. The system is preserved.

9. Geodynamic processes (energy, kinematics and dynamics) drive the mineral system.

10. Mineral systems operate at scales from the global to the microscopic.

Figure 8.4: A space and time illustration of a mineral system. In this system diagram, a mineral deposit is formed during a critical window of time when there is a conjunction of sufficient energy, permeability and depositional gradients to focus metal and fluid for ore concentration. The time period before formation ensures sufficient preparation and initial concentration of metal sources. The time period after formation ensures that the deposit is preserved, and not eroded. The numbers on the diagram refer to the parts of a mineral system listed in the text. In contrast to a petroleum system, fluids are not trapped in a mineral system; they are focused and exit the depositional site, leaving a geochemical dispersion footprint that may be preserved at scales many times larger than the deposit itself.
The benefit of a mineral system is that its scale is many orders of magnitude larger than the mineral deposit itself, which is just a favourable symptom of an effective system. This means that explorers can use the much larger scale indicators of the ore system in their search for the deposit itself. For example, a deposit only 500 m wide may have a fluid outflow zone many tens of kilometres wide, such as in the Eastern Goldfields. Similarly, the zone of depletion of the metal-rich source rock may be many tens of kilometres wide, such as in Broken Hill. These wide ‘alteration’ footprints then become amenable to remote sensing or geophysical detection, and thus can be used to vector more effectively and cheaply to ore.

Given the size and diversity of Australia’s mineral endowment, we have selected four key hydrothermal mineral provinces: the Victorian goldfields; the Eastern Goldfields in Western Australia; the Proterozoic zinc belt that spans New South Wales, Queensland and the Northern Territory; and the Olympic Dam Iron-Oxide-Copper-Gold (IOCG) Province in South Australia. These four giants are interesting not only for their history, but also because they illustrate the concept of a mineral system.

**Victorian goldfields—the gold rush that changed a nation**

The discovery of Au in Victoria was the first of the major minerals-related economic booms in Australia. In addition to the wealth created in Bendigo and Ballarat and then transferred to Melbourne, this gold rush began to transform
Australia from a continent populated by the relatively few Aboriginal people and European (largely British and Irish) immigrants to the multicultural society of today. Victoria’s immigrant population increased from about 10 000 in 1840 to 500 000 in 1860 (Box 1.2). The mining history of the Victorian goldfields has influenced the Australian character in other ways. For instance, the Eureka Stockade rebellion was, at least on the surface, a dispute about mining licences, and the first wave of non-European immigration to Australia was the Chinese miners who came to work the Au and stayed to create businesses.

When, in early 1849, a young shepherd, Thomas Chapman, unearthed 38 oz near Amherst in what was to become the Victorian goldfields, a nascent gold rush was nipped in the bud by troopers ostensibly sent to enforce trespass laws, although the real reason may have been to prevent mass desertions of workers from rural farms and the growing city of Melbourne.

According to official records, payable Au was first found in early 1851 at Clunes (Figure 8.5), about 130 km northwest of Melbourne. However, possibly because of its remoteness, this goldfield did not experience the mad rush seen at Ophir in New South Wales. When first visited by troopers in late July, only 50 men were working the goldfields, although Clunes for a short time became the largest inland town in Victoria. The first major rush in Victoria was to Ballarat, after Au had been discovered by John Dunlop and James Regan as they returned to Melbourne from Clunes. By the end of September 1851, nearly 1000 men were seeking Au, and the Governor of Victoria was compelled to adopt the New South Wales licensing system. Within a year, around 20 000 diggers were trying their luck in the Ballarat goldfield (Box 8.1). The attraction was strong, as, in the year 1856 alone, more than 20% of Tasmania’s convicts tried to abscond, many drawn to the Au riches of Victoria.

The discovery of Ballarat opened a floodgate; within a year, Au had been discovered at Mount Alexander, near Castlemaine, and then Bendigo (Figure 8.5). At first, most Au was mined from alluvial workings, although this was mostly exhausted by 1900. The earliest years were also the richest; for most of the 1850s, Victoria produced 70–90 t/year of Au. After 1860, production declined steadily until around the turn of the century, which saw a small revitalisation of production (to 25–30 t/year). By 1930, production had virtually ceased, with less than 1 t/year. Minor revivals (to 5 t/year) occurred during the Great Depression in the mid- to late 1930s and in the recent Au boom from the late 1980s to now. The Victorian goldfields did not, however, experience the renaissance seen in the Eastern Goldfields of Western Australia, possibly because the nature of the Victorian deposits (nuggety) made them less amenable to the advancements in metallurgical (carbon-in-pulp) and bulk-mining methods that have driven the most recent Au boom.

Victoria’s golden riches: gifts from the Benambran Orogeny

The formation of Victoria’s goldfields is intimately linked to the evolution of the Lachlan Orogen. This orogen, which makes up most of the Tasman Element of eastern Australia, formed as a convergent margin that was active through the mid- to late Paleozoic assembly of Gondwana and Pangaea between 490 Ma and 230 Ma (Chapter 2). Although eastern Australia was mineralised throughout this assembly, the most important metal-forming period was the 490–435 Ma Benambran cycle, which produced a series of island and continental arcs and backarc basins that extended from northern Queensland to western Victoria and were cratonised during the 440–435 Ma Benambran Orogeny (Figure 2.33).

The most significant deposits of the Benambran cycle formed near its conclusion. In the central Lachlan Orogen, porphyry Cu–Au, epithermal Cu–Au and Au-only deposits mostly formed at 440–435 Ma, largely associated with emplacement of potassium-rich (shoshonitic) volcanic centres during late extension of the oceanic Macquarie Arc. In the Victorian goldfields of the western Lachlan Orogen, contraction associated with the Benambran Orogeny formed most lode-Au deposits (Figure 8.6, Box 8.2). The closeness in time and space of these two contrasting mineral systems presents a conundrum in understanding the Benambran convergent margin.

Figures 8.6a and 8.6b–c illustrate two possible geodynamic scenarios to account for this conundrum. The first involves the attempted subduction of a seamount or microcontinental block, resulting in the locking up of the arc at ca 440 Ma (Figure 8.8a). Rollback and slab tearing associated with this lock-up resulted in extension and alkaline magmatism with associated porphyry Cu–Au deposits in the Macquarie Arc. Compression
The discovery of vast quantities of gold (Au) in Victoria in the early 1850s had a major impact on Victorian economic development and on that of the rest of Australia. Gold was Australia’s most valuable export commodity from 1851 to 1870, and at its peak in 1852 the mining sector comprised more than 35% of Australian gross domestic product.

A boom in one sector or region requires an adjustment to resource allocation in the economy as a whole and is almost always associated with changes to income redistribution. The overall impact of the gold rush was overwhelmingly positive, although there were some negative impacts in some sectors of the economy that were forced to adjust in the short and medium term. Wages for gold miners rose rapidly, increasing five-fold from 1851 to 1852 (Figure B8.1a), leading to increases in wages in other sectors and temporary shortages of labour. Attracted by high wages for miners, labour flowed into Victoria, and the population increased by more than 450% from 1851 to 1860 (Figure B8.1b, Box 1.2). Although some of this inflow came from other states (particularly South Australia and Tasmania), most of the increase was accounted for by immigration. This large increase in the supply of labour mitigated the upward pressure on wages.

The rapid expansion of the mining sector placed considerable inflationary pressure on goods and services (Figure B8.1a). Although there were dramatic increases in prices for domestically produced and consumed goods and services, prices for traded commodities were relatively stable because Australian importers and exporters were (and are) generally price takers on world markets and the exchange rate was fixed. Higher wages increased the supply costs for businesses, putting further upwards pressure on prices. Overall, consumers received higher incomes but faced increased prices, while producers of traded goods (particularly wool) experienced increased costs but received unchanged output prices.

There was considerable investment in public infrastructure in Victoria as a result of the gold rushes. An increased demand for transport and telegraph services, particularly in regional areas, was combined with increased revenue and an improved credit standing. This growth in regional infrastructure benefited the agricultural sector when the mining sector declined, enabling growth to remain strong for a decade after the boom peaked.

Similar pressures are present in today’s economy as a result of the current mining boom, which is centred largely in Western Australia and Queensland. Demand for Australia’s mineral exports has driven up the value of the Australian dollar, causing ongoing adjustments in other sectors, primarily the manufacturing and tourism industries, as they absorb the impact of the high Australian dollar (Chapter 9).
inboard of the arc deformed the Western Lachlan, resulting in lode-Au mineralisation. Alternatively, the West and Central Lachlan were separated by a transform, the Baragwanath Transform, which accommodated extension, and porphyry Cu–Au deposits, to the northeast, but contraction, and lode-Au deposits, to the southwest (Figure 8.6c). A third option, not shown in the figure, is that the Macquarie Arc was translated southwards from its original position during oroclinal folding associated with the later (ca 410 Ma) Bindian Orogeny.

The early Paleozoic rocks of the Bendigo and Stawell zones lie in a wedge-shaped extensional basin, the ‘Castlemaine basin’, between Proterozoic blocks to the west and east. At the surface, the Bendigo Zone is dominated by Early Ordovician turbidites with lesser Cambrian basaltic rocks (Figure 8.5). Cambrian-aged mafic volcanic rocks in the Stawell Zone are associated with the fault that marks the western boundary of the adjoining Bendigo Zone. Interpretation of the deep seismic reflection data suggests that mafic volcanic rocks form a thick wedge beneath the Ordovician turbidites (Figure 8.7). The basalt within these zones has both tholeiitic (iron—Fe-rich) and boninitic (Mg-rich) associations. The basalt geochemistry has been interpreted as indicative of an extensional backarc basin setting for the Bendigo and Stawell zones. Moreover, these basalts are also enriched in Au, and they may have been one of the main sources of metal (Figure 8.4).

The Cambro-Ordovician fill of the Castlemaine basin is transected by a series of, mostly, moderately to shallowly west-dipping faults,
some of which have apparent reverse motions (Figure 8.7). The margins of the basin are defined by inward-dipping faults that juxtapose basin fill against Proterozoic basement rocks and are most likely the original basin-bounding faults. The faults within the basin also probably initiated as normal faults related to basin formation, but were inverted into reverse faults during the ca 440 Ma Benambran and later orogenies. This early basin architecture forms a fundamental control on the richness of the Victorian goldfields, particularly in the Bendigo Zone, as it provided not only Au-enriched source rocks but also pathways for later fluid flow during reactivation of the early structures.

Isotopic dating of the Au deposits (Box 8.2) shows that the Victorian goldfields experienced three separate Au mineralising events, the first at 440–435 Ma, associated with the Benambran Orogeny; the second at 420–410 Ma, associated with the Bindian Orogeny; and the last at 380–365 Ma, associated with early stages of the Kanimblan cycle (Box 8.2). Of these, the earliest (Benambran Orogeny) was most prolific, producing more than half of the total Au from the Victorian goldfields. This event differs from the later events in the Victorian goldfields, and Archean Au events in the Eastern Goldfields Province (see below), in that it was not synchronous.
with granite magmatism. The oldest granites appear to have been emplaced 25 Ma after the Benambran-aged Au was deposited. These granites overlap the Bindian Orogeny, and many of the early Kanimblan deposits have a close spatial and/or temporal association with magmatism.

Most Au in the Stawell and Bendigo zones is spatially located within 5 km of the major first-order faults, many of which were initiated during basin development. However, these faults are generally unmineralised. The most significant goldfields in the Stawell Zone are in the hangingwall of the Moyston Fault, and most Au in the Bendigo Zone is associated with west-dipping back thrusts (Figure 8.7). In detail, the Au deposits are associated with second- and third-order faults and associated folds (Figure 8.8). The first-order faults acted as the main fluid conduits that linked Au-enriched mafic volcanic rocks deeper in the basin with the second-order faults, which provided a throttle for the metal-rich fluid, focusing it into favourable structural and/or stratigraphic sites for deposition (Figure 8.8).

In the Bendigo and Stawell zones, the dominant Au depositional sites are structural. In most cases, uniformity in Ordovician siliciclastic basin-fill did not create sufficient chemical gradients to deposit Au. Rather, the Au is hosted in saddle reefs along anticlinal closures, in cross-cutting and bedding-parallel veins, and in tensional veins in fold closures (Figure 8.8). The auriferous veins are commonly associated with sericitic (white mica) alteration halos and hosted mainly in sandstone units, which were able to fracture in response to the tectonic stress in a brittle manner and thus create dilatant zones (space). When the metal-rich fluids encountered this space, the pressure of the fluid dropped and the metal-rich fluids expanded, causing phase separation or boiling, and hence deposition of Au (and quartz).

Having produced 80% of the Au from the Victorian goldfields, the Bendigo Zone dwarfs the adjacent Stawell and Melbourne zones in terms of endowment, whether measured on an acreage basis or in total Au produced. The Bendigo Zone forms the deepest part of the Castlemaine basin and is characterised by a greater abundance of mafic volcanic rocks at depth (Figure 8.7). In contrast, the Stawell Zone, which produced only 8% of Victorian Au, has a lower abundance of mafic volcanic rocks, and the Melbourne Zone, which has produced little Au, particularly during the Benambran event, is apparently not underlain by mafic volcanic rocks (Figure 8.7). The apparent correlation between the abundance of Au-enriched mafic volcanic rocks and Au productivity highlights the importance of an enriched source for Au metallogeny (Figure 8.4).

**Key factors in forming the Victorian goldfields**

The Victorian goldfields illustrate some features that may be fundamental to forming giant mineral systems. These goldfields formed during the assembly of Gondwana–Pangaea and are associated with a major stress switch from extension (basin formation) to compression, associated with the Benambran Orogeny. As shown above, this orogeny was the main energy driver in the mineral system and was likely caused by the accretion...
Geochronology is an essential tool for understanding the formation of ore deposits. Knowing when a mineral deposit formed is also of vital importance from an economic viewpoint as it has implications for how and where new resources might be found. In the vast majority of cases, the timing of ore formation is tied to the evolution of the geological domain in which deposits are hosted. As mineral deposits are generally the result of tectonic processes that operate in well-defined geological environments, constraining the timing of gold (Au) mineralisation in the Victorian goldfields was critical not only to the understanding of how, why and where these enormously rich ore systems developed, but also to deciphering the processes that dominated the tectonic evolution of southeastern Australia at 490–350 Ma.

Prior to the mid-1990s, the geochronological and tectonic framework of the Au-bearing rock sequences in Victoria was only very broadly constrained by general structural interpretations, the age of the sedimentary rocks, and the approximate timing of deformational events and the intrusion of magmatic rocks. There was considerable debate about whether mineralisation occurred during one ‘climactic’ event or in stages. The cause for the Au endowment was also contentious, with some scientists favouring granites, which account for more than 30% of the outcropping rocks in Victoria, as the ultimate driver.

As Au cannot be directly dated, determining its age has to rely on the indirect dating of ‘proxy’ minerals such as hydrothermal mica, feldspar or arsenopyrite, which are commonly associated with, and assumed to have formed concurrently

West-dipping reverse fault zone and associated fault fill and extension veins from Wattle Gulley gold mine, Victoria.

Image courtesy of Stephen Cox, Australian National University
with the Au. Indirect age determinations can also be obtained from the dating of intrusive rocks that truncate or are truncated by an Au-bearing quartz vein. In all instances, formation ages can be determined by means of analytical techniques that use radiogenic isotope systems such as Ar–Ar, K–Ar, Pb–Pb, U–Pb, Re–Os and Sm–Nd: ratios between the parent and daughter pairs provide precise age constraints.

In the past 15 years, numerous studies have been undertaken with the aim of resolving the age of mineralisation, and its relationship to magmatism, in the Victorian goldfields. These data have greatly advanced our understanding of the geotectonic setting in Victoria and processes that formed one of the world’s richest Au provinces. Most importantly, Au mineralisation across Victoria was not the result of a province-wide mineralising event. Instead, the deposits formed episodically and in response to a diachronous west–east progression of deformation, metamorphism and exhumation typical of a developing mountain range. Major Au deposits in the west (e.g. Stawell) and central parts (e.g. Ballarat, Bendigo) formed at ca 440 Ma and are significantly older than smaller deposits in the east (e.g. Woods Point) that formed at 380–370 Ma. The first phase of Au, at 420–400 Ma, was younger than the first phase of gold mineralisation, but the second period of magmatism was coeval with the second period of Au mineralisation at 380–370 Ma. All of these processes were intimately linked to an extensive period of terrane collision in the Paleozoic along the Palaeopacific margin of proto-Australia (Chapter 2; Figure 2.26).

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The age of Au mineralisation in Victoria has been constrained mainly by $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of K-bearing white mica (sericite) in altered rock associated with Au-bearing quartz veins. The $^{40}\text{Ar}/^{39}\text{Ar}$ method is a variant of the K–Ar method, based on the radioactive decay of $^{40}\text{K}$ to $^{40}\text{Ar}$. The $^{40}\text{Ar}/^{39}\text{Ar}$ method involves converting stable $^{39}\text{K}$ into $^{39}\text{Ar}$ via neutron irradiation of the sample in a nuclear reactor, prior to isotopic analysis. The $^{40}\text{Ar}/^{39}\text{Ar}$ ratio is then measured in a gas-source mass spectrometer and represents a proxy for the daughter to parent isotopic ratio ($^{40}\text{Ar}/^{40}\text{K}$), thus allowing calculation of an age. Stepwise heating of the sample, either in a furnace or by laser, progressively liberates Ar from the sample, and an age can be calculated for each heating step, producing the age spectrum seen in Figure B8.2. Consistent ages from multiple consecutive heating steps provide confidence in the geological meaning of the ages and can be combined into a so-called plateau age. Depending on the geological history of the sample, $^{40}\text{Ar}/^{39}\text{Ar}$ ages can be interpreted to record the time the mineral crystallised.
The Eastern Goldfields—Australia’s Fort Knox

The Eastern Goldfields (WA) is Australia’s premier Au province, with around 4200 t of Au recovered in a little over a century from mines stretching more than 600 km from Norseman in the south to Wiluna in the north (Figure 8.9a). The jewel in the crown is the Golden Mile at Kalgoorlie, with more than 1600 t of Au mined. The region is also renowned for its Ni, ranging from the world-class deposits at Kambalda and Leinster to more infamous examples, such as Poseidon’s Windarra deposit near Laverton (Chapter 9).

The Maduwangka people, whose traditional land encompasses Kalgoorlie in Western Australia, had their lives changed in 1893 when three Irish Au prospectors—Paddy Hannan, Dan Shea and Tom Flanagan, discovered Au near Mount Charlotte. Within days of their discovery of 8 lbs of Au nuggets, more than 700 Au diggers pegged their claims in and around Kalgoorlie. The area was originally known as Hannan’s Find, and later changed to Kalgoorlie, meaning ‘silky pear bush’ in the Maduwangka language.

This Au discovery coincided with the ‘Panic of 1893’ that prompted bank crashes in Melbourne, and encouraged 40 000–50 000 Victorians to head west, helping to quadruple Western Australia’s population during the 1890s. The timing was also favourable for cashed-up British bankers, who provided needed capital in the hope of winning a share of the ‘Westralian’ bonanza.

Figure 8.7: Composite seismic section across the Victorian goldfields, showing the relationship of Au deposits to structural and lithological architecture. Note the fault-bound, wedge-shaped Stawell and Bendigo zones, which host most of the Au. Note also the Cambrian mafic rocks throughout most of the crustal section. The location of individual seismic traverses is shown in Figure 8.6. (Source: Willman et al., 2010)
For more than a century since then, the fortunes of the region have waxed and waned, largely driven by metal prices, as well as available technology. By 1903, the population of Kalgoorlie was 30 000, many of whom had migrated from the eastern colonies. These ‘Toothersiders’, as they were known, overwhelmingly voted for federation in 1901, ensuring that Western Australia joined the Commonwealth of Australia. By early 1976, the population had declined to just over 19 000.

The combination of high inflation and a stagnant economy threatened the existence of Kalgoorlie; today, the town, twinned with Boulder, is a thriving regional city of more than 33 000 permanent residents, plus a large fly-in/fly-out (FIFO) workforce based in Perth. As the past has shown, however, favourable economics and technological innovation will determine whether this jewel remains bright.

Being located in semi-desert, Kalgoorlie has been, and continues to be, constrained by its water supply. As elsewhere in arid Australia, early prospectors had little water and had to resort to dry blowing techniques to ‘pan’ for Au. Water was so precious that liquor was reportedly used to clean wounds in the local hospitals. In 1903, the first reliable water supply was delivered via a 557 km-long pipeline from Mundaring in the hills to the east of Perth. This was a major engineering feat in its time (Chapter 7).

Although some of the finds opened up in the late 19th century are still being mined, many new Au deposits have been discovered in the past two decades. Noteworthy examples are the Wallaby and Sunrise Dam, in rock types not traditionally considered prospective for Au. These deposits were...
discovered by sophisticated geological, geophysical and geochemical exploration techniques, many developed or refined by Australia’s innovative exploration and mining industry (Box 8.3).

**Eastern Goldfields: a favourable convergence in time and space**

The important features of the giant Au mineral systems of the Eastern Goldfields (Figure 8.9) include the rapid formation of new crust and basins on the rifted edge of an old cratonic block, followed by the development of deep-crustal faults and the intrusion of magmas from metasomatised mantle sources. A series of tectonic stress switches, giant energy systems that produced major crustal melting, an effective structural focus for fluids and metal, and a suitable physico-chemical complexity all facilitate metal deposition.

Most significant lode-Au provinces develop in an accretionary tectonic setting on the extended margin of an old cratonic block. Major crustal age subdivisions and structures are identified in a neodymium (Nd) isotope model-age map (Figure 8.9b). This map is a proxy for the age of the crust; it shows that the Eastern Goldfields are located on the extended margin of an older continental block. These accretionary margins are associated with long-lived retreat of the subduction zone by the rolling back of the hinge zone, driving extension behind the subduction zone and ultimately crust formation. This extension can be punctuated by phases of contraction (compression), which are driven by hinge advance, slab shallowing or collisions. The terminal phase, and commonly the Au mineralisation phase, is associated with collision, culminating in cratonisation and, hence, preservation.

The Yilgarn Craton records a long geological history, with the earliest elements older than 3000 Ma. Towards the end of the Archean, the craton underwent a rapid crustal growth phase, doubling its size between 2750 Ma and 2630 Ma, particularly along the eastern margin of the proto-craton to form the Eastern Goldfields Supergrenerane (Chapter 2). Basins formed in the upper crust to more than 10 km thickness. They were not filled.
with turbidites as in the Victorian goldfields, but with thick accumulations of mostly mafic volcanic rocks (greenstones). The mid- and lower crusts were built with thick granite batholiths, with a combined total thickness exceeding 30–40 km. This is an example of a granite–greenstone terrane, a characteristic rock association of the Archean.

Deep seismic reflection profiles across the Eastern Goldfields reveal important deep faults, some of which transect the entire crust (Figure 8.10). As was the case in the Victorian goldfields, these faults played a key role in greenstone basin formation. Later, they provided pathways for metal-rich fluids to flow from the deep crust and/or mantle during mineralisation. Most of the major Au districts in the region are located in the hangingwall of these faults.

Structural controls may even extend into the mantle, which can be partly mapped by seismic tomography (Chapter 2). Records across the Yilgarn Craton of the variations in seismic wavespeed from distant earthquakes provide a velocity structure for the upper mantle below. A high-velocity layer is imaged at around 120 km beneath the Eastern Goldfields, and this has been interpreted as the delaminated remnants of dense lower crust. The Golden Mile at Kalgoorlie, the home of the Super Pit, is located approximately 120 km above the edge of this high-velocity layer. This edge has been interpreted as a boundary (structure), and it is interesting to note similar ‘structures’ beneath other major deposits of the Eastern Goldfields (Figure 8.11). If these features are associated with mineralisation, then they illustrate the truly remarkable scale of a mineral system.

Giant mineral systems require vast amounts of energy. The crust hosting the Golden Mile deposit is believed to have developed in an energetic tectonic environment, possibly a backarc position, during a period of vigorous crustal growth. Inferred subduction beneath the Eastern Goldfields would have done several important things: it would have taken oceanic crust deep enough to melt to form voluminous granite; provided an extensional driving force during periods of slab retreat to form basins; hydrated and fertilised the upper mantle with Au and volatiles; and brought hot mantle to the base of the crust, providing a thermal driver for magmatism and fluid flow.

Other signals of the energy in the system are recorded by the komatiites, which require extreme temperatures (>1300°C) to form. The region around Kalgoorlie hosts the greatest volume of these rocks anywhere on Earth. They were erupted in a single geological event (2715–2705 Ma) from an anomalously hot upwelling mantle that was a rich source of Au. These ultramafic rocks, together with other greenstone rocks, were deposited into basins that were controlled by active growth faults during extension. It is no coincidence that the largest Au (and Ni) deposits occur adjacent to these basin-controlling faults.

When an imposed stress exceeds the yield strength of the crust, the crust breaks. Such breaking is manifest as faults, which are the main pathways for fluid flow in a hydrothermal mineral system because intact rock (like granite) is essentially impermeable. Stress also provides a source of energy to drive the fluids (Figure 8.4). Changes in stress, such as direction, mode (extension or contraction) or magnitude, can also be important triggers and drivers in a mineral
The Eastern Goldfields underwent several periods in which the prevailing stress changed. Many of these changes accompanied the deposition of Au, especially when the stress directions were at an angle to the prevailing structural grain of the rock packages. During extension, fluids tend to be drawn down into the crust; during compression, fluids tend to be squeezed and driven upwards in the crust.

Granite makes up around 65% of the area (Figure 8.9a) and forms the major component of the crust, both at the surface and at depth. Most granite is of the tonalite-trondhjemite-granodiorite series, which forms from the melting of hydrous mafic rocks, including oceanic crust, at high pressure (Chapter 10). Major crustal growth by granite emplacement occurred between 2680 and 2665 Ma, mostly beneath the overlying greenstone basins. The crust was thickened by the emplacement of enormous volumes of felsic magma into the mid-crust. A gravitational instability was thus developed, with dense greenstones on top of weak, hot and less dense granites. The density instability was relieved by extension, possibly also driven by delamination of the lower crust, the remnants of which are imaged in the seismic tomography of the upper mantle (Figure 8.11). Extension of the lithosphere had a number of important consequences for the Au mineral system:

- It created a series of detachment faults that seismic reflection data show as cutting deep into the crust (Figure 8.10), producing fluid pathways connecting the mantle. These pathways allowed the drawdown of basinal fluids into the crust, where they interacted with rocks or mixed with upward-moving magmatic-hydrothermal, metamorphic or mantle-derived fluids.
• These faults also localised the emplacement of magmatic rocks, including syenite, lamprophyre and Mg-rich granites that are spatially associated with many Au deposits (Figure 8.12a) and are the products of melting fertilised mantle.

• In the mid- to upper crust, extension resulted in a high geothermal gradient and associated metamorphism of the greenstones, generating fluids.

Extension also ‘dropped’ the thickest greenstone basins, which have the capacity to host most of the Au, deeper into the crust, thereby preserving them from later erosion.

Domes and regional anticlines are the most favourable structures for hosting large Au deposits, and they occur over the domain to deposit scale in the Eastern Goldfields. In some locations, domes stacked one above the other are linked with the deep-penetrating faults described above (Figures 8.10 and 8.13). This architecture is highly effective in focusing fluids/magmas and energy from deep in the crust or mantle into the upper crust. Computer models show that these fault-bound domes focus fluids upwards into the domal crests, especially where the dome underlies a basin containing a fluid seal (such as a shale).

The final tectonic stages in the evolution of the Eastern Goldfields saw a change to compression, with folding and strike-slip faulting, and accompanying high-temperature metamorphism and the emplacement of a new type of granite (Figure 8.12b). These low-Ca granites were emplaced rapidly (2655–2630 Ma) across the
Much of Australia’s recent Au production has come from the Eastern Goldfields of Western Australia (Figure B8.3a). The increase in mining activity in the region from the early 1980s provides a good example of how changes to prices and costs drive production decisions in the mining industry. The price of Au had soared by the end of the 1970s, which was followed by a steep rise in Au production in the 1980s (Figure B8.3b). Higher prices increased the profitability of existing projects, and encouraged investment in further Au exploration, production and processing, and in new technologies at each stage of the Au supply process. Similarly, the reverse has been true. When prices fall in Australian dollar terms, production tends to decrease and exploration activity slows or stops.

The adoption of new technologies also contributed to the major increase in production in the 1980s (Figure B8.3b). Carbon-in-pulp and carbon-in-leach processes that enable Au to be recovered from low-grade (as little as 1–2 g/t Au) ore deposits were introduced over the period 1983–1990. These production technologies increased the availability of ‘economically feasible’ Au resources. They also improved the likelihood of successful exploration activity by increasing the chance that extraction of an identified resource would be considered economically viable. New exploration technologies, such as bulk-cyanide-leach Au analyses, were also developed and adopted in the 1980s.

Mining production decisions tend to involve long time lags, as exploration activity and capital investment decisions are made several years in advance of production commencing. The Australian Au supply can be modelled with relationships between production, capital investment and exploration expenditure. The price of Au accounts for around 40% of the variability in exploration expenditure, particularly for less advanced or ‘greenfields’ projects. Changes in exploration activity (expenditure) are the major driver for production changes. Gold exploration expenditure peaked in 1987–88 as a result of the higher prices and adoption of new technologies of the 1970s and 1980s (Figure B8.3b).

Au exploration expenditure in Western Australia rose by 26% to $452.5 M in 2010–11—almost 70% of the national expenditure. The Eastern Goldfields is the dominant province, with exciting new opportunities on the margins. The Tropicana Au deposit (Figure 8.1; Appendix 8.1.1), for example, is hosted in high-grade gneisses at the boundary of the Yilgarn Craton and the Albany–Fraser Orogen. This is a significant new Au play in a remote part of Western Australia. The company expects 300–400 people to be employed at the mine, producing 200 000–450 000 oz per year over 10 years.

Discovery of the Tropicana deposit in 2005, one of very few recent greenfields discoveries in Australia, has led to an exploration rush to the Yilgarn–Albany-Fraser boundary. Virtually all of this region has been taken up for exploration, and significant additional discoveries have been made, which will lead to further economic development of this remote region.
entire Yilgarn Craton (Figure 8.9a). They were formed by the melting of older granites in the mid- to lower crust (Chapter 10), and were emplaced into the cores of the upper-crustal domes, providing heat that drove fluid flow and, possibly, fluids themselves, during the final and most significant Au event (2647–2630 Ma). The timing of their emplacement coincided with the final stage of major heat loss from the crust, which stabilised the lithosphere and preserved the Yilgarn Craton as an entity for the next >2.5 Ga.

The mineral-system concept predicts that broad outflow zones should emanate from the depositional site, altering a large region around the deposit (Figure 8.4). The surface expression of alteration associated with Au mineralisation can be large, locally with dimensions of tens of square kilometres. The general pattern of alteration is asymmetric in the Eastern Goldfields (Figure 8.14). Its signal can be mapped as variations in the composition of white mica, using hand-held instruments such as PIMA (Portable Infrared Mineral Analyser) or air- or satellite-borne multispectral scanners. Most of the Au was deposited along the gradient in white mica composition between phengite and muscovite. These gradients can reflect changes in redox, temperature or pH of the altering fluid(s). Stable-isotope studies of C, S and O, together with pathfinder elements such as bismuth (Bi), molybdenum (Mo), W, Li, arsenic (As) and antimony (Sb), as well as the distribution of alteration minerals themselves, suggest that Au mineralising fluids came from a number of sources: (1) reduced basinal and metamorphic fluids; (2) oxidised felsic magmas, especially those from a metasomatised mantle source; and (3) potentially reduced mantle fluids.

The depth expression of alteration associated with the Au mineralisation is also large. The magnetotelluric technique (MT) data measure the electrical properties at depth in Earth and can be used to infer the presence of deep structures, fluids and alteration zones. Beneath Kalgoorlie, there is a large zone of anomalous conductivity in the upper crust and mantle, which may be a result of alteration on a lithospheric scale. Large-scale alteration has also been inferred from seismic reflection data, where ‘bland zones’ of seismic reflectivity near the base of the crust may mark an alteration zone.

Gold deposition (Figure 8.12c) can occur by a variety of mechanisms, including fluid mixing; fluid-rock reaction, especially in iron-rich lithologies; phase separation; and vapour condensation. The effectiveness of these processes is one of the major determinants of deposit size and grade.
Key factors in forming the Eastern Goldfields

Why are the Eastern Goldfields so rich? Like the Victorian goldfields, the Eastern Goldfields formed during a major period of continent assembly—in this case, possibly associated with assembly of the Kenorland supercraton (Chapter 2). The Abitibi Subprovince in Canada, the other major Archean lode-Au province in the world, formed by similar processes over a similar time period, and was possibly part of Kenorland. These two provinces formed rapidly, with most crustal growth occurring within a period of 100 Myr or less. This contrasts with the older granite-greenstones of the Pilbara Craton, which also formed during the Archean but over a billion years (Chapter 2). The Pilbara Craton has an Au endowment orders of magnitude less than the Eastern Goldfields, highlighting the importance of rapid crustal growth in Au metallogeny. This rapid growth promoted high Au endowment in three ways: (1) the initial development of deep crustal-penetrating faults, followed by their reactivation during stress switches; (2) the emplacement of Au-enriched source rock derived from the mantle; and (3) a vast amount of concentrated energy that drove fluid movement together with stress switches. Although many of these features are also apparent in the Victorian goldfields, the data from the Eastern Goldfields emphasise the importance of deep structures linking domes with enriched mantle, stress switches and high heat flow for Au endowment.

Proterozoic Zn–Pb deposits: Broken Hill and Mt Isa

By the mid-1860s, pastoralists began dividing up the Barrier Ranges in southwestern New South Wales into a series of sheep stations. As in Victoria, many shepherds also worked as prospectors, initially for Au, and later for Cu and Ag. Discovery of Ag gave rise to the town of Silverton in 1882.
(Figure 8.15a), but remoteness inhibited its development. In September 1883, Charles Rasp climbed to the top of a long, narrow ridge locally named ‘the broken hill’ and sampled ironstone at the top, hoping to find tin. He found, however, Ag and Pb, although in quantities that could not be profitably mined, shipped and processed at the time. Rasp formed a syndicate with six others from the Mount Gipps sheep station to take out a mining lease and sink a shaft. Public floating of the syndicate in 1885 created the Broken Hill Proprietary Company Limited, which eventually became BHP Billiton Ltd, currently Australia’s largest and the world’s sixth largest company.

Sinking of the shaft did not initially produce the rich ore expected by the syndicate. Although Ag and Pb were present in the rocks, they were not sufficiently rich. Rather, ore, rich in silver chloride, was being tipped onto the mullock heap. Only the vigilance of one syndicate member discovered this blunder, and Broken Hill was on its way to becoming recognised as the largest accumulation of Zn and Pb on Earth.

The arrival of the railway from Port Pirie (SA) in 1888 vastly helped the economics of the deposit, because ‘ore’ from the early shafts suddenly could be mined at a profit, and the future of the Broken Hill deposit seemed assured. However, in the early 1890s, Broken Hill was hit by a triad of calamities: the price of Ag dropped sharply during the ‘Panic of 1893’; the rich oxide ores began to be exhausted, leaving lower grade and metallurgically more difficult sulfide ores; and the mines experienced their first major strike, the Eighteen Weeks strike of 1892. The first two problems were partly solved by the third problem. After the strike was broken, wages were decreased by 10%, and the working week increased from 46 hours to 48 hours. A solution to the problem of sulfide ores was froth flotation, developed in Melbourne in 1903 by Charles Potter, G D Delprat and Auguste de Bavay. This technology produced a much cleaner separation of ore metals and allowed processing of 5.7 Mt of low-grade ‘waste’, valued at the time at £30 M. This process was a revolution in the mining industry as it allowed exploitation.
of complex sulfide ores in Australia and overseas (Chapter 1). Two of the three inventors of froth flotation were not chemists, but brewers!

Although many technical problems at Broken Hill were solved early in the 20th century, the history of Broken Hill in the following half-century was turbulent, tied not only to fluctuations in Pb and Zn prices, but also to a rising union militancy fuelled by health and safety concerns, the prosperity of some (not all) mines, and the conservatism of most mining companies. Up to the 1920s, Broken Hill had one of the highest levels of industrial unrest in Australia. This period also saw a consolidation of the field, with the number of companies decreasing through closure and merger from 11 in 1920 to 3 in 1940, when BHP left the field. Now only one company is actively mining the Broken Hill lode, and the city of 19,500 people is diversifying its economy with tourism and the arts.

Mt Isa in northwestern Queensland has a very different history from that of Broken Hill. The Mt Isa Province, although hosting a number of major Zn–Pb deposits, began life as a Cu province (Appendix 8.1.1). The first mineral discovery of malachite and native Cu was made near present-day Cloncurry by prospector Ernest Henry in 1867; this became the Great Australia mine. In the early 1880s, Henry and other prospectors made Cu discoveries through much of the Mt Isa Province. The first Zn discovery was the still-undeveloped Dugald River deposit in 1881. However, it was not until 1923 that John Miles discovered Pb- and Ag-rich gossan at what would become the Mt Isa mine.

At first, the Mt Isa deposit was exploited in a chessboard of small leases worked by individual miners, but this began to change with the incorporation of Mt Isa Mines Ltd in 1924. By November 1925, Mt Isa Mines was the only large player, although some small mines continued to operate for 20 years. At the time, Mt Isa was the most distant mine from any port in Australia. This tyranny of distance and the relatively low grade of the Mt Isa ores discouraged investment, and it was not until 1927 that exploration began to define a large sulfide ore body. Metallurgical test work demonstrated that concentrates could be extracted from the ores using a suite of processes, including flotation, which was first developed for Broken Hill. However, the Great Depression and capital demands for development of the Mt Isa mine intervened. By 1930, funds could not be raised, and it looked as though the mine would close before the first ores had been smelted.

The saviour was American Smelting and Refining Company (ASARCO), which made significant investments and became a major shareholder in Mt Isa Mines. In 1931, the first Pb was smelted. Unlike Cu, which is present in numerous small deposits, prospects and showings in the Mt Isa Province Zn–Pb deposits are uncommon but can be extremely large. Including Broken Hill, 5 of the world’s 10 largest Zn–Pb deposits are present in the Australian Proterozoic zinc belt, but discovery of these deposits has been spasmodic. After Mt Isa in 1923, the next deposit in this belt, Hilton, was discovered in 1948, followed by Here’s Your Chance (HYC, also known as McArthur River) in 1955 and Century in 1990.
These and the smaller Lady Loretta (1969) and Broken Hill-type Cannington (1990) deposits were discovered through systematic exploration by major companies. The discoveries became the impetus for developing towns and settlements in outback Australia and spawned some of Australia’s major mining houses.

The Australian Proterozoic zinc belt: riches from the breakup of Nuna

The central third of Australia is underpinned by rocks that were mostly deposited during the Proterozoic (Chapter 2). The eastern margin of this Proterozoic block, which extends from the Curnamona Province in the south to the Georgetown Inlier in the north (Figure 2.8), formed as a series of basins during the breakup of Nuna, Earth’s first supercontinent (Box 2.5). Nuna amalgamated between 2100 Ma and 1750 Ma, and began to breakup at ca 1700 Ma. With breakup came the formation of vast sedimentary basins, which continued to develop until 1600–1590 Ma, when contractional deformation terminated basin formation in most areas. Although the Mt Isa and Curnamona provinces are currently separated by younger rocks, including the Neoproterozoic and Phanerozoic Officer and Amadeus basins (Figure 2.9), the provinces were likely contiguous between 1700 Ma and 1590 Ma (or even younger). This correlation is based upon similarities in their geological history and metallogenesis, and on continuities in geophysical datasets when later basins are removed.

The first hints of Nuna’s breakup might have begun as early as ca 1780 Ma, when an extensional basin dominated by continental basalt and fluvial to shallow-marine sedimentary rocks developed on pre-existing basement in the Mt Isa Province. However, extension leading to Nuna’s breakup did not begin in earnest until ca 1690 Ma, when turbiditic siliciclastic rocks, accompanied by tholeiitic basalt, were deposited in the Curnamona Province (Willyama Supergroup) and along the eastern margin of the Mt Isa Province (Soldiers Gap Group) (Figures 8.15, 8.16 and 8.17). Sedimentation continued with a mixture of shallow- to moderate-water depth siliciclastic and carbonate rocks, which were deposited as thick sequences between ca 1660 Ma and ca 1590 Ma.

The pre-1660 Ma basins were most likely the product of the separation of Proterozoic Australia from Laurentia to the (present-day) east as Nuna.
Convection of hot fluid through the basin was an efficient way of extracting the Zn and Pb from the sediments in the basin and concentrating the metals in the ore fluid. This process also altered the rocks, producing impermeable layers and zones (seals) that focused the fluids (see Did you know? 8.2). The hot fluids became less dense and rose up along active fault systems that breached the seals, towards the seafloor. These metal-bearing hot fluids cooled rapidly when they mixed with cold seawater at or just beneath the seafloor (Figure 8.17a). This large change in the physical conditions of the ore fluid resulted in deposition of Zn and Pb as a series of semi-massive to massive sulfide lenses (e.g. Broken Hill, Cannington and Pegmont).

broke up (Figure 2.30). Extension associated with this initial rifting produced deepwater basins that were extensively intruded by high-level mafic sills (Figure 8.17a). These rift-related mafic rocks provide a number of ingredients to this mineral system. The intrusion of mafic sills into a sedimentary basin alters the temperature gradients, facilitating the convection of seawater through the basin. The mafic rocks are Fe rich, so, in combination with the high heat flow, the Fe²⁺-rich rocks converted the convecting seawater into a relatively high-temperature (ca 250°C), reduced, H₂S-rich fluid (Figure 8.17a). A fluid with these chemical characteristics can carry significant Zn (and Pb), but little Cu (Appendix 8.3.1).
Figure 8.15: The Proterozoic Australian zinc belt, showing geology of (a) the Curnamona Province, and (b) Mt Isa Province. The locations of deposits discussed in the text are shown.
As the mineralisation at Broken Hill and in the east of Mt Isa have been affected by subsequent medium- to high-grade metamorphism, the grain size (Figure 8.18a) and, possibly, the tenor (value) of the ores have been upgraded, enhancing the economics of mining and metallurgy of the Broken Hill and Cannington mines.

As breakup of Nuna continued, the extensional basin widened, and there was a concomitant decrease in heat flow and development of the overlying passive margin or sag basin beginning at ca 1660 Ma. Unlike the older underlying basins, the younger basins did not develop coeval mafic volcanic and intrusive rocks. They were filled with siliciclastic and carbonate rocks (Figures 8.16 and 8.17b). Without the heat engine of the earlier mafic intrusions, fortunately for us, there was another way to drive seawater deep into a basin. Cauliflower chert (Figure 2.29) and halite pseudomorphs in rocks of the clastic-carbonate sequences are indicators of evaporites and highly saline conditions. Seawater interacting with these evaporite-bearing rocks would have generated basin fluids that are highly saline and dense. Highly saline fluids are a very effective solvent for dissolving metal, particularly when oxidised, from the rocks through which it passes, even at low temperature. The Mesoproterozoic oceans and atmosphere were now oxygenated (Chapter 2); these saline oxidised fluids became dense and flowed downwards, increasing in temperature to around 200°C. They stripped Zn and Pb from the pre-existing volcanic rocks deep within the basin, and produced regional-scale semi-conformable alteration zones dominated by hematite-bearing assemblages. These alteration zones, with a scale of tens of kilometres, are much larger than the deposit (Figure 8.17), making this element of the mineral system a bigger target for exploration (Figure 8.4). The metal-bearing fluids became hotter due to the geothermal gradient deep in the basin, making them buoyant and prone to rising up tectonically active faults that focused fluids into local sub-basins higher in the crust (Figure 8.17c).

Distant forces—for example, at plate boundaries—can influence the internal dynamics of basins. We see this today with the Flinders Ranges uplift in South Australia being driven from the plate boundary in New Zealand (Chapter 2). Apparent polar-wander paths are a fossil record of past plate movements. Sharp bends in the apparent polar-wander path are generally interpreted as evidence for collisions and plate reorganisation. The apparent polar-wander path for northern Australia has several bends that coincide with the periods of known
mineralisation (Figure 8.19). Therefore, fluid flow was likely initiated by these far-field tectonic events (Figure 8.17b). The ca 1640 Ma McArthur River deposit was likely triggered by the Liebig Orogeny, which is found 800 km (present-day) to the south and occurred when the Warumpi Province was accreted onto the North Australian Element (Chapter 2). As these basins were distant from plate margins, the evidence for these deformational events may not be obvious within the deposits themselves. This is another example of the large scale in which a mineral system operates (Figure 8.4).

Although distal events triggered hydrothermal fluid flow, localisation of ores was controlled by local factors such as faults and basin facies. All major Mt Isa-type deposits in the Australian zinc belt are associated with faults that were active at the time of mineralisation. In many cases, they were initiated as normal faults, some of which may have been inherited from earlier basin systems, as was the case in the Victorian goldfields and Eastern Goldfields. At the McArthur River deposit, however, ore deposition was possibly localised in a pull-apart basin associated with the Emu strike-slip fault system (Figure 8.17b).

Once the metal-rich fluid flowed into the sub-basin, it migrated either to the seafloor or laterally below the seafloor (Figure 8.17b), where changes in temperature, pressure and perhaps chemistry drove the metal-rich fluids to deposit their metals. The Zn and Pb were deposited as the metal-rich fluids mixed with an H$_2$S-bearing reduced fluid. This reduced fluid could have been sourced from anoxic seawater or a reduced diagenetic fluid from the basin. H$_2$S can also be produced by the

**Figure 8.17:** Schematic models for (a) Broken Hill-type mineral system, (b and c) Mt Isa-type mineral system from McArthur River. In the Broken Hill-type mineral system, extensional faults most likely controlled seawater drawdown and the upflow of the metal-bearing fluid. Seawater evolved into ore fluid along stratiform aquifers, resulting in the development of extensive stratiform albitic alteration zones that were oxidised and leached of Zn and Pb. Metal deposition occurs as the fluids are quenched when mixed with seawater at or just below the seafloor. In the Mt Isa-type mineral system, dense evaporative brines were either drawn or deep basinal brines were released by distal tectonic drivers to move upwards along basin-controlling faults. Base metals are leached during regional fluid-rock interaction. Base metals are deposited either at the seafloor upon interaction with H2S-bearing seawater or at depth in the sedimentary pile, where H2S is provided either by mixing with H2S-bearing fluid or by organic reduction of sulfate in the ore-forming fluid.

BHT = Broken Hill-type; PAH = polyaromatic hydrocarbon
reduction of sulfate by microbes, which derive their energy from this process and, interestingly, generate oxygen as a by-product. Sulfide- and organic carbon-rich dolomitic siltstones favour these reduction processes, and typically host Mt Isa-type Zn–Pb deposits. These depositional horizons are also conductive to electricity and therefore amenable to mapping using geophysical techniques. They also correspond to the maximum flooding surfaces when local sea-level was its highest, making them amenable to mapping using sequence-stratigraphic techniques (Figure 8.16).

The very fine-grained ores formed by these processes can present challenges to ore processing. At the Mt Isa and nearby Hilton–George Fisher deposits, recrystallisation associated with greenschist facies metamorphism has coarsened the ores sufficiently to facilitate metallurgical processing. In contrast, the fine-grained McArthur River deposit (Figure 8.18b) has not been metamorphosed and so requires more complex and costly processing; it was not mined until 40 years after its discovery in 1955, when metallurgical advances allowed exploitation.

Key factors in forming the Australian Proterozoic zinc belt

Like other major mineral systems in Australia, Zn–Pb systems in the Proterozoic zinc belt are responses to changes in the geodynamic setting. As we explained above, these deposits are temporally and genetically associated with the breakup of Nuna. Although the associated mineral systems operated in an overall extensional environment, the exact timing seems to have been controlled by adjustments in plate motion, which changed local stress fields, triggering flow of seawater or basinal brines that evolved into ore fluids at depth within basins. In some cases, structures controlling fluid flow appear to be inherited from pre-existing basins. Whereas Broken Hill-type deposits are associated with thermal anomalies related to rifting and may have mantle input for some metals, isotopic and fluid inclusion data suggest a crustal source of metals and a normal geothermal gradient for Mt Isa-type deposits. This differentiates Mt Isa-type mineral systems from other giant Australian mineral systems, in that mantle involvement was not present, possibly because most metals involved in these systems, particularly Pb, are enriched in the crust relative to the mantle and bulk Earth (Appendix 8.3.1).

Olympic Dam IOCG Province: new era of discovery

The discovery of the Olympic Dam deposit in northern South Australia is legendary in the history of Australian mineral exploration. This story begins in 1861 in the Moonta area (Figure 8.20), when Irish shepherd Patrick Ryan discovered Cu minerals in a rabbit burrow. The Moonta mines subsequently became major contributors to the South Australian Cu industry for the rest of the 19th century and into the 20th century. However, at the end of World War II, production ceased for more than two decades, only restarting in 1969 with the reopening of mines at Burra, Kanmantoo and Mt Gunson (Figure 8.20). The new interest also spurred a new round of exploration, but in a manner that differed substantially from the early
discoveries. This new exploration was based on scientific exploration models funded by major mining companies.

As an example of this new way of doing exploration, Western Mining Corporation Ltd (WMC) undertook an Australia-wide search for Proterozoic Cu based on the concept that altered basalt acted as a source of Cu in sediment-hosted Cu deposits. This search quickly focused on South Australia, where altered basalts and a number of Proterozoic Cu deposits were known, including those at Moonta. Based on a mineral system model developed in 1972, a multidisciplinary team was set up by WMC to search for Cu. The model envisaged Cu being leached by oxidised fluids from basalts located in the lower parts of a basin and being transported upwards along faults, where Cu deposition would occur through chemical reduction of the fluid on encountering reduced parts of the sedimentary package. A critical step in the discovery of Olympic Dam was the release in 1974 by the Bureau of Mineral Resources of aeromagnetic and gravity data over the Stuart Shelf of northern South Australia. The WMC team recognised the potential of several coincident magnetic and gravity anomalies for sediment-hosted Cu deposits of the type predicted in their model. After a lineament analysis, five anomalies were highlighted, and a drilling program commenced in 1975 near Roxby Downs Station. This was no ordinary program, however, because it was predicted from the geophysical modelling that the target depths would be very deep, to hundreds of metres, and in a remote, true ‘greenfields’ region. Drillhole RD1, sited near the Olympic stock water...
Formation of a supergiant: the Olympic Dam IOCG + U deposit

When the Olympic Dam deposit was discovered in 1975, the mineralised hematite-rich breccias were unfamiliar in terms of known mineral deposit types, and certainly differed from the style of sedimentary-hosted Cu deposit expected by the WMC explorers. The discovery of Olympic Dam was thus a major factor in the later recognition of a completely new class of mineral deposit, known as iron-oxide-copper-gold (IOCG) deposits.

The slow-changing, nearly flat landscape of outback South Australia today (Chapter 5) could not have been much different at 1590 Ma. A cataclysmic event spanning large parts of the Proterozoic continental blocks now found in South Australia, the Northern Territory and Queensland resulted in one of Earth’s great outpourings of magma, known as the Hiltaba event. This event was focused in the Gawler Craton of South Australia, an Archean to Proterozoic cratonic block largely covered by younger sedimentary rocks (Chapter 2). The ultimate cause of melting that formed the extensive and voluminous Gawler Range Volcanics and Hiltaba Suite granitic intrusions is still not well understood.

Whatever the cause, the magmas resulting from crustal melting were superheated and enriched in ‘high-field-strength-elements’ such as thorium (Th), rare-earth elements and U, some of which were concentrated in the Olympic Dam deposit. Mantle melting also occurred, which resulted in production of mafic volcanic and intrusive rocks, particularly along the eastern boundary.
of the Archean cratonic core. This boundary was imaged by a seismic reflection traverse over the Olympic Dam deposit (Figure 8.21). The seismic data indicated that the boundary was a northeast-dipping suture juxtaposing Archean and Paleoproterozoic domains. As was the case in the Eastern Goldfields, this mineral system also records a large conductor in the magnetotelluric (MT) data at depth beneath the Olympic Dam region (Figure 8.21). This suture may have terminated a period of convergence that involved northeast- to north-dipping subduction below the Olympic Dam IOCG Province. In this scenario, the mantle below the province would have been fertilised during subduction, facilitating generation of high-temperature melts (A-type) during extension associated with the magmatic event. As we observed in the previous mineral-system examples, the crustal 'architecture' set up prior to mineralisation at 1590 Ma was crucial for focusing mantle and crustal melts, and also hydrothermal fluids implicated in the formation of the Olympic Dam deposit.

The Gawler Craton is covered by extensive regolith (Chapter 5) and by many sedimentary basins, making geophysical methods one of the few cost-effective exploration tools. The vast amounts of Fe deposited in these systems mean that potential fields have been very useful—in particular, the ‘inversion modelling’ of gravity and magnetic data in 3D. Such modelling at Olympic Dam suggests that magnetite-rich alteration zones extend to depths of around 20 km (Figures 8.21 and 8.22).

Copper–Au-rich hematite alteration, on the other hand, is modelled in the uppermost 5 km or so (Figure 8.21). These data, together with the seismic reflection and magnetotelluric data, show that the Olympic Dam deposit, gigantic as it is, represents just one part of a crustal-scale ore-forming system that involved major faults tapping the mantle, and hydrothermal fluid flow on a regional scale in the upper and middle crust.

Over the past decade, broadscale studies of the Gawler Craton and discoveries of new iron oxide copper–gold (IOCG) deposits have shown that Olympic Dam is not alone as once thought but is part of a metallogenic belt, the Olympic Dam IOCG Province, extending more than 500 km along the eastern margin of the Gawler Craton (Figure 8.20). Earlier studies of the Olympic Dam deposit recognised a minor component of magnetite in the deposit, with Cu, Au and U overwhelmingly associated with hematite-rich breccia bodies. We now know that the IOCG hydrothermal systems are systematically zoned, with shallow hematite-sericite–chlorite alteration assemblages associated in places with Cu–Au ± U mineralisation, and deeper magnetite-rich assemblages accompanied by either biotite- or potassium-feldspar-rich assemblages, but with generally less Cu, at least in this part of Australia. Also at deep levels, and more regionally widespread, are zones rich in albite, actinolite or clinopyroxene (indicating Na–Ca metasomatism) (Figures 8.23 and 8.24).

Differential uplift and erosion within the Olympic Dam IOCG Province has resulted in ‘exposure’ (although still below young cover sediments and regolith) of different crustal levels (Figures 8.20 and 8.22). For example, in the Moonta district and Mount Woods Inlier, mainly deeper levels are now in the near surface.
It was not until 1988 that the first Cu was produced from what has emerged as one of the world’s greatest ore deposits. Olympic Dam ranks as the world’s largest single deposit of U, fourth largest Cu deposit, and fifth largest Au deposit. Total resources (including past production, as of June 2009) stood at 9.23 Gt @ 0.86% Cu, 0.33 g/t Au, 0.027% U_{3}O_{8}, and 1.5 g/t Ag.

Production totalled 197 kt of Cu, 3.62 t of Au, 30.1 t of Ag and 3987 t of U in 2011, a year when government approved a proposal for a staggering six-fold increase in production. This proposal involves excavating an open pit 4 km long and 1 km deep. Water requirements are one of the critical issues for the proposed expansion, and a coastal desalination plant (more than 320 km distant) is the preferred option (Chapter 7).

Long-life mines are a prize sought not only by mining companies but by states and nations. The impacts of Olympic Dam on the South Australian economy and regional development have been huge. The Roxby Downs township created by the mine has grown to a community of 4500 inhabitants. Olympic Dam has provided an important boost to employment in South Australia and across the Australian mining industry. Annual royalties of more than $30 M are paid to the South Australian Government. Present production contributes $2.0 B to the gross state product, and directly employs around 4150 people. The proposed expansion is estimated to add $18.7 B (in 2008 dollars) to gross state product over 30 years in net present value terms compared with a ‘business as usual’ scenario.
and dominated by magnetite–biotite and albite–actinolite alteration assemblages. Because Cu–Au mineralisation is generally only weakly developed in the magnetite-rich zones in the Olympic Dam IOCG Province, these regions are thought to have lower potential for large hematite-rich IOCG deposits such as Olympic Dam.

Conversely, the shallow crustal levels that existed at 1590 Ma in the Olympic Dam region appear to have been preserved, and it is here that two major deposits have been discovered in the past decade: Prominent Hill and Carrapateena (Figure 8.20). Although each deposit appears to be at least an order of magnitude smaller than Olympic Dam, both show many of the same features as their big neighbour, such as hematitic alteration assemblages and brecciated zones; they are clearly part of the same mineral system (Did you know? 8.3).

Although reconnaissance in nature, radiogenic isotopic studies suggest that a substantial proportion of the Cu in the Olympic Dam deposit was sourced from mantle-derived rocks or magmas. These magmas are represented here by mafic/ultramafic dykes of Hiltaba Suite age and/or by mafic volcanic rocks within the co-magmatic Gawler Range Volcanics. Stable isotope and geochemical studies point to the presence of two,
or possibly even three, different fluid sources: 1) hypersaline high-temperature brines; 2) highly oxidised, sulfate-rich lake water or groundwater; and 3) CO$_2$-rich magmatic fluid.

The role of magmatic fluids is controversial, as is the origin of the breccias, which are even more extensive within the host Roxby Downs granite than the 9 Bt of hematite-rich ores. Phreatic, phreato-magmatic, hydrothermal and tectonic processes have all been proposed as contributing to breccia formation. More recently, the concept of deep CO$_2$ effervescence from magmas, perhaps triggered by mixing or mingling of mafic and felsic melts, has been proposed as a driver for brecciation. Geophysical datasets point to large-scale geodynamic processes operating through the entire crust. More work is required to assess this model, and test whether a low-density magmatic fluid also carried other volatiles such as fluorine (F), phosphorus (P), sulfur (S), and even some Cu and Au into the Olympic Dam deposit.

Key factors in forming the Olympic Dam IOCG Province

All these observations can be integrated into a mineral-system model (Figure 8.24). The model illustrates the crustal scale of the hydrothermal system, its deep controlling architecture, the roles of multiple fluids, and the importance of both felsic and mafic magmatism in the system. Unlike the other major mineral systems discussed here, the Olympic Dam IOCG Province is the product of two separate geodynamic systems: an early convergent system that fertilised the mantle and set up a crustal architecture, and a later extensional system that produced high-temperature crustal- and mantle-derived magmatism and associated mineralisation. These two different events occurred more than 100 Myr apart. These crustal and mantle processes have produced a large-scale, zoned mineral system, the effects of which can be mapped at the crustal scale using seismic, magnetotelluric, gravity and magnetic data. The system involved Cu-bearing oxidised fluids that reacted with rock to produce the hematitic alteration assemblages that characterise the Olympic Dam deposit. As this deposit formed in the very uppermost crust, a key factor in this mineral system is preservation (Figure 8.4).

Giant Australian mineral systems

Despite forming at various times and in quite different geodynamic settings, Australia’s major mineral provinces and associated mineral systems have many common factors (see also Chapter 9).
The most consistent commonalities of these factors are an association with changes in regional stress patterns, links to global- and/or continental-scale geodynamic processes, an association with a thermal event, and links with major faults and shear zones. In addition, many of the deposits formed at or near margins of major contemporary crustal blocks, a relationship also noted from many petroleum systems (Chapter 4).

Energy is a critical driving factor in all mineral systems. Mineralisation accompanied thermal events, as indicated by coeval magmatism or regional metamorphic events. This is best expressed in the Eastern Goldfields Province, where the major period of lode-Au mineralisation overlapped granite emplacement, contractional deformation and regional metamorphism. The Olympic Dam IOCG Province was accompanied by voluminous high-temperature magmatism, and Broken Hill-type deposits in the Proterozoic Zn belt are associated with coeval mafic magmatism. These magmato-thermal events drove fluid flow, and, in some cases, these magmas may have provided metal and/or fluids. Conversely, Mt Isa-type mineral systems and the upgrading of banded iron-formation to iron ore (Chapter 9) involved lower temperature, oxidised fluids that were driven by processes other than magmatism, such as basinal fluid flow driven by density differences and accompanying far-field tectonic forces.

In all major mineral provinces, mineralisation is associated with a switch in the stress regime at the province to continental scales. This can involve a change from extension to contraction (or compression to transpression), as in lode-Au
provinces in the Victorian goldfields and Eastern Goldfields. Alternatively, mineralisation can be associated with a switch from contraction to extension, as in the Olympic Dam IOCG Province, the Proterozoic Zn belt and the Hamersley iron ore province (Chapter 9). In at least one case, mineralisation in the Proterozoic Zn belt seems to be associated with the initiation of strike-slip faulting. These stress switches are commonly controlled by global- and continental-scale processes or cycles, such as the supercontinent cycle (Figure 2.20).

Because most of the rocks present at the crustal level where these hydrothermal mineral systems operate are essentially impermeable, all of Australia’s major mineral provinces are associated with faults and/or shear zones. These structures provide the plumbing system for fluid flow. The association between ore and structure occurs at many scales. For example, in lode-Au provinces, entire districts, not individual deposits, are associated with major crust-penetrating structures; the deposits generally are associated with second- or third-order structures. Major crust-penetrating structures provide fluid pathways that tap fluid and metal sources, but the amount of fluid flowing along these pathways can overwhelm the reactive capacity of wall rocks. Reaction occurs along lower order structures because smaller fluid fluxes do not overwhelm reactants, so ore deposition can effectively occur along these structures.

Another factor that characterises some major mineral provinces is a direct or indirect link to the mantle. In three of the five major Australian mineral provinces considered, a direct or indirect mantle contribution of metal (and possibly fluids) is likely. Seismic reflection data suggest direct tapping of the mantle by crust-penetrating faults in the Victorian goldfields and the Eastern Goldfields. In the Olympic Dam Province, a likely source of Cu and possibly Au is mantle-derived mafic rocks. In the Proterozoic Australian Zn belt and in the Hamersley iron ore province, a direct mantle link is less clear.

Factors that characterise some, but not all, major Australian mineral deposits include a relationship to the Great Oxygenation Event (Chapter 3), direct or indirect sourcing of metal from the mantle, and a spatial association to the edges of major crustal blocks. Prior to the Great Oxygenation Event, which began ca. 2460 Ma, most surficial fluids on Earth, including seawater and meteoric fluids, were reduced. The oxidation of the atmosphere produced oxidised and sulfate-rich surficial fluids, which under some circumstances can be very potent low-temperature ore fluids for dissolving and transporting U, Zn and Cu (Appendix 8.3.1). However, Fe is highly insoluble in such fluids. Hence, after the Great Oxygenation Event, the availability of low-temperature oxidised fluids allowed formation of Mt Isa-type Zn–Pb deposits, as well as other Cu and U deposits. When these fluids passed through banded iron-formation, they would have dissolved silica, carbonate and phosphate, which are gangue minerals, but left the Fe. The result was the relative upgrade of Fe content of these rocks to form the prized high-grade hematitic iron ore (Chapter 9).

We must also consider the metal source in a mineral system (Figure 8.4). The original differentiation of Earth and subsequent tectonic processes led to certain elements being concentrated in either the
mantle or the crust (Appendix 8.3.1). Siderophile metals, such as Ni, platinum (Pt) and Au, are enriched in the mantle relative to the crust, so the mantle or mantle-derived rocks are excellent sources of these metals relative to crustal rocks. In contrast, elements such as Pb and U, and, to a lesser extent, Zn, are concentrated in the crust relative to the mantle, suggesting that crustal sources are best for lithophile and some chalcophile elements. These relationships are consistent with the patterns observed in major Australian mineral provinces.

Mineral systems that have a component of metal and/or fluid sourced from the mantle are closely located with respect to major crustal boundaries, either convergent or divergent boundaries. For example, lode-Au deposits formed near convergent margins in both the Victorian goldfields and the Eastern Goldfields, most likely as a consequence of the accretion of blocks, some of which may have been exotic. IOCG deposits in the Olympic Dam and other Australian provinces are spatially associated with major boundaries between crustal blocks, as indicated by both seismic reflection, magnetotelluric, magnetic, gravity and radiogenic (Nd and Pb) isotope data. Broken Hill-type deposits are also associated with these boundaries.

In all of Australia’s major mineral provinces, many or all of these factors have converged during a critical time window to make the mineral system operate. Additionally, most of these provinces are located in crustal blocks that have been preserved from later loss through erosion or tectonism, possibly because the blocks were cratonised quickly after mineralisation (Figure 8.4). These factors may be the principal geological reasons why the provinces discussed here have provided much of Australia’s mineral wealth and have been important drivers of the nation’s growth and development. This tectonic stability is one of the reasons that the continent is old, flat and red (Chapter 5).

**Metalliferous exploration and mining: future challenges**

In the next half-century, the Australian metallic mining industry faces a number of challenges, both in meeting ever-increasing expectations that businesses operate in a manner responsible to environment and society, and in maintaining...
and increasing the resource base. Over the past decade, businesses have increasingly used the ‘triple bottom line’—planet, people and profit—to determine best practice. The greatest impact of this new approach has been enhanced environmental practices (compare ‘old’ with ‘modern’; Figure 8.2). Given societal expectations, the trend to higher environmental standards will increase. However, this trend conflicts with the current move to mine larger, lower grade deposits that have bigger environmental footprints, presenting a major challenge to industry.

A second environmental challenge to the mineral industry is the appetite of mines for water and energy, inputs that can be difficult to provide in remote locations. Finding a source of water (Chapter 7), particularly in competition with other industries, can be just as important as defining ore reserves. The cost of diesel-generated electricity has led some companies to consider solar and other alternative energies as a source of power for remote operations.

Industry also faces challenges in maintaining its skill base in the face of changing lifestyles, and the reluctance to work (and live) in remote, generally arid locations. A related challenge is building infrastructure for a large work force. The preferred fly-in/fly-out (FIFO) option (Chapter 9), which became widespread after the introduction of the fringe-benefits tax, can cause strain on staff and their families. Making a stable career in the industry can also be difficult. The boom and bust of the resources cycle (Figure 8.3) has historically led to imbalances in skilled staff; during booms, there are insufficient personnel to support the industry, whereas, during busts, job security is poor and many skilled workers lose their jobs and leave the industry, often for good.

The other major societal issue facing the industry is ensuring that traditional owners gain from mining. Many mining operations in Australia are remote and located on land owned or claimed by traditional owners, who historically have not shared in the wealth and other benefits of mining. Legislation now requires greater consultation and negotiation with traditional owners when deposits are discovered, leading to agreements between industry and land councils to ensure that the wealth is shared through royalties and jobs. Clashes between traditional culture and the industry still occur.

Of at least equal importance to meeting societal expectations is the challenge of maintaining and increasing the resource base. Australia owes its position as a major mining country to successes of past prospecting and exploration. This position is underpinned by a relatively small number of major to world-class mines, and some of these are nearing the end of their mining lives (Appendix 8.1.1). Although Australia’s Au and base-metal resources have grown strongly over the past 30 years, most of this growth has been through the addition of resources at existing mines, and not the discovery of new deposits. Despite large expenditures, only a handful of new major or world-class deposits have been discovered in the past 20–30 years, leading to the perception that Australia is mature in terms of mineral exploration (Chapter 11).

The early discoveries were mostly exposed at the surface or could be detected at the surface using geological, geochemical or geophysical methods. In the 1960s, this began to change, and discoveries began to be made under significant thicknesses of cover (Chapter 11). The most significant discovery was Olympic Dam in 1975, under 300 m of cover.

8.3: Why is hematite so important?

Hematitic alteration represents the effects of oxidised hydrothermal fluids acting in the presence of abundant Fe; these fluids are considered to have carried some, if not most, of the Cu, U and Au to form Olympic Dam and the other IOCG deposits in the province.

The reaction of these Cu-bearing oxidised fluids with chemical reductants appears to have been a critical process in the formation of the Olympic Dam deposit. Whether the reductants—for example, magnetite, pyrite, or Fe$^{2+}$-bearing silicate minerals—were already present in the host rocks or were present in a second, reduced fluid that mixed with the oxidised fluid remains uncertain. The process of fluid mixing is believed to have resulted in Cu, U and Au deposition.

Did you know?

Hematite is so important because it represents the effects of oxidised hydrothermal fluids acting in the presence of abundant Fe. These fluids are considered to have carried some, if not most, of the Cu, U, and Au to form deposits like Olympic Dam and the other IOCG deposits in the province. The reaction of these fluids with chemical reductants appears to have been a critical process in the formation of the Olympic Dam deposit. Whether the reductants—such as magnetite, pyrite, or Fe$^{2+}$-bearing silicate minerals—were already present in the host rocks or were present in a second, reduced fluid that mixed with the oxidised fluid remains uncertain. The process of fluid mixing is believed to have resulted in Cu, U, and Au deposition.

Image by Chris Fitzgerald
Discoveries since have been made under cover, with a consequent increase in discovery costs, as the testing of deep targets and concepts is inherently more expensive.

The higher cost of deep exploration means that one of the major challenges to exploration is the development of new methods. Using a mineral-systems scientific framework, the methods should include development of robust 4-D predictive geological models; cover maps and new detection methods; and concepts such as the role of the deep crust, the mantle and major crustal boundaries and lineaments in localising mineralisation. These methods will focus exploration prior to expensive drilling, and if successful they will shift the negative perception that Australia is a ‘mature’ exploration destination. Many of Australia’s known mineral provinces extend under cover (e.g. Figure 8.5), making Australia highly prospective for further discoveries.
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Challenges