Australia's metalliferous mineral wealth

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Abstract: Australia is a continent with substantial metalliferous mineral resources and a relatively small population. Large parts of the continent are underlain by ancient Archean and Proterozoic rocks. It has a rich mining history since Europeans first began settlement in 1788, and now derives about 41% of export earnings from minerals (when coal, oil and gas are included). There have been a number of mining 'booms'; the early South Australia copper and Victorian gold rushes were largely self-financed, but the Western Australian gold rush of the 1890s and the iron ore boom of the 1960s, the nickel boom of the 1970s and gold boom of the 1980s involved substantial amounts of foreign capital. Currently there is strong Chinese interest in acquiring Australian mining operations and prospects. Australia now hosts four world-class mid-Proterozoic lead-zinc ore bodies, an early Proterozoic iron ore province with huge resources, the major Kalgoorlie camp of Archean gold, and the world's largest resources of heavy mineral sands. Finally it has Olympic Dam, which is by far the world's largest uranium deposit and also the fourth largest gold and copper deposit.

Australian geology is dominated by Archean and Proterozoic rocks together with extensive Phanerozoic basin cover (Fig. 1). There are two Archean cratons in Western Australia. The Pilbara craton is at least 3.2 Ga old while the larger Yilgarn craton is between 2.6 and 2.9 Ga old. The Gawler craton in South Australia is slightly younger and spans the Proterozoic/Archean boundary. The majority of the continent is underlain by Proterozoic rocks, locally with a cover of Paleozoic sediments. The eastern margin of the continent is bounded by Phanerozoic rocks, including a Palaeozoic volcanic arc, while the western margin has a narrow fault-bounded zone of mainly post-Palaeozoic sediments. The Australian continent has been geologically stable since the Cretaceous, apart from more recent volcanic episodes on its eastern fringe from Tasmania to Queensland.

As a result of decades of mineral exploration, Australia has become a major producer of iron ore, lead, zinc, copper, uranium, heavy mineral sands and coal (Table 1). Exports of metal ores in 2009-10 were worth A$45 billion, representing about 20% of the country's total merchandise exports by value, and there were also large exports of coal, oil and gas.

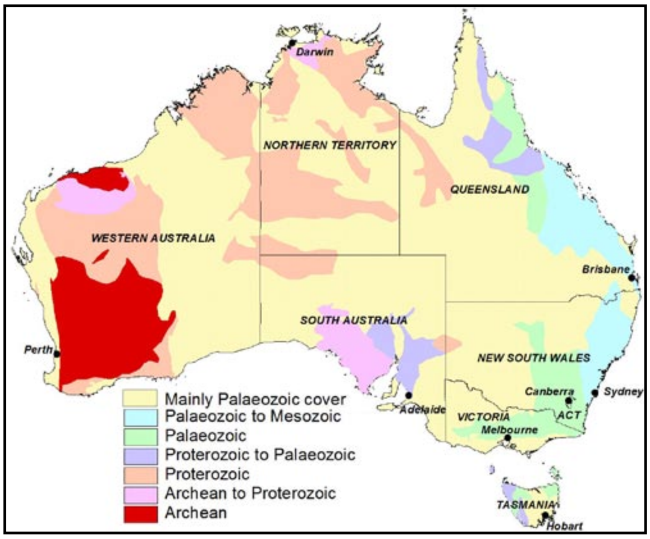

***Figure 1**. Australian geology (after Geoscience Austalia).*

Early years to 1900

Australia underwent a long period of weathering and erosion as it slowly drifted north after separating from Gondwana at the end of the Mesozoic epoch. This caused development of a thick regolith including oxidised gossans over many sulphide-bearing ore deposits and the deposition of widespread alluvial gold in many areas. The native population did not make use of minerals or metals, so these deposits remained undisturbed until the arrival of European settlers. However, a number of ochre deposits were mined for use as body paint and some ochres were sometimes transported and traded over hundreds of kilometers. The largest was probably at Wilga Mia near Meekatharra in central Western Australia (Wilson, 1969) where an estimated 50,000 tons of material was removed in a series of open pits and small galleries. Following the first European settlement at Botany Bay in 1788, local Triassic Hawkesbury Sandstone was

	Australia production tonnes	World production tonnes	Australia % of world	Rank
Bauxite	65,843,000	199,000,000	33.1	1
Copper	854,000	15,800,000	5.4	5
Diamond	*10.8 M ct*	*121.3 M ct*	8.9	6
Gold	242	2,460	9.8	3
Iron ore	394 M	2,248 M	17.5	2
Lead	566,000	3,900,000	14.5	2
Lithium	4,400	18,000	24.4	1
Silver	1,633	22,236	7.3	4
Tin	13,269	279,000	4.8	5
Titanium	1,900,000	10,300,000	18.4	2
Uranium	7,942	50,700	15.7	3
Zinc	1,290,000	11,400,000	11.3	3
Zirconium	474,000	1,320,000	35.9	1

***Table 1**. Australia's world ranking in mineral production 2009; there is little or no current production of chrome, vanadium, tungsten, kaolin, potash, molybdenum, rare earths or fluorspar, though significant resources of these are known (after British Geological Survey).*

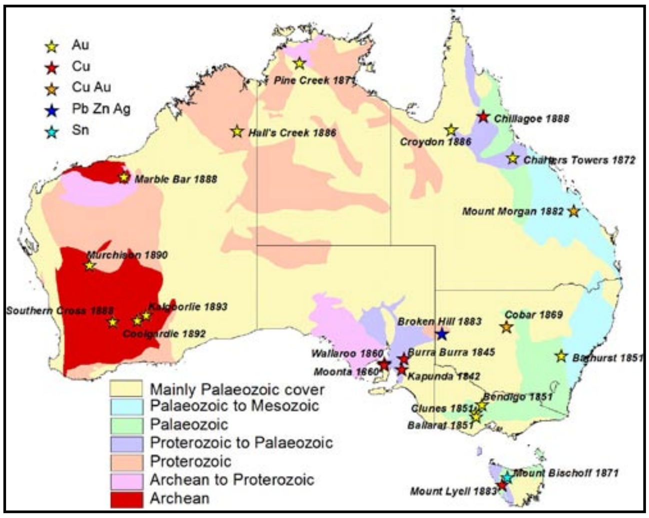

Figure 2. *Significant mineral deposits discovered by 1900.*

quarried for building use and coal seams were found at outcrop at Newcastle, north of Sydney. However, there appeared to be little prospect of metalliferous minerals in the narrow strip of land between Sydney and the 'impassable' Blue Mountains. There were tales of sporadic discoveries of gold and other minerals by shepherds and escaped convicts from the penal colonies of New South Wales and Tasmania, but these were not followed up.

The first mine (other than the early coal mines near Sydney) to be developed by Europeans in Australia was the short-lived Wheal Gawler lead mine, discovered in 1841 by Cornish immigrants in Glen Osmond near Adelaide in the free colony of South Australia. More lead veins were found nearby and a small smelter was erected, but all the mines closed in 1851 when the miners rushed to the newly discovered Victorian gold field. In 1842 a bright green outcrop of malachite (copper carbonate) was found at Kapunda, north of Adelaide (Fig. 2). The success of this mine encouraged further prospecting and the Burra Burra deposit, also of malachite, was found in 1845 in late Proterozoic dolomite. This was much larger and was worked for the next 30 years, providing £800,000 in dividends for the local investors. South Australia produced 10% of world copper output in 1850 and was known as the Copper Kingdom. In 1860 copper was found at Wallaroo and Moonta on the Yorke Peninsula south of Adelaide in early and mid Proterozoic rhyolitic porphyry and metamorphic rocks of the Gawler craton. These deposits proved to be even larger, producing 350,000 t of copper from 7 Mt of ore over the next 60 years. The rise of South Australian copper mining in the 1850s and 60s coincided with the decline of tin mining in Cornwall (Fig. 3) and the mines were worked almost entirely by Cornish miners and mine captains, keeping the same terminology and traditions (Pryor, 1962).

Figure 3. *Cornish-style engine house at Moonta mine, SA.*

Gold in eastern Australia

The California gold rush of 1849 caused many young Australians to try their luck in America. The New South Wales Government became worried about the lack of labour and offered rewards for the finding of 'payable gold'. In April 1851 gold was found by Hargraves, Lister and Tom at Ophir, near Bathurst, about 300 km west of Sydney beyond the Blue Mountains. Hargraves was awarded £15,000, but most was withheld after protests from his partners (Blainey, 1978). On 1st July 1851 the colony of Victoria broke away from New South Wales and later that month gold was found near Clunes northwest of Melbourne. Within a few months major deposits of alluvial gold had been found at many places nearby, including Bendigo and Ballarat and the Victorian gold boom began. As the native population had no interest in collecting gold, the product of many thousands of years of erosion had collected in streams and soils over the quartz veins or reefs in which it had formed. The population of Melbourne quadrupled in four years as the boom took hold. The authorities, unprepared for the change from a pastoral to a mining economy and having to cope with increased expenses of policing the gold fields, introduced the draconian Miner's Licence which cost £1 per month. This entitled the miner to work a piece of land of just 144 ft^2 (13.4 m^2), and had to be paid regardless of whether or not gold was found. Discontent with the aggressive policing of the licences led to the famous Eureka Stockade incident at Ballarat in 1854 where around 30 people were killed during a challenge to the government's authority. An enquiry led to most of the miners' grievances being settled with an annual Miner's Right costing £1 per year replacing the Licence and a reasonable mining claim system, with pegging of boundaries, that endured for the next century.

The Victorian gold fields were rapidly developed over an area of about 150 by 75 km. At first only alluvial and eluvial gold was recovered by panning and sluicing and then by shallow shafts to bedrock. This phase lasted for over 10 years with an annual production of over 2 M ounces of gold. The source of the gold was soon traced to outcrops of quartz veins or 'reefs' in the Lower Paleozoic slate and greywacke country rock. After initial shallow surface workings by

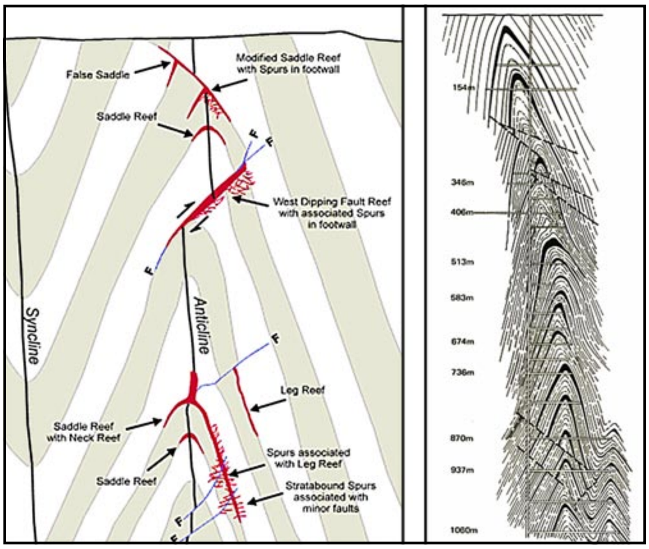

***Figure 4**. Schematic view of reef structures (left) and section of Great Extended Hustler's mine (right) showing saddle reefs in the goldfields of Victoria.*

small groups of prospectors, companies were formed to raise the capital for underground mining. The most productive areas of the reefs were in 'saddles' draped around the crests of faulted anticlines (Fig. 4). Lines of these saddles were followed for several kilometers in the Bendigo area with more than 5000 shafts up to 1200 m deep (Willman and Wilkinson, 1992). Part of the area was covered with Tertiary basalt that infilled and covered preexisting valleys, which also contained alluvial gold. These 'deep leads' were worked by sinking shafts beneath the basalt at depths of over 150 m (Canavan, 1988), and required considerable pumping to enable working to continue (Fig. 5). The area is noted for the number of nuggets, with over 1300 exceeding 20 ounces including the Welcome Stranger containing 2394 oz (68 kg) of gold (Fig. 6). Gold production peaked at 89 tonnes in 1856 and then began a slow decline until the First World War when it dropped from 12 t in 1914 to 4 t in 1919 and never recovered. Total production from Victoria is about 74M oz (2100 t). The Victorian gold field is now considered to be a classic example of the Slate Belt or Orogenic class of deposits formed by metamorphic fluids depositing quartz and gold in low-pressure zones at the hinges of anticlines, faults and other structures during the later stages of folding. The process may be assisted by granitic intrusions forming structural features or increasing heat flow.

A rich tin deposit was discovered by 'Philosopher' Smith in 1871 at Mount Bischoff in western Tasmania after a decade of prospecting (Blainey, 1967). Over

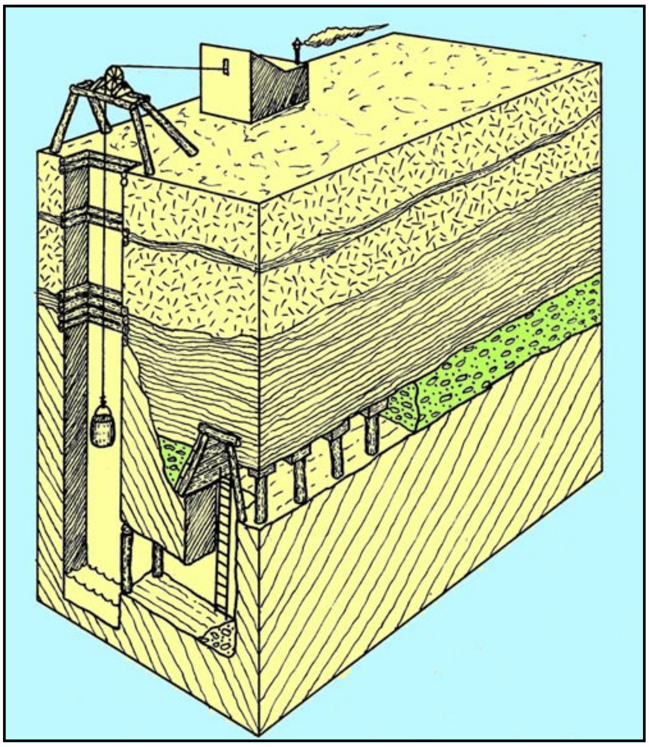

***Figure 5**. A deep level mine in the Victoria goldfields, with the payable deep lead in green (after Canavan, 1988).*

60,000 t of tin metal have been recovered from the skarn and greisen mineralization associated with a Devonian quartz-feldspar porphyry dyke swarm from a nearby granite intruding late Precambrian sediments. The resulting rush to the new mining field provided the impetus for further prospecting that led to additional discoveries in the region.

In 1882 a syndicate including William Knox D'Arcy, opened a gold mine at Mount Morgan on the Queensland coast (Blainey, 1978). The gold was in a prominent ironstone outcrop which was the gossanous capping to what later proved to be a major copper-gold deposit of volcanogenic massive sulphide (VMS) type in Devonian acid volcanic rocks intruded by granite. The gold and the underlying copper deposit were very profitable and D'Arcy's one third share was worth £6 million within three years. D'Arcy used his profits from the mine to live a life of luxury in England with

***Figure 6**. With its happy finders at Ballarat, the Welcome gold nugget was second in size only to the Welcome Stranger.*

IOCG: iron oxide copper gold class of ore deposits.
Sedex: sedimentary exhalative class of ore deposits.
VMS: volcanogenic massive sulphide type ore deposit.
BHP: Broken Hill Proprietary Company.
CRA: Conzinc RioTinto of Australia.
WMC: Western Mining Corporation.
WA, NT, SA, QLD, NSW: Australian states etc..

London and country houses. He also funded the first oil exploration in Persia in 1901 with a huge concession of 1.2M km^2 for 60 years in return for £20 000, some shares and a 16% stake in any oil found (Blainey, 1978). The exploration absorbed so much money that he was forced to sell much of his interest in the concession to Burmah Oil. After nearly abandoning the search, a major oil discovery was made in 1908 and the Anglo-Persian Oil Company was formed and opened a large refinery at Abadan in 1913. The sulphurous oil proved difficult to sell until Winston Churchill persuaded the British Government to buy 51% of Anglo-Persian just before the start of the First World War to supply the British navy with oil. The company later became British Petroleum. Mount Morgan continued in production until 1981 with a total output of 387,000 t of copper and 262 t (92M oz) of gold to be Australia's fourth largest gold producer.

Broken Hill

The major and iconic Broken Hill lead-zinc-silver deposit was found in 1883 when Charles Rasp, a boundary rider, prospected an ironstone outcrop in the extreme west of New South Wales. He brought back samples of galena and cerrusite and a number of prospectors flocked to the new discovery (Blainey, 1978). Rasp and six associates pegged 120 ha covering the 3 km outcrop along the centre of the lode and formed the Broken Hill Proprietary Company (BHP). They soon found the galena was silver-rich and the oxidized top of the deposit contained native silver and other silver-bearing minerals. A silver boom ensued with many companies staking claims around the BHP block. Some were successful in working the very rich oxidized silver-rich capping. Beneath, lay a series of phenomenally high-grade lead and zinc orebodies. At first only the lead-rich portions were worked as, although the zinc-rich material was also high in lead, it was impossible to separate the two metals economically. Thus large dumps of millions of tonnes of zinc-rich tailings accumulated in the first decade of mining.

The Broken Hill ore bodies form one of the world's largest natural accumulations of base metals. An estimated 280 Mt of ore containing around 30% combined metal existed prior to mining, and the ore currently mined has grades ranging from 2.5—15% Pb, 20–300 g/t Ag and 5–20% Zn. The large size of the orebody, and particularly the fact that the original prospectors secured large portions of the lode and had the funds and the vision to employ the best engineers to develop it, led to Broken Hill being in the forefront of many developments in mineral processing, mining techniques and ore genesis. The directors of BHP went for managers, not to Cornwall – then the source of most mining expertise in Australia – but to the western USA, where the great Comstock Lode in Nevada and the many mines in Colorado were encouraging the rapid development of mining and processing techniques. William Patton was hired as general manager of BHP at the enormous salary of £4000 and Herman Schlapp from Colorado became chief metallurgist (Blainey, 1978). Square-set stoping from Comstock, using large timbers, became the preferred mining method in the wide and unstable stopes of the Broken Hill mines.

The large amounts of zinc-rich 'waste' (6.5 Mt at 19% Zn by 1904) prompted an urgent search for a solution. A number of schemes were tried by many companies before various methods of froth flotation succeeded in producing separate lead and zinc concentrates for smelting around 1905. Flotation was first patented by Elmore in 1898 at the Glasdir copper mine in North Wales, and was th en developed separately and competitively by Delprat and by de Bavay and Potter, both brewing technologists. The process unlocked the full potential of the enormous orebody, and Broken Hill became a major world supplier of both lead and zinc. The development of the flotation process gave rise to a long and expensive litigation as the details of the various patents were compared (Mouat, 1996). No one actually knew exactly how flotation worked, least of all the numerous lawyers and judges who ruled on the merits of each method. Within a few years froth flotation was in use all over the world, having been developed in the intense competition around the Broken Hill field. It enabled the development of the large low-grade copper ores of the western USA and South America and was one of the century's outstanding advances in mineral processing.

The origin of the Broken Hill deposit has been investigated by many geologists. It occurs as a series of sub-parallel lenses over a width of 200 m and strike length of 14 km in highly metamorphosed mid-Proterozoic host rocks of gneiss and schist. Each lens has distinct proportions of lead and zinc. Numerous hypotheses have been advanced. It was not a quartz vein lode with which the early prospectors were familiar. There appeared to be no granite intrusion nearby giving rise to 'mineralising fluids'. An epigenetic replacement origin became the accepted theory with lens by lens replacement of the original rocks by successive pulses of 'mineralizing solutions' carrying lead and zinc. The metamorphism and complex structure were also advocated as important parts of the mineralizing process. However, some geologists were unsatisfied with these increasingly complex explanations. From the 1950s, Haddon King and then R L Stanton put forward the idea that the orebodies had been formed early in the depositional process, before deformation and metamorphism, and might even have been formed by hydrothermal solutions exhaling metal-rich fluids onto the sea floor with the metals being precipitated by reactions with hydrogen sulphide. This novel hypothesis attracted much criticism at the time but has gradually been accepted, with various modifications, as knowledge of basin dynamics and mineral chemistry has improved, and the 'Broken-Hill-type' ore deposit has become part of the Sedimentary Exhalative (Sedex) class of ore deposits.

Mount Lyell, Tasmania

In 1883 prospectors found another large ironstone gossan at Mount Lyell in the temperate rain forests on the west coast of Tasmania (Fig. 7). This had been missed by a protégée of Murchison, Charles Gould, who had led two Government-sponsored expeditions across the island twenty years before to look for gold and had even camped for a week a short distance from the gossan. Gould named the three largest local peaks Owen, Sedgwick and Jukes after strong opponents of Darwin whose *Origin of Species* was published just before Gould left England. The three smaller peaks were named after Darwin and his supporters, Lyell and Huxley (Blainey, 1967). The prospectors blasted, crushed and panned the gossan to recover small amounts of gold, but were convinced that it concealed a larger deposit, like that at Mount Morgan in Queensland. The company they formed struggled for a few years before collapsing in debt.

By chance, a group of Melbourne mining financiers came to Tasmania to invest in the then-bonanza Zeehan silver mines, on the back of the Broken Hill silver boom. They were led by Bowes Kelly who had bought a fourteenth share in the Broken Hill Proprietary mine for £200. Within six months it was worth £70,000 and within six6 years was worth £1,250,000 including dividends. The Melbourne group heard about Mount Lyell and sampled the mine. The samples were salted with gold but also contained significant percentages of copper. The original owners thought they were selling a failing gold mine; the purchasers hoped they were buying a large copper mine. The Melbourne group paid £5000 for a controlling interest in the mine and floated The Mount Lyell Mining Company with 100,000 £1 shares – within six years each share would be worth £6. However, the early years were difficult, with costly transport and labour and a difficult ore body. The discovery of a bonanza pod of 850 t of ore with silver at over 1000 oz/t and over 20% copper yielded a profit of over £100,000 and kept the company solvent until a rack-and-pinion railway using the Abt system had been built to connect with the port of Strahan 33 km away. Finally, in 1896, the newly appointed American metallurgist, Robert Sticht, proved that the pyritic copper ore could be smelted using pyrite as the main fuel, with coke only at start-up, and quartzite as a flux. The resulting sulphur dioxide fumes devastated the steep slopes of the surrounding mountains, but the process proved economical and profitable, even though the grade of the main orebody decreased with depth.

***Figure 7**. Mineral-rich Mount Lyell in Tasmania.*

***Figure 8**. The worked-out Iron Blow open pit at Mount Lyell, Tasmania (photo: CMT).*

The Mount Lyell company engaged in intense competition with a rival on the field, the North Lyell Company. This had a much richer orebody but was managed from Britain. The North Lyell directors insisted on all materials, including bricks for smelters, being sourced from the home country, which caused unnecessary delay and expense. They also insisted on a separate railway to the sea. The Mount Lyell company was managed from Melbourne and the directors made frequent visits. The buildings were erected using local timber saving money and time. Within a few years the North Lyell company was bankrupt and taken over, in 1903, by Mount Lyell, which found that the North Lyell ore was rich in silica and therefore self-fluxing (Blainey, 1967).

Mount Lyell's ore has continued in almost continuous production until the present day. The original Iron Blow massive pyrite open-pit (Fig. 8) was replaced by the Prince Lyell open-pit working a semi-vertical stockwork of sulphide veins before underground operations on the Prince Lyell orebody commenced in the early 1970s. The group of varied deposits in the

The meaning of 'resources'
The term 'resources' has been used to include both ore reserves and resources (which have specific meanings and financial implications). They have been gathered form a wide variety of sources, including published company figures on company websites, scientific papers and journal articles. The text includes 'resources' from deposits that have been worked over a long time, some that have been worked out and others yet to commence production. The meanings of the terms reserves and resources have changed with time, so the values stated in the text should not be used for any purpose without thorough checking.

Mount Lyell area is now recognized as a classic set of VMS deposits in the Cambrian Mount Read Volcanics. They incorporate massive sulphide, stockwork, chert breccia and banded lead-zinc orebodies as well as a secondary ore deposit of native copper in Ordovician clays. The total mineral endowment of the Mount Lyell deposits has been calculated at 311 Mt at 0.97% Cu and 0.31 g/t Au (Seymour *et al.*, 2007). After many years as an independent company the Mount Lyell Mining and Railway Company was bought by Consolidated Gold Fields Australia in 1965 and is now owned by Sterlite Industries of India. Mining of 1.8 Mt ore in 2009/10 produced 23,160 t of copper. Current resources are estimated at 14.3 Mt at a grade of 1.3% Cu.

A lead-zinc deposit was discovered in 1894 by a prospector seeking gold at Rosebery in western Tasmania about 30 km north of Queenstown. The township was named after the British Prime Minister at the time. However, it was to be another 40 years before the fine-grained intimately intergrown galena and sphalerite minerals could be effectively and efficiently separated to produce the metals. This deposit is also hosted in the Mount Read Volcanics.

Gold at Kalgoorlie

In the 19th century Western Australia appeared to have relatively few mineral deposits, although only a small number of exploratory parties had traversed it due to the lack of water. Lead and copper veins were worked after 1850 in the Northampton area, near the coast north of Perth. The veins are hosted in shear zones in mid-Proterozoic gneiss associated with early sub-parallel dolerite dykes. Total production was about 77,000 t of lead and 2500 t of copper. Gold was found at Hall's Creek in the Kimberleys in 1884, and the ensuing rush brought many prospectors to the area. As they spread out, gold was found in the Pilbara two years later and then east of Geraldton in the Murchison and at Southern Cross east of Perth (Wilson, 1969). In September 1892 Bayley and Ford found the Coolgardie field; Bayley rode into Southern Cross to register his finder's reward claim with 554 ounces of gold (nearly 16 kg, worth around £600,000 today). The effect was sensational, and hundreds made their way to Coolgardie, including a small Irishman, Paddy Hannan (Casey and Mayman, 1968). Within a few years Coolgardie had an impressive stone-built Mining Warden's court, flourishing mines and a burial ground that was filling rapidly due to numerous outbreaks of typhoid. In June 1893, Paddy Hannan and his companions found alluvial gold where Kalgoorlie now stands (Fig. 9). Prospectors rapidly realized that gold was found almost exclusively in the relatively narrow 'greenstone belts' and not in the more extensive areas of granite. It is now recognized, following the systematic remapping of the Yilgarn shield by the Geological Survey of Western Australia in and after the 1960s, that the greenstone belts occur as sequences of ultrabasic lavas, basaltic lavas, rhyolites and clastic sedimentary rocks. There are also numerous

Figure 9. *The statue of Paddy Hannan in Kalgoorlie (photo: D Graham).*

acid, basic and ultrabasic intrusive rocks. The ultrabasic lavas are komatiites and commonly exhibit 'spinifex texture' with long crystals of olivine. This has been interpreted as a quench texture of a very hot fluid, and appears to be restricted to Archean komatiites (Fig. 10).

The new Coolgardie-Kalgoorlie gold rush coincided with an Australian financial crisis that caused bank failures and company insolvencies. However, English capital was looking for an investment at this time and gold and other mining shares promised exciting returns. English money flooded into Australia, with 94 WA gold mines floated in London in 1894 (Fig. 10). There were of course some scams and scandals. A quartz vein at Londonderry near Coolgardie yielded 10,000 ounces in 1894 from a hole 1.5 m long and 1.2 m deep (worth around £10M today) including a 100 kg lump containing nearly 40% gold! The lease containing the hole was bought for £180,000 by the Earl of Fingall who was seeking investments for an English syndicate. The hole was sealed and Fingall returned to Britain to raise 700,000 £1 shares in the Londonderry Gold Mining Company to develop the 'mine', of which only £50,000 was for working capital, the rest went on promoters'

Figure 10. *Spinifex texture in komatite at Ruth Well, Pilbara.*

and vendors' shares. An output of five tonnes of gold in eight weeks was predicted. The hole was duly re-opened and found to contain almost no more gold.

Fortunately, the area survived the bad publicity. With few exceptions, the rich surface shows at Coolgardie failed to continue at depth. However, those at Kalgoorlie were the opposite, with little surface gold but with rich ore shoots continuing to depths of over 600 m in the Archean amphibolites and serpentinite host rock. Within ten years a pipeline using a revolutionary locking-bar system had been constructed to bring water over 550 km from Perth to Kalgoorlie; until then water had to be condensed from salt lakes using local timber as fuel (Casey and Mayman, 1968). The price of water dropped by around 90% as a result of the pipeline. Gold production in Western Australia rapidly climbed from 3 tonnes in 1893 to reach a maximum of 64 tonnes in 1903. The Golden Mile has continued in production to the present day with 50M oz (over 1400 tonnes) of gold extracted by 2003.

From 1900 to 1960

The first half of the 20th century saw continued development of some existing mining areas, the decline of many of them and the slow emergence of the major Mount Isa deposit (Fig. 11).

The original BHP mine leases, at the crest of the boomerang-shaped orebody, were approaching exhaustion by 1915 and the directors decided to diversify into steel making. This required coking coal, which they worked in mines near Newcastle. So BHP, the biggest industrial enterprise in Australia, grew up based on iron ore from the Proterozoic banded iron deposits of South Australia and the coal of the Hunter Valley, northwest of Sydney (Blainey, 1978). The other Broken Hill companies, Broken Hill North, BH South and the Zinc Corporation all continued to develop their orebodies at increasing depths along both ends of the 'boomerang'. The last remaining workings on the Broken Hill field are Perilya's Southern Operations and CBH Resources' Rasp Mine in the centre of the lode. Perilya are mining about 1.5 Mt of ore per year with reserves of 14.7 Mt at 5.3% Zn, 4% Pb and 42 g/t Ag and resources of 12.7 Mt at 8.9% Zn and 6.8% Pb and 67 g/t Ag. The Rasp Mine is intended to extract the high-grade pillars left unmined from the old Main Lode orebody and also the unmined Western Mineralisation. The total resources were stated by CBH Resources in 2009 as 16.5 Mt at 6.6% Zn 5.1% Pb and 89 g/t Ag. It was bought in 2010 by Toho Zinc of Japan. Production is expected to commence in 2012.

An amalgamation of several Broken Hill mines formed the Electrolytic Zinc Company during WW1 to produce zinc domestically when they were cut off from Germany, which had previously taken their zinc concentrates for smelting. They built their reduction works at Risdon, near Hobart in Tasmania, to take advantage of cheap hydroelectricity, with the first zinc being produced in 1918. They then went on to acquire the Rosebery deposit from Mount Lyell, which realized that it could not raise the funds to build its own zinc works in western Tasmania. However, Mount Lyell had done the pilot-plant work to enable the complex Rosebery ore to be separated economically. Rosebery began full-scale production in 1936 and has continued to the present day with current production at 700,000 t/yr of high grade ore (12% Zn, 4% Pb, 0.3% Cu, 1.7 g/t Au and 125g/t Ag). It is now owned by Minmetals Resources Ltd of China and has current reserves and resources of 16.9 Mt at 11.8% Zn, 4.0% Pb, 0.4% Cu, 136g/t Ag and 1.8g/t Au.

Exploration during the 1930s in the Captain's Flat area, near Canberra, previously worked largely for gold from 1882 to 1899, proved a substantial deposit of copper, lead and zinc. Connection to the rail network in 1937 enabled Lake George Mines to open a mine which operated until final closure in 1962. Total production was over 4 Mt of ore with an average grade of 10% Zn, 6% Pb, 0.67% Cu and 1.8 oz/ton Ag (Glasson and Paine, 1965). The lens-like orebodies occur in strongly folded Lower Palaeozoic volcano-sedimentary rocks and are now thought to be of volcanic exhalative origin. The area is now being investigated by various companies.

The Western Australian goldfields expanded and developed in the early 20th century, but only a few small deposits were discovered after WWI. The larger mines such as Sons of Gwalia at Leonora (managed by Herbert Hoover for a time) and Big Bell near Cue continued until the early 1960s (Fig. 12). By then only Kalgoorlie and Norseman were still producing, as the gold price had been pegged at $35 per ounce since 1934. A number of mines on Kalgoorlie's 'Golden Mile' were working over 300 separate ore bodies on many levels down to almost 1000 m deep by 1960. The gold is hosted in faults, shear zones or quartz vein systems in Archean greenstone belts, with some in pyrrhotite bodies within banded iron formations, such as at Mount Magnet. The 1930s saw an upsurge in prospecting due to the Great Depression and the state government's

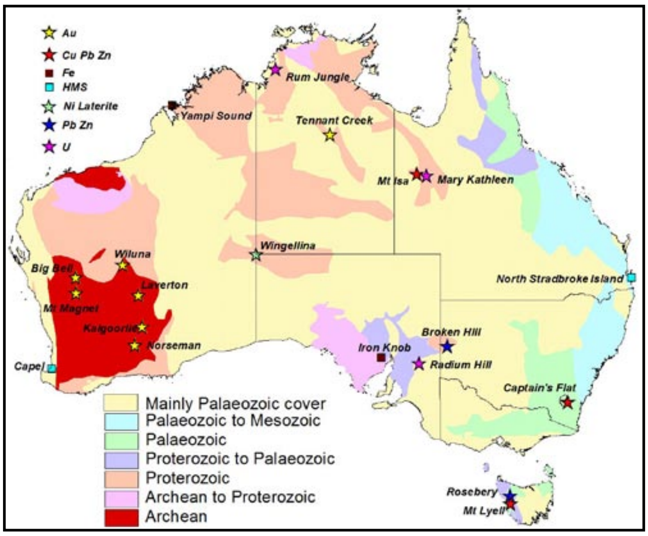

Figure 11. *Significant mineral discoveries from 1900 to 1960.*

***Figure 12**. Shaft headgear at the Sons of Gwalia gold mine.*

assistance by providing tools and continuing the State Batteries (small crushing and processing plants) that treated small mines' gold ore at a subsidised charge. The Australian Government also introduced a 'Gold Bounty Bill' of £1 per ounce in 1930 to maintain employment in the goldfields and assist national balance of payment problems. The outback legend of Lasseter's Reef was revived and in 1930 an expedition led by Lasseter attempted to rediscover the fabulous gold-rich quartz reef he claimed to have found when travelling from Alice Springs to the WA gold fields in 1897. The expedition ended in acrimony and disaster, with Lasseter dying alone in the bush (Blainey, 1978). The 1930s also saw the start of the Kalgoorlie-based company Western Mining Corporation (WMC) which was unusual in being headed by mining engineers and geologists and in always spending a significant amount on exploration. This far-sighted policy was to pay dividends in the coming decades. An early success for WMC was the development from 1936 of the Crown, Maraora and Princess Royal gold mines at Norseman, which have now produced over 5 M ounces of gold (over 140 tonnes). Victorian gold production declined sharply in the early 20th century, and had almost disappeared by the early 1920s.

There was a minor rush to mine alluvial osmiridium (a natural alloy of osmium and iridium) in serpentinite near Adamsfield in Tasmania 50 km west of Hobart in 1925 (Bacon, 1992). Osmiridium had been known in northwest Tasmania for some years; in fact the only recorded (up to that time, in 1913) *in situ* occurrence in the world in rock was in serpentinite near Waratah, and an Osmiridium Act had been passed in the Tasmanian Assembly in 1919 to regularize the small industry. The rush to Adamsfield by up to 1000 miners led to a ten-fold increase in output to over 3000 ounces when the price was over £30 per ounce. Interestingly there was a penalty for including osmiridium in panned gold as the two were difficult to separate except by dissolving the gold in mercury. The rush only lasted a few years before the price dropped to less than £10 per ounce.

Mount Isa

The great Mount Isa lead-zinc-copper-silver mine in northwest Queensland took many years to develop fully (Fig. 13). It was discovered by a prospector in 1923 and had a long gestation because of its isolation (Blainey, 1960). Over 11,000 m of surface drilling was completed between 1927 and 1931, which was then an astounding amount for a deposit yet to go into production. A number of companies controlled it, but it was not until the American Smelting and Refinery Company (Asarco) bought it in 1930 and installed Julius Krushnitt as general manager that output began. The deposit is another Sedex deposit comprising a series of sub-parallel steeply dipping lenses of lead and zinc sulphide in mid-Proterozoic metasediments adjacent to the major Mount Isa N-S fault and is similar to the Broken Hill deposit but of lower metamorphic grade. Just before WWII, a major, separate copper deposit was discovered at depth, adjacent to the lead-zinc lenses, in an unusual silica-dolomite host rock. The silica-dolomite hosted copper probably formed later than the lead-zinc with mineralising solutions using the same Mount Isa Fault as a focus and a conduit. This was a major source of copper during the war, when. Mount Isa, like Broken Hill, was a company town completely reliant on mining. By 1960 the mine was a major producer of lead, zinc, copper and silver. In 1947 exploration along the Mt Isa fault discovered the similar Hilton deposit 24 km north of Mt Isa. However, this did not go into production until 1990 when the George Fisher mine was opened. Reserves and resources of the Hilton deposit totaled around 58 Mt at about 8% Zn, 5% Pb and 100 g/t Ag in 2005.

Small high-grade deposits of gold, and later copper, were found from 1932 around Tennant Creek in the Northern Territory, 600 km west of Mount Isa. In 1949 a shaft sunk by Australian Development found gold in ironstone with grades of 50–60 oz/ton (about 1500 g/t). By 1960 the Nobles Nob mine had produced £8.5 million worth of gold and paid £4.5 million in dividends (Blainey, 1978). It continued production until 1985 for a total of a million ounces from 2 Mt of ore. Another company, Geo Peko, later used geophysics to locate high-grade copper-gold orebodies in pipe-like lenses of

***Figure 13**. Mine buildings above an old open pit at Mount Isa.*

magnetite along shear zones at depth in the host Lower Proterozoic sediments. A number of small to medium size mines (up to 15 Mt) such as Warrego, Peko and Juno were developed in the 1960s and 70s. Warrego produced 1.3M oz of gold and 91,500 t of copper, but the field is now inactive.

In 1955 Carpentaria Exploration, the exploration arm of Mount Isa Mines, found a major lead-zinc deposit of similar style to Mount Isa on the McArthur River in the Northern Territory. At first named HYC (Here's Your Chance) it took 40 years before the first ore was produced from this enormous orebody containing over 200 Mt at a grade of 10% Zn and 4% Pb in mid-Proterozoic unmetamorphosed sediments of similar age to those hosting the Mount Isa deposit 500 km to the south (Murray, 1975). For many years, the very fine grained and intimately intergrown sulphides of lead and zinc proved impossible to separate economically, and the deposit lay in limbo after the sinking of an exploration shaft in the early 1960s. The McArthur River deposit, like the Mount Isa lead-zinc deposit, is now considered to be important members of the Sedex class of mineral deposits, as described at Broken Hill. Iron ore was mined in South Australia by BHP from a series of Lower Proterozoic banded iron formation deposits in the Middleback Ranges such as Iron Baron, Iron Duke and Iron Knob and also from Koolan Island off northwestern Western Australia (Fig. 14). In 1938 an iron ore export ban was imposed, partly to curb growing Japanese influence and partly to conserve the apparently diminishing resources. About 100 Mt of iron ore was mined to the end of 1963 (Canavan, 1965), mainly by BHP for domestic consumption. This impressive figure was to be dwarfed in the coming decades. Exploration in the 1950s by BHP discovered significant Proterozoic oolitic iron ore deposits at Roper Bar and Constance Range in northern Queensland with several hundred million tonnes of resources. However, the iron ore export ban remained in place until 1962 when the growing discoveries in the Pilbara made it redundant.

***Figure 14**. Banded iron formation in the Pilbara, though this outcrop is of sub-economic material.*

The 1950s saw a national surge in uranium prospecting using the newly developed Geiger counter. Booklets were distributed to prospectors describing the characteristics of uranium minerals and how to look for them. Numerous cash rewards of up to £25,000 were collected for the discovery of several deposits such as Mary Kathleen near Mount Isa and Rum Jungle in the Northern Territory. These, together with Radium Hill in South Australia which had been found in 1906 and worked sporadically for radium in the 1910s and 1920s, were worked to produce uranium for Britain's nuclear weapons programme and then for power generation.

Mining of coastal sand dunes for heavy mineral sands containing rutile (TiO_2) and zircon ($ZrSiO_4$) began on the east coast in 1945 on North Stradbroke Island south of Brisbane. Similar deposits rich in ilmenite ($FeTiO_3$) were discovered around Capel and Bunbury, south of Perth, in 1955 (Baxter, 1990). By the late 1960s Australia was a major exporter of rutile and ilmenite for paint manufacture.

Bauxite

In 1955 geologists from Consolidated Zinc were looking for with prospects for oil and saw the red-brown cliffs around Weipa mission in northern Queensland on the coast of the Cape York Peninsula. Sampling showed it to be high-grade pisolitic bauxite at around 50% Al_2O_3 and production from this remote location began in 1961 by Comalco (Commonwealth Aluminium Corporation) from an original resource exceeding 3000M t. The Weipa deposit is now a major producer at a rate of over 16 Mt/y. A similar deposit was also found in 1955 at Gove in Arnhem Land in the Northern Territory, and was developed by Nabalco (North Australian Bauxite and Alumina Company), a joint venture between Alusuisse and CSR (Colonial Sugar Refiners). It is now a major producer of bauxite and alumina in spite of its remote location. Now, both are owned by Rio Tinto, and Australia produces a third of the world's bauxite (Table 1).

In 1957 Western Mining Corporation discovered large resources of bauxite in the Darling Range south-east of Perth in Western Australia. A mining lease of over 12,000 km^2 was granted and, although it is only 27-30% Al_2O_3 (one of the lowest grades worked economically anywhere), production in a joint venture with Alcoa started at the Jarrahdale deposit in 1963. The bauxite had previously been regarded as uneconomic as it was high in silica and relatively low in alumina. However, a WMC geologist, Roy Woodall, realized that the silica was due to quartz (non-reactive with the caustic soda used in treatment), not clay as in many bauxites, and could be easily removed, thereby upgrading the bauxite. Several mines are now active, including Alcoa's Huntly mine, which is the world's largest bauxite mine at 23 Mt/yr, and Worsley's (majority owned by BHP Billiton) Boddington mine at 12 Mt/y. Alcoa's WA refineries now satisfy 13% of world alumina demand.

From 1960 to 1975

This was a period of major discoveries and developments in iron ore, nickel, uranium and mineral sands (Fig. 15), and a huge increase in mineral exports to the rapidly developing economies of Japan and South Korea. It was also marked by the quiet decline of the gold mining industry as the price was still pegged at $35/oz. By 1975 only the Mount Charlotte low-grade, large-scale, underground mine was in operation, mining quartz stockwork mineralization at Kalgoorlie.

Iron ore in the Pilbara

The decade began with the discovery of immense deposits of high grade massive hematite in the Pilbara region of north-western Western Australia (Fig. 16). Although the presence of iron ore had been known for many years, no serious work had been done because the area was so remote and over 150 km from the coast where there were only small ports. Realizing that the export embargo was about to be lifted, the WA state government called for tenders in 1961 for mining companies to apply for exploration rights (Temporary Reserves or TRs) to large areas of prospective ground. A consortium of Consolidated Gold Fields Australia and the American companies Cyprus Mines and Utah Construction was granted several TRs in the Port Hedland region covering areas of Archean volcanic and sedimentary rocks. The consortium concentrated on the Mount Goldsworthy area where some drilling had already been carried out by the Geological Survey. Within four years 4M t/y of iron ore was being railed 200 km to Port Hedland for export to the booming Japanese and South Korean blast furnaces and steel mills, and the WA iron ore boom had begun (Fig. 17).

This was just a foretaste to the development of the enormous deposits in the 2500 Ma old late Archean-early Proterozoic rocks of the 2500 m thick Hamersley Group rocks in the Hamersley Range, several hundred kilometers south of Port Hedland.

In 1952, Lang Hancock, a wealthy grazier with a large cattle station in the area, noticed extensive iron

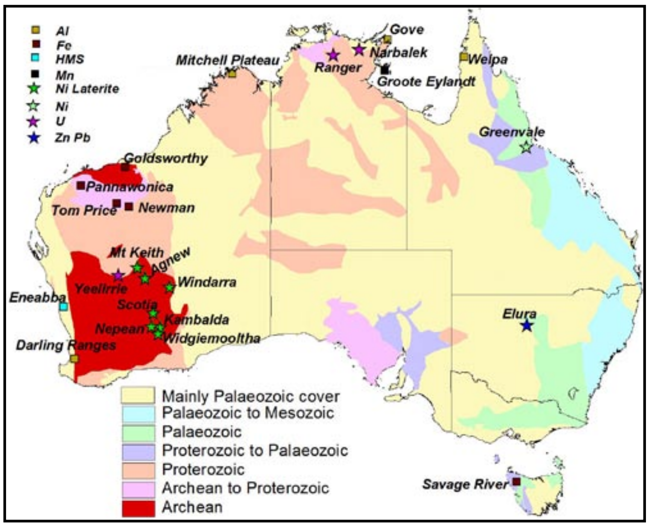

***Figure 15**. Significant mineral discoveries from 1960 to 1975.*

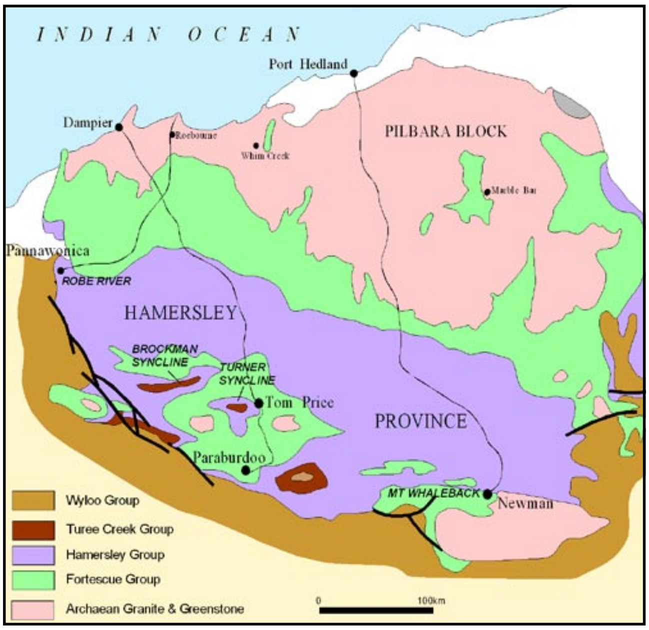

***Figure 16**. Outline geology of the Hamersley Range (after Data Metallogenica).*

ore indications when flying over the area. Ground inspection revealed numerous outcrops of massive hematite. However, due to the export embargo it was impossible to peg any claims. Hancock pressed for the abolition of the embargo, but was unable to reveal his discoveries until it was lifted. He then pegged a number of areas in 1961 and sold the mining rights to Rio Tinto and Kaiser Steel. Production from the Mount Tom Price deposit began in 1966 based on an initial ore reserve of 900 Mt at a grade of 64% Fe (Fig. 18). The ore is railed 300 km to the coast at Dampier. A similar deposit was discovered by Stan Hilditch in 1957 at Mount Whaleback 200 km east of Tom Price while prospecting for manganese (Fig. 20). He too could not peg the deposit and had to wait until the embargo was lifted. Exploration by AMAX with partners BHP and CSR proved an initial resource of 1700 Mt also at 64% Fe. Production by the Mount Newman Iron Ore Company began in 1969 with ore railed 400 km north to the coast at Port Hedland.

Both these deposits occur in the Dales Gorge Member of the Brockman Iron Formation, a 600 m thick unit of banded iron formations (BIFs), shales and sandstones. The first economic orebodies were found where the BIFs, which are alternating laminations of chert and

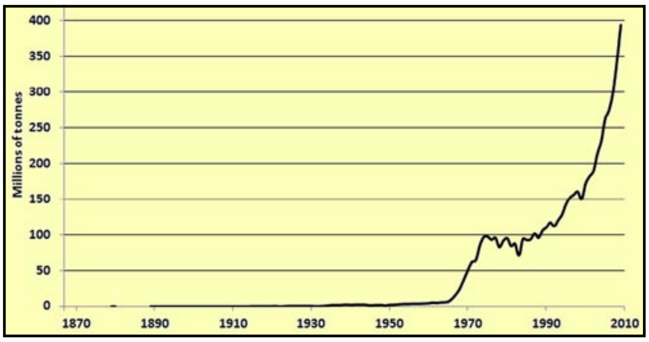

***Figure 17**. Iron ore production in Australia (after Mudd, 2009).*

Figure 18. *The large open pits extracting iron ore at Mount Tom Price (photo: RTIO).*

hematite containing about 35% Fe, have been enriched by groundwater movement to form deposits of massive hematite. The base of the Brockman Iron Formation is marked by a distinctive resistant layer, named Bruno's Band after the geologist Bruno Campana who worked for Rio Tinto (Fig. 19). This feature enabled the discontinuous outcrops of the Brockman Formation to be mapped rapidly from the air. Dr Campana states that within a year hundreds of hematitic orebodies had been located aggregating 4 billion tons of iron ore ranging from 58% to 64% Fe. In 1969 Dr Edward Teller was consulted by Hancock Prospecting on the feasibility of using nuclear explosives to mine ore or to construct harbours more efficiently than conventional explosives. Fortunately this initiative came to nothing.

The early exploration in the Hamersley Province concentrated on the Brockman Iron Formation as it formed prominent outcrops. However, the underlying Marra Mamba Formation, which did not crop out so obviously, was also found to contain substantial mineralisation. This is now mined by BHP Billiton from an area west of Newman called Mining Area C. The Brockman section of this area was investigated by the Goldsworthy consortium in the late 1960s and early 1970s, but the Marra Mamba unit was then ignored as it was in a low lying flood plain with few outcrops.

Another significant iron ore deposit at Savage River in north-western Tasmania began operations in 1966 from a series of massive magnetite-pyrite lenses in late Precambrian schists and amphibolites. Concentrated magnetite slurry was pumped 85 km north along a pipeline to a pellet plant at Port Latta at the rate of 2.5 Mt/yr at a grade of 65% Fe for export to Japan.

A major bauxite area was found by AMAX in 1965 at Cape Bougainville and the Mitchell Plateau in the Kimberleys of Western Australia and resources of 1200 Mt of high-grade bauxite identified. However the deposits, now mainly owned by Rio Tinto Alcan, remain undeveloped due to the lack of infrastructure in this region.

In 1962 BHP examined a known occurrence of manganese on the remote Groote Eylandt in the Gulf of Carpentaria in the Northern Territory. It was soon apparent that this was of major significance and production began in 1966. The deposit is of sedimentary origin and occurs in Lower Cretaceous marine sands, clays and gravels overlying Middle Proterozoic sandstones with a lateritic capping (Bolton *et al*., 1990). The ore horizon is around 3 m thick and is worked in open cut mines by GEMCO (Groote Eylandt Mining Company); a joint venture between BHP Billiton and Anglo American. The total pre-mining resource was about 200 Mt at grades exceeding 40% manganese. Current production of over 4 Mt/yr is over 15% of world high-grade output.

Figure 19. *Drilling for iron ore in Marra Mamba formation at Bungaroo, in the Hamersley Range, with crags along the Bruno's Band across the distant hillside (photo: RTIO).*

Figure 20. *Whaleback Mountain iron ore mine in the Pilbara.*

The nickel boom

In January 1966 Western Mining Corporation, a small Western Australian gold mining company, intersected 2.7 m of massive sulphides containing 8.3% nickel in an exploration drillhole at Kambalda, south of Kalgoorlie. Its announcement in April 1966 caused a stock market sensation as there was a world shortage of nickel due to a long strike in the Canadian mines and the price had soared. Western Mining had been exploring for some years looking for base metals south of Kalgoorlie along a 'greenstone belt' of Archean basic and ultrabasic lavas surrounded by granite on the premise that the area might be an analogue of similar rocks in the Abitibi belt of the Canadian Shield which host gold and also base metal deposits, including nickel.

John Morgan and George Cowcill had been prospecting in the area since 1939, and in September 1964 brought some samples of a bright green gossanous rock to Western Mining (Fig. 21). They had found them years earlier but they did not contain gold or copper. In the mid 1950s they had taken them to the School of Mines in Kalgoorlie, thinking they might contain uranium, but were told they had traces of nickel. In 1964, knowing that Western Mining were in the area, they took the samples to Roy Woodall, a senior WMC geologist (Woodall and Travis, 1969). He took out a Temporary Reserve over the Kambalda area and started exploration as, based on geological surface mapping, he suspected that there might be nickel sulphide deposits beneath the gossanous outcrops that were traced around a domal outcrop of ultrabasic extrusive rocks in contact with basalts and sedimentary rocks. Six holes were drilled with only the first hole intersecting mineralization. Fortunately the drilling of this first hole was continued beyond its target of the contact between the ultramafic extrusive rock and basalt, and intersected high-grade nickel mineralization that had been structurally displaced into the underlying basalt. No nickel was then known in WA, apart from some lateritic nickel discovered by INCO in 1954 in the Wingellina area of the Giles complex near the SA/NT border. A remote prospect then of no economic interest. Wingellina has since proved to have substantial resources.

The WMC nickel strike took the Australian stock market by storm. As more results were announced, WMC shares rose sharply reaching $76 before further share issues diluted the stock and brought prices down. Sinking the Silver Lake shaft into the Lunnon orebody, the first of many mines in the Kambalda district, started in July 1966, just 6 months after the discovery hole, and production began in April 1967 (King, 1973). Kambalda was developed as a company town to serve the needs of WMC's growing number of mines around the Kambalda dome, but Kalgoorlie boomed with over 200 mineral exploration companies based there by the late 1960s, together with supporting geophysical,

Figure 21. *Nickel gossan, mainly of garnierite, from the Kambalda region.*

analytical and drilling companies. All the world's major mining companies were there, plus a legion of small to medium sized local companies. The boom was fed by major industrial unrest at the then leading nickel producers at Sudbury in Canada. The spot price of nickel rose sharply from under $2000 per tonne at the end of 1968 to over $7000 by the end of 1969.

The pages of the Kalgoorlie Miner newspaper were full of lists of mineral claims and of company prospectuses, some of very dubious quality. By the end of the decade all a company needed to float on the stock exchange was to have about 100 rectangular 'claims' each of 300 acres with some nickel analyses in the hundreds or thousands of ppm and some 'ultrabasic rocks' (undefined) on at least some of the claims. The prospectors who pegged the claims were paid in shares in the soon-to-be-floated company, 200,000 or so shares were issued at a face value of 20 cents and promptly opened at 50c to $1 or so. Everyone was happy. Judicious announcements kept the share price volatile until the next company issue came along. One prospectus map purported to show the outlines of 'the ultrabasic'. What it actually showed, in a fairly remote area 100 km northeast of Kalgoorlie, was the outlines of a dry salt lake copied from an old Geological Survey map! Another group of claims of very dubious ancestry had samples assaying 5% nickel, which was astoundingly high. Unfortunately the samples were nickeliferous laterites swept into the creek-bed claims from higher, more promising WMC ground – the only alluvial nickel deposit ever reported! The worthless claims were later sold for $1 million to a minor exploration company. In 1972 a small exploration company, Leopold Minerals, announced an intersection of 7.5 m at 3.3% Ni in a new area near Nullagine in the Pilbara (Sykes, 1978). The assays appeared suspiciously like those from the WMC Kambalda camp; this were confirmed when the promoter was arrested at Perth airport trying to leave for Singapore, and a parallel hole, drilled under police supervision, failed to show any sign of mineralisation. The original material probably came from a WMC core store adjacent to a road.

A number of real deposits, soon to become mines, were found (King, 1973). John Jones, a wealthy grazier turned prospector, found the small 1.3 Mt Scotia deposit north of Kalgoorlie that was worked by Great Boulder Gold Mines who closed their Kalgoorlie gold mine and used the plant to process the ore. Metals Exploration discovered the Nepean deposit near Coolgardie in 1968, and WMC continued to find and develop deposits around Kambalda. Metals Exploration also found the world-class low-grade Mount Keith deposit with over 250 Mt at 0.6% Ni in 1969. The major mining companies were relatively unsuccessful; most of the early discoveries were made by prospectors working for junior companies. One exception was the Perseverance (now Agnew) deposit north of Leonora that was found by Australian Selection in 1971 with 33 Mt at 2.2% Ni and is still in production under BHP Billiton's Nickel West operations, which are also mining the Mount Keith deposit. The total amount of nickel mineralisation found at Kambalda now exceeds 100 Mt at a grade of around 3.5% Ni (Fig. 22).

Then there was Poseidon. In March 1969, Ken Shirley, a prospector working for this small exploration company, found a nickeliferous gossan over ultrabasic rocks near the small township of Laverton, 300 km NE of Kalgoorlie. He followed a discontinuous line of ultrabasics and found additional gossanous outcrops where the ultrabasic was in contact with a banded iron formation or jaspilite. He pegged the whole 8 km line of ultrabasics, and the company started routine exploration. Within a few months shallow drilling had shown indications of nickel sulphides and at the end of September 1969 Poseidon announced that they had found a substantial nickel deposit. The shares (only two million were on issue) had been trading around $1 and immediately jumped to $6 and then $12. Further news took them to $50 by the end of November. The company announced resources of 4 Mt at 2.4% Ni at the AGM just before Christmas, which took the shares to $130. They then rocketed to a peak of $280 in February 1970 before falling back through $50 by April and were only $39 by December 1970 (Sykes, 1978). The development of the mine took a couple of years and the orebody proved poorer and more complex than expected, leading to cash-flow and mining problems. Eventually the company were taken over by WMC and the mine was worked until 1990. At its peak the company was valued at over $700 million, but only about $250 million of metal was recovered. Following the recent discovery of additional mineralization, the mining of this deposit is scheduled for the future.

The Tasminex scandal in January 1970 was due to overoptimistic interpretation of minimal information during the Poseidon bubble. Tasminex had floated in October 1969 with two million shares at 25 cents. In early January 1970 these had reached $3.50 in line with the general optimism of the market. On 27th January 1970 the shares shot up to $18. The next day, following a newspaper interview with the chairman Bill Singline, a Tasmanian transport owner, they rose to $96 after he mentioned that 'massive sulphides' had been struck

***Figure 22**. Nickel production in Autralia (after Mudd, 2009).*

during drilling at Mount Venn 100 km east of Laverton and helpfully suggested that the find 'could be bigger than Poseidon' (Sykes, 1978). However, analysis of the sulphides found they were actually valueless massive pyrite with minimal nickel content and the share value rapidly retreated. A subsequent enquiry found that there had been substantial insider trading but the main culprit was grossly misleading and optimistic statements from company officials who were not professional exploration geologists.

The Poseidon boom so increased the pace of exploration that the WA Minister for Mines announced an indefinite ban on claim pegging from 3 February 1970, as there was such a backlog of unprocessed claims at the various Mining Registrar offices throughout the state. This led to a frantic search for new ground until the ban was lifted, with new regulations, on 5 June 1970 (King, 1973). On that day hundreds of geologists and prospectors were camped out throughout the bush waiting for the new regulations to be broadcast on state radio at 12 noon (Fig. 23). The amendments were modest; claim posts were 1.5 m high, instead of 1 m, and more trenches had to be dug along the sides of the claims. A frantic rush ensued with lines of rival claims intersecting and overlapping; one area was claimed by three companies who had approached it from different directions. Then the claims had to be registered on a first-past-the-post system at the relevant Mining Registrar's office. The resulting conflicting claims were mainly resolved by negotiation in the local Mining Warden's courts.

One astonishing fact to come out of the nickel boom was that nearly all the discoveries were made by prospectors finding surface gossans and not by geologists with all the geochemical and geophysical methods. The thick surficial cover and paucity of outcrop, coupled with highly saline groundwater, initially rendered 'modern' methods relatively ineffective and the traditional prospecting was the most successful method. However, many gossans were difficult to distinguish from the ubiquitous laterites and ironstones, and many promising blocks were carefully analysed and rejected as worthless.

Figure 23. *Claim pegging at Yokradine Hills, near Lake Barlee, Western Australia.*

Away from nickel

Almost no one was looking for gold during the nickel boom. Gold was still only $35 per ounce, geochemical analysis was slow and costly, and the notion was that 'all the gold had been found'. Most nickel exploration geologists passed countless old gold mines and trials without a thought that there might be more to be found (Fig. 18 or 18a). However, there were a few enthusiasts who thought that payable gold could be found.

Other discoveries during this exciting period included the major Ranger, Jabiluka, Koongarra and Narbalek uranium finds in 1969 and 1970 in the Northern Territory's Arnhem Land. They are all unconformity-type deposits, forming at the contact between Lower Proterozoic basement and overlying Middle Proterozoic sandstones. Jabiluka and Koongarra remain undeveloped for various reasons, including the wishes of the local indigenous community; the former is close to the boundary of the Kakadu National Park. Narbelek was found by the small explorer Queensland Minerals and caused great stock market interest because of the very high grade of the ore (1.84% U_3O_8) and the few shares on offer. However, because of environmental and other concerns, the deposit was not exploited until 1979 when a four-month campaign extracted all the ore, which was treated over a longer period to produce 10,858 tonnes of U_3O_8 by 1988, more than any Australian uranium deposit to that time. The site has now been completely restored. Ranger was found by the medium-sized mining company GeoPeko and is now owned by Energy Resources Australia (ERA), a subsidiary of Rio Tinto. The controversial operation of a large open pit uranium mine in a World Heritage area adjacent to the Kakadu National Park, with a monsoonal climate and a long history of habitation by indigenous peoples has resulted in extremely close supervision and monitoring of the mine and associated facilities. Production began in 1981, and thrty years later Ranger was the second largest uranium mine in the world, with an annual output of 5240 t of U_3O_8. Reserves total 24 Mt at 0.1% U_3O_8.

Another type of uranium deposit, completely new to Australia, was found by WMC at Yeelirrie, near Wiluna in WA, in 1970, demonstrating the breadth of that company's expertise in exploration. The company had decided to look for uranium in WA using a sandstone-hosted model derived from mineralisation in the western USA. They realised that many of the salt lakes occupied earlier (Tertiary and Cainozoic) river channels that derived their sediments from the large expanses of Archean granite. Recently published national maps showed a number of radiometric anomalies, some associated with old channels. It was generally thought that the anomalies were due to potassium from the weathering of feldspars, but a field check showed that some were caused by uranium. Prospecting along a fence line discovered blocks of highly radioactive yellow carnotite ($K_2(UO_2)_2(VO_4)_2.3H_2O$). A total resource of 35 Mt was established at a grade of 0.15% U_3O_8 for a total of 52,500 tonnes U_3O_8. The deposit was formed in calcrete (calcium and magnesium carbonate) in an ancient palaeo-channel developed over millions of years. The carnotite ore zone is 3 m thick, about 9 km long and up to 1.5 km wide. It caused an immediate rush to survey all salt lakes with radiation detectors. A number of similar, but smaller deposits were found, but at the time the Australian Government's policy of only three uranium mines ruled out any development while the existing mines were in operation. The deposit, still unmined, is now owned by BHP Billiton.

A new area of heavy mineral sands containing economic levels of ilmenite used in paint manufacture, as well as zircon and rutile, was found by chance at Eneabba, north of Perth, in September 1970 by a farmer drilling post holes. He noticed that the sand from excavated holes was black and dense, so he contacted local ilmenite mining companies, such as Western Titanium, who were based around Capel, south of Perth. Within a short time a major pegging rush began with one company alone pegging over 1000 claims and flying a radiometric survey over several hundred kilometres of coast. The deposit was in high-level, fossil shorelines up to 20 km inland from the coast, where the local topography in late Tertiary to early Pleistocene times had caused longshore drift to deposit the denser heavy minerals in embayments (Shepherd, 1990). The deposit was rapidly drilled out and consists of several parallel high-grade lenses over a 5 km long zone containing around 30 Mt of recoverable heavy minerals (Fig. 24).

A large carbonatite (alkaline igneous intrusion) was found in 1967 by Utah Development at Mount Weld 35 km south of Laverton in WA and drilled in the early 1980s by Union Oil as a phosphate, niobium and tantalum prospect (Duncan and Willett, 1990). It was later taken up by Lynas Corporation, which currently claims it is 'the richest known deposit of rare earths in the world' with a total resource of 1.4 Mt of REO (Rare Earth Oxides) at grades of up to 14% in zones within the 3 km diameter intrusion.

Figure 24. *Drilling to prove the ilmenite-rich heavy mineral sands at Eneabba.*

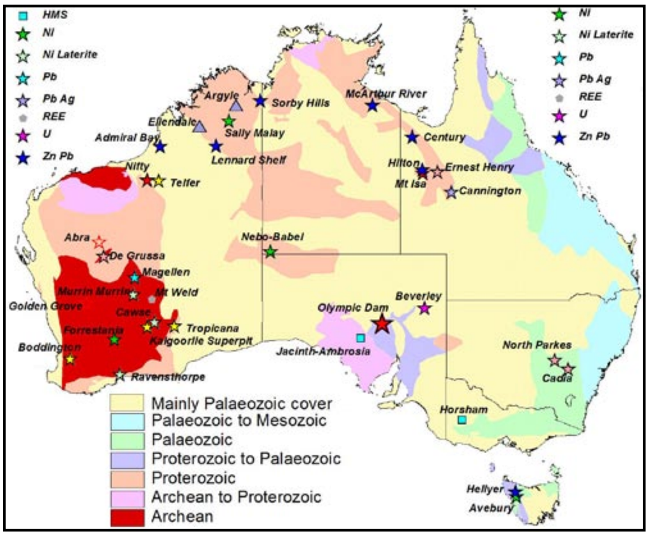

Figure 25. *Significant mineral discoveries since 1975.*

The major Elura lead-zinc-silver deposit was discovered by Electrolytic Zinc Corporation in 1973 about 40 km NNW of the old mining town of Cobar in central New South Wales. This enigmatic deposit consists of several semi-vertical, pipe-like massive sulphide bodies with a vertical extent of up to 1000 m in Lower Devonian meta-siltstones (Schmidt, 1990). There are no igneous rocks in the area. The main sulphide is pyrrhotite, which causes a strong magnetic anomaly to act as a drill target. The pre-mining resource totalled around 45 Mt with grades of 8.5% Zn, 5.3% Pb and 69 g/t silver. The mineralisation is now thought to be the result of overpressured basinal fluids being released during metamorphism and depositing minerals in low-pressure zones within faulted anticlines with some interactions with the host rocks. Mining started in 1983 and after passing through various ownerships the deposit, now called Endeavour, was bought in 2010 by Toho Zinc of Japan.

From 1975 to 2011

This period has been dominated by the new gold rush, the ever-increasing output and export of iron ore, major copper and lead-zinc discoveries in Queensland and New South Wales, and the discovery and development of Olympic Dam – the world's largest single mineral deposit. There was also a spate of developments of surface-mined nickel laterite deposits, with only one achieving continued production, and a group of high-grade nickel deposits (Fig. 25). And a world-class diamond deposit was discovered in the Kimberley.

Historically Australia had been considered 'Terra Nullius' or belonging to nobody before the arrival of European settlers. However, following the historic Mabo ruling of 1992 which recognized Native Title, many groups of indigenous peoples asserted their right to be consulted on the development of ancestral areas. The Mabo case has caused additional responsibilities for mining companies to research possible ownership of land containing mineral deposits by traditional peoples and to work with them and the State Governments to provide suitable employment and other opportunities. Companies also need to work with the indigenous population to avoid heritage sites.

Return to gold

The rise in the world gold price from $35 per ounce in 1972 to $600 /oz by 1980, coincided with development of rapid, reliable, low cost and high-precision analytical methods for gold, with detection levels down to 2 parts per billion (ppb). Along with a general depression in base metal prices, mining companies turned towards concentrating on gold exploration. It is telling that a major publication on Australian economic geology, published in 1975, contained just 10 pages on gold in WA but 100 pages on nickel (Knight, 1975). The gold section was entirely on existing deposits, with no new finds mentioned. The next volume, published in 1990, devoted 120 papers (out of 261) specifically to gold, and mainly to new deposits, illustrating the rapid rise in gold development (Hughes, 1990).

The first major gold deposit to be discovered was Telfer in the remote Patterson Ranges of WA 400 km east of Port Hedland (Dimo, 1990). Newmont Mining, an American company with large gold mines in Nevada, was informed of a large gossanous area in Proterozoic sediments, possibly of copper, by a prospector who had found the area in 1970. However, he did not peg the area and did not suspect that it contained gold, when the low price meant that no Australian company was interested. However, Newmont, being a gold mining company, did consider gold and in 1972 visited the area and pegged it as a gold prospect. A major open-pit mine was opened in 1977 and produced 6 M ounces of gold to 2000, when the presence of minor copper at depth made it uneconomic. The processing operations were revised, and the mine reopened in 2007 as an open-pit mine with a final planned depth of 650 m and an underground operation working ore shoots that extend beyond 1500 m depth. Current reserves are around 400 Mt of openpit ore containing 11M oz gold and 400,000 t copper, along with 37 Mt of underground ore containing 2M oz and 120,000 t copper. There are also extensive potential resources.

From the late 1970s onwards a new mining industry was rapidly developed in Western Australia based on opening increasing numbers of small to medium sized open-pit gold mines (Woodall, 1990). These were located using soil sampling and shallow, reverse-circulation drilling around old mines that had worked quartz veins and shear zones with high-grade gold at 10 g/t; the new deposits contained low-grade veins and disseminated mineralization. Very selective, but large-scale, open-pit mining and strict grade control, coupled with the use of the new carbon-in-pulp technique for recovery of the fine-grained gold, was used to achieve economic operation from deposits with grades down to 1 ppm. A number of the mines, such as the Plutonic mine north of Meekatharra, were subsequently extended as underground operations using spiral decline ramps for access. Total Australian gold production (mainly from WA) rose rapidly from 18 tonnes in 1981 to 313 tonnes in 1997 (Fig. 27). The remaining deep, narrow-lode mines on the famous Golden Mile at Kalgoorlie (Lake View and Star, North Kalgurli and Great Boulder) had all closed by 1974 leaving only the large-scale, underground block-caving Mount Charlotte operation.

The rising gold price renewed interest in the area in the late 1970s, and in 1983 a series of small open pits were opened. A flamboyant entrepreneur, Alan Bond, bought controlling interests in every key lease in 1987, but by 1989 financial problems forced him to sell to

Figure 26. *The Superpit that is now extracting gold from the entire zone of veins at Kalgoorlie; the town is at top left, and the mineral processing plant and waste tips are on the right (photo: KGMA).*

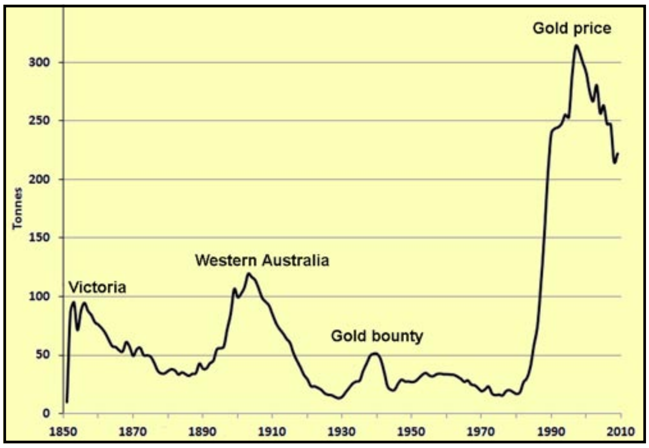

***Figure 27**. The peaks of annual gold production in Australia (after Mudd, 2009).*

Kalgoorlie Consolidated Gold Mines (KCGM), a joint venture between Homestake Gold of Australia and Gold Mines of Kalgoorlie (GMK), a WMC subsidiary. KCGM developed the Superpit, a major open-pit that encompasses a large area of the Golden Mile and will eventually be 3.8 km long, 1.4 km wide and over 500 m deep (Fig. 26). Current operations mine 85 Mt of rock per year, including 12 Mt of ore, to produce up to 800,000 oz (22.7 t) of gold. In 2001 Homestake merged with Barrick and in 2002 GMK was taken over by Newmont. The Golden Mile produced its 50 millionth ounce of gold (over 1400 tonnes) in 2003. The Superpit is scheduled to continue in production until 2021.

In 1979 the Geological Survey of Western Australia discovered a gold anomaly in soil during a routine regional mapping programme near Boddington in the Darling Ranges 100 km southeast of Perth. The area is in the Saddleback Greenstone Belt of the Western Gneiss Terrain. It had previously been explored for bauxite deposits, and Reynolds Australian Mines Pty re-analyzed, for gold, some of the old bauxite exploration vacuum-drill samples, and discovered gold in surficial laterites and clays overlying a low-grade, porphyry-style, gold-copper deposit. Without doing any additional drilling, a gold resource was defined. Gold deposition was at a redox front at or near the Tertiary water table (Symons *et al.*, 1990). Open pit resources

***Figure 28**. A 350-tonne truck from the Superpit, in the St Barbara's Day parade in Kalgoorlie (photo: D Graham).*

***Figure 29**. Old workings on gold veins exposed in the end wall of the new Superpit at Kalgoorlie.*

of 60 Mt at 1.6 g/t gold made this deposit one of the largest discovered up to that time. Mining the surficial deposit began in 1987 and was completed in 2001. After a prolonged hiatus, the underlying primary deposit, now owned by Newmont Mining, started operations as a major open pit mine in July 2009, and is producing at an annual rate of up to 1M ounces of gold along with 30,000 t of copper. The pit will eventually be over 4 km long, 1 km wide and up to 700 m deep. Resources are stated at over 20M oz of gold and over 1 Mt of copper.

Interestingly over 75% of Archean gold (~120M ounces) has been produced from the Norseman-Kalgoorlie Belt which only makes up a small proportion of the total Yilgarn greenstone area (Huleat and Jaques, 2005). The Southern Cross Belt has produced 10M oz; the Leonora-Wiluna Belt 12M oz and the Laverton Belt 25M oz (Fig. 30). Significant new discoveries are still being made. In 2005 a joint venture between Anglo Ashanti and Independence Mining found the major Tropicana deposit southeast of Laverton at the northern end of the Frazer Mobile Belt; a previously unprospected area of late Proterozoic rocks striking northeast at the southeast margin of the Yilgarn craton. The series of near-surface deposits at Tropicana now contain over 88 Mt of resources at a grade of 2.3 g/t Au for a total of 6.4M oz of gold with open ended extensions at depth and along strike in an area of 15,000 km^2 over a length of 330 km. It is expected that other gold deposits will be discovered in what is now considered to be a new gold province. Mine construction has recently commenced, with the first gold pour expected in mid 2013. A small company, Gold Road Resources, currently has much of the poorly explored Yamarna Belt, northeast of Laverton, under licence and has made several small discoveries associated with a major shear zone recognized during recent state mapping.

Figure 30. *One of the many worked-out open pit gold mines in the Leonora-Wiluna mineral belt.*

The intensive exploration for gold since the 1980s, and the development of many open pit mines throughout the Yilgarn Shield, has led to a much greater understanding of its regolith – the veneer of post Archean (mainly Cainozoic) material up to 30 m thick on top of the ancient rocks. What was termed undifferentiated overburden in the early 1970s is now recognized as the product of a complex interaction of weathering and erosion, with many chemical processes that are either complete or ongoing. The work of Charles Butt at the CSIRO and Richard Mazzuchelli, chief geochemist of WMC, coupled with the development of new analytical techniques, lower levels of detection and computerized statistical analysis, enabled the detection of more subtle targets. Now, the full range of GPS positioning, geochemistry, air- and satellite-borne multi-spectral mineral analysis and 40 years of experience are employed to understand the regolith for mineral exploration and environmental purposes.

Another trend in Western Australia was the recognition that there were extensive deposits of lateritic iron-oxide nickel-cobalt mineralization overlying many of the ultrabasic rocks of the greenstone belts (Fig. 31). Lateritic nickel had been largely ignored during the early nickel boom of the 1960s and 70s as the high capital costs of the complex processing plants deterred significant interest. A successful laterite deposit was mined from 1974 to 1993 at Greenvale, in northern Queensland, by Metals Exploration and Freeport on reserves of 40 Mt at 1.57 % Ni and 0.12 % Co; it had a refinery at Townsville on the coast, and the mine site is now fully restored. However, the availability of cheap sulphuric acid from the WMC nickel sulphide smelter at Kalgoorlie and natural gas from the offshore Northwest Shelf, led to prospects being developed at Murrin Murrin, Cawse and Bulong, all northeast of Kalgoorlie. The high-pressure acid-leach process was used, but the high capital cost of the equipment (which operates at 250°C and 45 atmospheres pressure) and severe and prolonged problems with development, as well as a fluctuating nickel price, saw only the Glencore-owned Murrin Murrin mine near Leonora survive. Even this has yet to achieve its planned output of 40,000 t of nickel and 5000 t of cobalt; it is currently producing around 30,000 t of nickel per year from reserves of 196 Mt at 1.05% Ni and 0.078% Co.

Another laterite deposit at Ravensthorpe on the south coast of WA was developed by BHP Billiton from 2004 to 2008 as an open pit mine with a capacity of 50 000 t/yr nickel. After costing over $2000M, it was unable to achieve economic production at the then-depressed nickel price, and was closed after a year of operation. The project was bought by First Quantum Metals for $340M in 2010, and commercial production commenced in late 2011. It is estimated that the mine will produce 28,000 t/yr over its expected mine life of at least 30 years.

After a hiatus of almost 20 years with no significant new nickel sulphide discoveries in the Yilgarn craton, a junior company, MPI Minerals, discovered the very high-grade Silver Swan deposit north of Kalgoorlie in 1995 with an initial resource of 650,000 t at 9.55% Ni. The deposit was discovered after reassessing the results from previous explorers. Production started in 1997, as the first of a number of small, but generally high-grade, nickel sulphide deposits, especially in the Southern Cross area. There, Western Areas NL have over 5 Mt of reserves at a grade of around 3.3% Ni in the Flying Fox, Spotted Quoll and Diggers deposits. Much higher grades occur in some of the deposits.

Western Mining Corporation discovered a number of new deposits in the Kambalda area from the mid 1990s (Fig. 32), but then divested its numerous Kambalda

Figure 31. *Lateritic caprock, widespread in Western Australia.*

Figure 32. *The Silver Lake nickel mine near Kambalda.*

mines after 2000 to a number of junior companies such as Independence and Panoramic who have continued to develop them and have discovered a number of extensions or new ore bodies. Smaller nickel deposits have been developed at Savannah (formerly Sally Malay) in the Kimberleys, in an unusual remobilized skarn in Palaeozoic rocks at Avebury (near Zeehan in Tasmania), and at Radio Hill near Karratha in the Pilbara, where an innovative biological leach process to extract nickel and copper from this low-grade deposit is being tested. The last two are currently on care and maintenance pending an upturn in the nickel price. A new prospective province has recently been announced in central Australia where the Nebo-Babel occurrence in late Proterozoic rocks of the Giles complex in the Musgrave Block near Wingellina was found by WMC in 2000. One early drill hole intersected 26 m at 2.5% Ni, 1.8% Cu and 0.4 g/t PGE (platinum group elements) giving promise that this remote area could achieve major significance. A preliminary resource was reported in 2007 of 393Mt at 0.3% Ni, 0.3% Cu and 0.18g/t PGE (Geoscience Australia, 2012). Exploration by BHP Billiton and junior companies is continuing.

Copper, lead and zinc

Following the Kambalda nickel discoveries and the subsequent surge in exploration, attention also turned to another common type of deposit in the Canadian Shield – the VMS copper-zinc deposit exemplified by the giant Kidd Creek site near Timmins, Ontario. These deposits are generally hosted in acid volcanic rocks, usually near a contact with basic volcanic rocks as described in the seminal report by Sangster (1972). A number of mainly international companies started looking in the 'greenstone' belts of the Yilgarn and Pilbara cratons for rhyolites and other acid volcanic rocks. This work was assisted by the ongoing remapping of the shield by the state geologists as earlier mapping had not differentiated the various components of the greenstone belts. A few small deposits were known, such as Whundo (Figs. 33 and 34), Whim Creek and Mons Cupri in the Pilbara and Murrin Murrin in the Yilgarn (Reynolds *et al.*, 1975), but the acid volcanic rocks were not delineated on airborne magnetic maps, unlike the magnetite-bearing basic and ultrabasic rocks associated with nickel deposits. The Pilbara VMS deposits are some of the world's earliest ore deposits known, with the small North Pole baryte deposit dated around 3490 Ma and the Big Stubby lead-zinc-baryte deposit near Marble Bar occurring in rocks dated at 3472 Ma (Fig. 24).

A small company, Aztec Exploration, recognized gossans at outcrop at Golden Grove near Yalgoo in the northwest Yilgarn in 1971, and by the mid-1970s a joint venture with Amax and Electrolytic Zinc had established resources of 15 Mt at 3.4% Cu hosted in a thick rhyodacitic sequence (Smith, 2003). Low metal prices caused development to be delayed until 1990, but the separate Gossan Hill copper and Scuddles zinc

Figure 33. *Copper-zinc-rich gossan in bleached and weathered surface rock at Whundo, in the Pilbara.*

mines, now owned by Minmetals Resources of China, are currently producing at a rate of 30,000 t of copper and 75,000 t of zinc per year from copper resources of 26.9 Mt at 2.6% Cu and 0.5% Zn and zinc resources of 9.7 Mt at 11.7% Zn 1.0% Pb and 0.5% Cu with significant silver and gold.

The gossan above the small Teutonic Bore deposit near Leonora was discovered by Carpenteria Exploration in 1974. It was drilled by Australian Selection in 1976 to reveal a small high-grade VMS deposit with resources of 2.2 Mt at 3.5% Cu, 11.1% Zn, 0.9% Pb, 52 g/t Ag and 0.2 g/t Au at the contact of acid and basic/intermediate volcanic rocks. This was largely mined out by BP / Mt Isa Mines between 1980 and 1985. The area was owned by Jabiru Metals who found two additional lenses of mineralisation of similar size and grade (Jaguar and Bentley) that are currently in production. The new owner is Independence Group, a mid-size Western Australian company. Recently another WA exploration company, Sandfire Resources, announced the discovery in 2009 of a very-high-grade copper-gold VMS deposit at DeGrussa near Meekatharra, but in Paleoproterozoic volcanic and sedimentary rocks of the Bryah Basin, located north of

Figure 34. *Drilling to prove nickel reserves at Whundo.*

the Yilgarn craton. Initial drilling results included such outstanding figures as 9.1 m at 34.9% Cu and 3.3 g/t Au and 53.1m at 17.3% Cu and 2.5 g/t Au from chalcocite (Cu_2S) in the supergene zone near the surface. The mine began production of Direct Shipping Ore (requiring no on-site treatment) in February 2012 from the high-grade supergene zone in the open pit. A decline 1250 m long reached the massive sulphide ore at a depth of about 200 m in March 2012, showing the rapid pace of development. Total current resources of open-pit and deep-mine mineralization are 14.33 Mt at 4.6% Cu and 1.6 g/t Au. Exploration for additional VMS deposits is continuing at DeGrussa and by other companies in many other parts of the Yilgarn and Pilbara cratons.

The very large and complex Sedex-type Abra deposit was discovered in mid-Proterozoic rocks of the Bangemall Basin, between the Yilgarn craton and Hamersley, during a basin-wide search for base metal mineralization by Amoco Minerals in the mid-1970s, in response to the recognition that the rocks are of similar age and composition to those hosting the major Mount Isa deposits in Queensland (Boddington, 1990). Initial regional geochemical sampling proved disappointing, until GeoPeko joint ventured into the prospect and drilled a hole in 1981 into a discrete magnetic anomaly. There they intersected a wide zone of base metal mineralisation under 270 m of barren cover, including 27 m at 6.1% Pb, 194 m at 3.1% Pb and 19 m at 1.1% Cu with 3.68 g/t Au. Significant barium and iron oxide mineralisation is also present in the thick, hydrothermally altered, sedimentary sequence. Subsequent drilling has outlined large resources of 93 Mt at 4% Pb and 10g/t Ag and 14 Mt at 0.6% Cu and 0.5g/t Au. The site is now owned by Hunan Nonferrous Metals Corporation of China, but is yet to be developed.

The Magellan lead deposit, possibly the largest lead carbonate deposit in the world, was discovered in 1993 north of Wiluna. Mineralization is in a quartz sandstone and siltstone formation of the Proterozoic Yerrida Basin, situated between the Yilgarn craton and the Hamersley. It consists of zones of secondary lead carbonate (cerrusite) and sulphate (anglesite), and is interpreted to have originally replaced a carbonate-hosted base-metal deposit which became enriched in secondary lead minerals through prolonged and extensive weathering of primary base-metal sulphide

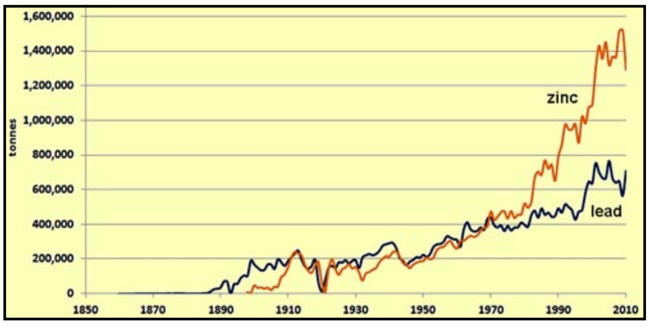

Figure 35*. Australian lead and zinc production to 2010 (after Mudd, 2009).*

minerals. Although mining commenced in 2005, the deposit is currently on care and maintenance, due in part to reported issues related to lead contamination at the Esperance port in 2007 and at the Port of Fremantle in 2010. It is currently owned by Ivernia of Canada.

The large Admiral Bay lead-zinc deposit was accidently discovered in 1981 when an oil exploration hole intersected a thick sequence of mineralized Ordovician carbonate rocks at a depth of 1280 m under a thick cover of Silurian and younger rocks in the centre of the Palaeozoic Canning Basin in northwestern WA (Connor, 1990). The mineralisation is associated with the major Admiral Bay growth fault. Subsequent drilling by CRA from 1986 to 1992 outlined a large resource with 10-20 m thick, upper zinc-dominant and lower lead-dominant, zones over a length of 20 km along the fault trace. The deposit is now owned by Kagara Zinc, which has established a resource of 72 Mt at 3.1% Zn, 2.9% Pb, 18 g/t Ag and 11% Ba; Kagara had intended to sink an exploration shaft, 6.7 m in diameter and 1400 m deep, to enable detailed underground reserve drilling to be carried out, but is currently in administration. The deposit is of the Mississippi Valley Type (MVT) class of platform carbonate-hosted lead-zinc deposits. Its discovery sparked a worldwide check of oil drill holes into carbonate reservoirs that might have also intersected mineralization, as the pale brown, iron-poor sphalerite might easily be missed in drill mud chippings.

Another large MVT province occurs on the northern edge of the Canning Basin in Devonian carbonates of the Lennard Shelf in the Kimberley District of WA. The area contained pre-mining zinc-lead resources of 41 Mt at 7.9% Zn and 3.2% Pb. A number of companies have worked several deposits in the area since the 1970s but all faced erratic and generally depressed base metal prices and difficult mining conditions in this remote area, so production has been sporadic. The deposits are now owned by Meridian Minerals which has established resources of 17.7 Mt at 5.5% Zn and 4.0% Pb. Meridian has recently been taken over by Northwest Nonferrous of China.

In the Phanerozoic Bonaparte Basin, located in the far northeast of WA, Sorby Hills is another MVT project. Although discovered in 1971, it still has not been developed. The current proposal is for open-cut mining to commence in 2013 on six of the thirteen separate but adjacent carbonate-hosted, near-surface lead-silver-zinc deposits. Current ownership is a 75:25 joint venture between KBL Mining Ltd (an Australian company) and China's largest silver and lead smelter, Henan Yuguang Gold and Lead Company.

Kimberley diamonds

Australia is not famous for its gem minerals, except for precious opal, which has been mined for many years. Coober Pedy was the earliest field found, in 1915, but was followed by Andamooka in northern South Australia, Lightning Ridge in New South Wales and

Figure 36. The open-pit at the Argyle diamond mine.

several minor localities in Queensland. Australia now produces around 95% of world gem opals. Coober Pedy is best known for white opals and Lightning Ridge for black opals. The opals formed by dissolution of silica during long periods of weathering of Cretaceous and other sedimentary rocks in the Tertiary period and its reprecipitation in nodules that gradually hardened over a long time. They occur as irregular patches and lenses of common opal, and rarely of precious opal. They are generally mined by individuals or small groups due to their irregular and unpredictable occurrence. Coober Pedy is famous for the underground miners' houses and churches that are favoured as escapes from extremely high temperature in summer.

Small numbers of alluvial diamonds have been recovered in New South Wales and elsewhere. Then the Argyle diamond pipe was discovered near Kununarra in the Kimberleys in 1979 after a seven-year search by Ashton Mining and then CRA (later Rio Tinto). The Kimberleys were chosen due to their similarity to areas hosting many African diamonds (Kimberley in South Africa and the Kimberleys of Western Australia were both named after the English Earl of Kimberley who was a prominent politician in late Victorian times). Panning of stream sediments was used as the main exploration technique. A number of small diamonds were found, leading to the discovery of several lamproite pipes in the Smoke Creek near Lake Argyle. In October 1979, the main Argyle AK 1 pipe was found, and the Argyle Diamond Mine was commissioned as an open pit in December 1985 (Fig. 36). The mine quickly became the world's largest diamond producer with outputs in excess of 30 M carats per year. However, only 5% were gem diamonds; the rest were brown and black industrial diamonds, known as bort. The mine soon became famous for producing almost the entire world output rare pink diamonds (described by the company as beyond rare). The mine's diamonds also tend to be small, so the larger pink diamonds, which make up less than 0.1% of the gem diamonds, command high prices in an annual tender process. In 2010 only 55 diamonds were available. A 12.76 carat pink diamond (the largest to date and valued at over $1M) was found in February 2012. The Argyle open pit is scheduled to close when an underground block-caving operation is developed for full production at 9 Mt of ore per year from 2013, extending the mine life to 2019 and beyond.

The Ellendale mine is another diamond mine in the Kimberley. Extraction from several lamproite pipes commenced in 2002 by Kimberley Diamond, and in 2007 the mine was sold to Gem Diamonds, a London-listed company. Ellendale is one of the world's best sources of highly prized fancy yellow diamonds, all of which are sold exclusively to the luxury jeweller Tiffany. The mine produced over 766,000 carats during its first five years of operations.

Olympic Dam – the mega-deposit

Western Mining Corporation, already known as leaders and innovators in Australian exploration, startled the mining world in November 1976 by announcing the discovery of a major copper deposit on Roxby Downs Station in South Australia. WMC had been spending an average of 56% of its profits on exploration through the 1960s and 1970s and was well known in the industry for encouraging research and supporting geologists to take higher degrees in areas relevant to their work. They had already been looking for copper since the early 1960s, with ventures in the Kimberleys, in the remote Warburton Ranges on the NT/WA/SA border and for Copperbelt-style deposits in cupriferous shales in the Hamersley Ranges. In 1969 a geologist, Doug Haynes), was given leave to study for a PhD, taking as his research the release of copper from basalt when magnetite is oxidised to hematite. By 1972 WMC had an exploration tool that enabled them to select potential copper-bearing areas. The idea was that oxidation and alteration of large volumes of suitable basalt might release copper that could migrate up faults into reducing sedimentary basins and deposit either syngenetic copper on the sea floor or epigenetic copper in suitable buried host rocks, such as carbonates (Fig. 37).

Figure 37. Endless and nearly flat desert in South Australia, beneath which was found the giant Olympic Dam orebody.

The Stuart Shelf in South Australia was chosen as a test area because it contains basalts in the southern part of the shelf that might underlie NeoProterozoic to Cambrian sediments on the shelf. The shelf also hosted a number of small sediment-hosted copper occurrences, as at Mount Gunson. WMC used the published government gravity and aeromagnetic surveys to indicate areas of denser magnetic rocks that could be basalts able to act as source rocks. An academic geologist, Tim O'Driscoll, had developed a system of structural analysis to reveal major tectonic lineaments. The Mount Gunson area showed interesting gravity and magnetic anomalies combined with a major WNW/NNE lineament intersection, but an even stronger one was found to the north in the Andamooka area on Roxby Downs Station (O'Driscoll, 1986).

A drillhole location was chosen, using the Olympic Dam (constructed during the 1956 Melbourne Olympic Games) as a water source (the next drill site was at Appendicitis Dam!). The hole, RD1, was drilled through 335 m of Late Proterozoic horizontal limestones, sandstones and shales before ending, on 30 July 1975. in 76 m of a dark-coloured breccia full of hematite but with no visible copper mineralization. This was initially thought to be altered basalt stripped of copper, and, while disappointing, at least proved the theory was correct. As there appeared to be no copper, the breccia was not analysed as a priority so two months elapsed before the results were completed. These came as complete surprise as they revealed that it contained an average of 1.05 % copper. The copper was present as fine-grained bornite, similar in colour to hematite, rather than as yellow chalcopyrite. However three more holes were drilled, and these found no copper. The fifth hole was similar to the first, but the next four were barren or of very low grade. The decision to drill the tenth hole was typical of WMC management at the time in supporting their exploration team and trusting to their judgement. The gamble paid off when RD10 intersected 170 m of 2.12 % copper. This was announced to the world at the WMC AGM in November 1976. Early in 1977, further analysis revealed completely unexpected and very significant contents of gold and uranium. This caused great problems for the anti-nuclear, labour, state government then in power.

Drilling continued with more misses than hits, but RD17, 19 and 20, drilled 2 km east of Olympic Dam, proved significant thicknesses of high grade mineralisation and confirmed the major scale of the discovery. BP entered a joint venture in 1979 to acquire 49% of the project by spending $300 million and in the same year the labour state government was defeated by the pro-mining liberal party in an election dominated by the Olympic Dam development. The Whenan exploration shaft, just 6.5 m by 3.5 m and named after Ted Whenan who had drilled RD1, was started in 1980 to provide access to the orebody for bulk samples and underground development drilling. In 1982 the first resource estimate was released of 2000 Mt at a grade of 1.6% Cu, 600 ppm U_3O_8, 0.6 g/t Au and 3.5 g/t Ag. The mine development continued to be a contentious

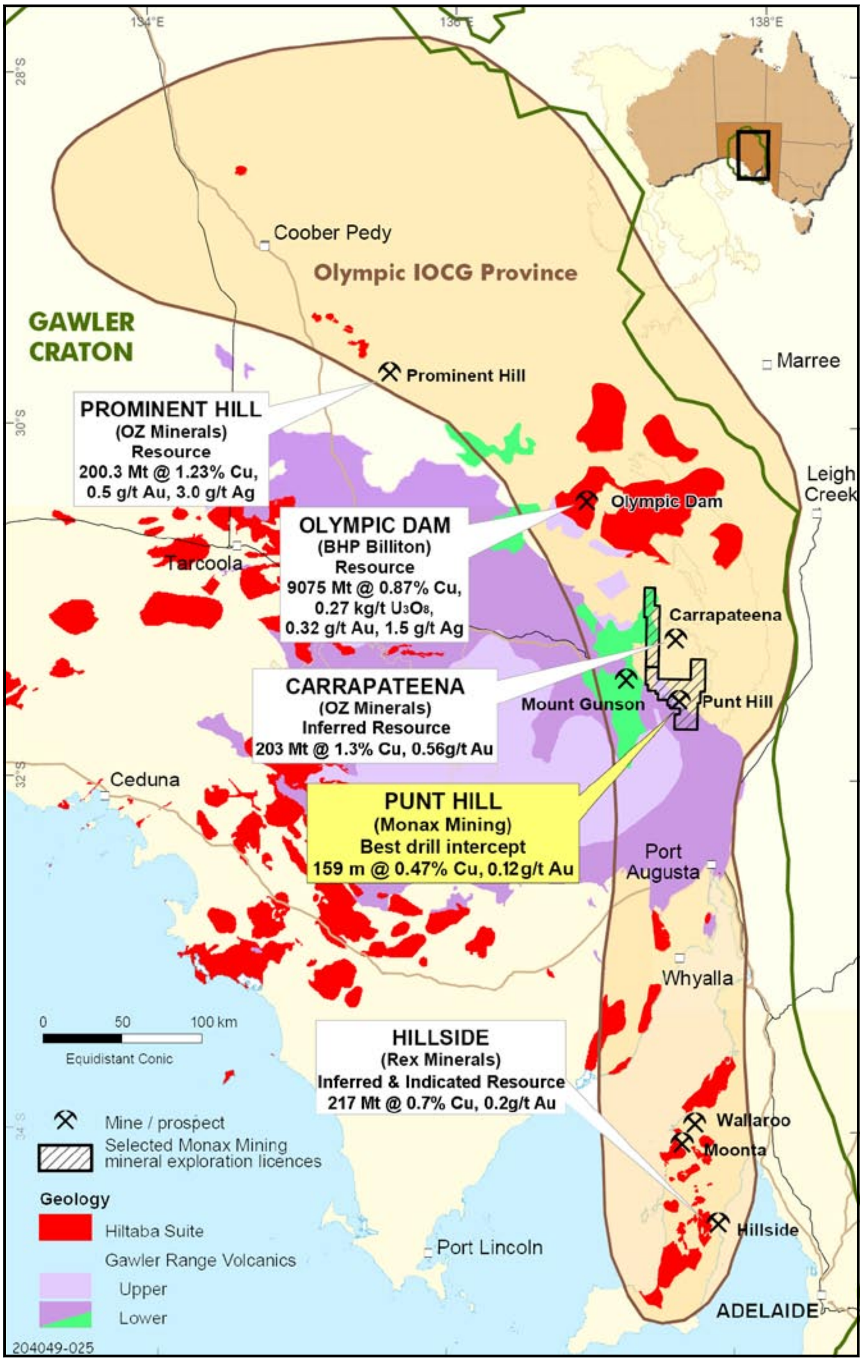

***Figure 38**. Geology of Olympic Dam and adjacent orebodies, (after Monax Mining).*

issue in South Australia, particularly due to the planned production of uranium, and there were demonstrations at the mine. However, both major parties supported the mine as a major contributor to South Australia's economic development for many years to come.

The decision to develop the deposit was taken in December 1985 and construction started in March 1986. The mine and processing plant were commissioned in 1988 at an initial rate of 45,000 t Cu, 1700 t U_3O_8 and 70,000 oz Au. This has been progressively increased over the years and the mine is currently operating at around 10 Mt/yr of ore at a grade of 1.98% copper and 540 g/t U to produce 220,000 t/yr copper, 4000 t/yr uranium, 80,000 oz/yr gold and 800,000 oz/yr silver.

Exploration over the years has continued to increase the overall resources of the deposit, which currently stand at about 9000 Mt containing around 80 Mt Cu, 2.45 Mt U_3O_8 and 93M oz Au. It is the largest uranium deposit in the world by far, and is the fourth largest deposit of both gold and copper. The deposit is largely confined to a hematitic breccia developed in sedimentary rocks associated with a NW-trending graben along a major crustal lineament. The rocks are extensively altered by hydrothermal fluids that may have been focused by the lineament (Roberts and Hudson, 1983). Apart from large amounts of iron, copper, uranium, gold and silver, the deposit also contains elevated amounts of fluorine and rare earth elements such as lanthanum and cerium.

WMC was taken over by BHP Billiton in 2005, and plans have recently been submitted to expand output further by developing an open pit mine producing 40 Mt/yr of ore to yield 500,000 t Cu, 15,000 t/yr U_3O_8, 500,000 oz/yr Au and 2.9M oz/yr Ag for well over 50 years. The open pit will require stripping more than 300 m of barren overburden to expose the ore and will eventually be 3 km long, 2.8 km wide and 1 km deep.

The discovery of such a large and unusual deposit has engendered much research both into its origin and as to whether other similar deposits exist. There is a general consensus that, among other factors, the Hiltaba Granite suite, major intersecting crustal lineaments, tectonic and hydrothermal brecciation and long-lived or successive pulses of basinal brines and metamorphic fluids have all played significant roles in the location and formation of the deposit. The Olympic Dam discovery led to the recognition of a new worldwide class of Iron Oxide Copper Gold (IOCG) mineral deposits. They are a varied group with hematite or magnetite as the iron oxide and all have significant contents of rare earths though not all have significant contents of uranium, copper or gold.

Several similar deposits have recently been found in the same general area and setting in South Australia (Fig. 38). The most important are the Prominent Hill and Carapateena deposits. Prominent Hill was discovered by the junior company Minotaur Exploration in 2001 under 100 m of cover and put into production by OZ Minerals as an open pit in 2009. Underground mining will commence in 2012. Ore reserves in June 2011 were 72.3 Mt at 1.13% Cu, 0.64 g/t Au and 3.03 g/t Ag, with total resources of 214.9 Mt at 1.23% Cu, 0.5 g/t Au and 3.5 g/t Ag.

Figure 39. *Australian copper production (after Mudd, 2009).*

The Carapateena deposit was discovered in 2005 by the small exploration group RMG, using funds from PACE, the SA Government drilling incentive. The top of the cylindrical deposit is 470 metres below surface and the deposit extends over a vertical depth of at least 1000 m. Teck Resources drilled 33 holes totaling 45,504 m to delineate an inferred resource of 203 Mt at 1.31% Cu, 0.5 g/t Au, 6 g/t Ag and 270 ppm U_3O_8 for the southern part of the partly explored deposit. The best hole intersected a spectacular 905 m at 2.17 % Cu and 0.89 g/t Au from a depth below surface of 506 m. The deposit was bought by OZ Minerals in 2011 who intend to develop it in the near future. A recent press release (15 February 2012) by OZ Minerals cites a drill hole intercept of 1060 m at 1.88% Cu, 0.69 g/t Au, 7.4 g/t Ag and 204 ppm U_3O_8.

Exploration is continuing in the area. A number of companies have land holdings and further discoveries have already been made, such as Tasman Resources and Rio Tinto's joint venture Vulcan prospect, where mineralization at low-grade but similar in style to Olympic Dam has been intersected in PACE-assisted boreholes at depths exceeding 850 m.

A similar IOCG deposit, Ernest Henry, named after an early prospector, was discovered near Mt Isa in 1993 during a contentious joint venture between WMC, Hunter Resources and Savage Exploration (a junior company). Savage had pegged a claim for iron ore in 1974 following a government aeromagnetic survey. They did little with it, and in 1989 WMC, who were looking for base metals, selected areas for detailed search. These included ground owned by Hunter Resources with whom WMC joint ventured as operator. WMC carried out a geophysical survey in 1990 which crossed into Savage's land, though no survey pegs were visible to mark it. WMC approached Savage in March 1991 for an option over various leases, including the area surveyed the year before. This was agreed in October 1991. Later that month the first drillhole put down by WMC intersected a major, intrusive, breccia-hosted, copper-gold deposit of Middle Proterozoic age on Savage's ground. Savage claimed that WMC had prior knowledge that the area was interesting. WMC conceded that errors had occurred and paid substantial damages (Metal Bulletin, 29 July 1993). It later sold its interest to Mt Isa Mines who developed the deposit. Ernest Henry originally contained 127 Mt at 1.14% Cu and 0.55 g/t Au, and was developed as an open-pit mine. Xstrata, who took over Mt Isa Mines in 2003, are converting the mine to a large underground sub-level caving operation to extend its life to 2024 with annual production of 50,000 t Cu.

A number of significant discoveries of copper-gold, Permian, sub-volcanic, breccia-hosted deposits have been made in northeastern Queensland near Charters Towers since the 1970s. The largest are Mount Leyshon and Kidston, both with resources of around 2-3M oz gold. The area was well known for small, low-grade gold deposits that had been worked since the 1870s with mines stopping at the water table (Teale and Lyons, 2004).

The WMC copper exploration initiative that discovered Olympic Dam also located the significant Nifty copper deposit in the Neoproterozoic Paterson Province of northern WA (near the Telfer copper-gold deposit) in the mid-1970s. This is a sediment-hosted, structurally controlled copper deposit with total resources of at least 60 Mt at a grade of 2.3% copper (Roach, 2010). It is now owned by the Indian company Aditya Birla Minerals and has an annual production of about 2 Mt of ore.

Cannington and Century

The Cannington orebody, discovered by BHP in 1990, is a major, mid-Proterozoic, sediment-hosted, silver-rich, lead-zinc deposit 250 km SSE of Mt Isa within the Diamantina Orogen. This orogen also hosts the Broken Hill ore deposit, and is thrust-faulted against the Carpentaria Orogen to the west which hosts the Mt Isa deposits. Cannington contained a pre-mining resource of 45 Mt at 11.1% Pb, 4.45% Zn and 500 g/t Ag and was commissioned in 1997 with full production by 1999. The underground mine is currently producing at a rate of 3 Mt/yr to be the world's largest producer of silver and lead with 6% and 7% of total world production respectively. Access is by a decline that is 5.25 km long and reaches to a depth of 600 m. The deposit is now owned by BHP Billiton and is a fly-in/fly-out operation. The trend towards this style developed in the 1980s to service small open-pit gold mines, thus avoiding the need to build a permanent township and to attract workers who would not live in an outback environment.

Century, discovered in 1990 by CRA Exploration, is a major, mid-Proterozoic, sediment-hosted, lead-zinc deposit 200 km NNW of Mount Isa, containing 105 Mt of ore at a grade of 12% Zn. The name refers to the 100 years between the first mining lease in the area and CRAE finding the deposit. It is now owned by Minmetals Resources of China. The area was known for minor lead veins in Cambrian carbonates but was not considered particularly prospective for stratiform deposits. The flat-lying, 45-m-thick orebody of laminated massive sphalerite and bituminous shale is contained within a mid-Proterozoic shale, siltstone and sandstone unit with a small and inconspicuous outcrop (Broadbent *et al.*, 1998). The ore contains almost no pyrite, so there was no conspicuous gossan to be noticed by earlier prospectors. Zinc soil anomalies were thought to be due to the minor lead veins until a sample of the discovery outcrop was analysed. The deposit was originally thought to be Sedex-style, but the strong bituminous content has led some people to consider that it formed well after sedimentation in an oil trap situation where zinc-rich metalliferous fluids were ponded in an organic-rich anticlinal trap. There was a long period of negotiation with Native Title claimants before development commenced in 2000, at a current rate of 500,000 t Zn per year. The orebody extends to 1.4 km by 1.2 km, and the open-pit mine is scheduled to close in 2015 as no extensions to the ore have been found. Minmetals Resources plans to replace its production by exploiting the Dugald River orebody,

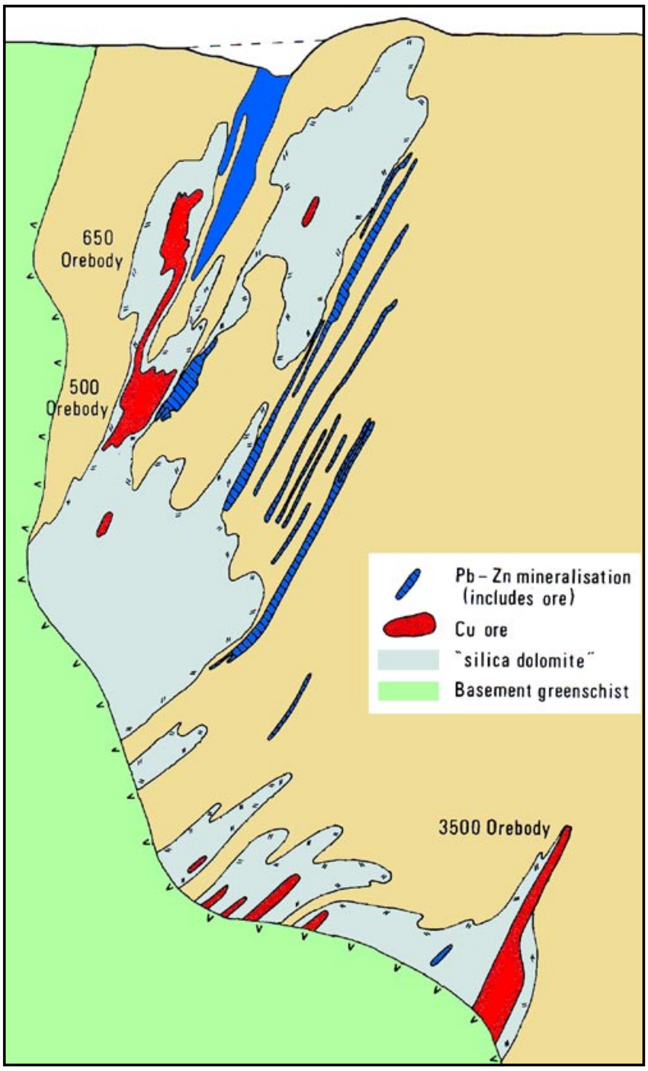

Figure 40*. Cross section, 1600m deep, through the series of orebodies at Mount Isa (after Perkins, 1990).*

another large Sedex-style lead/zinc deposit 100 km northeast of Mount Isa. This was discovered in 1881 and has been investigated by drilling intermittently since the late 1940s. It currently has resources of 48 Mt at 12.1% Zn, 2.1% Pb and 44 g/t Ag. The deposit is hosted in black shale and consists of a single lens over 2 km long and from 5 to 30 m wide which has been drilled to depths of at least 1000m. The mine life is estimated to be 23 years.

Mount Isa Mines continued to develop its adjacent lead-zinc and copper orebodies (Fig. 40). It was acquired by Xstrata in 2003 and currently annual output is about 6 Mt of copper ore from the Enterprise and X41 underground mines to produce 370,000 t Cu in concentrates and as anodes. Xstrata also extracts 8.6 Mt lead-zinc ore from the George Fisher underground mine and two open pit mines, to produce 355,000 t Zn in concentrates and 140,000 t of lead bullion with 6.8M oz Ag. The Enterprise mine reaches a depth of 1900 m making it Australia's deepest mine. In 2010 it had combined reserves and resources of 78 Mt at 3.3% Cu, and the X41 mine had 78 Mt at 2.1% Cu. The open-pit lead-zinc resources total over 100 Mt at a grade of about 7.5% Pb+Zn. The total pre-mining mineral endowment of the Mount Isa camp is around 400 Mt at grades of about 14 % Pb+Zn and 125 g/t Ag making it one of the world's largest base metal deposits (Huston *et al*., 2006).

More iron in the Pilbara

Exploitation of the Hamersley iron ore province has continued to develop and expand with the development of new ore bodies and new types of deposit. The already burgeoning iron ore output, boosted by demand from China, was further increased by the arrival of the Fortescue Metal Group (FMG) to join the original Rio Tinto and BHP companies. FMG developed a 24 Mt/yr mine at Cloud Break, a railway 250 km long and a new port at Port Hedland, all within just two years from 2006 to 2008. Their operations have already been expanded to 55 Mt/yr with a new mine at Christmas Creek, and there are plans for further increases and a new port near Dampier.

Figure 41. *Folded, sub-economic, banded iron formation exposed in the Hamersley Gorge.*

A 'Midwest' province of iron ore operations in WA is mining enriched portions of Archean banded iron formations east and southeast of the port of Geraldton. The first was by BHP in the 1960s at Koolyanobbing mine, north of Southern Cross, to supply its Kwinana steel works near Perth. This deposit is now mined by Cliffs Resources who export 8 Mt of direct shipping ore annually through the port of Esperance 600 km southeast of the mine. Other operations now export from the Jack Hills, Koolanooka, Extension Hill, Tallering Peak, and Karara, while a number of other deposits are under active exploration.

Annual Australian output of iron ore was 394 Mt in 2009, with the majority derived from the Hamersley Province (Fig. 17). This is 17% of world output and is backed by 34.5 Gt of Economic Demonstrated Resources, of which 80% are in the Pilbara Region and most of the rest is in other areas of Western Australia (Geoscience Australia, 2012).

The origins of the deposits have been investigated, and it is now thought that there were two major ore-forming periods in the Proterozoic and the Mesozoic (Kneeshaw *et al*., 2003). The older deposits generally have no relationship to present day topography, whereas the later ones have a strong correlation with it. Both formed by prolonged processes of supergene enrichment from the original 35% Fe to economic levels of over 60% Fe. Each period was accompanied by the development of irregular detrital deposits derived from the major bedded deposits. During Tertiary times additional detrital ores were deposited in drainage channels as long sinuous bodies, and many deposits of the various bedded, detrital and channel ores are now known. The original concept, of a broad basin with excellent lateral continuity of thin and thick beds over hundreds of kilometers in a low-energy chemical sediment environment, was challenged in the 1990s when high-energy carbonate and volcaniclastic turbidite beds attributed to volcanic eruptions and bolide impacts began to be recognized at a number of horizons through much of the sequence.

Gold again

A new copper-gold province has been developed since the 1980s west of Bathurst, NSW, based on the discovery of large-tonnage, low-grade, porphyry-copper deposits, similar to those mined in the Andes, but not previously recognized in Australia. The Northparkes deposit, near Parkes, was discovered by GeoPeko in 1982 in Ordovician andesitic volcanics and quartz monzonite porphyry intrusions. It is now operated by Rio Tinto, and comprises a number of ore bodies of disseminated chalcopyrite in quartz stockworks. An open-pit mine opened in 1992, followed by a series of block-caving underground mines in 1996, which operate at 5 Mt/yr at a grade of about 0.6% Cu. It currently has total reserves and resources of 440 Mt at 0.6% Cu and 0.3 g/t Au. Further exploration, including 140 km of drilling, is planned to extend the life of the mine beyond 2024.

Cadia Hill is a similar but larger deposit near Orange, and was discovered by Newcrest in 1992. Its open-pit mine is currently operating at around 16 Mt/yr at a grade of 0.6% Cu, while the underground block-caving Cadia, Ridgeway and Ridgeway Deeps deposit produces about 5 Mt/yr at the same grade. An even larger deposit has been discovered at Cadia East with total resources of 2300 Mt at 0.28% Cu and 0.44 g/t Au. This is planned to be a panel-cave mine operating at 16 Mt/yr with a life in excess of 30 years and will be the largest underground mine in Australia.

The Cowal mine, near West Wyalong and operated by Barrick in a major, porphyry-style gold deposit within Ordovician volcaniclastic and intrusive rocks, produced 298,000 ounces of gold in 2010. Reserves were stated by Barrick in 2010 at over 129 Mt containing 3.5M oz Au, with a mine life of at least 15 years.

Further exploration to the south, along the trend of the Lachlan Fold Belt, is revealing additional deposits of the porphyry class, including Dart Mining's Unicorn molybdenum-copper deposit near Corryong in northeastern Victoria which Dart claims has similarities to the major Henderson molybdenum deposit in Colorado. Current resources announced by Dart total over 100 Mt at 0.039% Mo, 0.057% Cu and 3.1 g/t Ag.

The old Victorian gold field, which had been moribund since the 1920s, was investigated from the late 1970s by WMC. They targeted the Bendigo field (Fig. 42), as this had been the most productive area with 22M oz from 11 parallel lines of anticlinal 'saddles' of quartz reef worked to around 750 m depth. The underlying idea was that the saddles carried on below this depth and that modern mining, pumping and processing techniques could recover large amounts of gold economically. WMC spent 15 years gathering data on over 2000 companies, modeled over 300 shafts and put down 45 km of drill holes without establishing sufficient mineable resources. This research was carried on by Bendigo Mining, which floated specifically to develop the Bendigo field. The company spent $105 million over 8 years drilling 110 km of boreholes, driving the Swan decline 5.5 km to a depth of 850 m to access one of the anticlinal lines, and analyzing a hundred 100-t bulk samples and 30,000 t of development samples. They estimated that 11M oz of gold should be present between 750 m and 1500 m depth with an average grade of at least 9 g/t, and they planned to recover at least 200,000 ounces of gold per year. However, when mining began in 2006 the results did not live up to expectations. The average grade for 130,000 t mined in six months was only 5.5 g/t at a total cost of $600 per ounce when the gold price was between $550 and $700. The nugget-rich nature of the gold-bearing mineralization caused severe problems in reconciling the grade estimated from drilling and trial mining to that actually achieved during production. Bendigo changed its name to Unity Mining in 2010 and is now operating at about 25,000 oz per year. The nearby Ballarat and Fosterville gold fields have also had a renaissance, and are currently in production by AuRiCo Gold at a rate of 100,000 oz/yr.

***Figure 42**. The farmlands of Victoria, where gold was once worked and new reserves are being found.*

Exploration in the fertile Mount Read Volcanics on Tasmania's west coast continued to discover new orebodies. The small Que River (3.3 Mt) and medium-sized Hellyer (16.5 Mt) high-grade copper-lead-zinc-silver-gold VMS deposits were found by Aberfoyle in the 1970s and 80s and are now worked out. The small but high-grade Henty orogenic lode gold deposit (2.8 Mt at 12.3 g/t Au), found by Renison Goldfields Consolidated in the 1980s, has already produced 1.2M ounces since production began in 1996. It is now owned by Unity Mining who are making additional discoveries.

Heavy mineral sands

A major new heavy mineral sand province was discovered by CRA in 1981 near the town of Horsham in southeastern Victoria. It occurs in Tertiary sands on the eastern edge of the Murray Basin, which occupies around 300,000 km^2 in southeastern Australia. Unlike the eastern and western coastal deposits, this was not a strand-line fossil beach deposit but is thought to be formed in an offshore basin during storms that resulted in the sorting of the various mineral fractions. The deposits occur in long, thin lenses. The province was found during regional exploration for a variety of targets, including gold in the pre-Tertiary basement and gold, uranium and heavy minerals in the Tertiary basin sediments (Williams, 1990). The deposits are unusual in being rich in rutile and zircon, rather than ilmenite, and the minerals are very-fine-grained, making them more difficult to separate than the coarser coastal deposits. The CRA leases were taken over by Iluka, and production started from the Douglas deposit in 2004; it currently achieves annual rates of 75,000 t of rutile and 70,000 t of zircon. Initial resource estimates were 4900 Mt at a grade of 2.8 % heavy minerals, but Iluka's current Murray Basin reserves and resources total around 300 Mt at grades of 12-24% total heavy minerals, of which about 50% are ilmenite, 15% rutile and 12% zircon.

Project	State	Output	Company
Kunwarara	Qld	100,000	Australian Magnesium Corp.
Main Creek	Tas	80,000	Pacific Magnesium Corp.
Arthur River	Tas	190,000	Crest Magnesium
Woodsreef	NSW	80,000	Pacific Magnesium Corp.
Leigh Creek	SA	50,000	South Australian Magnesium Project
Batchelor	NT	10,000	Mount Grace Mining
Latrobe	Vic	100,000	Latrobe Magnesium
Murrin Murrin	WA	NA	Anaconda Nickel

***Table 2**. Projects for producing magnesium, with outputs as annual tonnage, as proposed in 2001 (after Sandford, 2001).*

A number of other companies are currently exploring in the Murray Basin. Iluka has also discovered a similar but zircon-rich province (50% of the heavy minerals are zircon) along ancient shore lines of the adjacent Eucla Basin, also in Tertiary sediments, on the edge of the Nullarbor Plain. Total reserves are about 350 Mt at 4-6% heavy minerals made up of 50% zircon, 28% ilmenite and 5% rutile. The Jacinth-Ambrosia deposit came into full production in 2010 at a rate of 300,000 t/yr of zircon, which is about 25% of current world consumption. The ancient mineralized shoreline stretches over 1200 km from South Australia into Western Australia. Diatreme Resources recently announced a positive feasibility study for their Cyclone deposit, located in WA 25 km west of the SA border. Their project has the potential to mine ore at 10 Mt/yr for 10 years.

There was considerable interest at the turn of the century in the possibilities of major magnesium metal production from Australia in conjunction with developments in the automotive industry. A number of major projects were proposed (Table 2); all were based on mining magnesite except for extraction from chrysotile tailings at Woodsreef and from brown coal fly-ash at Latrobe.

None of these projects progressed beyond the feasibility stage, apart from Kunwarra which was abandoned in 2003 when only 5% complete. All were unable to raise the necessary finance, as their prospective automotive partners would not commit to buying magnesium until the metal was being produced.

Government support

The mining industry has been considerably assisted for many years by various research arms of the national and state governments. The national Bureau of Mineral Resources was established in 1946 and carried out a large number of small and large surveys in most parts of Australia. Initially focused on uranium exploration, it developed expertise in airborne magnetic and radiometric surveys which proved hugely useful during the nickel boom when the aeromagnetic map was frequently the only source of geological information for the prospector looking for slightly magnetic basic and ultrabasic volcanic rocks which might host nickel deposits. It was subsumed into the Australian Geological Survey Organisation when that body was formed in 1992, and then became Geoscience Australia in 2001. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) also carries out widespread research in geological, mineralogical, environmental and other issues of relevance to the minerals industry.

Each Australian state maintain some form of Geological Survey and Mines Department that carry out geological mapping, manage mineral licences and leases and maintain historical records of production data, drill cores and exploration information. From time to time they have also encouraged exploration with various forms of incentives, including paying for speculative drilling, carrying out targeted mapping programmes and creating promotional literature. These schemes can be found on the various state websites that are listed in the references. They also have increasing amounts of on-line data, maps and other resources, much of which can be freely downloaded.

The future

A large number of significant discoveries and developments have been made in Australia in the past 170 years, and the country is now a major producer and exporter of a wide range of mineral commodities. All of these discoveries, with the exception of Olympic Dam, Prominent Hill, Carapateena, Abra, and Admiral Bay, were located in exposed host rocks. There are substantial reserves and resources remaining around the existing deposits, and new deposits will be found in the vicinity but these will be largely exhausted over the next few decades. Many of the major deposits, such as Kalgoorlie, Mount Isa and Olympic Dam, occur adjacent to major, deep-rooted crustal lineaments or dislocations that focused the flow of mineralising fluids to enable the deposition of minerals in suitable host rocks and environmental conditions. Future exploration will have to develop methods of locating and investigating suitable host rocks and structural situations under increasing depths of barren cover. These methods will include more powerful and discriminatory seismic, magnetic and electromagnetic techniques, as well as more sophisticated geochemical methods to detect leakages of elements from concealed orebodies. Exploration over the past forty years has varied in intensity and target commodity, but expenditure is now approaching Aus$2500M annually (Fig. 43).

A recent trend has been the rapid acceleration in the depletion of ore deposits, exemplified by the working out of the major Century deposit in just 16 years between 2000 and 2015. This growing trend increases the urgency for the need to discover more major deposits capable of being worked economically at high rates.

Australia will continue to be a major producer and exporter of a wide variety of minerals and metals. It currently does not produce significant quantities of

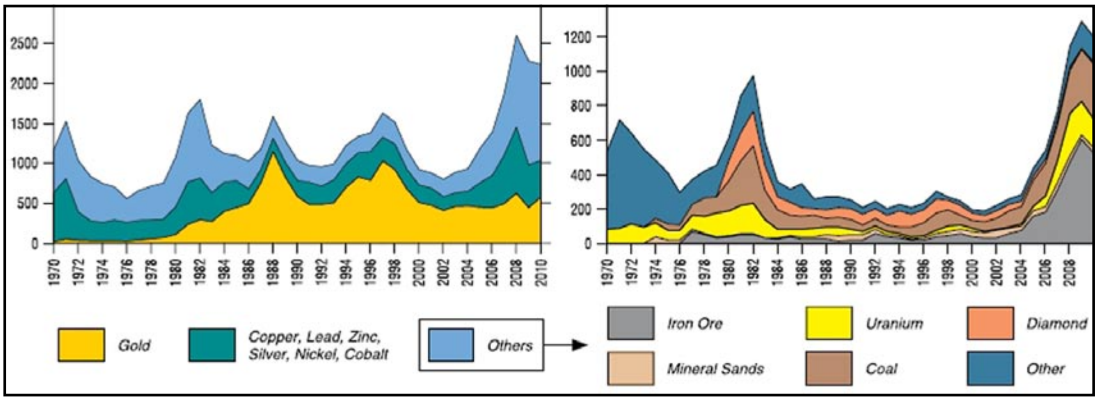

Figure 43. Annual expenditure, in M A$, on mineral exploration in Australia between 1970 and 2011 (after Senior and Huleatt, 2012).

potash, baryte, chromite, platinum group elements, rare earth elements, fluorspar, tin, tungsten, molybdenum and phosphate. However, there are known deposits with large resources of most of these minerals.

The Mount Weld deposit in WA is a world-class resource of rare earths, and initial mining commenced in mid-2008 with the ore currently stockpiled; processing is expected to commence soon. Newmont's recently discovered O'Callaghan deposit near its Telfer gold mine is a major, sub-horizontal, tungsten skarn deposit at a depth of 350 m below surface at the contact of granite and overlying limestone. It has probable reserves of 57 Mt at 0.34% WO_3 and indicated resources of 69 Mt at 0.34% WO_3 (Geoscience Australia, 2012). Moly Mines Molyhill deposit (formerly Spinifex Ridge) in the Pilbara is a world-class molybdenum resource with 650 Mt at 0.05% Mo, 0.08% Cu and 1.8 g/t Ag. There are several major titanium-vanadium prospects in WA of which the Barrambie deposit near Meekatharra with resources of 100 Mt at 0.82% V_2O_5 and the Speewah deposit in the Kimberleys with resources of 3600 Mt at 0.30% V_2O_5 and 2% Ti are the largest. The Cambrian-hosted Phosphate Hill deposit near Mt Isa, with large resources of 32% P_2O_5, has been worked sporadically since its discovery in 1966. It is now owned by Incitec Pivot Fertilisers who have recently developed an open-pit mine with a capacity of 900,000 t/yr to manufacture fertilisers using sulphuric acid from the Mount Isa smelter. There are also numerous promising platinum deposits, including the Munni Munni deposit near Karratha in the Pilbara; its resource of 24 Mt at 2.9 g/t Platinum Group Metals, in a large layered intrusion dated at 2920 Ma, was established by Hunter Resources in the 1980s. The deposit is now owned by Platina Resources, but no production has taken place.

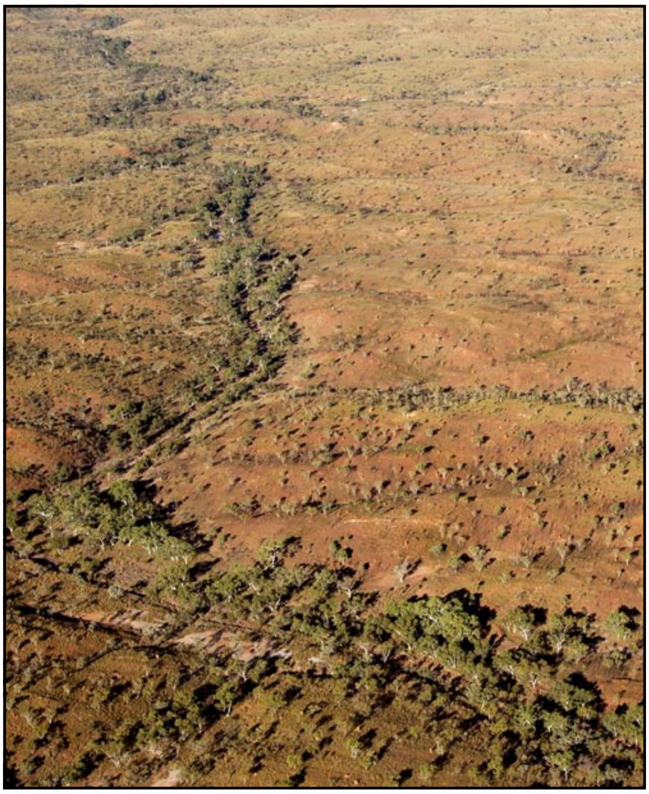

Figure 44. The Australian Outback, where mineral orebodies still await discovery.

The mining industry can have environmental problems. It is a major user of water, and conflicts have occurred over water use in agricultural areas, such as in the Orange and Cadia areas of New South Wales during periods of drought. Some trends can be anticipated, and there will continue to be increasing foreign ownership of Australian resources, particularly with the upsurge in Asian investment in the mining sector. It will continue to be a highly regarded country for mineral exploration and exploitation, though the recent hotly-debated federal Mineral Resource Rent Tax on profits from iron ore and coal, and the newly introduced Carbon Tax, are causing major mining companies to reconsider some of their future investment decisions. But however situations develop, Australia is sure to continue to be a major supplier of the world's minerals.

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Dr Gavin Mudd of Monash University Melbourne is thanked for access to his historic production statistics of Australian mining, from which production graphs have been made. Images have been kindly provided by Rio Tinto, KGMA and Copper Mines of Tasmania. The abundance of material on many company and national and state geological survey websites has been of substantial assistance. The author also thanks Prof Geoffrey Blainey whose book *The Peaks of Lyell* sparked his interest in Australian mining and its history. Two reviewers are thanked for comments that substantially improved the text.

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