The age of metals

Archaean to Palaeozoic metalliferous structures

Archaean

Early crustal tectonism was dominated by widespread igneous activity and metamorphism, which produced the distinctive volcanic belts (greenstones) and granite–gneiss complexes that typify Archaean shield terrains. Sediments are mainly of detrital material and banded iron formations. Archaean mineralisation resulted from a high level of igneous activity from a sulphur-rich mantle source.

Yilgarn and Pilbara Blocks

The Archaean is represented by the *YILGARN* and *PILBARA BLOCKS* of Western Australia, the oldest cratons in Australia. The chief economic minerals are nickel and gold, associated with the greenstones.

Gold province. Gold deposits are widespread in Archaean cratons, and are characteristically associated with the greenstone belts, more specifically with mafic rocks and their associated sedimentary rocks. Yilgarn gold has dominated Australian gold production. Historically, the richest deposits have been those within a major mineralised zone extending from **Norseman** to **Wiluna**, including the legendary 'Golden Mile' at **Kalgoorlie**. Nearly all of the gold deposits are closely associated with Archaean volcanic rocks. Silver, arsenic and antimony are common associates of the gold ores. The gold occurs in quartz lodes and, less commonly, in banded ironstone.

Lower grade ore left behind during early mining has become increasingly viable economically. Wide, low grade near-surface zones surrounding worked-out veins, for example at **Paddington** north of Kalgoorlie, are now major exploration targets.

Nickel sulphide province. Nickel sulphide mineralisation is largely confined to the ultramafic igneous rocks. The principal deposits are concentrated in the **Norseman–Wiluna** belt, especially in the **Kambalda** area; other important deposits occur at **Mount Windarra**, **Forrestania**, and in the **Agnew–Mount Keith** area. Cobalt, platinum and palladium accompany the nickel.

The economically significant deposits are either intrusive or volcanic. Intrusive deposits, represented chiefly by the **Agnew**, **Mount Keith** and **Forrestania** deposits, tend to be large and low to medium grade and are more suited to opencut mining. More attractive economically are the volcanic-associated deposits, which tend to be smaller, higher grade deposits mineable by underground methods, represented by **Kambalda**, **Widgiemooltha**, **Nepean** (mine reopened in 1985) and **Mount Windarra**.

Other minerals. Copper–zinc deposits occur at **Teutonic Bore**, **Mons Cupri** and **Golden Grove.** They represent early examples of volcanogenic base metal sulphide deposits.

Iron ore deposits formed by enrichment of parts of banded iron formations occur at **Koolyanobbing**, **Weld Range**, **Mount Gould** and elsewhere in the *YILGARN BLOCK*, and at Mount Goldsworthy (now worked out), **Shay Gap**, **Sunrise Hill** and **Kennedy Gap** in the *PILBARA BLOCK*. Vanadium–titanium–iron deposits are associated with mafic–ultramafic rocks (as at **Barrambie**). Also represented are pegmatitic tin, tantalum, tungsten, beryllium, molybdenum, lithium and niobium (as at **Greenbushes**, **Pilgangoora** and **Mount Mulgine**), and felspar (as at **Londonderry** and **Wialki**).

The barite deposits at **North Pole** are stratiform bodies associated with chert within a greenstone sequence. Metamorphosed limestones are a source of talc at **Three Springs** and **Mount Seabrook**. Magnesite occurs at **Bandalup**.

Strongly mineralised Archaean dolerite, Mount Charlotte gold mine, Kalgoorlie (W.A.)
Gold is associated with the altered paler rock surrounding the white quartz veins.

Early Proterozoic

The important mineral deposits of the Early Proterozoic were laid down in the sediments of basins surrounding the Archaean cratons or formed in orogenic zones. The metals represented are mainly iron, uranium, gold, copper and manganese. In the orogenic zones mineralisation associated with volcanic activity contained larger amounts of lead than formed in the Archaean.

Sediments were laid down in the *HAMERSLEY BASIN* concurrently with the development of mobile zones along the unstable north-eastern margins of the Archaean cratons. The mobile zones, which subsequently stabilised to form the North Australian Craton, are now exposed as the *HALLS CREEK PROVINCE*, the *PINE CREEK*, *ARNHEM*, *THE GRANITES–TANAMI* and *TENNANT CREEK INLIERS* and the *NICHOLSON BLOCK*. The *PATERSON PROVINCE* stabilised at about the same time.

Hamersley iron province. In the *HAMERSLEY BASIN* the sedimentary group containing the Hamersley iron ore deposits consist of a sequence of five main banded iron formations separated by shale, limestone and volcanics and now exposed over an area of 100 000 km^2. The ore, which is mainly hematite, occurs in the lower three banded iron formations. Deposits are most abundant in the south-central portion of the *HAMERSLEY BASIN*, where the intensity of folding and faulting is greatest. **Newman**, **Mount Tom Price** and **Paraburdoo** each contain over 1 billion tonnes of high grade (60–65%) iron ore.

A small proportion of the iron ore occurs as limonite—notably at **East Deepdale**, **Deepdale** and **Yandicoogina.** It accumulated by the fixation of iron in the beds of meandering rivers draining the Hamersley province during the Tertiary.

Economic resources of the *HAMERSLEY BASIN* total more than 20 billion tonnes, although this probably represents less than 0.1% of the original iron deposits of the basin; the remainder has been lost through erosion or exists as lower grade deposits or unenriched banded iron formations.

Kimberley Basin province. The sediments of the *KIMBERLEY BASIN* include iron formations which in **Yampi Sound** reach ore grade. Their origin is different from that of the *HAMERSLEY BASIN* ores, having formed as hematite-rich pockets of detrital sediment deposited concurrently with the enclosing rocks.

Pine Creek province. The *PINE CREEK INLIER* is extensively mineralised, with uranium, copper, silver–lead–zinc, iron, gold and tin–tungsten–tantalum–molybdenum all occurring. The deposits fall into three main types:

- The bulk of the uranium, gold, copper and iron is associated with sedimentary carbonaceous shales, including Australia's major uranium deposits—**Jabiluka**, **Ranger**, **Nabarlek** and **Koongarra** in the Alligator Rivers area east of Darwin.
- Much of the silver–lead–zinc was concentrated in pyritic carbonaceous shales by nearby volcanic activity and includes the **Woodcutters** and **Browns** deposits of the earlier mined Rum Jungle field.
- The third deposit type is vein mineralisation associated with granite intrusions later in the orogenic development. Minerals include gold, silver–lead–zinc, copper, tin and tantalum (**Bynoe Harbour**), and tungsten.

Tennant Creek province. The Tennant Creek field (gold–copper–bismuth) within the *TENNANT CREEK INLIER* encompasses nine major mined deposits, including **Warrego** and **Nobles Nob**, and about 120 smaller lodes distributed over an area of 3500 km^2. All known economic deposits in this field are associated with lodes in sedimentary and volcanic rocks and are typically composed of quartz, hematite and small amounts of magnetite.

Paterson province. Gold mineralisation of a different type, involving a two-stage process, occurs at **Telfer** in the *PATERSON PROVINCE*. Here, gold-bearing sulphides in deeply buried sediments were leached and the gold reprecipitated at higher grades in an oxidation zone near the surface.

Halls Creek province. Economically significant diamond-bearing lamproites occur in interactive belts bounded by major faults that were active in the *HALLS CREEK PROVINCE* from the Early Proterozoic to at least the end of the Palaeozoic.

The east Kimberley diamond area consists of a small group of kimberlites and lamproites, including the rich **Argyle** pipe, now the centre of a large scale mining project. The west Kimberley area includes a number of lamproites of varying but lower grade than Argyle, among them **Ellendale, Calwynyardah** and **Noonkanbah.**

Other mineralisation in the Halls Creek province includes lead–zinc–nickel (**Sally Malay**), copper and minor gold.

The Granites–Tanami and Nicholson provinces carry respectively gold and uranium mineralisation and uranium, copper, gold and tin mineralisation.

Middle Proterozoic

The Middle Proterozoic was notable for the formation of large sedimentary deposits of lead–zinc–silver sulphides, which are directly related to the increasing abundance of living organisms during this period. Sulphur fixation by algae and bacteria in the metal-rich seas caused an increase in precipitation of metalliferous sediments, typically in deep-water black shales.

In addition an increasing abundance of marine life in shallow seas was instrumental in the development of thick carbonate (limestone and dolomite) sequences, formed partly from the accumulation of their remains. These carbonate rocks became the loci for later stratabound and vein mineralisation, particularly of copper and uranium. Lead became proportionally more abundant in base metal associations while iron and gold, though still significant, waned in relative importance.

This increase in the abundance of primitive life forms also resulted in the formation of the earliest oil deposits. Oil of this age has recently been discovered in the *McARTHUR BASIN*.

Major tectonic events of the Middle Proterozoic were instrumental in the emplacement of the very large and economically valuable mineral deposits at **Broken Hill** and **Mount Isa**, and the more recently discovered **McArthur River** (N.T.) deposit.

At this time a large and probably continuous rift system opened up, extending some 1500 km from western New South Wales to the Northern Territory. Water depth in this extensive down-faulted rift varied over time and along its extent but salinity and dissolved metal content were generally very high. Lead–zinc–silver sulphides were deposited in the deeper parts while copper mineralisation associated with volcanic activity along the rift margins built up in the sediments of the shallower parts. Later, strong metamorphism caused by intense folding and faulting resulted in local concentrations of very large mineral deposits.

While these three major deposits all have similar histories, there are significant differences in their mineralisation. The paucity of copper at Broken Hill relative to the very large lead–zinc–silver orebody and certain stratigraphic differences suggest that the water was much deeper here than at either of the other two. The much larger copper deposits at Mount Isa and McArthur River are associated with siltstone–dolomite sequences laid down in much shallower water.

In the Willyama and Mount Isa provinces stratiform lead– zinc–silver is the dominant deposit type. Other major minerals are copper, iron, uranium, tin and tungsten; gold, cobalt and manganese are locally important. In contrast, mineralisation is dominated by stratabound gold and copper in the Georgetown province, and by iron, copper and gold in the Gawler Province.

Mount Isa province. At **Mount Isa** separate lead–zinc–silver and copper orebodies occur in pyritic and dolomitic black shales and siltstones at the top of a predominantly sandstone–volcanic succession. Similar lead–zinc–silver mineralisation occurs on a smaller scale at **Hilton**, **Dugald River** and **Lady Loretta**.

Willyama province. This province is extensively and very diversely mineralised. Apart from the large, rich lead–zinc–silver orebody at **Broken Hill**, lesser deposits of copper, tungsten, tin and uranium as well as minor gold, iron, nickel, platinum, beryllium, bismuth and barium (**Mount Mulga**) also occur. The extent and diversity of mineralisation become greater towards the south-east with increasing metamorphism.

McArthur Basin province. Stratiform lead–zinc mineralisation is widespread in the *McARTHUR BASIN*, but reaches significant grades and dimensions only in and around the **McArthur River** deposit. Other mineralisation includes a distinctive copper deposit in a volcanic breccia pipe at **Redbank**, uranium associated with dolerite-filled fault zones at **Westmoreland**, and sedimentary iron deposits at **Constance Range**, **Roper River** and **Hodgson Downs**.

Gawler province. Iron ore deposits similar to but more highly metamorphosed than those of the *HAMERSLEY BASIN* occur in the **Middleback Ranges**. The main deposits lie at the base of downwarps in strongly folded rock sequences.

Other Middle Proterozoic mineralisation includes numerous small granite-associated tin–tungsten–molybdenum lodes (at **Molyhil**), and vein and stratabound copper–lead–zinc (at **Attutra**) in the *ARUNTA BLOCK*; and vanadium-bearing magnetite (at **Jameson Range**) and lateritic nickel (at **Claude Hills**) associated with mafic intrusive rocks in the *MUSGRAVE BLOCK*.

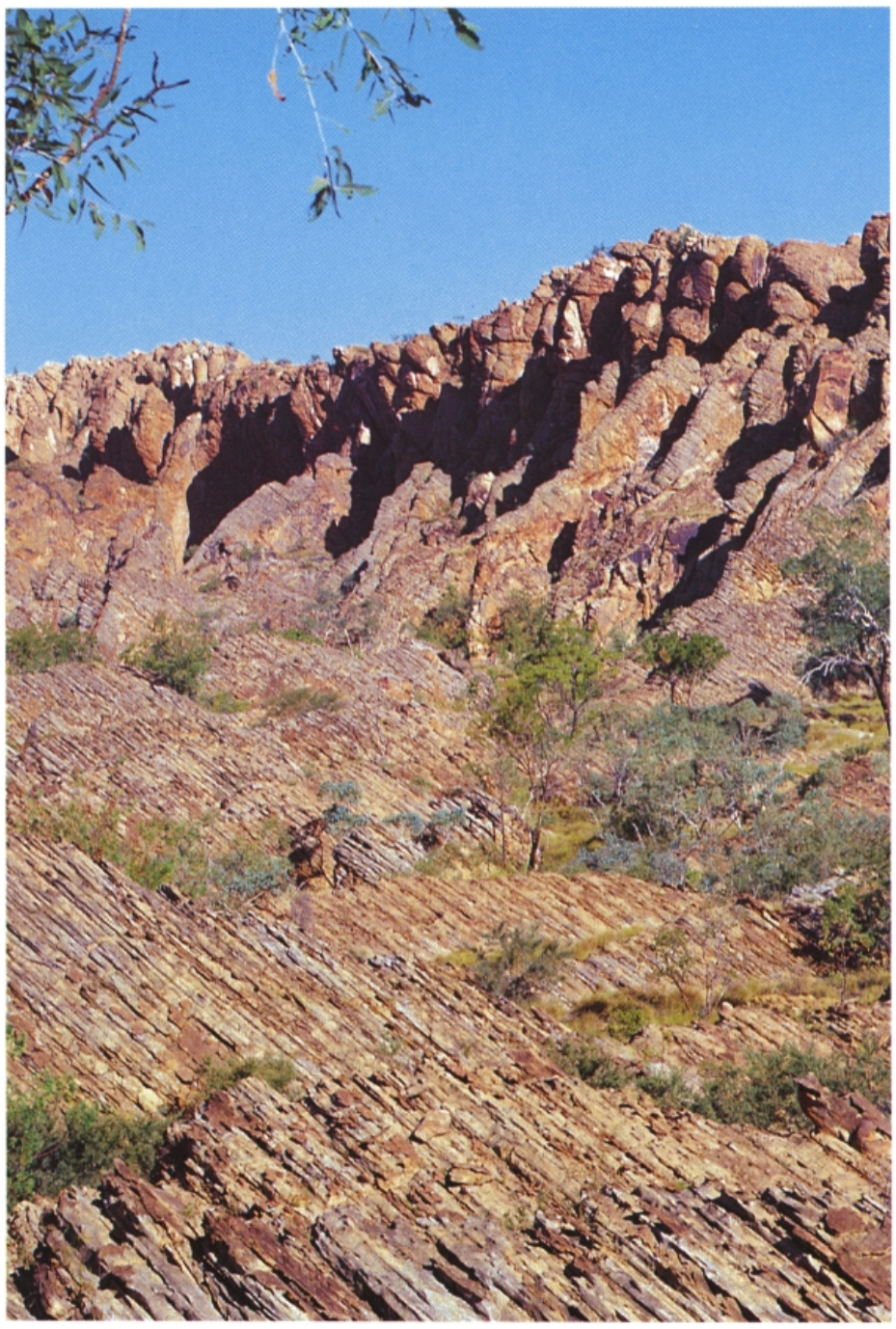
Even though mineralisation occurred during this period in the *GEORGETOWN INLIER* it was not until much later, in the Palaeozoic, that minerals were concentrated into deposits, by remobilisation resulting from extensive granite intrusions. This Palaeozoic mineralisation is discussed under *'LACHLAN FOLD BELT, Queensland'* on page 31.

Late Proterozoic

The Late Proterozoic was a time of world-wide consolidation of Precambrian (Archaean and Proterozoic) cratons. Uplift and erosion of the exposed cratonic areas resulted in the accumulation of extensive sequences of terrigenous and shallow marine sediments. The sequences contain abundant oxidised sandstones, evaporites and carbonates. Major stratabound copper and/or uranium deposits have long been known in association with these rocks overseas; recognition of this ore environment in the *ADELAIDE GEOSYNCLINE* and at **Mount Gunson** on the *STUART SHELF* led to the discovery of extensive stratabound copper–uranium–gold mineralisation at **Olympic Dam**, and elsewhere on a smaller scale.

STUART SHELF. The enormous copper–uranium–gold–silver deposit at **Olympic Dam** lies in hematite-rich, unmetamorphosed terrigenous sediments at the intersection of major structural lineaments. The deposit, of some 2 billion tonnes, contains an estimated 32 Mt of copper, 1.2 Mt of uranium, 1200 t of gold and 7000 t of silver.

ADELAIDE GEOSYNCLINE. Moderate mineralisation was introduced or reconcentrated during metamorphism, copper being the major metal. It occurs as small high grade vein deposits, previously mined at Kapunda, Burra and Blinman. Rich barite deposits also occur—as vein type (**Truro** and **Oraparinna**) or as stratiform associated with limestone. Gold, lead, zinc and silver are widely distributed but of minor importance. Altered limestones are a source of talc at **Mount Fitton** and magnesite at **Copley**, **Balcanoona** and **Robertstown.**



Rugged sandstone escarpment of the Abner Range, McArthur Basin (N.T.)
The Abner Range consists mainly of sandstones which are about 1500 m.y. old. In the mid 1980s the world's oldest known 'free' oil was found in Middle Proterozoic siltstones overlying these sandstones near the Roper River to the north-west.

Palaeozoic

Consolidation of the Australian Proterozoic cratons was followed by development of the composite Tasman Fold Belt, which cratonised progressively northwards and eastwards during the Palaeozoic. The Tasman Fold Belt is partly overlain by cratonic cover sediments, leaving exposed a series of blocks of different ages and with different metalliferous characteristics. These blocks are:

- the *KANMANTOO FOLD BELT* in South Australia and north-western New South Wales, which stabilised in the early Palaeozoic;
- the *LACHLAN FOLD BELT*, which stabilised in the mid Palaeozoic and also includes the *DUNDAS TROUGH* in western Tasmania and the *ANAKIE INLIER, LOLWORTH–RAVENSWOOD BLOCK* and *HODGKINSON FOLD BELT* in Queensland; and
- the *NEW ENGLAND FOLD BELT*, which stabilised in the late Palaeozoic.

These blocks contain a great variety of metalliferous deposits as well as important industrial mineral deposits, notably limestone, magnesite and clays.

Remnant orebody in the now worked out Mount Morgan copper–gold mine (Qld)
Since its discovery in 1882 this rich Middle Proterozoic orebody, situated in a belt of volcanic rocks, has produced over 250 t of gold—an Australian record. In 1981 the orebody was exhausted but retreatment of tailings in recent years has netted around 1.5 t of gold annually. The enormous crater, quarried from a hill and now partly filled with water, is 2.5 km long, 2 km wide and 360 m deep.

KANMANTOO FOLD BELT. In South Australia this fold belt consists of sediments laid down in a deep basin that formed on the southern portion of the *ADELAIDE GEOSYNCLINE*. Copper is the main metal, occurring as stratiform sulphides in slightly metamorphosed pyritic shales (at **Kanmantoo**), and in later remobilised vein deposits. Minor vein deposits of iron, gold, silver, lead, zinc, uranium, arsenic, mercury and barium also occur. Pegmatitic felspar occurs at **Gumeracha**.

LACHLAN FOLD BELT, Tasmania. Some deposits in north-western Tasmania may possibly be related to initial stages in the formation of the Tasman Fold Belt there, or be even earlier in age. These include the **Savage River** iron oxide–iron sulphide mineralisation in mafic volcanics.

Many of the mineral deposits in western Tasmania, however, are associated with sediments and volcanic rocks deposited in the *DUNDAS TROUGH*, a deep marine basin flanked to the east by a volcanic island chain. Major volcanic activity resulted in massive sulphide mineralisation including the deposits at **Rosebery**, **Que River** and **Hellyer** (lead–zinc–copper–silver–gold) and **Mount Lyell** (copper–gold). Mafic bodies intruding the trough sequence contain nickel (a minor, intermittent source of supply before World War 2), gold and osmiridium.

Late orogenic granites intruded extensively throughout Tasmania. In the west granite-associated mineralisation includes the major carbonate replacement tin ore bodies such as **Renison Bell**, which ranks among the world's largest primary tin deposits, **Cleveland, Mount Bischoff** and the tungsten skarn ore bodies of **Kara** and **King Island**, the latter associated with Palaeozoic granite intrusions into the older Proterozoic rocks. The fissure lead–zinc–silver veins previously mined at Farrell, Magnet and Zeehan are related to these granites.

A different style of mineralisation to that in western Tasmania is associated with the late orogenic granites which intruded in the north-east. Here, vein tin–tungsten deposits (as previously mined at Aberfoyle, Lutwych, Storeys Creek and Mount Oakley for example) are small though numerous.

LACHLAN FOLD BELT, Victoria. Australia's largest Palaeozoic accumulation of gold is contained in the Victorian part of the *LACHLAN FOLD BELT*. The lode gold occurs mainly as quartz veins or reefs. Much Victorian gold of the past was won from rich alluvial deposits concentrated by weathering and erosion of the lode gold ores. Arsenic is commonly associated with the gold in eastern Victoria whereas antimony–gold deposits are widespread in central Victoria.

LACHLAN FOLD BELT, New South Wales. The most important mineralisation consists of deposits of base metal sulphides formed by hot solutions permeating the sediments around submarine felsic volcanoes. They were deposited along the margins of ancient rift zones at **Cobar** (copper) and **Elura** (lead–zinc–silver), both extensively remobilised since deposition; **Woodlawn** (lead–zinc– silver–copper); and **Benambra** in north-eastern Victoria (lead–zinc–silver–copper).

Volcanogenic copper–iron sulphide deposits occur at **Girilambone** and **Cadia**. Gold and copper deposits formed by hydrothermal mineralisation occur in the **Galwadgere**, **Temora**, **Parkes**, Peak Hill, Forbes, Sofala–Wattle Flat (north of Bathurst), Wellington, Molong and Orange–Cargo areas of central New South Wales.

The granite batholiths that form the Snowy Mountains are poorly mineralised though deposits of tin (including **Ardlethan**), tungsten, gold and other minerals are associated with granites further west.

Serpentinite belts east of Gundagai host deposits of chromium (at Coolac) and, to the north, magnesite (at **Thuddungra** and **Fifield**) and platinum (at Fifield). Stratiform barite deposits are associated with felsic volcanics at **Kempfield** and **Gurrunda**. Pyrophyllite occurs in altered felsic volcanics at **Pambula.**

LACHLAN FOLD BELT, Queensland. Similar patterns of mineralisation are displayed in parts of Queensland where the *LACHLAN FOLD BELT* now lies exposed as the *ANAKIE INLIER*, the *LOLWORTH–RAVENSWOOD BLOCK* and the *HODGKINSON FOLD BELT*. However, volcanogenic massive sulphides are uncommon; the major mineralisation is granite-associated and occurs as abundant small but rich ore deposits. It is associated with Palaeozoic igneous activity that also affected adjacent areas of the Proterozoic *GEORGETOWN INLIER*.

High grade veins, pipes and skarns are abundant in zones surrounding the granite intrusions, and rich alluvial deposits of tin and gold derived from these hard rock lodes are widespread. Tin, tungsten and molybdenum occur at **Herberton**, **Wolfram Camp**, **Mount Carbine** and **Bamford Hill**, and gold occurs at **Clermont** and in the **Charters Towers** area. Gold is disseminated in sub-volcanic breccia zones at **Kidston**, now one of Australia's largest gold producers, and **Mount Leyshon**, and in skarns at **Red Dome**. Other mineralisation includes stockworks of porphyry copper–molybdenum, skarn deposits of uranium, and vein and skarn deposits of base metals. A volcanogenic base metal deposit, predominantly copper, occurs at **Balcooma**.

NEW ENGLAND FOLD BELT, New South Wales and Queensland. The important deposits of the New South Wales portion comprise vein and replacement mineralisation associated with extensive igneous activity. In the past this area has been an important Australian source of tin, tungsten, antimony and molybdenum. Mineral associations include antimony–gold–silver–arsenic (at **Hillgrove**), tin–tungsten–arsenic–silver (at **Tingha** and **Emmaville**) and gold–silver at **Drake.** Asbestos (at **Woodsreef**), chromite, talc and magnesite are associated with serpentinite belts north of Tamworth.

In the Queensland portion serpentinites north-west of Rockhampton host asbestos, chromite, talc and magnesite (**Marlborough**). Volcanogenic sulphides are represented by the once important **Mount Morgan** and Mount Chalmers gold–copper deposits near Rockhampton. Sub-volcanic and disseminated porphyry copper (with minor molybdenum and gold) mineralisation is abundant, mostly in small sub-economic deposits. The **Cracow** and **Mount Rawdon** gold deposits are subvolcanic, while **Gympie** gold is a sediment-hosted deposit.