

**ATLAS OF
AUSTRALIAN RESOURCES
Third Series**

Volume 3

AGRICULTURE



Division of National Mapping, Canberra, 1982

PREFACE

This volume presents Australian agriculture in the late 1970s from a geographic viewpoint. Most emphasis is placed on where the major crops are grown and the main types of livestock grazed, both in relation to each other and to climate, soils and landforms. This is in keeping with the underlying theme of the Atlas, which is concerned, as the title implies, with the spatial distribution of resources and their use.

Most of the maps have been derived to some degree from the 1:5 million scale map of land use in Volume 1, *Soils and Land Use*. Readers wanting a regional treatment of agricultural land use should find that volume of particular interest.

Agriculture in Australia lends itself well to presentation in maps because of its extent and the availability of uniform statistical information about many of its facets.

The volume might properly be dedicated to the farming community: underlying nearly all maps are statistics for shires (or their equivalents) aggregated by the Australian Bureau of Statistics from annual agricultural census forms returned by farmers.

Other sources of data were the many published maps and reports bearing on the nature and location of farming activities. Landsat imagery also proved to be useful. What a contrast there is between statistics derived from agricultural census returns and images taken from a satellite 900 kilometres above the earth, with each image providing a record of the land surface over an area of 34 000 square kilometres! With so much information available, it takes self-discipline to achieve a synopsis appropriate for a national atlas, especially one for a country with an area of 7.7 million square kilometres.

Many of the 21 maps in this volume deal with individual

items, such as wheat, or with several related items. But an understanding of Australian agriculture also calls for synthesis. Therefore, in dealing with grazing density, the author has used livestock units to equate beef and dairy cattle with sheep. Other examples of synthesis will be found in the maps of farm types and agricultural productivity, both of which are based on small-area statistics not previously available.

The nine maps at 1:10 million scale have also been published separately in National Mapping's *Australia Small Scale Thematic Map Series*.

In the previous edition of the Atlas comparable material for the late 1960s was presented in five large map-sheets and in five separate commentaries—'Croplands', 'Crop Production', 'Livestock', 'Sheep and Wool', and 'Grasslands'. Comparison of the present volume with these maps and those of the first edition, produced in the 1950s, not only highlights major changes in Australian agriculture over the last three decades but also indicates advances in geographic knowledge, cartography and printing.

The volume was planned and produced by National Mapping staff. On page 24 the author, Frank Bullen, acknowledges the valuable contributions made by those outside National Mapping—mainly staff members of CSIRO, the Bureau of Agricultural Economics and the Australian Bureau of Statistics.

Colleagues within National Mapping's Geographic Branch assisted the author in the preparation of map data and commentary material. Laurance Hazlewood supervised the geographic work and Murray de Plater, assisted in turn by Phil Woodward, Graham Leahy and Ruth Dodd, was responsible for cartographic production.

Trevor Plumb

Editor

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VOLUMES PUBLISHED

1. Soils and Land Use
2. Population
3. Agriculture

VOLUMES IN PREPARATION

- Climate
- Geology and Minerals
- Water

GENERAL INTRODUCTION

Settled agriculture, never practised by the Aboriginal inhabitants, was introduced to Australia by Europeans in the late 18th century. After early setbacks, due largely to the unfamiliar environment, agriculture has consistently provided almost all the food consumed domestically and, until the early 1970s, the bulk of export income.

Agricultural production has greatly increased in this century, and particularly since the Second World War, through large increases in improved pasture, cropping, fertiliser usage and irrigation, aided by scientific and technical advances. However, due to even greater increases in other sectors of the national economy, agriculture's contribution to the gross domestic product has declined from nearly 20% in the early 1950s to about 5%. Nevertheless agricultural products still form a large proportion of Australia's exports, amounting to about 40% by value in recent years.

Australia's 180 000 farms cover 500 million hectares, or about two-thirds of the land surface, and produced commodities worth \$A11 000 million in 1979-80.

Livestock have always formed the basis of Australian agriculture and still do, despite recent large increases in cropping. By far the largest proportion of agricultural land is used for grazing and, even where cropping is important, more than 80% of the land is grazed except in some of the small areas of intensive cropping.

The geography of Australian agriculture strongly reflects *effective rainfall*, which is the amount of rain available for plant growth after run-off and evaporative loss. Australia has universally hot summers and mild winters; temperatures low enough to stop plant growth only occur in relatively small upland areas of the south-east and Tasmania. Evaporative losses are accordingly high in summer and winter rain is more effective for plant growth and agricultural productivity. Even in the northern half of the continent, which receives much more rain in summer than in winter, the most productive areas are those which receive significant winter rain, as on the Pacific coast and hinterland of Queensland.

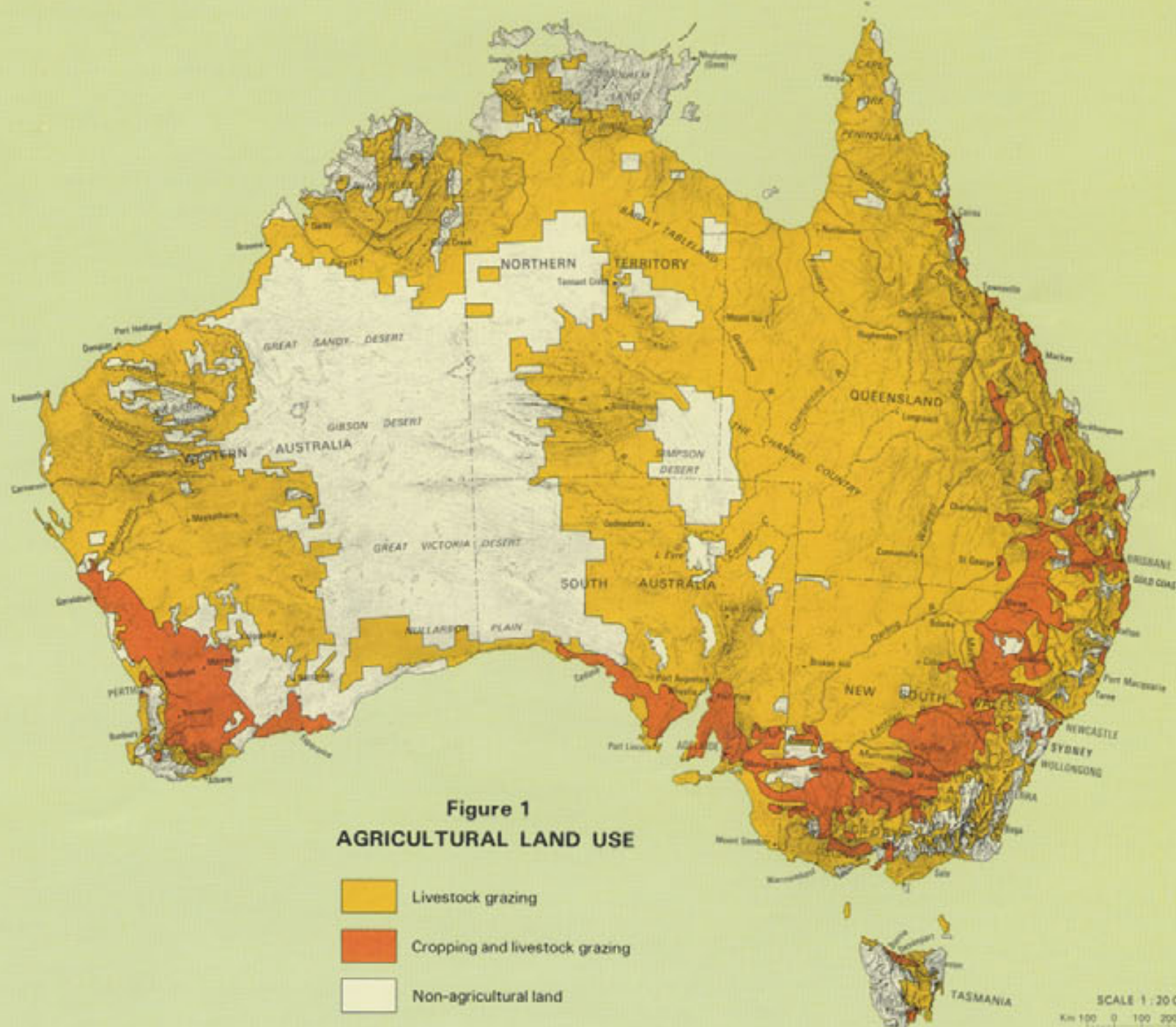
Australian agricultural land (Figure 1) can be broadly divided into three zones:

- The pastoral zone of the semi-arid inland and monsoonal north, where livestock graze on native pastures at low stocking rates and crops are virtually absent.
- The wheat belts of the sub-humid south and east, which contain most of the cropland. Even so, more than 80% is grazing land, much of which is sown pasture grown in rotation with crops. Stocking rates are, accordingly, much higher than in the pastoral zone.
- The high-rainfall livestock zones of the humid south and east, coastward from the wheat belts, where grazing predominates but which also contain relatively small areas of intensive cropping. The livestock are grazed mainly on permanent sown pasture, particularly in the south, and the average stocking rate is the highest of all three zones.

Most of the agriculturally unused land in the interior is desert, while nearer the coast it is mostly forested mountain and hill country.

The pastures, the resource upon which the grazing livestock depend, are described in the first topic of this volume. The spatial distribution and productivity of the main types of livestock and of the major crops are mapped and described in the following two topics. The final topic deals with the economic units of agricultural production—the farms—and with the economic productivity of farm land.

Nearly all the maps in this volume are based on data collected by the Australian Bureau of Statistics at the annual agricultural census of 31 March 1976. If available, figures for 1980 have been added in the text and tables. The 1976 figures were the most recent statistics when map compilation began and they refer to a year in which agricultural production was not abnormally affected by the weather. Much of Australia received above-average rainfall in the years immediately preceding 1975-76 but since then prolonged droughts have affected large areas.



Geology

*Speersburg and Skarrup
sandstone strata with
minor faulting exposed in
a road cutting near Pen-
ment House, Canberra.*



Four billion years of rock formation

For all life forms the most important zone of the earth is the thin outermost rocky shell—the earth's crust. Averaging only about 10 km thick under the oceans and about 30 km under the landmasses, the crust is relatively much thinner than the shell of a hen's egg. Importantly, however, the crust contains chemical elements that are essential for plant and animal life.

Oxygen and silicon are the most abundant elements, together comprising more than 75% of the crustal rocks, mostly in the form of silicate minerals. The most common of these is quartz (silicon dioxide). Eight other elements (aluminium, iron, calcium, sodium, potassium, magnesium, hydrogen and phosphorus) make up virtually all the remaining 25% of the crustal rocks. These elements occur in a large variety of combinations as rock minerals with an equally wide variation in composition and physical characteristics.

There are three main types of crustal rock, categorised according to their mode of formation—igneous, sedimentary and metamorphic.

Igneous rocks—the most common crustal rocks—have resulted from the solidification of molten material (magma) upwelling from below the crust. They have either been intruded into pre-existing crustal rocks or extruded onto the earth's surface and almost all are aggregates of silicate minerals with distinct crystalline structures.

Intrusive igneous rocks such as granite, which have cooled and solidified slowly while enclosed in the surrounding insulating crustal rock, are formed of large crystals. They have coarse-grained structures and relatively low densities.

By comparison **extrusive igneous rocks** such as basalt, which have formed from the rapid cooling and solidification of molten lava forced to the surface by volcanic activity, consist of small crystals. They have fine textures and relatively high densities.

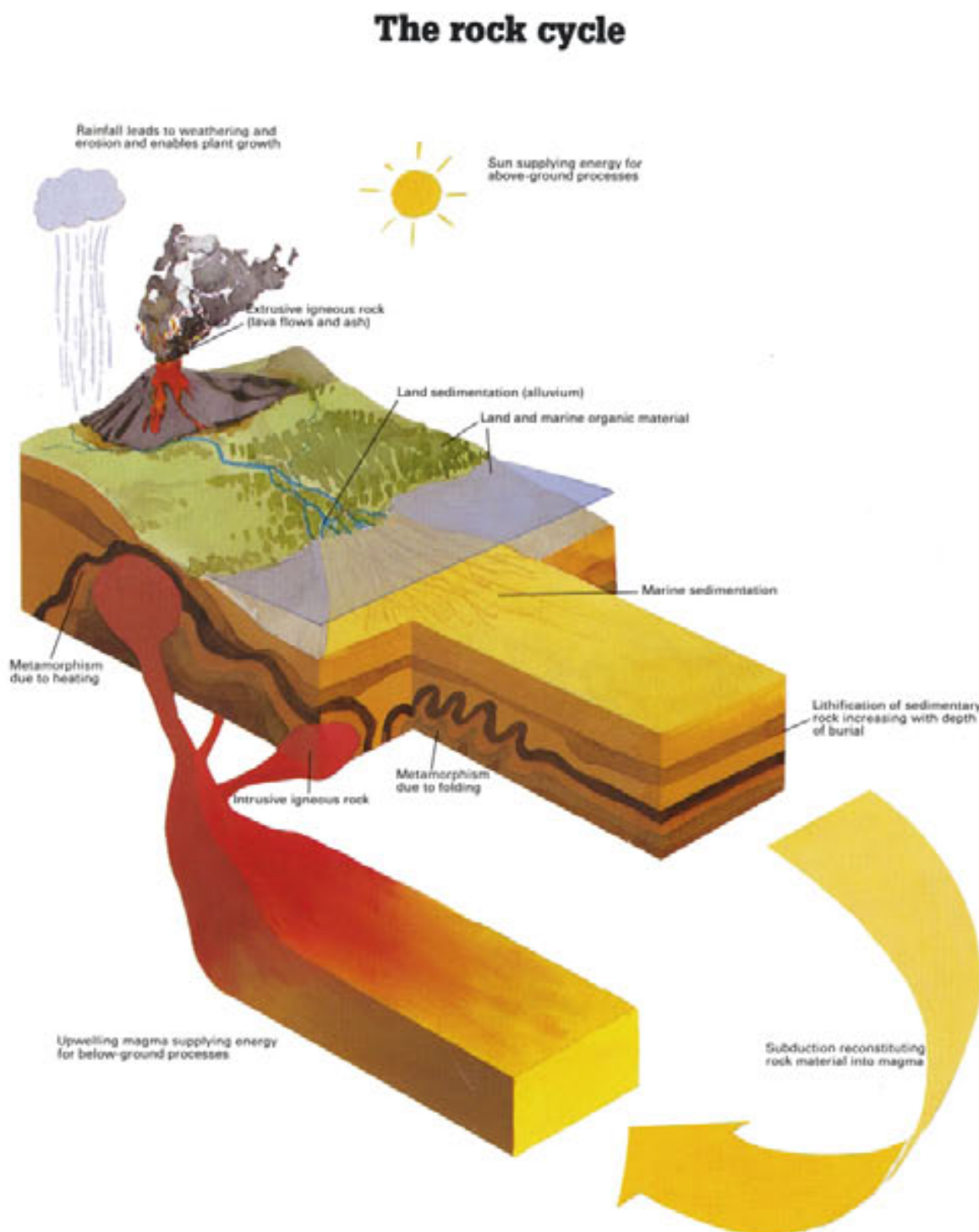
Igneous rocks are also broadly subdivided according to their chemical composition into acid or basic. **Acid rocks** (such as granite) have a large proportion of silica and are also termed *felsic* (containing much feldspar and silica). **Basic rocks** (such as basalt) contain much less silica

and, because they are often rich in magnesium and iron, are termed *mafic*.

Sedimentary rocks, as their name implies, mostly result from the deposition of weathering or erosional products of pre-existing rocks. They were mostly laid down in seas or freshwater lakes as sediments which later consolidated. Rocks formed in this way are termed *detrital* or *clastic*; sandstone is a common example.

Two other important types of sedimentary rocks have organic or chemical origins. **Organic sedimentary rocks** are composed of the calcareous remains of marine shells or corals forming fossiliferous limestone or of compressed plant material forming coal. **Chemical sedimentary rocks** have formed from chemical precipitation in seawater to form rocks such as crystalline limestone (from the precipitation of calcium carbonate) or chert (from a precipitate of silica). Rock salt and gypsum also belong to this type but result from evaporation of shallow seawater.

Metamorphic rocks have been formed by the alteration (metamorphism) of pre-existing rocks under conditions of extreme temperature and pressure caused by magmatic intrusion or tectonic activity. Metamorphism changes the texture (generally making the altered rock more flaky or plate-like) and increases the hardness and mineralisation. To a certain extent all rocks, except those formed in the most recent geological time, have experienced metamorphism and therefore degrees of metamorphism are recognised. For example a mudstone (a sedimentary rock) can be altered by mild metamorphism to a slate (a low grade metamorphic rock) or, under extreme conditions, to a gneiss (a high grade metamorphic rock).



Geological time

The earth's crustal rocks have been forming over a very long time—at least four billion years.

This long history of rock formation is conventionally divided into two eons, which can be further subdivided into eras and periods whose names were first applied by 19th century geologists working in the British Isles and Europe.

Some period names are derived from the names of ancient British tribes (for example the Cambrian, Silurian and Ordovician periods); others are named after areas or places where rocks of that age were first identified (for example the Devonian, Jurassic and Permian periods); while yet others were named according to the rock type most characteristic of the area where the periods were first studied in Britain (such as the Carboniferous, derived from the important British coal measures, and the Cretaceous, derived from the extensive English chalk deposits). Even though these names are not at all appropriate world-wide, they still remain in universal conventional use.

The two eons—the prime subdivisions of geological time—are termed the **Precambrian** (also called the Cryptozoic or 'time of hidden life') and, beginning about 570 m.y. ago, the **Phanerozoic** or 'time of obvious life'.

Up to the end of the Precambrian only life forms with soft bodies, such as jellyfish, worms and algae, had evolved so their fossilised remains in surface rocks are scarce and difficult to detect today. However, during the Palaeozoic Era, in the first part of the Phanerozoic Eon, life forms with hard shells, skins or bones evolved and as a result their fossilised remains are easier to detect and study.

By the beginning of the Mesozoic Era, some 200 m.y. ago, fish, insects, reptiles and land plants had evolved. This era was characterised by the large reptilean dinosaurs, though they became extinct at its end. The most recent era, the Cainozoic, which began about 65 m.y. ago, saw the main evolution of present-day land plants, birds and mammals including, most recently, mankind.

The following sections in this volume provide a brief overview of Australia's very long geological history, from about 3500 m.y. ago up to the present. The growth of the continent is traced through successive periods by deducing the changing distribution of land and sea, and the progression of crustal movements and igneous activity which together built up the land as we see it today.

The 1:5 million scale map 'Geology' shows the surface geology of Australia classified according to age of deposition of sedimentary rocks and in the case of igneous rocks their mode and age of formation.

The absolute age of igneous rocks can be determined by measuring the radioactivity of minerals within the rocks. Because radioactive elements disintegrate at a constant rate to give a known series of decay products it is possible, by analysis of some radioactive minerals in rocks, to estimate when the mineral was formed in the crust, thus giving the rock's absolute age.

Near the centre of the continent lies Ayers Rock (Uluru), one of Australia's most distinctive and best known geological features.

Ayers Rock is composed of sandstone laid down in the Precambrian. However, its present shape has developed gradually since the beginning of the Palaeozoic Era. Prior to this time the top of the

rock was probably level with the surface of the surrounding Amadeus Basin. It gradually became exposed as a result of the erosional lowering of the surrounding plains during the Palaeozoic and

Mesozoic Eras.

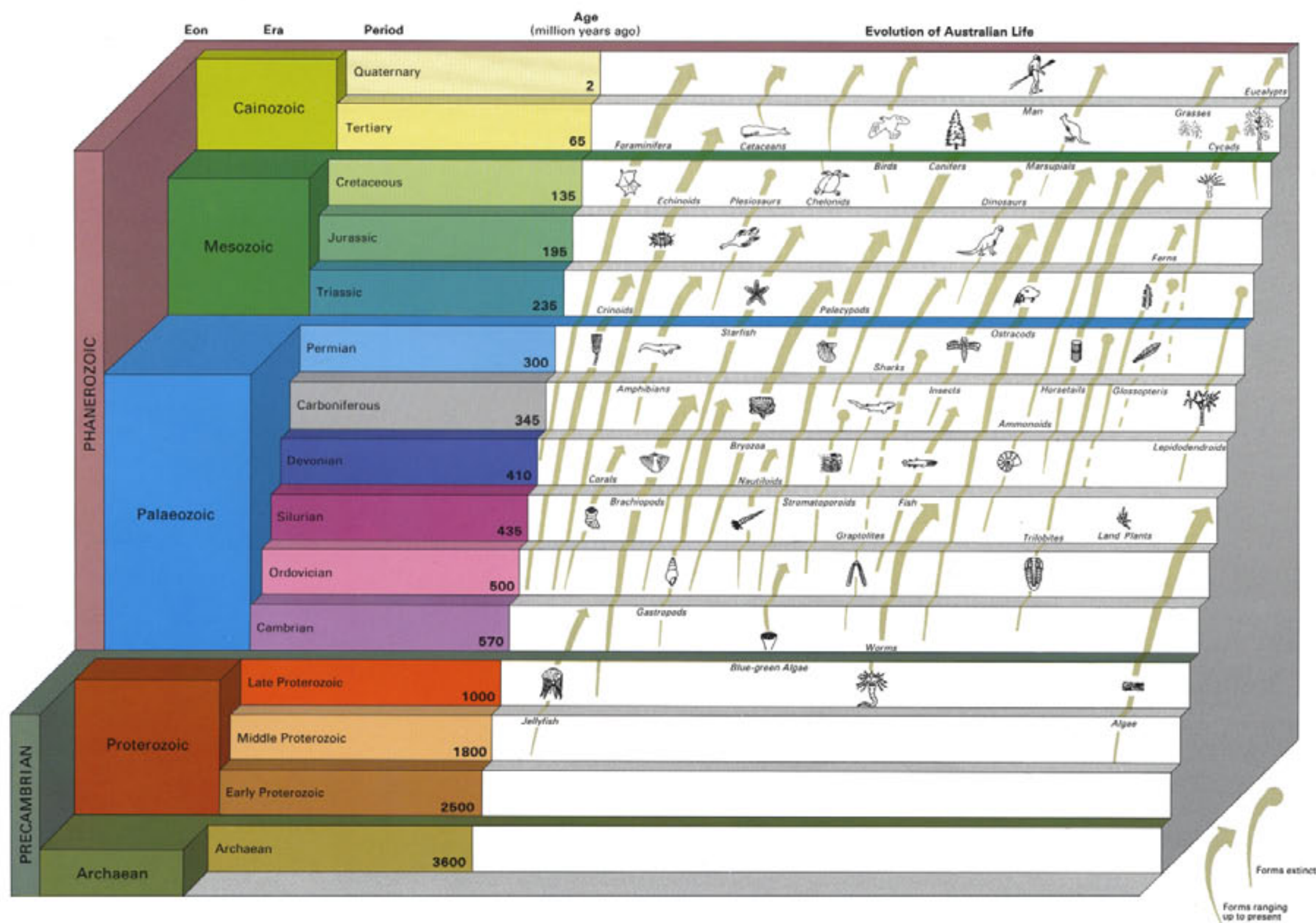
Ayers Rock was certainly in place by the end of the Cretaceous Period and has barely changed over the past 60 million years. The rock's resistance to

weathering, and in turn erosion by wind and water, stems from its massive structure and virtual absence of open joints.

Geological time is so vast in comparison to the time that mankind has been on earth that an analogy with a calendar year provides an interesting illustration. If the Phanerozoic Eon (which alone only covers about one-eighth of total geological time) was compressed into one year amphibians would be found crawling up onto the Australian continent for the first time in mid April; dinosaurs evolving in early July but then dying out in late October; and Aborigines migrating to Australia within forty minutes of New Year's Day.



Geological time-scale



A wandering continent

While measurements made today can give a very accurate estimate of crustal movement over the last 100 m.y. (the period over which most of the present oceanic crust has formed) and a fairly accurate estimate over the last 500 m.y., estimates of the global position and configuration of landmasses earlier than this are largely conjectural. Neverthe-

less, it can be estimated with reasonable confidence that around 500 m.y. ago Australia was part of a super continent (today called 'Gondwana') also composed of Africa, India, Antarctica and South America. Australia was a northward extension of this super continent, lying largely in the Northern Hemisphere and experiencing tropical conditions.

Earthquakes in Australia

Earthquakes occur when rocks move suddenly, usually to relieve pressure built up along fault lines and subductive zones. The vast proportion of earthquakes occur at tectonic plate boundaries though fortunately most of Australia is distant from this type of intense geological activity. However, 16 earthquakes of magnitude 6 or more on the Richter scale have been recorded in the last 100 years and, on average, 3.6 quakes exceeding magnitude 5 have occurred each year since 1960. The causes of such severe seismic activity on the otherwise very stable Australian crustal plate are not yet known.

The table below lists the eight most severe earthquakes that have caused property damage this century. Others of equal severity have occurred but in areas more distant from human settlement.

Damaging Australian earthquakes since 1900 and their relation to the Richter scale

Richter scale	Earthquake	Date	Intensity	Characteristic effects near epicentre
3			Unfelt	Detected only by instruments
			Slight	Similar to vibrations from heavy trucks
4	4.3 Lithgow (N.S.W.)	13.2.85	Moderate	Trees away; loose objects fall; slight damage
5	5.3 Warrnambool (Vic.)	14.7.03		
	5.4 Adelaide (S.A.)	1.3.54	Strong - very strong	Walls crack; some buildings collapse
	5.5 Robertson (N.S.W.)	21.5.61		
	5.5 Picton (N.S.W.)	9.3.73		
6	6.2 Cadoux (W.A.)	2.6.79		
	6.8 Tennant Creek (N.T.)	22.1.88	Destructive	Most buildings collapse; ground badly cracked
7	6.8 Meckering (W.A.)	14.10.68		
			Disastrous	Nearly all buildings collapse; landslides
8			Catastrophic	Total destruction

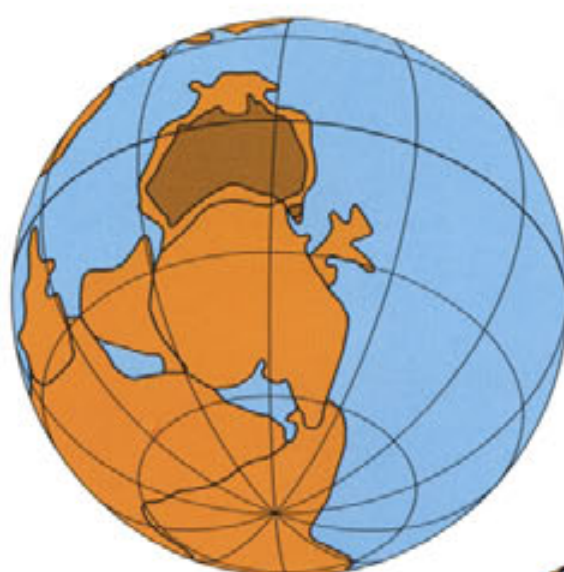
(Right) The most recent destructive earthquake, at Tennant Creek (N.T.) in January 1988, damaged buildings and services in the town and the nearby Alice Springs-Darwin gas pipeline. Total losses amounted to at least \$0.5 million.

(Far right) Spectacular faulting of the ground surface was caused by the severe quake at Meckering (W.A.) in 1968, when the town was virtually destroyed. The total cost of this earthquake, including damage which occurred in Perth, 120 km away, exceeded \$2 million.

480 million years ago



400 m.y. ago



Once good navigational charts of continental coastlines became available it was noticed that there was a close correspondence in the outline of many continents, particularly the east coast of South America and the west coast of Africa. This observation led to the theory that some of today's continents, including Australia, were once joined together as a super continent before gradually drifting apart over geological time.

While this theory was initially treated with scepticism the evidence for it is now overwhelming. Indeed, it is now possible to determine the movement of continents by very accurate measurement of intercontinental distances by laser ranging to the moon and orbiting satellites. These movements, averaging about 5-10 cm per year, are all that are needed to account for the extensive 'drift' of continents over the great length of geological time.

In addition to the close correlation of continental coastlines there is further evidence to support this theory. While flora and fauna of the southern continents are now largely dissimilar, related fossil plant types have been uncovered in many countries separated by vast oceans. This suggests that migration of species was easier in the past and that oceans did not separate the present continents.

Plate tectonics

The theory of continental drift is formalised in the study of *plate tectonics*, so called because the solid surface of the earth is now known to consist of about a dozen major 'plates' of rock, each moving separately.

These plates of solid rock consist of a thin veneer of crustal rock and a somewhat thicker layer (about 100-150 km) of denser sub-crustal rock (the *lithosphere*) resting on a much thicker layer of 'soft' rock (the *asthenosphere*). The asthenosphere consists of 'rock' in a plastic state due to the combination of great pressure and temperature and which, when occasionally squeezed to the surface as volcanic lava, changes to a liquid state with the reduction in pressure.

Within the soft layer there are narrow zones of convective activity sending up plumes of even 'softer' rock towards the surface. Where they reach the surface, magma is extruded as lava flows which solidify to form new crustal rock. Because this newly formed rock is denser than rocks forming the landmasses, it lies at a lower level and therefore forms the ocean floors. A near-continuous network of ridges—the *spreading margins*

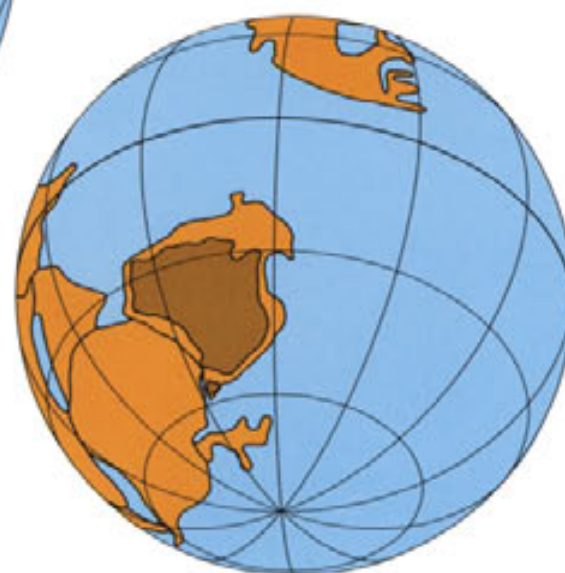
280 m.y. ago



Over the next 200 m.y. Australia, still part of Gondwana, drifted steadily south to very near the South Pole and experienced glacial

conditions in Carboniferous and Permian times. Australia then drifted generally northward but still as part of Gondwana.

200 m.y. ago



The super continent began breaking apart about 160 m.y. ago, though Australia and Antarctica remained attached to one another for about another 100 m.y.



shown on the accompanying map 'Major World Tectonic Plates'—occurs along this zone of volcanic activity, which lies mostly in the centre of the oceans.

Ocean floor crustal rock is continually solidifying and pushing previously formed rock away from both sides of the mid-ocean ridges. Platforms of crustal rock forming the continental landmasses such as Australia 'float' on the oceanic crustal and lithospheric rocks because they are less dense and are carried along on this moving carpet of denser rock. This process continues until the lithosphere and its floating platform of continental crust meet another crustal plate. Here one plate rides over the top of the other, driving its leading edge back down into the asthenosphere in what is termed a *subductive margin*. At the conjunction of continental plates major mountain building may take place, for example the Himalayas where the Eurasian Plate is overriding the Indo-Australian Plate. Where oceanic plates collide massive trenches may form at the subductive margins and some, such as the Mariana Trench east of the Philippines, are up to 10 km deep. Island arcs are often formed through associated volcanic activity.

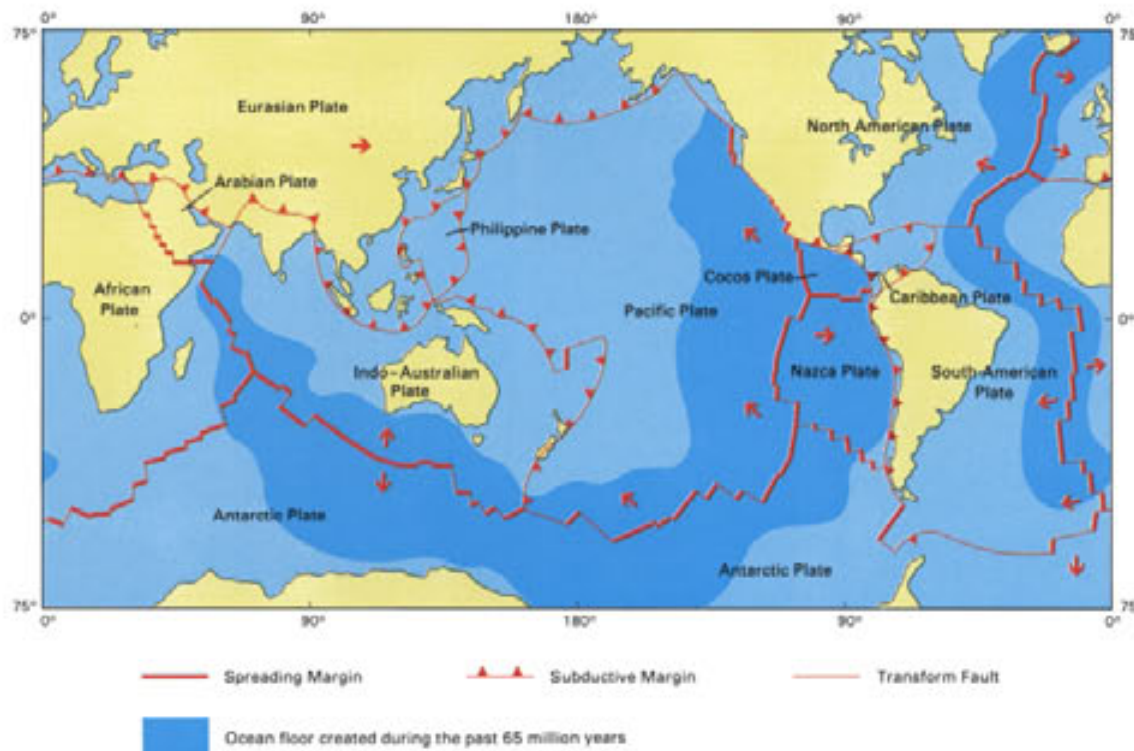
Alternatively the two plates may merely rub against each other along an extensive *transform fault*. Such faults are, nevertheless, regions of potentially hazardous earthquake activity as more sudden plate movements can quickly result in massive urban destruction and loss of life. Perhaps the most famous is the San Andreas fault in California, U.S.A. Over a long period the relative displacement of plates along transform faults may amount to hundreds or even thousands of kilometres.

The Indo-Australian Plate is currently experiencing both subductive and transform fault activity at its edges. The Australian continent, however, is considered to be relatively stable and at low risk from major earthquakes because the

landmass is generally distant from the plate margins. To the north-west it is being driven underneath the much larger Eurasian Plate. Here a deep oceanic trough has formed where Indo-Australian rock is being forced downward by the Eurasian Plate. But immediately to the north a line of islands (the Indonesian Archipelago) has formed as a result of intense volcanic activity associated with this subduction. Here crustal rock and much seawater have been returned to the asthenosphere from where, under intense heat and pressure, they have been forced back to the surface by violent volcanic eruptions.

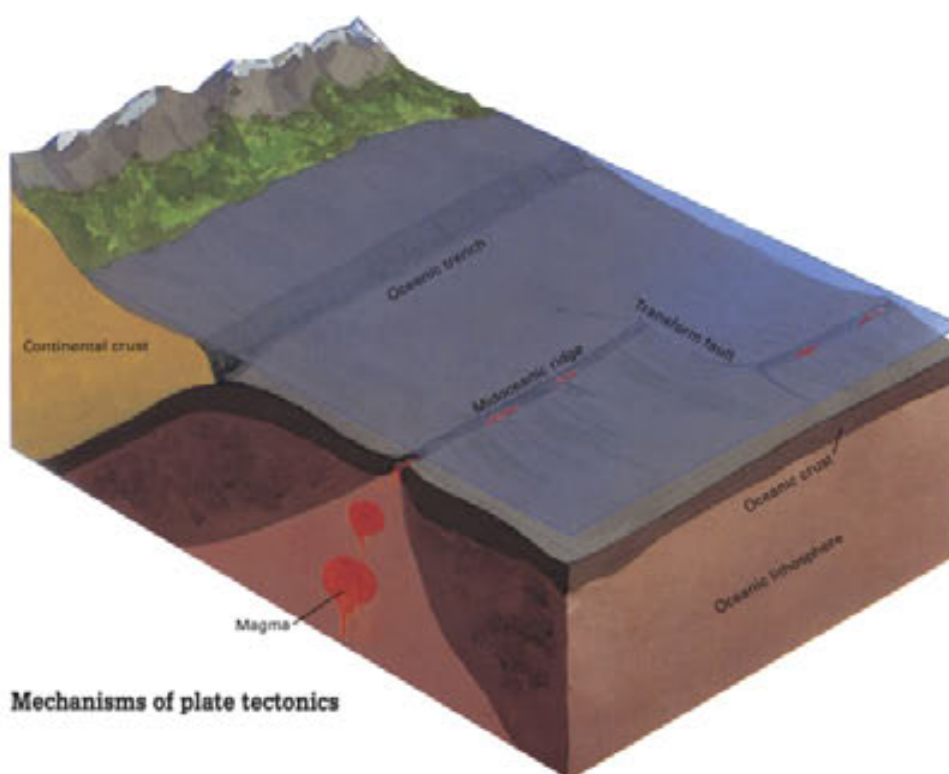
On the other hand, further east, where the Indo-Australian Plate is rubbing against less massive plates, transform faulting and crustal deformation (the strong folding of crustal rocks) is occurring. This has resulted in vigorous mountain building activity and some, though less violent, volcanic activity has given rise to the highlands of New Guinea and the New Zealand landmass.

The present global position of Australia is the result of many millions of years of floating on a moving carpet of denser rock. Its previous global positions can be estimated from the study of fossilised magnetic fields in rocks that contain easily magnetised minerals (most commonly iron). As igneous rocks solidify, their mineral components susceptible to magnetisation take on the local direction of the earth's magnetic field. Thus their latitude and orientation relative to the poles at the time of their formation can be measured. Also, because the earth's magnetic polarity reverses several times each million years (that is, magnetic 'north' becomes magnetic 'south' and vice versa), the chronology of the formation of oceanic crustal rock, which is highly magnetic, can be measured and interpreted in a way similar to the study of tree growth through annual growth rings.

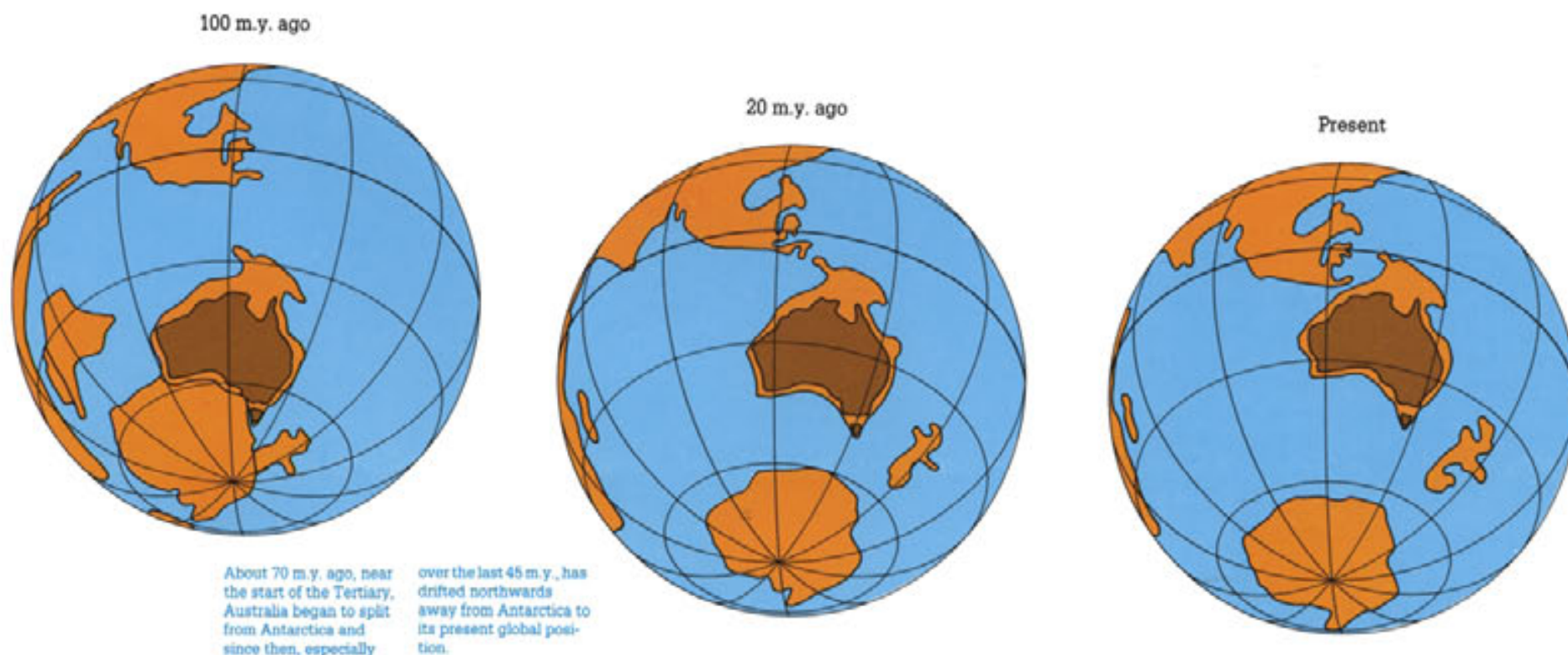


Major world tectonic plates

Adapted from Flint and Skinner (1974), Long (1974), and Plummer and McGeary (1985).



Mechanisms of plate tectonics



The building blocks of a continent

Cratons, the primary building blocks of a continent, are major structural units of the earth's crust. They generally consist of igneous and metamorphic rocks that have evolved through a cratonisation cycle of sedimentation, deformation, metamorphism and volcanism, gradually stabilising over millions of years. Those which make up the Australian continent are shown on the map 'Major Australian Cratons'.

As the cratons have stabilised, weathering and erosion have led to the accumulation of layers of relatively undeformed sedimentary rocks in broad downwarps over the surface of the craton. These craton covers, called basins on geological maps, are the secondary units of the continental crust. As the covers are derived from pre-existing rock they are merely rearrangements of the continental crust rather than additions to it.

Although Australia is everywhere

underlain by the major cratons much of the surface is now covered by craton covers, often leaving isolated blocks of exposed cratons as inliers of older rock surrounded by much newer cratonic cover rocks. The exposed cratons and craton covers that make up the surface of the continent are shown on the map 'Major Structural Elements'; the companion cross-section illustrates the relationship between them in south-eastern Australia.

Australia's cratons and craton covers

Cratons and craton covers formed during two major structural regimes: an older one which existed during the Archaean and Proterozoic, and a younger one spanning the Palaeozoic, Mesozoic and Cainozoic. Five major cratons and their covers belong to the older regime—the Pilbara and Yilgarn Blocks, the North Australian Craton, the North-East Orogens and the Central Australian Mobile Belts. The Tasman Fold Belt (which forms most of eastern Australia) developed during the younger regime.

The sequence of craton formation is generally one of eastward evolution from Archaean in the west to Cainozoic in the east. The oldest craton stabilised about 2300 m.y. ago at the end of the Archaean and is represented by the exposed Pilbara and Yilgarn Blocks in Western Australia. This craton may extend to the north and east below younger cratons and parts of it are probably represented by the oldest rocks in the Pine Creek Inlier (N.T.) and the Gawler Block (S.A.)—see 'Major Structural Elements' map.

At the time that craton covers, such as the Hamersley and Napperu Basins, were being formed on the stabilising Yilgarn and Pilbara Blocks the North Australian Craton began to develop in adjacent unstable regions. This craton eventually stabilised during Early Proterozoic times, about 1750 m.y. ago. Today, areas of this craton remain exposed as The Granites-Tanami, Tennant Creek and Arnhem Inliers, the Nicholson Block and the Halls Creek Province. The Kimberley Basin and parts of the Napperu Basin are the initial older cover of the craton while the McArthur, Birindudu and South Nicholson Basins represent younger cratonic covers. The Gawler Province and the Curnamona Craton stabilised at the same time as the North Australian Craton.

The North-East Orogens stabil-

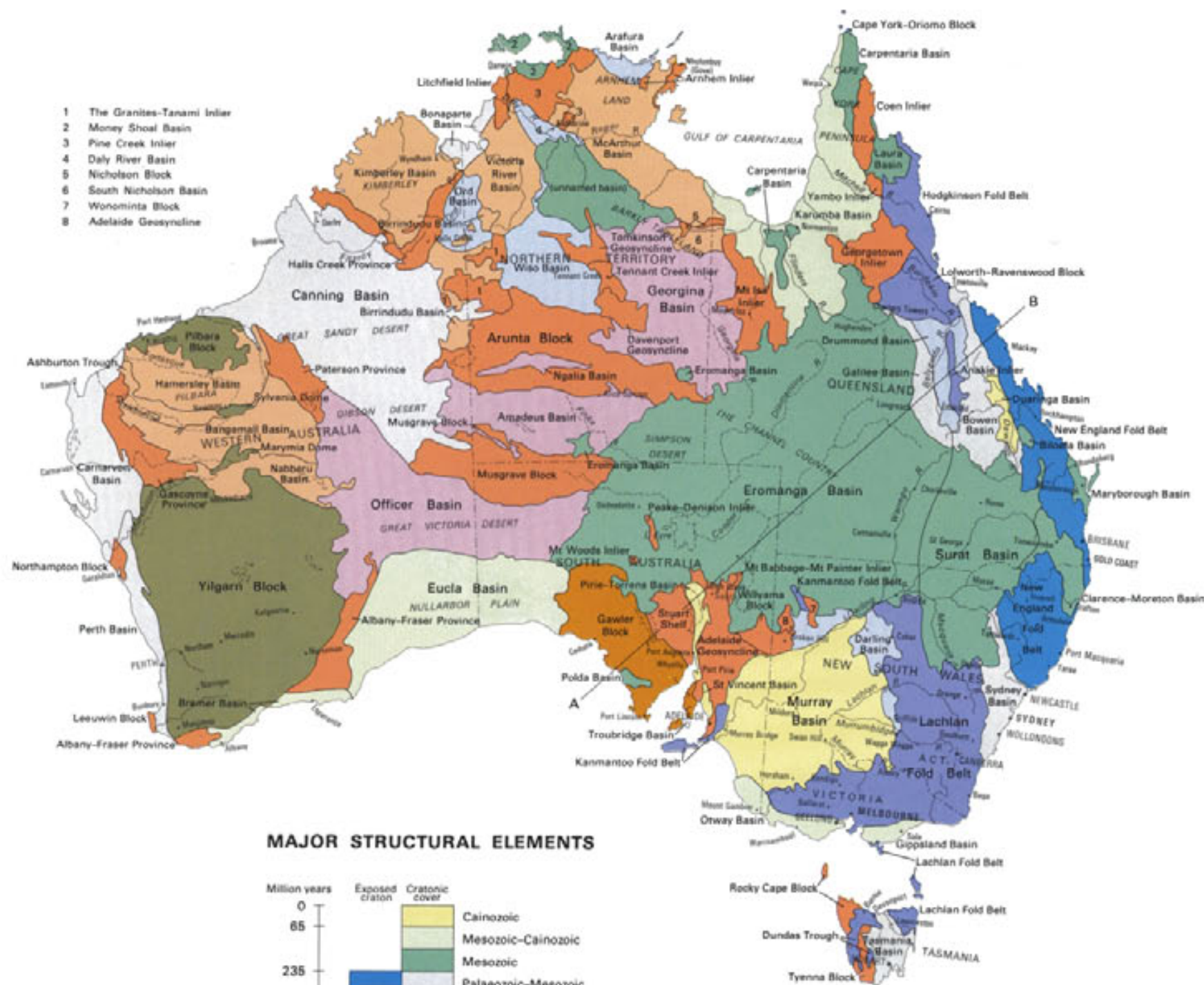
ised about 1200 m.y. ago in Middle Proterozoic times and are exposed today as the Mount Isa, Georgetown, Yambo and Coen Inliers. They are similar to the North Australian Craton and can be regarded as part of it. The craton cover that followed this stabilisation is preserved as the Victoria River and Bangemall Basins.

The Central Australian Mobile Belts are sandwiched between and draped around the older cratonic blocks in zones that remain relatively unstable. The Albany-Fraser Province and the Arunta and Musgrave Blocks represent the oldest parts; rocks of the Northampton Block are much younger, while the Leeuwin, Rocky Cape and Tyenna Blocks and the Mount Babbage-Mount Painter Inliers are younger still. The major craton covers are the Georgina, Amadeus and Officer Basins. Stabilisation of the mobile belts around 900 m.y. ago marked the end of cratonic development in the older regime; then followed nearly 300 m.y. of continental stability.

The exposed Palaeozoic to Mesozoic cratons of the younger regime shown on the 'Major Structural Elements' map are part of the Tasman Fold Belt. The oldest cratonic elements of this belt are the Dundas Trough and Kanmantoo Fold Belt. As these elements stabilised eastward, sedimentary trends continued, forming the Lachlan and Hodgkinson Fold Belts. Again, as these belts stabilised sedimentation had begun for the youngest Australian region—the New England Fold Belt.

Just as the cratonic elements of the Tasman Fold Belt developed successively so did its cover, much of which overlaps onto the Proterozoic and Archaean cratons. Some of these relationships are shown by the cross-section on page 11.

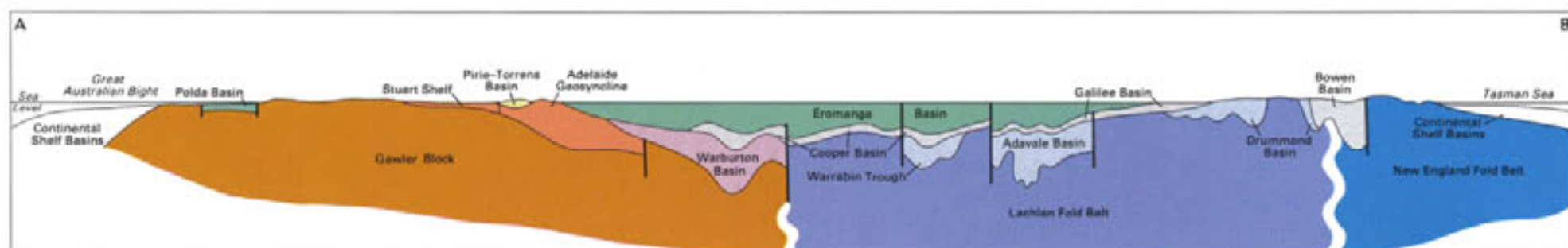




SOURCE: Adapted from map 'Major Structural Elements' (1979) in BMR Earth Science Atlas of Australia.

Generally the locations of Australia's mineral and fuel resources are closely related to particular structural elements. Many metallic mineral deposits such as those of copper, iron and gold occur in complexes of deformed igneous and metamorphic cratonic rock. On the other hand, fossil fuels (oil, natural gas and coal) have formed in the sedimentary basins of the craton covers.

The distribution of known mineral deposits and their host geological structures are shown on the accompanying two 1:5 million scale maps 'Minerals other than Fuels' and 'Fuels'.



Relationships between cratons and cratonic cover in south-eastern Australia

Adapted from Bureau of Mineral Resources (1979c).

The terms used to describe the cratons on the 'Major Structural Elements' map give an indication of their origins.

Blocks are stable areas of cratonic rock bounded by faults. Where portions of cratons are exposed at the surface and surrounded by younger rocks they are referred to as **inliers**. Blocks and inliers are the oldest exposed areas of rock, formed

during the Archaean and Proterozoic and found predominantly in western and central Australia. **Province** is the term used when the origin of the craton has been obscured by metamorphism and deformation.

Basins are large depressions which have formed on the surface of craton covers, usually as a result of broad down-warping prolonged by extensive periods of sedimentation.

Geosyncline, trough, fold belt and dome describe the most conspicuous attribute of the region so named. Geosynclines and troughs are generally deep, long trenches containing particular kinds of sediments and volcanics. Fold belts are regions where layers of rock have been severely folded as a result of surrounding crustal pressure and

movement. Apart from the Adelaide Fold Belt, which is a zone of folded cratonic cover rocks, all of the fold belts shown on the 'Major Structural Elements' map are exposed parts of the Tasman Fold Belt, the most easterly craton. Domes may form as a consequence of folding, the term specifically applying to underlying dome-shaped rock masses.

Orogens are geosynclines which have undergone metamorphism, deformation and a mountain-building phase, eventually stabilising to form cratons.

Mobile belts may contain any of the features so far described. The term implies that the region has been more unstable than most other areas. Central Australia, for example, was unstable for millions of years.

Surface rocks

Australia's land surfaces, as elsewhere on the earth, consist of varying proportions of hard rock, loose unconsolidated sediments and soil.

A knowledge of lithology—the study of the physical and chemical composition of rocks—helps in the

understanding of the history and structure of the earth's crust. Many mineral deposits of economic impor-

tance, for example, are found in certain types of rock. Rock type also influences soil fertility, the quantity and quality of groundwater, soil stability for engineering projects such as the building of roads and dams, and the availability of construction materials.

The map 'Surface Rocks' opposite shows in a generalised way where the main kinds of rocks and derived material occur. The rocks are broadly classified into five major categories according to the main processes by which they were formed.

Igneous rocks



Igneous rocks originate deep within the earth. They are forced through pressure into the upper layers of the crust or onto the surface, generally as a hot fluid or plastic mass which subsequently cools and solidifies into a hard, dense crystalline rock.

Volcanic (extrusive) rocks

- extruded as lava onto the land surface and sea floor
- having solidified quickly they are typically fine-grained and may have a glassy texture

Acid volcanic rocks

- have a high silica content, are light in colour and have solidified from lava of low viscosity
- mostly evident as exposed volcanic plugs, e.g. rhyolite

Basic volcanic rocks

- have a low silica content but are generally rich in iron and manganese minerals and hence dark in colour; have solidified from lava with a high viscosity
- occur most commonly as extensive basalt lava flows

Intrusive rocks

- solidified lava intruded into surrounding rocks and exposed at the surface by erosion
- occur as extensive sheet-like layers or large broadly spherical bodies (batholiths)
- having solidified slowly they are usually coarse textured, with large crystals

Acid intrusive rocks

- high in silica and hence light coloured and coarsely textured, often with large crystals
- most commonly granite, occurring at the surface as large exposed batholiths forming mainly upland areas

Basic & ultrabasic intrusive rocks

- have a low silica content but are richer in iron and other metallic minerals; usually coarsely textured, dark crystalline rocks
- commonly dolerite (though not as widespread as granite), usually occurring as dykes and sills in association with basic extrusive volcanic activity

Sedimentary rocks



Sedimentary rocks are produced by the cementing of unconsolidated sediments (generally under the weight of overlying material) into a cohesive, granular mass. The raw materials are derived from the erosion of previously existing rocks. They have been deposited as layers, mostly in marine conditions.

Siltstone, shale and mudstone

- consolidated very fine particles
- fine texture

Sandstone

- silica grains, usually cemented together by other minerals
- medium texture

Conglomerate, tillite and breccia

- mainly products of fluvio-glacial erosion and deposition
- conglomerate—rounded gravel and boulders cemented together
- tillite—consolidated clay of glacial origin
- breccia—shattered angular rock fragments bound together
- conglomerate and breccia are very coarsely textured; tillite has a very fine texture

Limestone and dolomite

- limestone—consists mainly of calcium carbonate; formed under water either by slow deposition of shells and animal skeletons or precipitated from calcium-rich sea water
- dolomite—a carbonate rock rich in both calcium and magnesium

Banded iron formation

- a finely-banded rock consisting of alternating layers of silica and high grade iron ore

Metamorphic rocks



Metamorphic rocks are formed by the alteration of igneous and sedimentary rocks under conditions of high pressure and temperature. Pre-existing metamorphic rocks can be further altered over time. New minerals formed during metamorphism reflect not only the temperature and pressure but also the composition of the pre-existing rock.

Classification of metamorphic rocks

- metamorphic rocks can be classified according to their degree of alteration
- the rocks least altered are termed 'low grade'; those most altered are 'high grade'

Low grade metamorphic rocks

- closely resemble the original parent material
- include rocks such as slate (slightly altered siltstone) and phyllite (slightly altered shale)

Medium to high grade metamorphic rocks

- pronounced alteration from parent material, with significant increase in hardness
- includes rocks such as marble (a highly altered limestone) and gneiss (a hard, banded rock derived from various parent rock types)

Surficial deposits and weathering mantles



Surficial deposits consist of unconsolidated erosional material which overlays the bedrock. They have been deposited mainly by water and wind, and range from a thin layer of sand to deep alluvium and clay. Weathering mantles are zones of decayed bedrock which have developed *in situ* at or near the surface.

Surficial deposits

Alluvial material

- clay, silt, sand and gravel transported in streams and deposited in stream beds, floodplains, deltas, etc.

Colluvial material

- rock debris accumulated at the base of slopes through downhill movement

Quartz sand

- sand with a high silica content forming dunes and plains. Sandplains result from wind removing finer material; dunes from the accumulation of wind-blown sand

Evaporite

- deposits formed by the evaporation of saline water and the precipitation of salts in lakes and coastal lagoons
- common evaporites in Australia are gypsum and salt

Weathering mantles

Laterite

- a hard capping resulting from seasonal weathering of surface bedrock, usually under tropical conditions
- some elements have been leached out while others have been concentrated at the surface
- the main Australian laterites are bauxite (mined for aluminium) and iron-rich ferricrete

Silcrete

- a hard capping developed through enrichment of surface material by silica

Calcrete

- calcium concentrated in surface horizons of soils to form a hard sheet

Calcarene

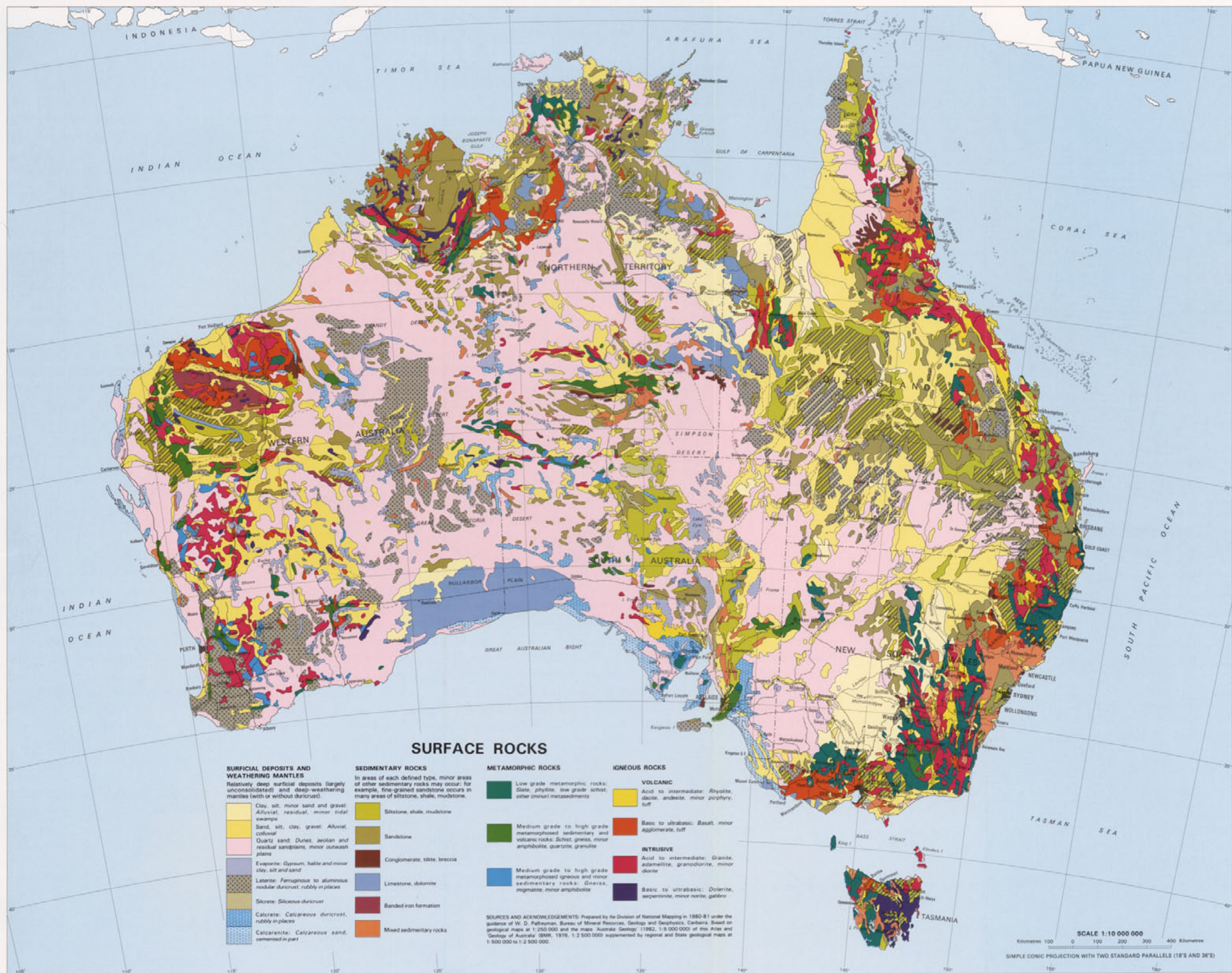
- sand deposited in dunes and partially calcified

1. Sheets of dolerite—a basic igneous rock—which were intruded during the Jurassic, now stand exposed to form the higher peaks of eastern and central Tasmania. Hard igneous rocks make up many of Australia's higher erosional surfaces.

2. Hawkesbury Sandstone, still maintaining near-horizontal bedding planes formed during deposition in a Jurassic sea, today forms extensive plateaux around Sydney. Sedimentary rocks like this make up many of Australia's moderately high erosional surfaces such as the Kimberley and Arnhem Land plateaux, and the Blue Mountains illustrated here.

3. Rock strongly metamorphosed to a hard gneiss by the nearby intrusion of a granite batholith. The paler contorted veins of pegmatite were injected into the darker gneiss. Together, metamorphic and igneous rocks form most of Australia's higher erosional surfaces.

4. Hard laterite or silcrete capped mesas are common throughout Australia's arid interior. Below the silcrete capping of the mesa shown here are colluvial fans of rock debris spreading down the escarpment to surrounding sandplains. Many types of parent rock have weathered to form hard mantles (duricrust), such as laterite and silcrete, which now make up most of Australia's moderately high and lower erosional surfaces. Sandplains and dune fields form the largest areas of recent deposition.



Geology from space



LEGEND

Cainozoic

- A alluvium
- D dunefield
- F fans
- TS Tertiary sediments
- QTS Quaternary/Tertiary sediments

Proterozoic

- L limestone
- PS Proterozoic sediments

Archaean

- B basalts
- G granites
- AS Archaean sediments
- SL Archaean sediments and lava

← d dykes



Since 1932 when the first aerial photographs for geological purposes were taken in Australia, remotely sensed pictures which view the terrain have played a major role in the mapping and interpretation of Australian geology. The launch in 1972 of the Landsat series of satellites made available for the first time images which provide much additional geological information. The large area overview (186 x 186 km per scene) has allowed a better understanding of geological relationships on a regional scale, and in some instances the development of new concepts to explain them.

The interpretation overprinted on the image above shows some of the rocks and surface materials that can be readily distinguished. It is a good example of the wide variety of geological information that can be interpreted from satellite imagery.

This type of image is referred to as 'false-colour' since the colours do not correspond to those seen by the eye. Green colours on the ground are shown as blue, red colours as green, and infrared radiation (invisible to the eye) as red. The brightest infrared reflections come from healthy vegetation and therefore the large trees which line the watercourse in this semi-arid area show up as red on the image.

The Landsat image illustrated here covers part of the Pilbara region of Western Australia, around Marble Bar, and is one of the more spectacular pictures of large geological structures taken from space. It also shows that geological information is most clearly revealed in scenes covering arid and semi-arid areas, where there is usually little vegetation to mask the rock and soil.

The most notable features on this image are the lighter coloured areas of Archaean granite batholiths (G)—light coloured because of their high silica content. They represent the exposed cross-sections of large igneous intrusions which pushed up into the basalt layers that were being extruded on the floor of the Archaean sea some 3500 m.y. ago. Continuing until about 2850 m.y. ago these intrusions severely compressed and down-warped the basalt caught between them (B)—dark coloured because of the low silica content of these mafic rocks—and heavily metamorphosed it into a hard 'greenstone' form.

The igneous intrusions also forced the overlying rock up above sea level and the erosion products from these islands (the earliest parts of the Australian landmass) built up as sediments (AS) on top of the basalts squeezed between them. Basaltic

lava also continued to extrude into these surrounding seas, interbedding with the sediments (SL), in which the near-parallel bedding layers can be clearly seen.

This sequence continued into the Early Proterozoic so that by its end, about 2000 m.y. ago, the granitic intrusions had ceased and the land created by them had been largely eroded away. Proterozoic sediments and interbedded basaltic lava cover a large part of this area (PS).

Sedimentation occurred in later eras but

only the more recent Tertiary (TS) and Quaternary (A, D and QTS) deposits are evident on this image.

Other noticeable features are the dark lines of dolerite dykes (d) cutting through the pale granite batholiths, the dark iron-rich colluvial fans (F) spreading out from the escarpment in the south, the sand dunes (D) of the adjacent Great Sandy Desert to the east, and the salt lakes surrounded by alluvium (A) in the bottom left-hand corner.



Archaean

3600 to 2500 million years ago



The geological history of Australia began early in the Archaean era, around 3500 m.y. ago, with the formation of rocks that now underlie much of the Pilbara region of Western Australia. Little is known of the origin and extent of these very old rocks, which are today severely folded and compressed. However, the sequence of events during the remainder of the Archaean, which lasted for over 1000 m.y., is better known.

The earliest rocks of the Pilbara consisted of silts, sands, iron-rich sediments and chert overlain and intruded by basic volcanic rocks. Between 3450 and 3000 m.y. ago they were folded, severely metamorphosed and uplifted to form mountain ranges interspersed with scattered volcanoes.

Over the next 300 m.y. troughs developed which first filled with volcanic material, then with iron-rich sediments and lastly with sandy and silty sediments interbedded with basic lava flows. Between 2700 and 2600 m.y. ago uplift associated with granite intrusions again occurred.

The formation of the Yilgarn Block to the south began sometime prior to 3100 m.y. ago with the deposition of sandy and silty sediments and some basic volcanics. This sedimentary sequence was subsequently uplifted, metamorphosed and partially melted to form a belt of high grade metamorphic rocks now lying along the west and possibly the north of this block. The history of the rest of the Yilgarn Block is less clear; the rock sequences closely resemble those of the Pilbara Block but they began forming much later, around 2700 m.y. ago.

To the east, in South Australia, the Gawler Block is younger still, having begun to form about 2600 m.y. ago just before the end of the Archaean. Sandy, silty and iron-rich sediments and basic volcanics were laid down but later uplifted, deformed and metamorphosed during the Early Proterozoic.

Little is known about the climate during the formation of these Archaean rocks. Nevertheless, life on earth had already begun and some of the oldest known fossils in the world—primitive life forms such as blue-green algae and bacteria—



have been found in Archaean rocks in Western Australia.

As a result of compression over thousands of millions of years Archaean rocks are characterised by a 'platy' mineral structure. In Australia 'greenstone' is a particularly characteristic Archaean rock, resulting from much-altered basic lava flows. This very resistant rock today forms ridges above the generally flatter and lower terrain of other Archaean rocks.

Economically exploitable deposits of gold, iron, nickel, copper and zinc occur in the Archaean rocks of Western Australia; iron, gold and copper also occur in rocks of this age in South Australia. Bauxite, resulting from the much more recent weathering of Archaean rocks, is abundant in the Darling Range near Perth.

The first crustal rocks formed about 4000 million years ago in the Archaean Era; some of these now form part of Australia. The first primitive life—bacteria and algae—evolved in the oceans around 3500 million years ago and fossil traces of the earliest life forms so far discovered (stromatolites) have been found in north-western Australia. Major nickel and gold mineralisation in Western Australia dates back to the Archaean.

Proterozoic

2500 to 570 million years ago



(far left)
Modern stromatolites along the shores of Hamelin Pool (W.A.)
These provide an understanding of fossil stromatolites, including some found near North Pole (W.A.), which formed an algal reef 3500 m.y. ago. A slice of this ancient reef displaying a stromatolite dome structure is shown below.

(left)
The Kombolgie Sandstone, Arnhem Land (N.T.)
About 1700 m.y. old, this thick and flat-lying Middle Proterozoic sandstone is strongly jointed and covers a wide area. It overlies Early Proterozoic rocks which host significant uranium deposits.

At the beginning of the Proterozoic the Australian landmass consisted of three or four isolated crustal blocks. By the end of the era, almost 2000 m.y. later, these blocks had coalesced to form almost all of the west and centre and significant parts of eastern Australia.

In the north deposition of iron-rich sediments and volcanics which had begun at the end of the Archaean in the Pine Creek Inlier (and probably also in the Litchfield Inlier) continued. During the Early Proterozoic these sediments were uplifted, metamorphosed and intruded with granite.

Further south, between the Pilbara and Yilgarn Blocks, large volumes of basalt poured into the Hamersley Basin, where it was deposited in association with river silts and sands between 2400 and 2000 m.y. ago. Depressed by the continually increasing weight of deposits this area was inundated by the sea and marine sedimentation commenced. Shallow water sediments—mainly sands and some silts and limestones as well as more basalt—were followed by deeper water sediments of silts and muds, mostly iron-rich. Sedimentation ended between 1800 and 1700 m.y. ago when the whole region was uplifted, folded and metamorphosed. Similar events occurred in the Nabberu Basin on the northern edge of the Yilgarn Block.

Thus the pattern was set and during the remainder of the Proterozoic more crustal blocks developed, both as adjacent additions to older Archaean or Early Proterozoic ones and then as new ones. The developmental process for each was essentially similar: marine sedimentation, usually with some associated volcanicity, followed by uplift, folding, metamorphism and granitic intrusion. The pattern of crustal development spread generally eastward to form, by the end of the Proterozoic, crustal blocks in what are today northern Queensland, western New South Wales and Tasmania. By this time, some 600 m.y. ago, a major portion of the crustal platform which now forms Australia was already in existence and the skeleton of the remainder had developed.

Because of a much larger geographical extent of sedimentation and a larger and more diverse fossil record, more is known about climates in the Proterozoic than in the Archaean. Evidence suggests that world climates were mostly mild and equable. However, glacial episodes occurred at the beginning and the end of the Proterozoic. During the later episode glaciers developed about 750 m.y. ago on highlands bordering the Adelaide Fold Belt, causing the deposition of glaciomarine sediments—morainic rock debris dropped from icebergs—and boulder clay (now compressed into tillite). Glacial sediments of similar age also occur in Proterozoic rocks ranging from the Broken Hill area to northern and north-western Australia.

Over the long Proterozoic Era life forms evolved from simple microscopic algae and bacterial organisms to a diverse range of much larger marine creatures including jellyfish and worms. Most significantly, the first creatures with hard body parts, for example sea shells (brachiopods), and animals with hard external skeletons (arthropods) such as crustaceans began evolving at the end of the Proterozoic. As a consequence fossil records from this time onward are more complete, increasing considerably our knowledge and understanding of subsequent geological events and environments.

Proterozoic rocks are of immense economic importance to Australia since they contain most of our largest metalliferous mineral deposits. Major mining centres and areas such as Broken Hill (lead, zinc and silver), Mount Isa (copper, lead and zinc), the Pilbara and the Middleback Ranges (iron), Tennant Creek (gold and copper) and the Alligator Rivers area (uranium) all exploit the mineral wealth of Proterozoic rocks.

So by the end of the Proterozoic, 570 m.y. ago, a major portion of Australia's crustal platform and a significant proportion of its mineral resources were in existence.

The 2000 million years spanning the Proterozoic—the era of 'formative life'—saw the evolution of the first multicellular organisms though life was still confined to the oceans. Much of the Australian continent was consolidated through mountain building and sedimentary deposition. Major metallic mineralisation included the Hamersley iron province, the base metal deposits at Broken Hill and Mount Isa, and the uranium deposits of the Alligator Rivers area.

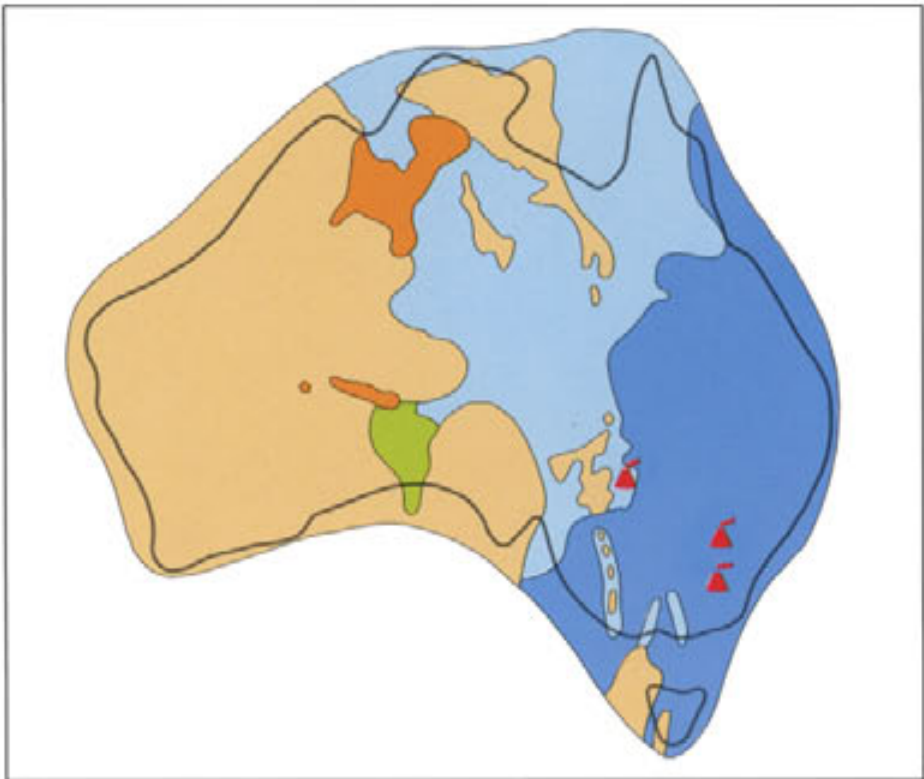
Palaeozoic

570 to 235 million years ago

Cambrian

570 to 500 million years ago

The foundations of eastern Australia were laid down. Life became abundant in the oceans and creatures with external skeletons or shells began to proliferate.



During the Cambrian the crustal blocks formed earlier were either dry land or under shallow seas. The land relief was generally low though mountain regions existed in what is now central and north-western Australia.

A significant early event was the outpouring of large volumes of basaltic lava which covered extensive areas in the north and also further south. In the shallower seas sedimentation consisted mostly of lime (derived from the increasingly abundant calcium-secreting marine organisms) with some sand and silt.

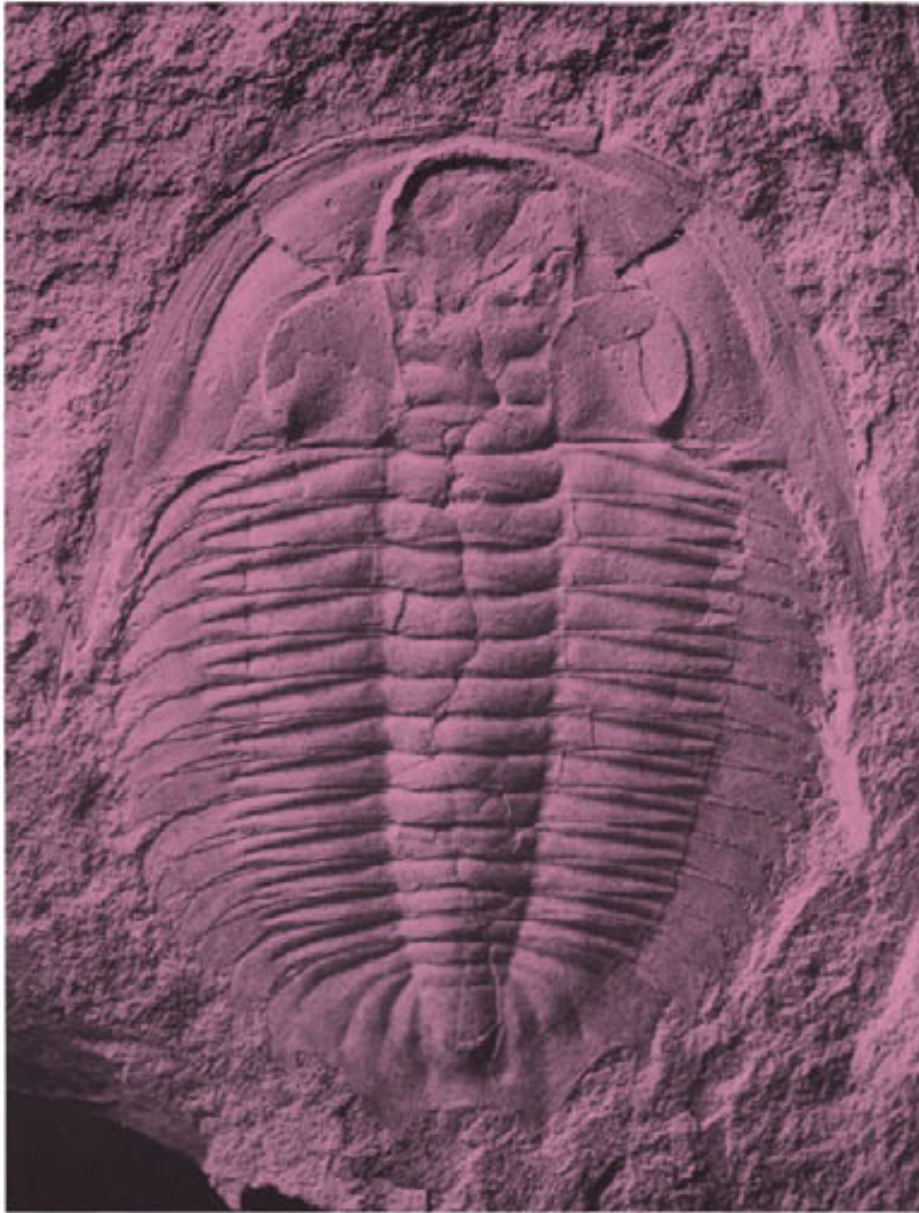
The 'construction' of eastern Australia began in the Cambrian. Early in the period the Kanmantoo Fold Belt (S.A.)—then a marine trough—was rapidly filled with a thick sequence of sand and silt. Further east, notably in the Lachlan Fold Belt, longitudinal troughs and submerged volcanoes formed in the deeper ocean and the troughs

quickly filled with sand, silt, mud and volcanic material. At the end of the Cambrian the Kanmantoo Fold Belt and what is now western Tasmania were uplifted, folded, metamorphosed and intruded by granite to cement a further section to the slowly growing Australian landmass.

During the Cambrian the Australian crustal platform was located just north of the equator and for most of the period experienced a warm to hot climate, causing the widespread occurrence of evaporitic sediments and limestone deposits.

Life forms during the Cambrian continued to evolve and diversify and, importantly, creatures with external skeletons or shells began to proliferate. Trilobites (large, segmented marine arthropods) and lamp shells were abundant and are now commonly found fossils. By the end of the Cambrian bivalve shells and squid-like creatures (cephalopods) were also abundant.

Alternating beds of limestone and shale, eastern Macdonnell Ranges (N.T.)
This mid to late Cambrian sequence was deposited in an extensive shallow sea during a period of fluctuating sea levels.



The complete fossilised external skeleton of a trilobite found near Mount Isa (Qld). During the Cambrian all life was still confined to the sea, where trilobites were common and widespread.

Key to

Palaeogeographic sketch maps on pages 16-23

showing the distribution of land and sea since the Cambrian

Deep marine

River, lake with coal swamp

Glacial

Shallow marine

Land undergoing erosion

Fluvioglacial

River, lake, aeolian

Flood basalt

Central-type volcano

SCALE 1:40 000 000

SOURCE: Adapted by W.D. Pallfreyman from maps in 'Phanerozoic Palaeogeography' in BMR Earth Science Atlas of Australia.

During the 235 million years of the Palaeozoic Era—the time of early life—life evolved from a comparatively few, small soft-bodied marine life forms to a diverse range of plants and animals inhabiting both land and sea. The invasion of the land by plants led to the formation of Australia's very large resources

of black coal. Continental rocks that now form Australia built up to their fullest extent and drifted—still as part of the Gondwana super continent—from the equator to near the South Pole before venturing northward at the end of the era.

Ordovician

500 to 435 million years ago

Despite sedimentation and volcanicity during the Cambrian most of what is now eastern Australia was still deeply submerged at the start of the Ordovician. However, these processes persisted in this area, gradually causing the sea to become shallower and isolated volcanic islands to emerge.

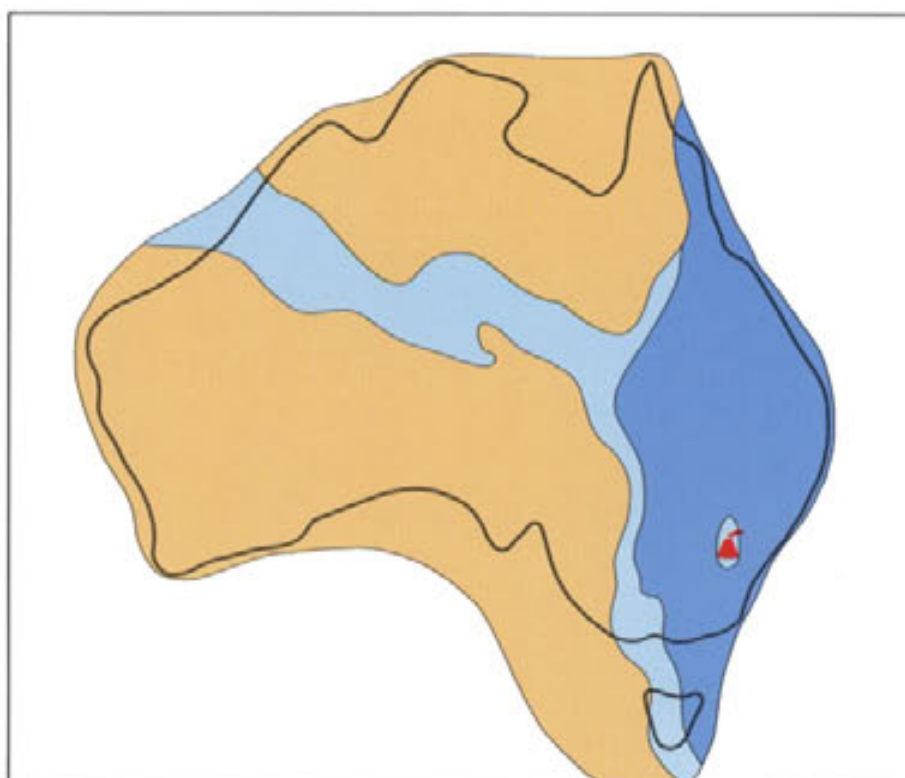
The remainder of the newly enlarged Australian crustal platform was mostly dry land during the Ordovician. Early in the period down-warping began in the Canning, Daly River and Bonaparte Basins, leading to shallow marine transgression and sedimentation of lime, sand and silt. The down-warping in the Canning Basin later extended eastward to cut across the new continent and cause shallow marine sedimentation in the Wiso, Amadeus and Georgina Basins in present-day central Australia.

As these shallow troughs filled with sediment the water in them slowly retreated. By the middle of

the Ordovician the smaller northern Daly River and Bonaparte Basins had dried out. Except for the deeper Amadeus Basin the larger trough to the south had also largely dried out by the end of the period.

During Ordovician times the Australian crustal platform had slipped south to lie directly across the equator. A generally warm climate prevailed, apparent from the occurrence of evaporitic sediments and limestones.

Life-form evolution during the Ordovician again led to an increasing divergence and complexity of existing species and the development of new ones. The abundant trilobites and shellfish of the Cambrian evolved further and proliferated. They were joined by new species such as graptolites (small planktonic organisms), sea-urchins (echinoderms) and the first corals and sea lilies (crinoids). Possibly the most significant event was the evolution of the first primitive fish.



Eastern Australia continued to form. The first vertebrates—primitive fish—evolved and some of the earliest fossils have been found in the Amadeus Basin of central Australia.

Silurian

435 to 410 million years ago

Throughout the Silurian the now well established Australian crustal platform remained predominantly above sea level. Uplift and folding, associated with granitic intrusion which had begun in the central area in the Ordovician, continued into the early Silurian and ended the marine transgression then still persisting in the Amadeus Basin.

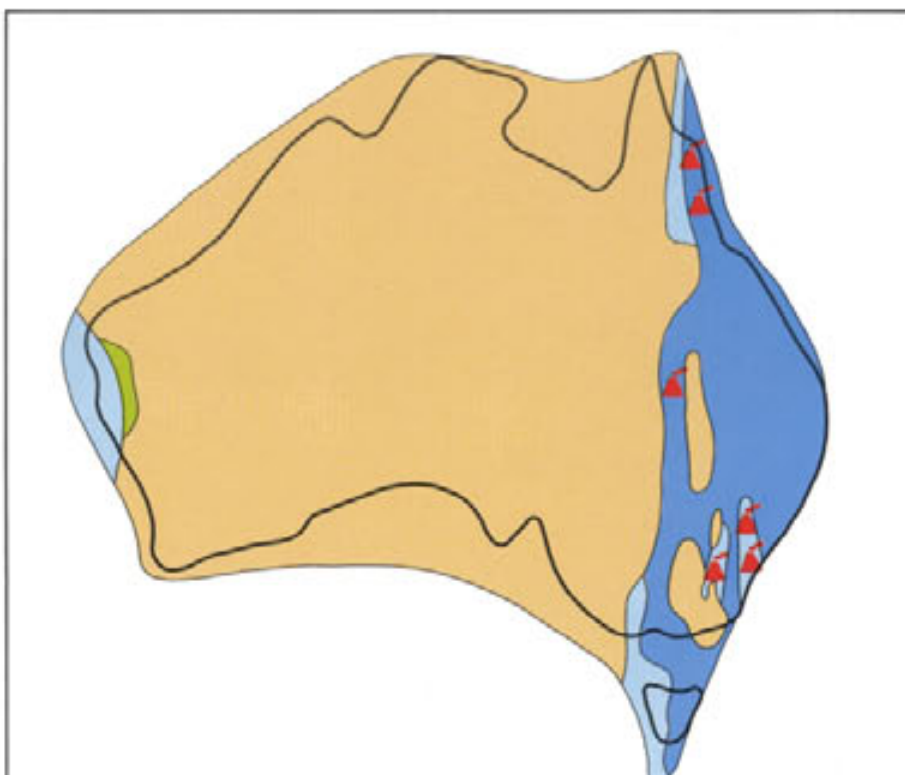
Similar uplift occurred in the south-east, extending the mainland coast eastwards and forming offshore islands in what is now termed the Lachlan Fold Belt. Elsewhere in this fold belt sedimentation of sand, silt and mud continued in the troughs that had remained submerged since the Ordovician. Volcanicity also continued, extruding lava over the seabed and in places forming volcanic island arcs.

In the west sand and silt were laid down by rivers on the underlying older rocks in the Perth and Carnarvon Basins whereas further north,

in the Canning Basin, shallow marine and evaporitic sediments accumulated.

The Australian crustal platform remained in the equatorial zone throughout the Silurian. A warm climate prevailed, leading to desert conditions and evaporitic deposition. Marine life including shellfish, corals, graptolites, trilobites, crinoids, cephalopods and various types of fish continued to proliferate and further evolve. However, the most significant evolutionary event in the Silurian was the invasion of the land (though only the wetter parts) by spore-bearing plants similar to present-day club mosses.

The granitic intrusion associated with the south-eastern uplift introduced the rich central Victorian gold deposits and, probably, the gold, silver-lead and copper deposits in central and south-eastern New South Wales.



Life, in the form of primitive moss-like plants, first appeared on land. In the shallow Silurian seas then covering eastern Australia great coral reefs were formed. These eventually became limestone formations such as those now found at Chillagoe (north Qld), and Jenolan and Bungonia (N.S.W.) where the limestone has dissolved to form extensive networks of caves. Melbourne is built on Silurian marine deposits and fossils are frequently found during construction work.

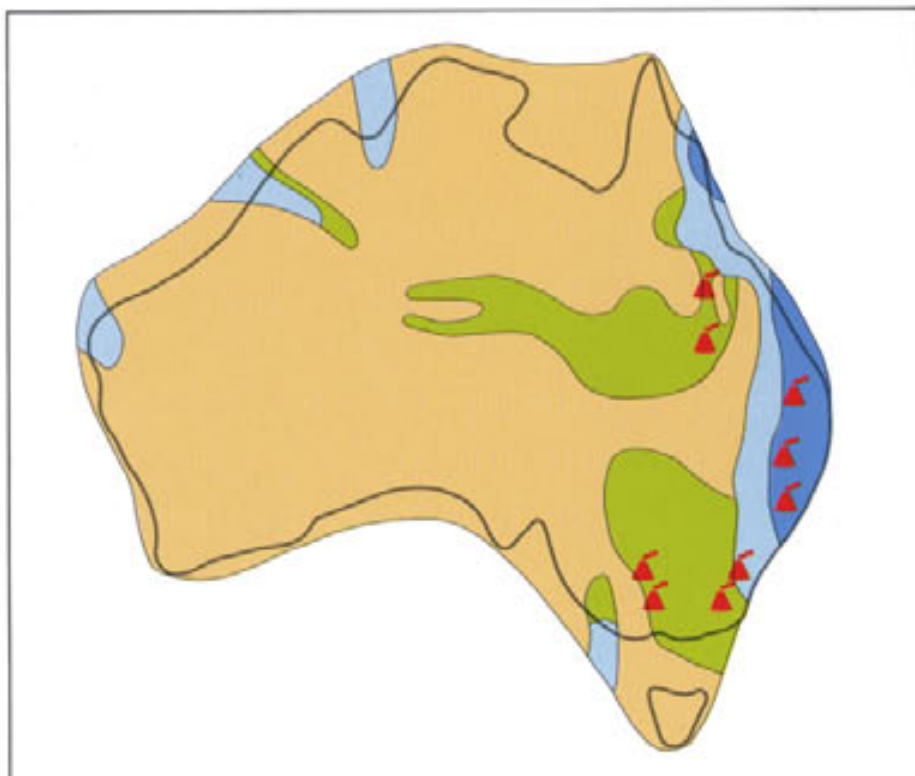


'London Bridge', a natural arch in Silurian limestone near Queanbeyan (N.S.W.) This arch has developed in recent times in limestone which originated as a small reef in the late Silurian.

Devonian

410 to 345 million years ago

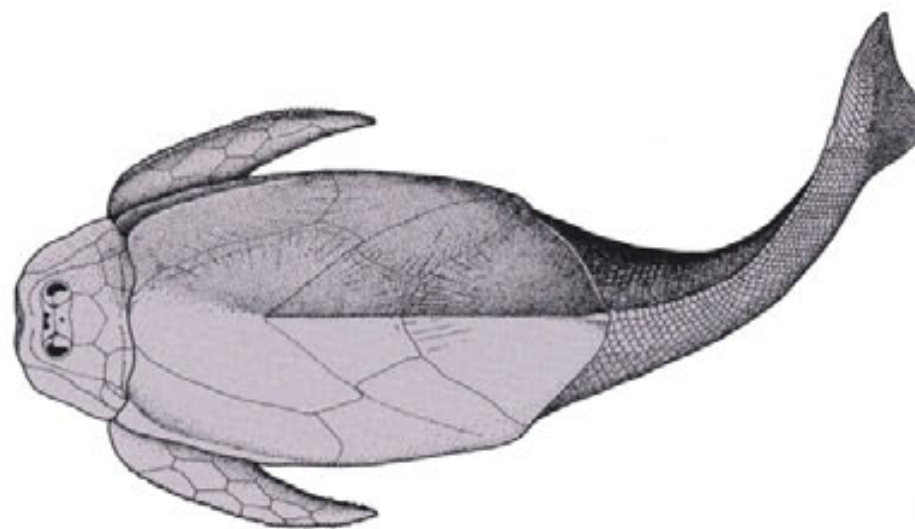
All but a small portion of what is now eastern Australia was raised above sea level for the first time. Land plants further developed with the evolution of tree-like club mosses. By the end of the Devonian the first thin seams of coal were already being laid down in club moss swamps. Air-breathing fish ventured ashore, giving rise to the first amphibians.



The distinctive Elder Sandstone of the Bungle Bungle Range, eastern Kimberleys (W.A.)
This residual landscape has resulted from the erosion of friable and heavily jointed late Devonian sandstone.



A 30 cm-long armoured fish reconstructed from fossil specimens found near Canowindra (N.S.W.). This fish was common in freshwater lakes and streams of eastern Australia during the late Devonian.



During the Devonian the now well-established western and central parts of the Australian crustal platform remained stable and mostly above sea level. However, crustal down-warping in the Carnarvon, Canning and Bonaparte Basins began in the first half of the Devonian and led to shallow marine incursions. In the Canning Basin silt and mud were first deposited, followed by shallow evaporitic deposits and coral reef formation as the sea shallowed. In the Carnarvon Basin deltaic sand and shallow water limestone accumulated. Only one small area of Devonian rocks, composed of sandstone with plant fossils overlain by thick limestone, is exposed in the Bonaparte Basin.

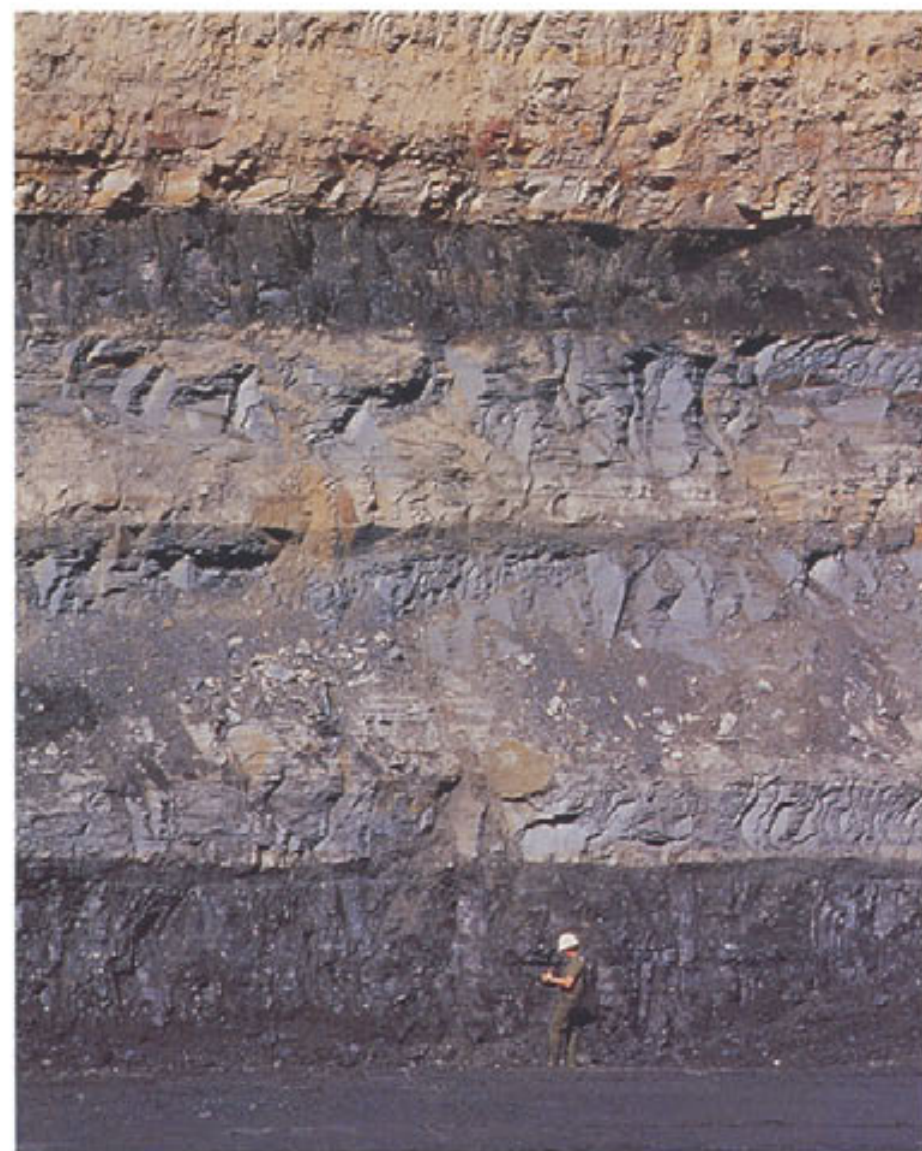
The only other area of extensive water sedimentation on the established crustal platform occurred in the Wiso, Georgina and Amadeus Basins, where an extensive river and lake system deposited sand and silt.

The major centre of tectonic activity and crustal development remained in the east and south-west. In the mid Devonian, around 360 m.y. ago, a period of folding and uplift, accompanied by widespread volcanic activity, occurred in the south-east and raised all but a small portion of what is now eastern Australia above sea level. In the Devonian seas off this newly formed shore both shallow and deep water marine sediments were laid down together with rhyolite and andesite

lavas from undersea volcanoes. Typical sediments were sand and grit, and iron-rich silts from which shale (particularly a red variety forming what are now termed 'red beds') was formed.

In Devonian times the Australian crustal platform—still attached to the Indian and Antarctic platforms—lay astride the equator. The climate was generally warm, leading to widespread evaporitic deposits and coralline limestone formed in warm seas. The abundant and diverse marine life of the Silurian seas increased and further diversified in the Devonian. Reef-forming corals were particularly plentiful and many new fish evolved. Brachiopods and ammonoids also proliferated but trilobites and graptolites began to decline. Land plants further developed with the evolution of giant club mosses but these were still confined to damp areas. By the end of the Devonian the first thin seams of coal were being laid down in club moss swamps.

The Cobar gold and copper deposits in central New South Wales were probably formed during the tectonic activity in the mid Devonian. The chromite and nickel deposits of north Queensland are also Devonian in origin. Limestones and sandstones of this period are extracted for cement and building material. Devonian sediments also form reservoir rock for natural gas in western Queensland.



Greta Coal Measures, Drayton opencut coal mine near Muswellbrook (N.S.W.)
Formed in swamps on a floodplain in the Permian, these black coal seams are interbedded with shale and siltstone and capped with sandstone.

Carboniferous

345 to 300 million years ago

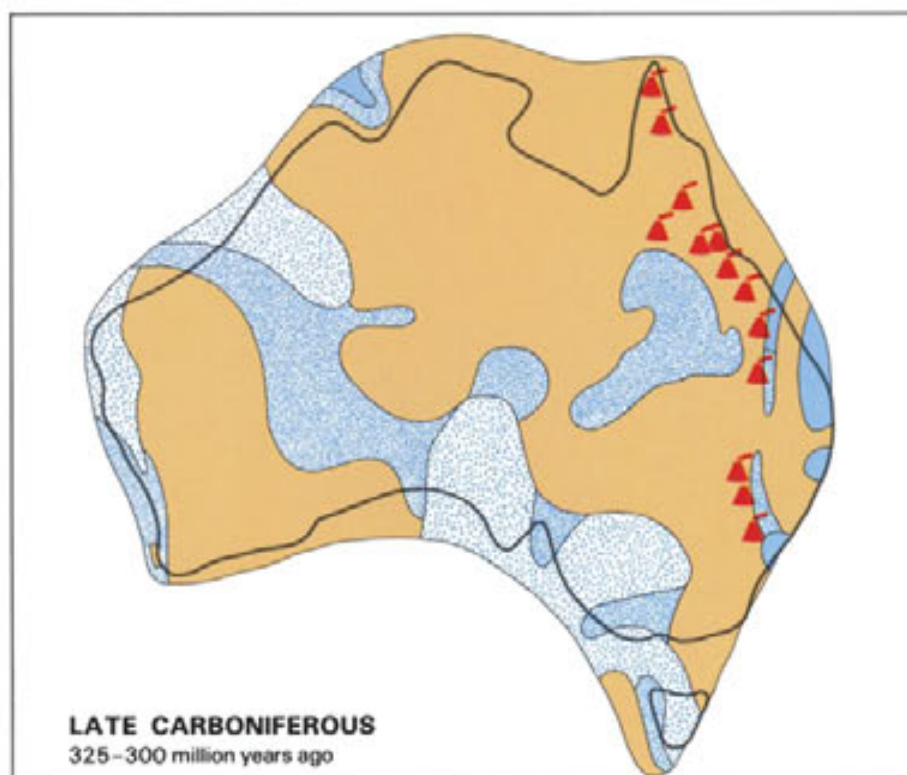
Early Carboniferous geological activity in eastern Australia was centred around northern New South Wales and southern Queensland. As before, sedimentation continued in surrounding troughs with much of the material originating from an active volcanic island arc in this area. Further east sedimentation in deeper water continued.

In central Australia river systems, formed during the Devonian, continued to deposit sand in the interior. In western and north-western Australia shallow marine sedimentation continued, with lime, silts and evaporitic sediments being deposited in the Carnarvon and Canning Basins. Some alluvial sands were also deposited in the Carnarvon Basin. Further north in the Bonaparte Basin silts and muds were laid down in deeper water.

During the late Carboniferous, commencing around 325 m.y. ago, the climate cooled markedly for the first time since the late Proterozoic as Australia drifted towards the

South Pole. By the end of the period much of the continent was covered by ice. Evidence for this glaciation is found in Carboniferous rocks from western, southern and south-eastern Australia where, in places, glacial pavements are still preserved together with extensive glacial till and fluvioglacial deposits. Shallow marine or river deposits occur away from the ice-covered area—in the Canning Basin of the north-west and in eastern Australia, where sands and silts containing boulders dropped from melting icebergs (dropstones) accumulated.

During the early part of the Carboniferous warm water faunas such as corals flourished in the Australian region. Club mosses thrived on land and were joined by seed-bearing ferns and horsetails. Later, as temperatures declined, many plants and animals became extinct but were replaced by others more adapted to the colder conditions.



In the Northern Hemisphere tropical conditions gave rise to luxuriant swamps which harboured the first winged insects and where reptiles first evolved. The Australian portion of Gondwana, however, was drifting towards the South Pole and experiencing increasingly colder conditions. In most of the Northern Hemisphere this period is known as the 'Age of Coal'—hence Carboniferous—but in Australia the major coal deposits were laid down later.

Permian

300 to 235 million years ago

The glacial conditions of the late Carboniferous persisted during the early Permian but had abated by the start of the late Permian, around 260 m.y. ago. The ice caps and glaciers had melted though cool climates persisted over much of the continent throughout the remainder of the Permian.

Following the deposits left by glaciers, marine sedimentation of sands, silts and limes took place in the Perth, Carnarvon, Canning, Bonaparte, Arckaringa, Tasmania, Sydney and Bowen Basins. These marine sediments contain dropstones in places, indicating the presence of icebergs. Towards the end of the early Permian the sea retreated and, with a general warming of the climate, coaly swamps formed in these basins and in the Officer, Cooper, Pedirka and Galilee Basins of central and north-eastern Australia. Such swamps are the origins of Australia's rich coal

deposits, particularly in the Bowen, Sydney and Collie Basins.

Throughout the early Permian uplift continued in eastern Australia, notably in the New England Fold Belt in northern New South Wales. By the late Permian, and extending into the Triassic, much of eastern and north-eastern Australia was further uplifted, folded and, in places, metamorphosed and intruded by granite.

As much of southern Australia was covered by ice during the early Permian the flora (glossopterids) and fauna were predominantly cold-adapted species. Then, as the climate improved in the late Permian the water temperature increased and marine organisms became more diverse. However, the close of the period saw the mass extinction of several ancient faunal groups though the cause is not known.



Swamp forests dominated by glossopterid trees flourished as Australia drifted away from the South Pole into a more temperate zone. These forests led to the formation of Australia's major black coal deposits, mostly in what are now the Bowen and Sydney Basins. One coal seam alone at Blair Athol (Qld) is more than 30 m thick. Insects, fish and large amphibians were plentiful but reptiles had still not appeared in Australia.



(far left)
Fossil glossopterid leaves from near Newcastle (N.S.W.)

(left)
Iron-stained fern and glossopterid leaves from coal measures near Dunedoo (N.S.W.)

Leaf fossils of the now extinct glossopterids are common in Permian sediments from all of the continents which once made up Gondwana. Cool temperate forests dominated by Glossopterid trees flourished at this time, and in eastern Australia led to the formation of vast coal deposits.

Mesozoic

235 to 65 million years ago

Triassic

235 to 195 million years ago

Australia's first reptiles appeared. Glossopterid trees and bushes were replaced by more modern plant forms such as conifers and tree ferns. The extensive sandstone plateaux which today form the Blue Mountains west of Sydney are the uplifted remnants of a deep accumulation of river sands in a Triassic coastal basin.



By the start of the Triassic Australia had drifted north away from the Antarctic region into a warmer climatic zone. This warmer climate, coupled with a lower and more seasonal rainfall, discouraged plant growth in inland areas that had previously supported coal-forming swamps in the late Permian. Coal formation did recur in the late Triassic, indicating the return of wetter conditions.

Little of the present continental landmass was covered by water in Triassic times though shallow marine and estuarine conditions did prevail in the Bonaparte, Canning and Perth Basins of the west and north-west, where fine sand and silt accumulated. At the end of the early Triassic, around 225 m.y. ago, these areas were uplifted.

In central and eastern Australia river sands and silts accumulated in delta regions of the Cooper, Tasmania, Sydney, Bowen and Galilee Basins in the early Triassic. At the same time uplift, folding and granitic intrusion took place to the east of the Bowen and Galilee Basins. Vol-

canic activity also occurred here and further south in the Sydney Basin.

In the early Triassic many new animal species appeared, replacing those which became extinct at the end of the Permian. The Triassic saw the proliferation of amphibians and insects as well as the appearance of the first reptiles in Australia. While brachiopods declined other marine animals such as squid, cuttlefish and nautilus increased in number and diversity.

The major change in flora came with the disappearance of the glossopterid trees and bushes that had dominated the Permian landscape of Gondwana and their replacement by cycads, tree ferns and conifers.

Apart from coal deposits in Queensland, Tasmania and South Australia, the only other economically significant Triassic mineralisation resulted from volcanic activity which had already begun in the Permian in northern Queensland, giving rise to the Mount Morgan copper-gold deposit.

Jurassic

195 to 135 million years ago

Gondwana began to break up in Jurassic times. Dinosaurs inhabited Australia whilst cycads, large tree ferns and conifers flourished in the warm, wet climate. Sediments laid down in large inland lakes now form the major sandstone aquifers of the Great Artesian Basin and reservoir rock for natural gas and oil resources in the Surat and Eromanga Basins.



In the early Jurassic the river systems in eastern Australia expanded rapidly. These eastward flowing rivers and their associated lakes shed a steady volume of sand, silt and mud into the Eromanga, Surat, Clarence-Moreton, Maryborough and Laura Basins. In places, coaly swamps reappeared. This process continued throughout the Jurassic and into the early Cretaceous, and much of the sand deposited over these millions of years now forms the major sandstone aquifers of the Great Artesian Basin.

Similar fluvial conditions prevailed in western and north-western Australia, where sand, silt and coal accumulated during the early and mid Jurassic in the Perth, Carnarvon and Canning Basins. Shallow marine incursions and sedimentation followed in these basins during the late Jurassic.

Around 160 m.y. ago Gondwana began to rift apart. The breakup first occurred on the western side of Australia, where major faulting took place just off the present-day coast as India drifted away. River and lake sediments accumulated in the rift valleys between these two continents. At the same time similar rift faulting probably affected southern and south-eastern

Australia as considerable volumes of basaltic lava, now mainly eroded away, covered parts of the Otway and Tasmania Basins. In the Tasmania Basin sills and columns of dolerite, once the cores and feeder dykes of this past volcanic activity, stand exposed today. Similar intrusive dolerite sills of the same age also occur in Victoria Land, suggesting that Antarctica and Australia were still joined.

The climate was generally warm to hot during the Jurassic, being drier early on and wetter in the later stages. Reptiles continued to evolve both on land and in the oceans, and became the dominant animal form throughout the period. Although scarce the remains of the first Australian Jurassic dinosaur, *Rhoetosaurus*, which was 15 m long and 5 m tall, have been found in western Queensland. Flora continued to diversify and flourish; forests of cycads and conifers were well established and a large tree fern (*Cladophlebis*) was so numerous and widespread that it has been termed the 'Jurassic weed'.

Jurassic rocks contain economic resources of coal, oil and gas in Queensland as well as acting as reservoir rocks for water in the Great Artesian Basin.

Deeply dissected Hawkesbury Sandstone, Grose Valley near Katoomba (N.S.W.) This horizontally bedded and now heavily eroded Triassic sandstone formation is characteristic of the Blue Mountains west of Sydney.



The Mesozoic, or time of 'middle life', saw the emergence of dinosaurs—the largest reptiles to ever roam the earth—and the first mammals and flowering plants. However, the dinosaurs and other giant reptiles became

extinct at the end of the era. Gondwana began to break up and Australia became a continental landmass in its own right. Significant resources of natural gas and oil are trapped in Mesozoic rocks in eastern Australia.

Cretaceous

135 to 65 million years ago

Sedimentation from rivers and lakes continued into the early Cretaceous, depositing sand, silt and mud across large areas of the continent. Coal continued to form in swampy areas.

A gradual world-wide rise in sea levels around 110 m.y. ago caused a major marine incursion of most of the continent, with dry land contracting to several groups of islands. In eastern and north-eastern Australia uplift and volcanic activity formed mountain ranges.

About 95 m.y. ago Australia and Antarctica began to separate. As happened earlier when India broke away from the west coast an ever-widening rift valley opened up, this time in the Otway and Gippsland Basins of Victoria, and filled with sand and silt. With this further breakup of Gondwana the Australian continental landmass began to assume its present-day shape.

Another major event was the development of a new continental fracture along Australia's south-east coast. As a result a now mostly submerged ridge known as the Lord Howe Rise began to drift eastwards, taking with it western New Zealand and initiating the formation of the Tasman Sea.

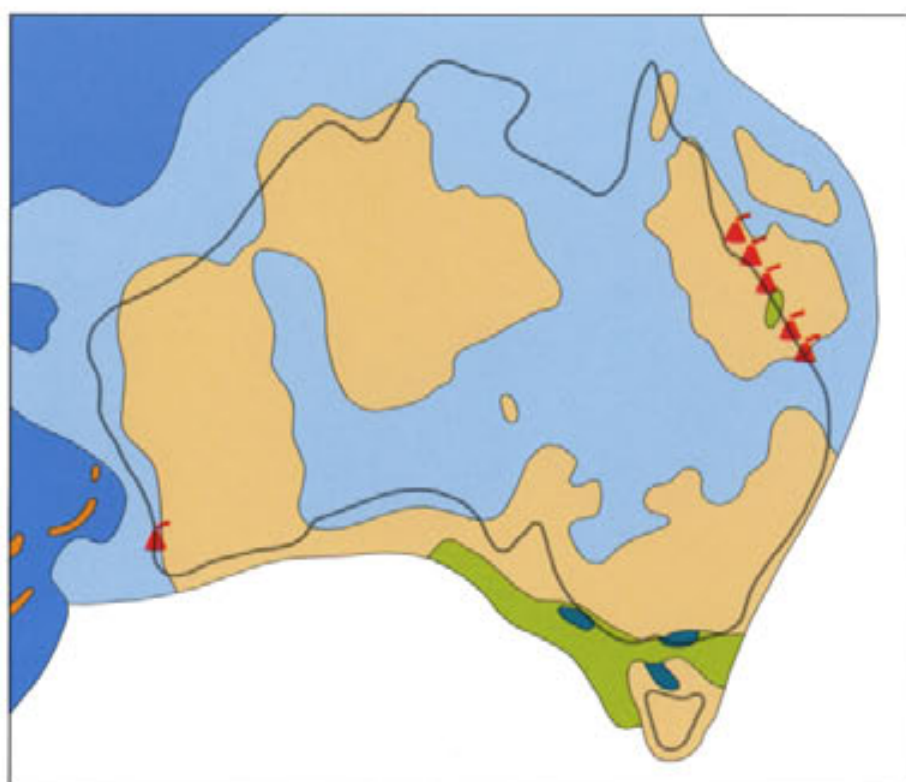
Towards the end of the early Cretaceous, around 100 m.y. ago, the

sea retreated from the north, east and central parts of the continent, reviving river and lake sedimentation. In the west marine sedimentation of sand, silt and lime continued in the Perth and Carnarvon Basins.

In Cretaceous times the climate was generally mild to warm, with rising temperatures towards the end. Scattered coal seams occur where conditions were locally humid. During the early Cretaceous the flora was much the same as that in the Jurassic, with abundant ferns and coniferous forests. However, late in the period flowering plants evolved and had become widespread by its close.

Reptiles continued to dominate the larger fauna though mammals had begun to evolve. An intriguing and as yet unsolved mystery was the mass extinction of many species of animal life, in particular the dinosaurs, at the end of the Cretaceous.

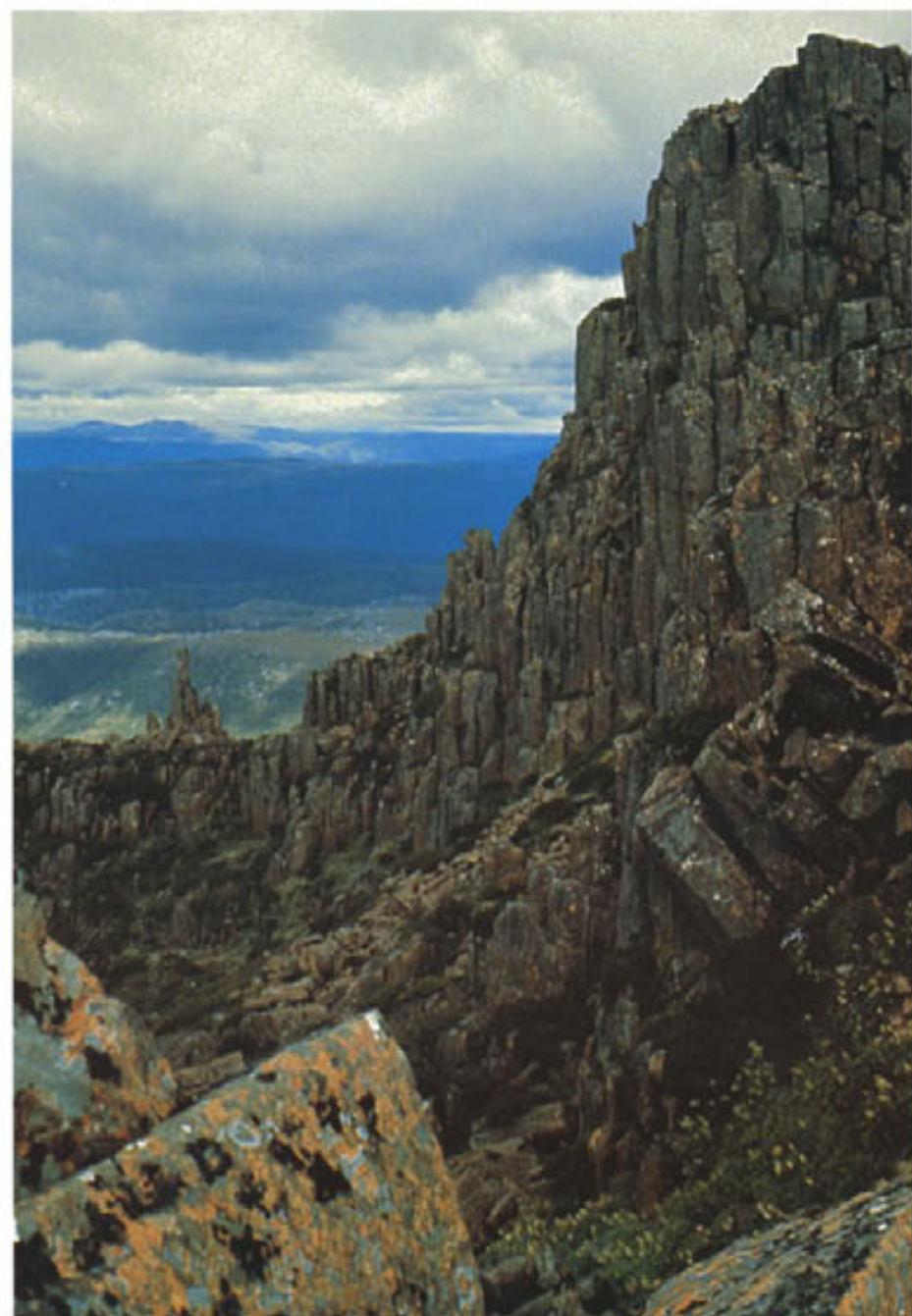
Coal deposits of Cretaceous age occur in Queensland, New South Wales and South Australia but are of little economic significance. Important manganese deposits laid down at this time are found on Groote Eylandt off the coast of the Northern Territory.



Australia and Antarctica began rifting apart. Flowering plants appeared and spread rapidly and Australia's first birds and mammals emerged. Mystery still surrounds the extinction of the dinosaurs at the end of the Cretaceous.



A reconstructed Australian landscape for Jurassic-Cretaceous times. A number of dinosaur species very similar to those found on other continents inhabited this environment. One unique to Australia was the very large *Muttaburrasaurus*, whose fossilised remains have been found at Muttaburra (Qld). The flora was dominated by conifers, cycads and tree ferns.



'Painted Cliffs', a sandstone rock-face on Maria Island, east coast of Tasmania. These cliffs have been formed through the erosion of horizontally bedded Triassic sandstone. Rings of precipitated iron oxide result from recent groundwater action.

Exposed dolerite intrusions, Cradle Mountain (Tas.)

Sheets of jointed Jurassic dolerite eroded into columns cap the higher peaks in the mountainous areas of central and eastern Tasmania.

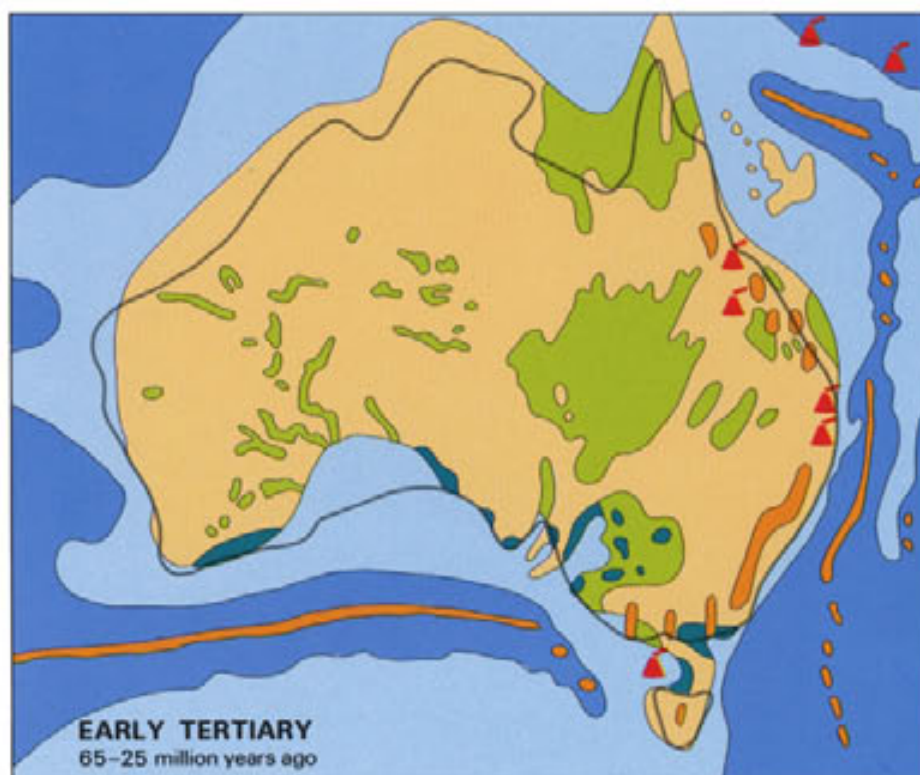
Cainozoic

65 million years ago to the present

Tertiary

65 to 2 million years ago

Broad uplifting of eastern Australia led to the formation of the eastern highlands. As Australia and Antarctica separated, the limestone of the Nullarbor Plain built up in the shallow sea separating them. Enormous brown coal deposits were formed in extensive swampy areas of southern Victoria. These coal deposits are considered to be the source of the oil and gas now being recovered from the Bass Strait fields.



Sentinel-like volcanic plugs and dykes of the Warrumbungle Range (N.S.W.)

The Warrumbungle Range (right) is a deeply dissected remnant of intense volcanic activity during the Tertiary. Prominent dykes, plugs and domes of solidified lava that has resisted erosion rise abruptly from the surrounding terrain. The 'Breadknife' (far right) is a striking example of one such preserved dyke.



The start of the Tertiary saw most continents nearing their present global positions. Though Africa and India had yet to collide with Eurasia and push up the Alps and the Himalayas, this recent major mountain-building event was fast approaching. Australia was probably still tenuously connected to Antarctica by an ever-widening and frequently flooded rift valley. However, quite early in the Tertiary, about 45 m.y. ago, the two continents finally separated. For the next 30 m.y. Australia's distinctive fauna and flora continued to evolve in relative isolation before Australia came into contact with the Eurasian Plate about 15 m.y. ago.

The thickest and most extensive Tertiary deposition occurred in the south, where the limestone of the Nullarbor Plain built up in a shallow but gradually deepening sea as Australia and Antarctica drifted apart.

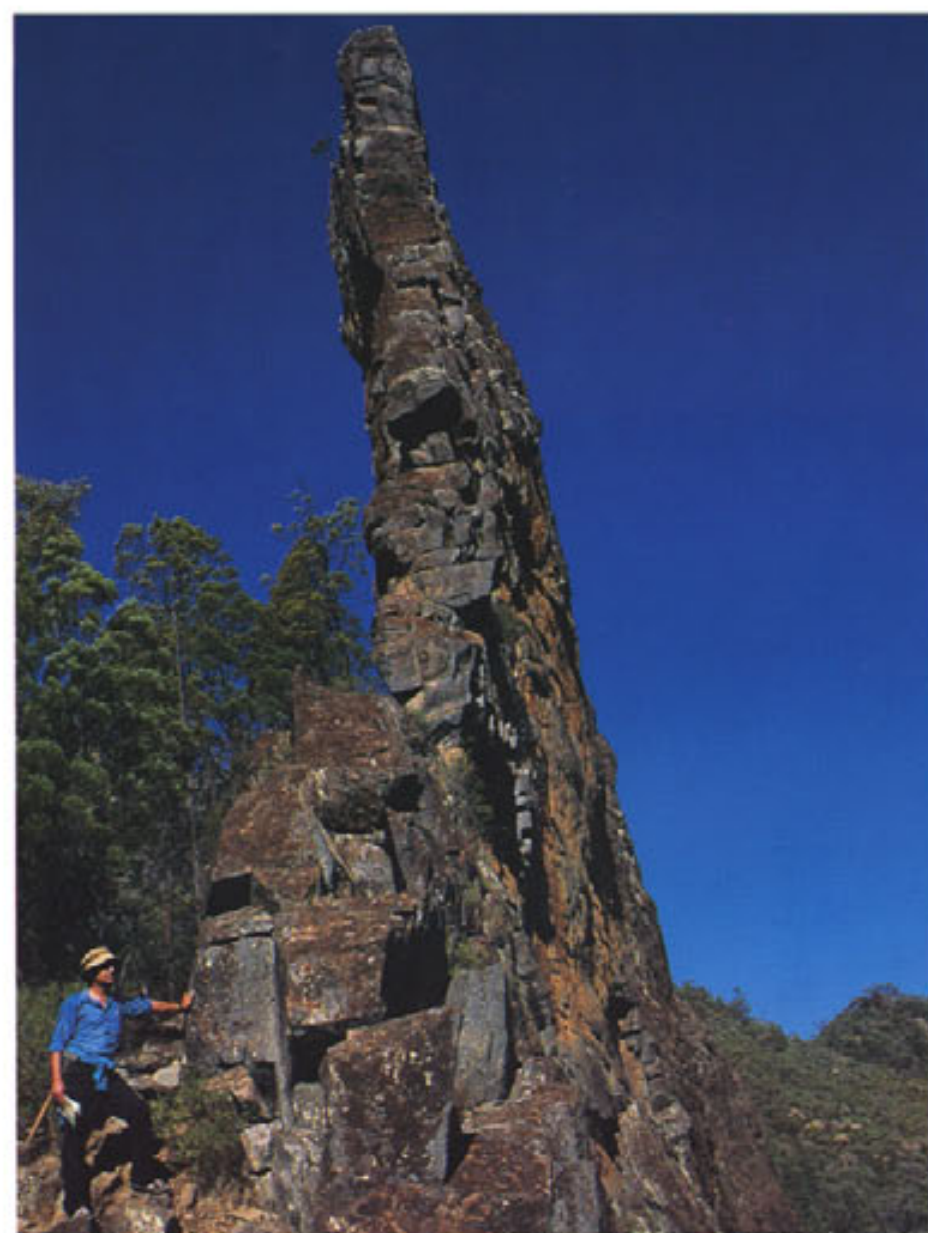
Under the influence of an apparently wet and hot climate, erosion planed the land surface down to flat and low levels. These climatic conditions also led to the widespread development of weathered surfaces of laterite and silcrete. Vegetation growing in extensive swamps in southern Victoria led to the formation of enormous brown coal (lignite) deposits, now a major source of that state's energy supply.

Beginning about 40 m.y. ago

major tectonic activity caused the general uplift of eastern Australia, forming the high but still gently sloping upper surfaces of the Snowy Mountains and the tablelands of New South Wales. Then, around 30 m.y. ago, eastern Australia began drifting over a 'hot spot' which caused a line of volcanic cones and basalt lava flows to progressively erupt over the next 25 m.y. The oldest are in the Atherton area of north Queensland; the youngest occur in south-central Victoria.

During the early Tertiary closed forests covered most of Australia. They consisted mainly of broadleaf and coniferous species of Gondwana origin and were host to a variety of possum-like animals. As the climate became drier the forests died out in all but a few more-humid areas, and open woodlands and grasslands began to dominate. Eucalypts, the trees so characteristic of Australia, did not evolve until about 35 m.y. ago, probably in response to the drier conditions and the now generally poor, leached soils.

Kangaroos, the most characteristic of Australia's mammals, are even more recent. They evolved into their present form only about 15 m.y. ago, taking advantage of the increasing expanse of open country as the closed forests of the early Tertiary gradually disappeared.



The Cenozoic, or era of 'new life', commenced with the demise of the dinosaurs and covers the evolution of most of the world's present-day flora and fauna. Australia and Antarctica finally separated quite early in the

era thus enabling Australia's unique plant and animal species to evolve during a subsequent 30 million year period of effective global isolation.

Quaternary

the last 2 million years

As the Australian crustal platform drifted to its present global position tectonic and volcanic activity, which had begun in the Tertiary, slowly abated. Down-warping and faulting near the centre caused the development of a large inland lake system, now much contracted to Lake Eyre and other salt lakes in central and northern South Australia.

Volcanic activity became more localised, with basalt lava flows extruding in northern Queensland and volcanoes erupting in the Mount Gambier area of south-eastern South Australia. The southern volcanoes were still erupting until about 5000 years ago and activity continued until as recently as 1500 years ago.

As Australia drifted towards the equator into the zone of desert-producing high pressure systems the climate became increasingly drier. However, this gradual climatic change was overridden by more rapid and extreme variations during a sequence of world-wide glacial periods beginning around 500 000 years ago—the *Pleistocene Ice Age*. At the peak of this ice age permanent snow covered the highlands of the south-eastern mainland and Tasmania, where glaciers sculptured the higher valleys into the smooth forms that can be seen today.

With so much water trapped globally in extensive ice sheets at the height of glaciation the sea level dropped some 200 m below its present-day level. As a consequence dry land was created

between the Australian mainland and New Guinea and Tasmania. The shelf on which the Great Barrier Reef later developed was also land at this time.

The much enlarged continental landmass almost linked up with south-eastern Asia, making the migration into Australia of its first human inhabitants—today's Aborigines—relatively easy. The climate was generally cool and arid and strong winds lifted and deposited loose sand to form the vast dune system which still exists today over much of the interior.

As the world climate warmed in recent times the sea gradually rose to its present level, separating Tasmania and New Guinea from the Australian mainland and enabling the Great Barrier Reef to form into what is now the world's largest bio-geomorphic structure.

Evolution continued in Australia with the appearance of species that exist today. In addition some giant marsupials, wingless birds and reptiles evolved but they all became extinct between 10 000 and 20 000 years ago. This was probably due to a contraction of suitable habitats as aridity increased and to man's impact on the environment through fire and hunting.

Australia's mineral resources were by now largely in place. The most significant recent event was the concentration of heavy minerals—rutile, ilmenite and zircon—in beach sands at a number of locations along the newly formed coastline.



Australia's most recent geological history saw the eventual evolution into their present-day form of many plant and animal species. The continent was first inhabited by man following global lowering of the sea level during the Pleistocene Ice Age.

As the sea level rose after the last glacial retreat New Guinea and Tasmania were separated from mainland Australia. Drowned river valleys such as Sydney Harbour were formed along the new coastline. The Great Barrier Reef developed on the submerging coastal plain off the eastern coast of Queensland.



Mount Schank, a volcanic cone near Mount Gambier (S.A.)

Displaying a virtually uneroded cone, Mount Schank is one of the youngest volcanoes in Australia. It consists of two impinging craters, both of which were created by explosive volcanic activity. Carbon dating has shown that the main activity occurred about 5000 years ago, certainly within the known period of Aboriginal occupation of the area.



Ribbon reefs forming part of the Great Barrier Reef, near Cooktown (Qld)

This vast reef system extends for more than 2000 kms along the continental shelf off the Queensland coast. The reefs, which are accumulations of limestone secreted by coral organisms over thousands of years, are still forming today.



Longitudinal sand dunes, Simpson Desert (N.T.)
Sandplains, typical of much of Australia's arid interior, developed initially from alluvium deposited on extensive plains

during a formerly wetter climate. With the onset of more arid conditions water tables dropped and vegetation disappeared, enabling wind to erode the loose sediments. Fine

particles blew away as dust, leaving behind the sand from which dunes were formed by the prevailing winds.



Iron ore mining on a massive scale at Mount Tom Price in the Hamersley Range (W.A.). This mine alone extends for nearly 8 kilometres and produces over 20 million tonnes of ore a year.

Minerals

The story of Australia's minerals is one of risk, hardship and achievement.

In a harsh unyielding land that continues to defy settlement, enterprising prospectors, geologists and exploration survey teams alike have faced the rugged outback conditions in their painstaking task of unlocking the secrets of the earth beneath them. Their difficulties have been compounded by the fact that much of the mineral wealth lies concealed beneath a thick cover of altered rock, sand and soil—the product of eons of weathering. Although many deposits were discovered by the early prospectors further riches have been revealed only relatively recently by the application of geoscientific principles and sophisticated exploration tools capable of penetrating the thick overburden.

Once discovered, the development of an isolated deposit usually involves the installation of all necessary infrastructure. Not only must mine and processing plant be constructed but transport facilities, power and water supplies, and township and community facilities must also be supplied. One benefit of mining often overlooked is that the establishment of mining communities in remote regions, for example Kalgoorlie, Broken Hill and Mount Isa or more recent townships such as Newman, Weipa and Moranbah, has helped to break down the isolation of the vast Australian interior.

Mineral resources

Australia's more significant mineral deposits as known by late 1984 are presented on the two 1:5 million scale maps 'Fuels' and 'Minerals other than Fuels'. The maps depict the type, location and size of mineral deposits, their state of exploitation, associated mineral processing facilities, and the larger mineral movements between mines and treatment plants or points of consumption.

As a general rule small deposits which are not being mined are not shown on these two maps though in some instances such deposits have been included as possible indicators of more widespread mineralisation.

The size class for each mineral deposit (small, medium or large) is based on an international classification developed by the Circum-Pacific Council for Energy and Mineral Resources but adapted and expanded to suit Australian circumstances by the Bureau of Mineral Resources, Geology and Geophysics. The limits of each class are given in Table 1.

The distribution of Australia's mineral deposits is closely related to the underlying geological structure. The two major kinds of struc-

tural units which make up the continent—cratons and craton covers—are shown as background information on the 1:5 million minerals maps: exposed cratons and Early Proterozoic sedimentary basins (craton covers) on 'Minerals other than Fuels' and sedimentary basins younger than Early Proterozoic on 'Fuels'. Their names are distinguished in the following text by the use of italic capitals, for example *YILGARN BLOCK*.

Continents evolve through time by a process of craton formation and subsequent deposition of sedimentary cover. Metallogenic evolution parallels such tectonic evolution.

In broad terms Australia grew from west to east. Nickel, gold and uranium are concentrated in the

oldest westerly cratons and iron in the associated craton cover. The major base metal deposits are associated with the somewhat younger central cratonic blocks. Eastern Australia is younger still and is host to tin, tungsten, tantalum and particular types of base metal and gold deposits.

In general the distribution of non-metallic (or industrial) minerals cannot be as closely correlated with structural units as can the metallic minerals because of the significant influence of non-geological factors. For example, the location of surficial deposits such as mineral sands, silica, opal and the various clays reflects weathering and geomorphological controls, while the formation of salt and gypsum is strongly climate-dependent.

Hydrocarbons are most developed in young (but not the youngest) sedimentary basins that formed relatively late in the evolution of the continent.



Prospecting in southern New South Wales

Australia's mineral industry is well established on a rich and diverse resource base. It provides raw materials to the manufacturing, construction, transport and power sectors. In fact, the mineral industry meets almost all domestic requirements for metals, industrial minerals and fuels used in the manufacture of a wide range of goods for consumption both in Australia and overseas. Additionally, as a major export earner minerals are responsible for around \$A15 billion annually in foreign exchange earnings.



SCALE 1:20 000 000

SOURCE: Derived from the maps 'Fuels' and 'Minerals other than Fuels' in this volume.



Table 1. Definition of mineral deposit class sizes

Mineral	Deposit size			Mineral	Deposit size		
	Large more than	Medium < >	Small less than		Large more than	Medium < >	Small less than
Major metals				Used mainly for Building and construction			
tonnes of contained metal				tonnes			
Aluminium [†]	200 000 000		100 000 000	Asbestos	10 000 000		100 000
Copper	1 000 000		50 000	Gypsum	100 000 000		5 000 000
Iron	100 000 000		5 000 000	Limestone	10 000 000		2 000 000
Lead	1 000 000		50 000	Used mainly for Chemicals and fertilisers			
Nickel	500 000		25 000	tonnes			
Tin	100 000		5 000	Phosphate rock	200 000 000		200 000
Zinc	1 000 000		50 000	Salt [‡]			
kilograms of contained metal				Sulphur [§]			
Gold	500 000		25 000	Other minerals			
Other metals				tonnes			
tonnes of contained metal				Barite	5 000 000		50 000
Antimony	50 000		5 000	Clays:			
Bismuth*				Bentonite [†]			
Cadmium*				Fireclay [†]			
Cobalt	20 000		1 000	Fullers earth [†]			
Lithium*				Kaolin [†]			
Manganese	10 000 000		100 000	Stoneware, tile and pipe clay [†]			
Molybdenum	200 000		5 000	Diatomite*	10 000 000		2 000 000
Palladium*				Dolomite			
Platinum*				Felspar*			
Silver	10 000		500	Garnet*			
Tantalum	100 000		1 000	Magnesite	10 000 000		100 000
Tungsten	10 000		500	Mica*			
Vanadium	10 000		500	Mineral sands:			
Fuels				Ilmenite	10 000 000		5 000 000
tonnes				Monazite	50 000		20 000
Black coal	1 000 000 000		100 000 000	Rutile	500 000		200 000
Brown coal	10 000 000 000		1 000 000 000	Zircon	1 000 000		500 000
Uranium	40 000		10 000	Peat*			
cubic metres				Silica	2 500 000		1 000 000
Crude oil	30 000 000		3 000 000	Sillimanite*			
Natural gas	30 000 000 000		3 000 000 000	Talc	10 000 000		1 000 000
Oil shale [§]	100 000 000		10 000 000	Vermiculite*			
Gemstones							
Diamonds*							
Opals*							
Sapphires*							
Other gemstones*							

* Individual deposits classed by BMR

† Individual deposits classed by state departments of mines

‡ Class limits refer to tonnes of bauxite

§ Based on production capacity of individual treatment centres

¶ Based on size of sulphide source

§ Oil content

Mineral sufficiency

Australia's sufficiency in mineral resources is indicated below. The size class of each commodity is based on the ratio of known resources to the current annual rate of production. However, this figure does not necessarily represent the life of known resources because of possible future changes in production rates and further mineral discoveries. Some very small or low grade deposits which would not have a substantial impact on resource sufficiency have not been taken into account.

Large resources (more than 30 years)

Aluminium	Nickel
Chromium	Oil shale
Coal, black	Opals
Coal, brown	Phosphate
Cobalt	Pyrophyllite
Copper	Salt
Diamonds	Sapphires
Dolomite	Silica
Gypsum	Silver
Iron	Sulphur (as metallic sulphides)
Kaolin	Tantalum and columbium
Lead	Tin
Limestone	Uranium
Lithium	Vanadium
Magnesite	Zinc
Manganese	
Monazite	
Natural gas	

Adequate resources (15–30 years)

Antimony	Garnet
Asbestos (short fibre)	Gold
Barite	Mica
Bentonite	Palladium
Bismuth	Peat
Cadmium	Platinum
Corundum	Pottery clay
Diatomite	Siliceous abrasives
Emerald	Talc
Felspar	Titanium (as rutile, ilmenite)
Fireclay	Tungsten
Fluorspar	
Fullers earth	

Small resources (less than 15 years)

Arsenic	Mercury
Asbestos (long fibre)	Molybdenum
Beryllium	Potassium
Crude oil	Sillimanite
Kyanite	Vermiculite

Mesas with iron-rich cappings in the Robe River area (W.A.)

The cappings of pisolitic (pelletised) limonite—a form of iron ore—are the uplifted remnants of secondary iron deposits which filled ancient river channels draining the Hamersley area during the Tertiary. These 'rivers of ore' are generally about 30 m thick, average 57% iron and extend for more than 200 kms along the Robe River valley.

The various patterns of mineralisation that have occurred over geological time are used in the following text as the basis for describing Australia's mineral resources.

In general, mineralisation within major metalliferous structures, as shown on the 1:5 million scale map 'Minerals other than Fuels', is summarised according to mineral 'provinces'. Each province denotes a geographic grouping of a particular type of mineralisation (characterised by one or a combination of metals) in an exposed craton or area of cratonic cover. Examples from the Archaean and the Proterozoic include the 'gold province' within the *YILGARN BLOCK*, the 'Broken Hill province' in the *WILLYAMA BLOCK* and the 'Hamersley iron province' in the *HAMERSLEY BASIN*. Mineral provinces in the Palaeozoic tend to coincide with parts or all of particular fold belts; hence Palaeozoic mineralisation is described in terms of these fold belts. A 'field' is part of a mineral province.

The major sedimentary-associated mineralisation which

began in the Palaeozoic and may still be continuing today is described under each individual mineral. This was the age of fossil fuel formation. The most recent mineralisation, associated with the largely unconsolidated surface cover, is also described in terms of each mineral.

Bold type is used from hereon in the text to distinguish the names of individual mines/deposits and treatment plants which appear on the maps 'Fuels' and 'Minerals other than Fuels', for example **Broken Hill**, **Blair Athol** and **Risdon**.

The distribution of mineral deposits through space and time displays patterns that parallel tectonic evolution and the growth of continents. These patterns resulted from the complex interplay of a variety of geological factors, including the degree of evolution of the crust, global patterns of cratons

and orogenic zones, the chemical composition of magmas emplaced at a particular place and time, whether the magmas were derived from the earth's mantle or by remelting of crustal material (and the nature of that crustal material), the distribution of sedimentary basins and the tectonic events which have affected the region over geological time.

In Australia the most important metalliferous ore-forming periods were a few comparatively short intervals in the Archaean, the Early and Middle Proterozoic, the Middle and Late Palaeozoic and the Tertiary-Quaternary. The most productive environments have been mafic-ultramafic volcanic rocks with minor sediments (gold and nickel in the *YILGARN BLOCK*); closed basin sedimentation (lead-zinc at **Mount Isa** and **Broken Hill**); secondary concentration (iron ore in the *HAMERSLEY BASIN*, lateritic bauxite); and felsic volcanic environments (gold, copper, lead and zinc in the Tasman Fold Belt).

How mineral deposits are formed

Mineral deposits are the products of normal igneous, sedimentary and metamorphic rock-forming processes. In special circumstances these processes have concentrated particular minerals in amounts substantially above their average crustal abundance.

Formation of most mineral deposits requires a coincidence of factors: a mineral source, transport and concentrating mechanisms and a favourable depositional site. Depending on the geological processes responsible, deposits are classed as igneous-associated or sedimentary-associated. However, many deposits show the effects of more than one process and may be partly igneous and partly sedimentary in origin.

In addition igneous and

sedimentary mineralisation may be modified and further concentrated during metamorphism; for example by remobilisation and redeposition of metals in structurally deformed zones such as faults or folds, or by recrystallisation into a coarser grained form. The complex Broken Hill silver-lead-zinc orebodies display features indicative of such a multi-stage history.

Finally, weathering, in particular groundwater movement, affects near-surface zones of all deposits and has been a significant factor in the formation of some orebodies or in increasing the grade of parts of them. The vast lateritic bauxite deposits of northern and western Australia are good examples of the role of weathering in ore formation.

Igneous-associated deposits

Igneous activity gives rise to a broad spectrum of deposit types. Variations among them reflect differences in host magma composition, depth of magma emplacement and the chemistry of the elements concerned.

The fundamental mechanism for the concentration of igneous ores is 'magmatic differentiation', a physico-chemical phenomenon whereby magmas do not crystallise homogeneously; rather, different minerals crystallise in a sequence depending on (among other things) their melt-

ing-points. This process tends to concentrate certain elements, particularly those forming minerals which crystallise early or late in the sequence. For example, early crystallising nickel sulphides may settle to the bottom of the magma in sufficient quantity to form ore deposits. At the other extreme, elements such as gold, tin and tungsten accumulate in the last remaining fluids of the magma and therefore tend to occur in the upper part of the igneous rock mass or in the rocks surrounding the upper part of the mass.

Sedimentary-associated deposits

The mechanical processes of sedimentation and chemical processes of precipitation tend to concentrate minerals in larger, more continuous deposits than those formed by igneous processes. These sedimentary-associated deposits are classified according to the ore-forming processes instrumental in their formation.

The broad classes of deposits are:

- *chemical and biochemical*—including limestone, evaporites

and some base metal and iron deposits;

- *organic*—particularly coal, oil shale and petroleum;
- *detrital*—where the valuable minerals are concentrated at the surface by the sorting action of water or wind; and
- *secondary*—formed through the concentration of valuable elements just beneath the surface by weathering.

Bauxite cliffs near Weipa, Gulf of Carpentaria (Old)
The red bauxite and underlying bleached clay visible in these cliffs developed during the Tertiary, evidently over several lateritic weathering cycles.



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 open-cut mining. More attractive economically are the volcanic-associated deposits, which tend to be smaller, higher grade deposits mineable by underground methods, represented by **Kambalda**, **Widgie-mooltha**, **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 feldspar (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**.

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 km². 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 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 km². 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.

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



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 metaliferous 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 down-warps in strongly folded rock sequences.

Other Middle Proterozoic mineralisation includes numerous small granite-associated tin-tungsten-molybdenum lodes (at **Molyhill**), and vein and stratabound copper-lead-zinc (at **Attuttra**) 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.

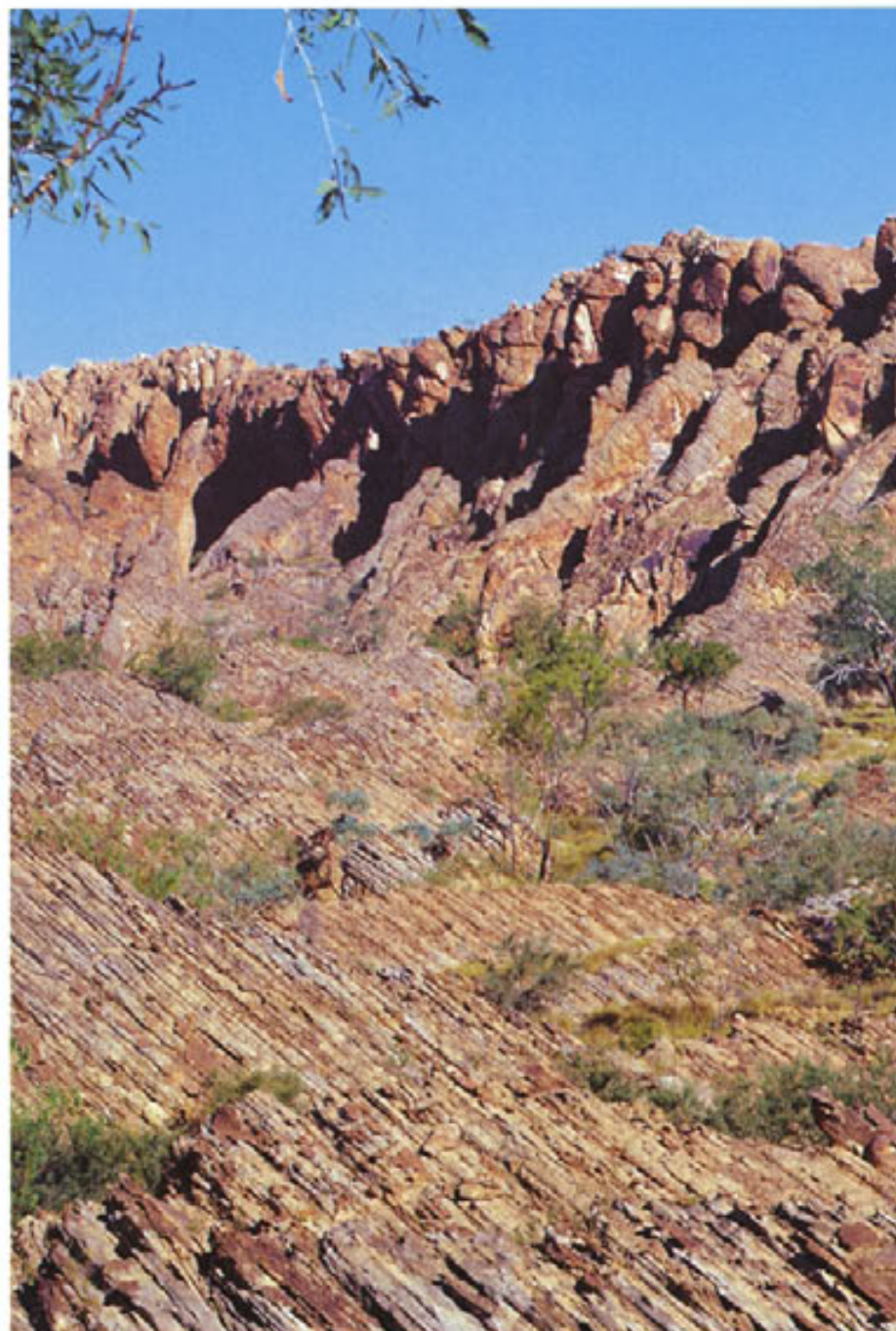
Late Proterozoic

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**, **Balcenoona** 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 metaliferous 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.

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 feldspar 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**,



Remnant orebody in the now worked out Mount Morgan copper-gold mine (Old)

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.

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**, **Lutwyche**, **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 **Galwagere**, **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.

The age of fossil fuels

Phanerozoic sedimentary basins

At times during the Phanerozoic* large parts of the Australian continent were covered by sedimentary basins which also extended offshore onto the present continental shelf.

Sedimentary rocks ranging in age from Proterozoic to Cainozoic underlie more than half the land area of Australia and nearly all of the continental shelf. Most of the basins are very old, so the likelihood that tectonic processes would have destroyed any initial petroleum reservoirs is increased. Compared with other producing countries, where petroleum resources are usually found in much younger sediments, Australia has only been seriously considered a good prospect for discovering significant oil and gas resources during the last two decades.

Though petroleum formation began in Australia as early as the Proterozoic significant quantities did not develop until the Palaeozoic and, in particular, the Mesozoic and the Cainozoic. Coal was formed from the Permian through to the Tertiary.

Australia's main proven hydrocarbon rocks thus span a wide range of geological time. Large parts of the continent, notably in the central-east, contain basins of differing age which overlap and overlap each other. Some basins even contain hydrocarbon-bearing sequences of different ages within their boundaries.

Coal

The evolution and rapid propagation of land plants in the Devonian was followed world-wide by the deposition of sediments containing plant remains which eventually became coal. Whereas the most extensive and productive coal measures of the Northern Hemisphere are of Carboniferous age, the main coal-forming period in the southern continents (then still joined together as 'Gondwana'), was not until after the Permian Ice Age.

Australia's major black coal deposits were formed in the Permian. Most were deposited in the **BOWEN** and **SYDNEY BASINS** along the newly formed eastern margin of the continent. Variations in the extent and quality of coal across the basins result from local differences in structural and stratigraphic history, and the kind of vegetable matter from which the coal formed.

Favourable coal-forming conditions persisted locally throughout the Mesozoic and Cainozoic, giving rise to deposits in the small, isolated **LEIGH CREEK**, **IPSWICH** and **CALLIDE BASINS** in the Triassic; then widespread coal measures of Jurassic-Cretaceous age in the **EROMANGA** and **CLARENCE-MORETON BASINS**; and huge brown coal deposits of Tertiary age in Victoria and, to a lesser extent, South Australia.

Permian

SYDNEY and **GUNNEDAH BASINS**. There were at least two periods of widespread coal formation. In the early Permian the Greta Coal Measures were formed, followed, late in the Permian, by the Illawarra, New-

castle, Tomago and Singleton Coal Measures. At up to 1450 m, the Singleton Coal Measures are the thickest in New South Wales and contain 28 significant coal seams.

Deposits occur in five major regions:

- Hunter (**Singleton-Muswellbrook**) has the largest resources and currently produces soft coking and thermal coal.
- Newcastle (**Newcastle-Lake Macquarie, Cessnock**) contains substantial resources of soft coking and thermal coal.
- Western (**Ulan, Lithgow area, Kandos**) contains mainly high energy thermal coal.
- Southern (**South Coast area, Burragorang Valley, Tahmoor, Berri**) is known for its premium quality hard coking coals.
- Gunnedah (**Boggabri, Gunnedah**) contains large resources of thermal coal and some soft coking coal.

BOWEN BASIN. This basin is a major source of high quality coking coal which ranges in age from early to late Permian, the latter being the most extensive. The principal deposits are mined at **Newlands, Goonyella, Riverside, Peak Downs, Saraji, Norwich Park, German Creek, Oak Creek, Gregory, Blackwater** and **Moura-Kianga**. Igneous intrusions have metamorphosed large parts of some coal seams, mainly in the north (e.g. at **Collinsville**), to high ash, natural coke.

Aggregate coal thickness is greatest in the Blair Athol Coal Measures (**Blair Athol**), at 40 m, with one seam alone measuring 33.5 m. A similar aggregate coal thickness exists in the small Wolfgang Basin (**Wolfgang**) nearby.

Less extensive Permian coal measures, generally of low rank, are preserved in the **GALILEE, OAKLANDS, ARCKARINGA, TASMANIA, BONAPARTE, PERTH, COLLIE** and **CANNING BASINS**.

Triassic

The **IPSWICH BASIN**, parts of the **CLARENCE-MORETON BASIN** and the **Fingal** area of the **TASMANIA BASIN** contain medium rank coals suitable for steam generation. The **TARONG** and **CALLIDE BASINS** contain bituminous coal amenable to open-cut extraction for power generation. Up to 18 seams of low rank coal occur in four small basins at **Leigh Creek (S.A.)**.

Jurassic

Jurassic coal deposits occur in the **CLARENCE-MORETON, SURAT, POLDA** and **PERTH BASINS**. The coals are mostly sub-bituminous, occurring in thin, lenticular seams.

Tertiary

Australia has about 8% of the world's economic demonstrated resources of brown coal, mainly in **GIPPSLAND BASIN (Yallourn-Morwell, Loy Yang)** east of Melbourne. With large reserves at shallow depth the deposits can be mined economically on a large scale for power generation.

Brown coal deposits are widespread across the south of the continent near the margins of Tertiary basins and in depressions on adjacent cratonic blocks, for example **Esperance (W.A.)**, **Wakefield-Lochiel, Mannum and Kingston (S.A.)**, and **Anglesea (Vic.)**.

Petroleum

In proportion to the extent of its sedimentary rocks, Australia is not particularly well-endowed with liquid hydrocarbons although it does have large deposits of natural gas. The main commercial hydrocarbon fields are offshore in the **GIPPSLAND, BONAPARTE** and **CARNARVON BASINS** and onshore in the **COOPER/EROMANGA, AMADEUS** and **BOWEN/SURAT BASINS**. Most deposits are in anticlinal traps in Tertiary or Mesozoic sandstone reservoirs overlain by shale caprocks.

Precambrian

Any oil or gas formed in rocks of this age is now generally considered to have long since been destroyed or squeezed out into other strata. However, what is believed to be the world's oldest oil was discovered in 1985 in Precambrian rocks of the **McARTHUR BASIN** though there are no commercial fields in rocks of this age in Australia.

The first well drilled in the **AMADEUS BASIN** recorded a small flow of gas from Precambrian limestone.

Cambrian/Ordovician

In the **AMADEUS BASIN** the **Palm Valley** (gas) and **Mereenie** (oil and gas) fields produce from sandstone reservoirs sourced from an adjacent thick marine shale.

Devonian

Commercial hydrocarbon accumulations have been identified in Devonian reservoirs only recently. In the **CANNING BASIN (Blina)** they are in and adjacent to fossil coral reefs built up along an ancient coastline.

Plans have been announced to develop the **Gilmore** field in the **ADAVALE BASIN**, where gas is trapped in continental to shallow marine sandstones.

Carboniferous/Permian

Hydrocarbons dating from this time are trapped in reservoirs formed in a variety of depositional environments. Currently the most important fields are in the **COOPER BASIN (Moomba area, Tirrawarra area)**. Here, hydrocarbons have been generated from plant matter in carbonaceous shales and coals interbedded with the reservoir sandstones formed in fluvial to lacustrine environments.

Hydrocarbons have been discovered in the **BOWEN BASIN** and significant gas fields are known in the **Denison Trough area**. Gas has been found in Permian marine limestones of the **PERTH BASIN (Woodada)** and in deltaic to marginal marine sandstones of the offshore **BONAPARTE BASIN (Tern, Petrel)**. The **CANNING BASIN** has proven reservoirs (**Sundown**) lying on top of the Devonian reef sequences referred to above.

Mesozoic

Like the Carboniferous and Permian, the Mesozoic was a time of extensive source, reservoir and caprock deposition within thick layers of sediments in shallow seas and inland lakes. Much of the eastern half of the continent as well as parts of its western margins were covered in this way, giving rise to the **Jackson area** and **Dulligari area** fields in the **EROMANGA BASIN**; to various fields including **Barrow Island** and **Harriet** (oil) and **North Rankin, Goodwyn, Angel, Scarborough, Gorgon** and **West Tryal Rocks** (gas) in the **CARNARVON BASIN**; to the **Jabiru** and **Challis** fields in the **BONAPARTE BASIN**; to **Scott Reef** and **Brecknock** (gas) fields in the **BROWSE BASIN**; to the **Dongara area** fields in the **PERTH BASIN**; and to the **Kincora area, Boxleigh area, Moonie** and **Alton** fields in the **SURAT BASIN**.

Much of the petroleum in the **SURAT BASIN** fields is thought to have been derived from underlying coal and shale sediments in the **BOWEN BASIN**.

Along the Rankin Trend in the offshore **CARNARVON BASIN** gas is trapped in Early Mesozoic reservoirs in fault blocks sealed by younger Mesozoic shales. In the **BONAPARTE BASIN** oil is trapped in Mesozoic sandstones which overlie Jurassic source rocks.

Tertiary

Once again, this was a time of luxuriant plant growth and abundant animal life. The huge brown coal deposits of Victoria laid down in this period are widely accepted as the source of the Bass Strait oil and gas fields. The **GIPPSLAND BASIN** contains the bulk of Australia's oil resources, the fields occurring in moderately folded, capped sandstones. Liquid hydrocarbons are probably still being generated there today.

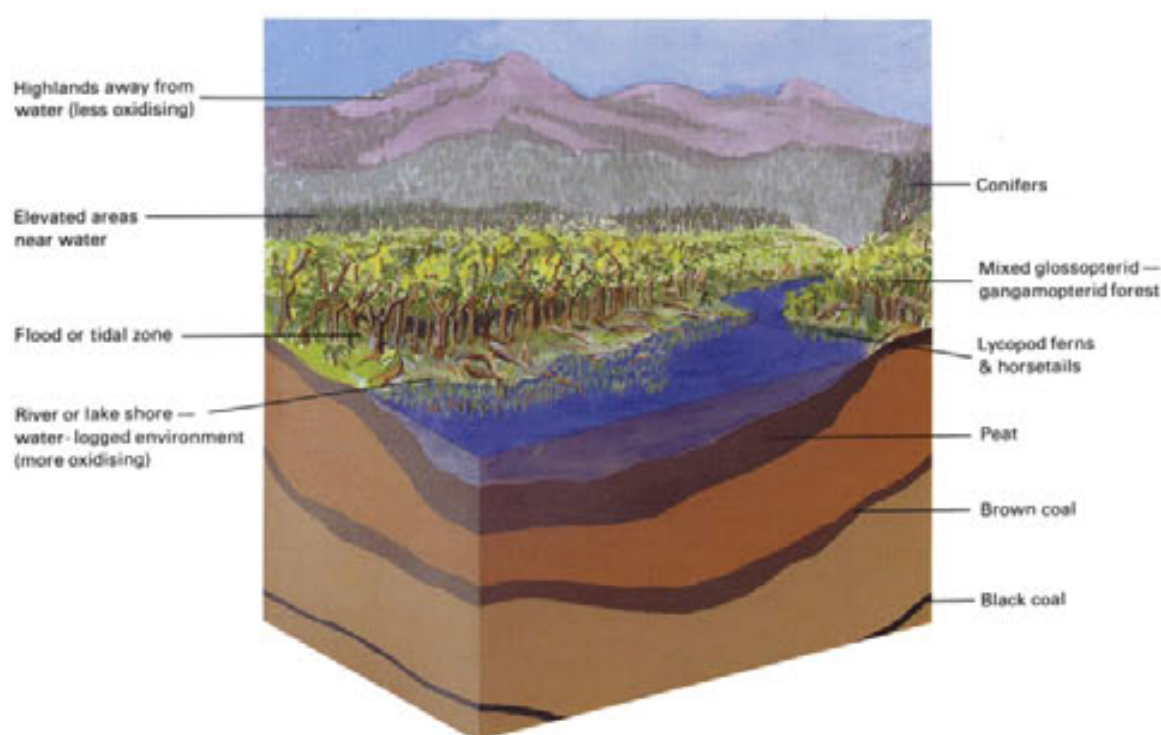
* The eon covering the Palaeozoic, Mesozoic and Cainozoic Eras—see geological time-scale diagram on page 7.

The hydrocarbons

Coal, petroleum and oil shale are fossil fuels formed predominantly during the Phanerozoic. Their energy is derived from the process of photosynthesis, in which plants and, indirectly, animals have stored solar energy in the form of complex carbon

compounds. The organic remains of plants and animals were preserved in sedimentary sequences and under certain conditions then chemically altered into hydrocarbons.

How coal is formed



Coal is a readily combustible rock, consisting mainly of carbonaceous material derived from the compaction and alteration of plant remains similar to those found in present-day peat bogs.

Coal has formed from the accumulation of abundant plant debris over long time intervals in a variety of landscape environments. These sites varied from dry land through to swamps and shoreline lagoons. Each had a distinct plant assemblage and water and oxidation levels which influenced the way the plant debris decayed. As a result coals with a wide range of properties have developed; they are classified on the basis of flora (coal type), degree of alteration (coal rank) and contained impurities (coal grade).

Formation of the first

substantial coal deposits commenced about 360 m.y. ago. The actual climatic conditions existing at the various times of coal formation are a matter of debate, although the cycles of climatic and sea-level fluctuation associated with ice-ages of the time were important.

A commonly held concept is that subtropical conditions were necessary to support a diversity of rapidly growing vegetation. However, in the case of some Australian coal deposits there is strong evidence to suggest that at times the climate prevailing during the accumulation of major deposits was cool-temperate, particularly as the associated sediments sometimes show the influence of glacial activity.

Coal formation begins with the accumulation

of enormous volumes of plant debris, commonly in stagnant swamps. Here, poor circulation minimises the influx of contaminating sediments and in combination with bacterial activity reduces the supply of oxygen, thus slowing oxidation of the accumulating organic material.

Partial decay transforms the accumulated plant material initially into peat. Subsequent burial by overlying sediments compresses and hardens the peat through increasing temperature and pressure. It has been estimated that a 120 metre-thick layer of plant debris is transformed over about 1.5 m.y. into a coal seam of only one metre in thickness.

This process of coalification yields coals of successively higher rank,

the highest rank coals having the greatest carbon content and calorific value and the lowest degree of moisture and volatile matter. The five broad ranks are peat, brown coal (lignite), sub-bituminous black coal, bituminous black coal and anthracite.

The use to which coal is put depends on its rank, type and grade. Particular kinds of bituminous coal are reduced to coke for use in the smelting of iron ore. 'Hard' coking coals can be converted directly to coke. In contrast, 'soft' coking coals are of lower rank and have greater volatility. They are usually mixed with hard coking coal to form a blend suitable for charging coke ovens. Lower rank sub-bituminous and brown coals are mainly burnt as 'thermal' or 'steaming' coal, particularly in the generation of electricity.

How petroleum is formed

Carbon dioxide + water + solar energy



Crude oil and natural gas are the liquid and gaseous fractions of petroleum. They are generated from source rocks—fine-grained, organic-rich sediments—which are often shales but also coals and some carbonates. The organic matter is derived largely from land plants, and lacustrine and marine plankton. These may be altered by bacterial action, and deposited and preserved in the sediments under low oxygen conditions. Various factors in this process will determine if the source rocks are capable of generating primarily oil or gas.

As the source rocks are buried under further layers of sediments, their temperature rises and they enter the critical temperature range in which the organic matter breaks down to yield petroleum. Most gas is formed at a slightly higher temperature range than oil.

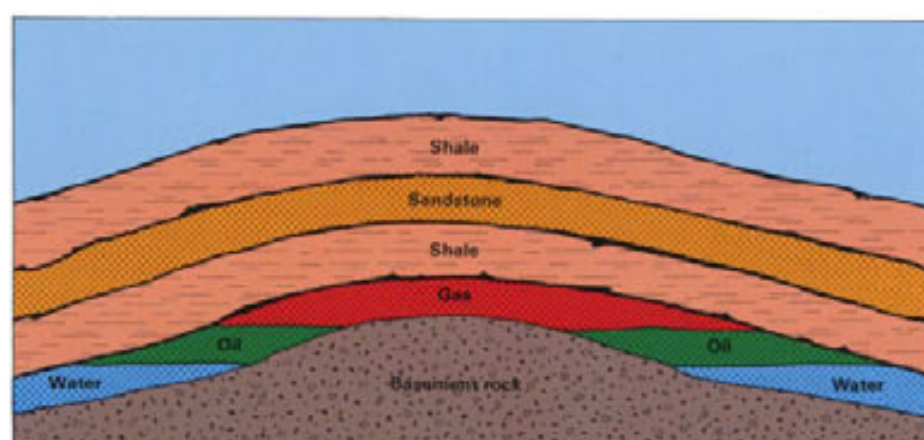
In general the liquid petroleum initially con-

sists of complex compounds. At higher temperatures these break down to simpler oils that are lighter and more mobile, and eventually to gas. Further heating causes the breakdown of the hydrocarbons to methane (dry gas) and as the sediments enter the early stages of metamorphism only a carbon residue is left. Thus with too shallow burial petroleum is not generated, but with too deep burial it is destroyed.

Petroleum expelled from source rocks moves upwards due to buoyancy through minute, interconnected pore spaces (which are generally water-bearing) in coarser grained rocks or along rock fracture planes. These migration routes may lead to traps which prevent the escape of petroleum at the earth's surface. Traps generally consist of porous and permeable reservoir rocks (such as sandstones) sealed by overlying impermeable cap rocks (such as

shales) to form a kind of subsurface structure which prevents further migration. Here the petroleum collects in the pores of the reservoir rock to form 'pools'. Oil can occur alone (sometimes with gas dissolved in it) or with an overlying gas cap. Natural gas commonly contains components which are gaseous under reservoir conditions but revert to liquid form (condensate) when temperature and pressure fall during extraction.

The whole process of source rock formation, petroleum generation, migration and accumulation is complicated and economic reserves of petroleum will not be found in an area unless suitable conditions have existed at the right times for each part of the process. Australia's petroleum deposits, formed mostly in a terrestrial environment, are dominated by gas, with the notable exception of the oil and gas fields of the Gippsland Basin.



Recent mineralisation

Cainozoic surficial deposits

Oil shale

Oil shale, a dark brown to black, fine-grained layered rock of low density, is rich in solid organic matter that yields oil when heated to about 500°C. The oil shales are commonly interlayered with other rocks, such as sandstone and ordinary shale which formed when sand or mud were swept into the 'oil shale' basin. The oldest known oil shale in Australia is of Cambrian age and occurs at depth in the **GEORGINA BASIN**.

Permian oil shales associated with coal seams occur in the **SYDNEY BASIN**, where they were worked from the mid 1860s to 1952, and in the **BOWEN BASIN**. Seams are thin and of limited extent but often high yielding. Permian oil shale has also been worked along the Mersey River in Tasmania (**Latrobe**).

More extensive Cretaceous oil shale deposits are thought to extend at depth throughout much of the **EROMANGA BASIN**. Seams at **Julia Creek** are, for example, about 10 m thick.

Cainozoic oil shale deposits occur in rifts in eastern Queensland (at **Rundle, Stuart, Duaringa, Lowmead, Condor, Nagoorin and Yaamba**). The deposits consist of several oil shale beds, some individually tens of metres thick, separated by barren shale beds. These deposits have minimal overburden and are amenable to open-cut mining. However, technical, economic and environmental problems at present remain a barrier to large scale exploitation.



A seam of precious opal in weathered sandstone at Mintabie (S.A.)

Opal consists of minute spheres of crystallised silica which variably diffract light into a kaleidoscope of colours. These spheres crystallised from silica-rich groundwater, the silica being trapped as a gel in joint and bedding planes above impermeable strata as the climate became more arid and the water table fell. The silica was derived from the weathering of sandstones and sandy mudstones during wetter Tertiary times. These sediments were deposited on the edge of a Cretaceous sea which closely matched the margin of the Great Artesian Basin, along which opal mining takes place today.

The largely unconsolidated surface cover of rock fragments, soil, blown sand and alluvium (now commonly referred to as the 'regolith'), which rests upon solid rock, contains two major types of mineral deposits—those concentrated through deposition (*detrital* deposits) and those formed through chemical alteration of the near-surface rocks (*secondary* deposits).

Detrital deposits

When rocks are weathered and eroded some chemically stable minerals are little affected and accumulate *in situ* if the topography is flat or are carried down drainage channels by streams. The winnowing effect of streamflow separates the light from the heavy minerals, such as gold or tin, which accumulate as deposits in favourable places. Wave and wind action have a similar sorting effect on beach sands; deposits of rutile, ilmenite, zircon and monazite are formed in this way. Some gemstones, particularly diamonds and sapphires, are also found in detrital deposits.

Mineral sands

The east coast of Australia, from Byfield near Rockhampton to the mouth of the Hawkesbury River north of Sydney, is fringed by beaches, plains and dunes containing heavy mineral deposits. In Western Australia they extend intermittently from Eneabba, 270 km north of Perth, to the far south-western corner of the state.

The heavy mineral components of economic interest are the titanium-bearing oxide minerals *ilmenite* and *rutile*, the refractory mineral *zircon* and the rare-earth mineral *monazite*.

The sands of the beach-dune systems represent accumulated material eroded from the land and carried seawards by rivers. The coastal plains were built up during a time of falling sea level, allowing steady advancement of the beach line with continued sediment influx. Some deposits mined in Western Australia are now 30 km inland from the present coastline whereas along the east coast most are close to present-day beaches.

Average heavy mineral grades are 20% in Western Australia, where ilmenite is predominant, but less than 5% in eastern Australia.

The remainder of the sand is mostly quartz or silica.

Diamonds

In the past small quantities of alluvial diamonds have been mined intermittently in several parts of Australia. More recently, the Smoke Creek deposit, downstream from the lamproite pipe source rock at **Argyle** in the Kimberley region of Western Australia, has been an important source.

Sapphires

Australia's sapphire deposits occur in stream alluvium in the **NEW ENGLAND FOLD BELT** (**Glen Innes** and **Inverell**) in northern New South Wales and the **ANAKIE INLIER** (**Anakie**) in central Queensland. The sapphires are thought to have originated at great depth near the crust/mantle boundary and then been carried to the surface by volcanic activity before being released during subsequent weathering and erosion.

Secondary deposits

Chemical alteration of rocks by circulating groundwater during weathering has formed many valuable mineral deposits. Some elements may be carried away, while others are concentrated in particular zones in relation to the surface and to the water table. Clays and talc are common products of weathering. In some circumstances many elements are removed and the chemical composition of the near-surface rocks may be changed profoundly. Bauxite and laterite are formed under such circumstances.

Bauxite

Australia's most important regolith mineral is bauxite. Large world-ranking deposits occur in the Darling Range east of Perth and at **Cape Bougainville** and **Mitchell Plateau**

in Western Australia; at **Gove** in the Northern Territory; and in the **Weipa** area of far north Queensland.

Bauxite is localised in pockets within the extensive laterite cover which has developed on Archaean rocks of the **YILGARN BLOCK** in the Darling Range area (at **Jarrahdale, Del-Park, Huntly, Willowdale** and **Mount Saddleback**). The **KIMBERLEY BASIN** bauxite deposits—**Cape Bougainville** and **Mitchell Plateau**—formed on basic volcanics and interbedded sediments. Although they are higher grade than the Darling Range deposits their economic viability is diminished by the remoteness of the Kimberley region.

The **Gove** bauxite deposit formed over Mesozoic sandstones which overlie the Precambrian crystalline basement of the **ARNHEM INLIER**. The very large **Weipa** deposits in the **CARPENTARIA BASIN** were formed on Tertiary sandstone and siltstone during several lateritic weathering cycles.

Lateritic nickel

The **Greenvale** nickel orebody in north-eastern Queensland consists of a series of residual weathering mantles formed on serpentinite. Even though average grades approach those of sulphide nickel deposits the lateritic nickel is in silicate or oxide form and is thus more costly to process because of higher energy requirements.

Manganese

Extensive secondary manganese deposits occur in the eastern parts of the **HAMERSLEY BASIN** (**Ripon Hills, Ant Hill, Mount Rove, Mount Nicholas** and **Balfour Downs**). The manganese was concentrated in two stages of enrichment, the first during the Proterozoic and the second in the Tertiary.

Opals

The main fields are in central Queensland (**Opalton-Yowah**), northern New South Wales (**White Cliffs** and **Lightning Ridge**) and northern South Australia (**Andamooka, Coober Pedy** and **Mintabie**), where the opal was formed by deposition of silica from groundwater in the enclosing sediments.

Phosphate rock

Australia's sedimentary phosphate ranges in age from Cambrian to Tertiary. The middle Cambrian deposits of the **GEORGINA BASIN** are the largest. Of these the **Phosphate Hill, Sherrin Creek, Lilly Creek, D-Tree, Lady Annie** and **Lady Jane** deposits, all formed in shallow water, are the most significant. The principal phosphate horizon, the **Beetle Creek Formation**, is a series of phosphatic siltstones (phosphorite) and cherts overlying limestone and basal sandstone conglomerate.

Phosphate is associated with early Cambrian limestones in the **KANMANTOO FOLD BELT**, apparently formed during a Tertiary weathering cycle.

Manganese

A world-ranking manganese province extends over an area of 150 km² on **Groote Eylandt** (N.T.). The deposit occurs as a single, relatively flat Cretaceous sedimentary unit averaging 3–4 m in thickness. The orebody comprises pebbles, cobbles and boulders of manganese oxides, in a sandy clay matrix, which were precipitated from seawater in a shallow, sheltered basin.

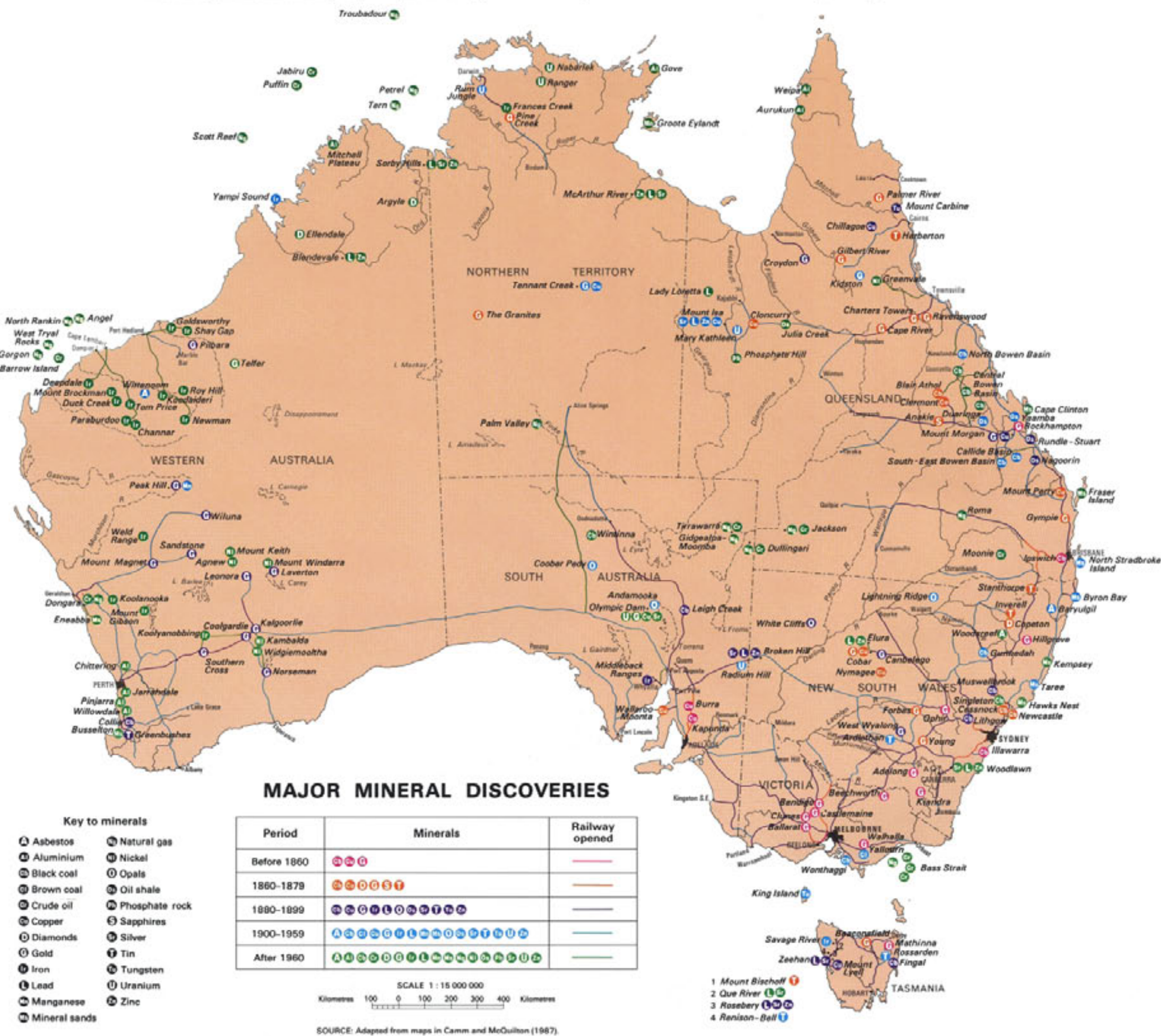
Mineral industry

Since the mid 1800s the mineral industry has not only helped to mould much of Australia's history but has also made a very important contribution to the national economy. Over the last 20 years it has expanded several fold and minerals now exceed the combined agricultural-pastoral sector as the mainstay of the economy and of export trade. This situation is likely to continue given the enormity and variety of the country's mineral resources and current production levels, which for many minerals rank amongst the world's largest.

Australia's annual value of mine production is around \$20 billion and the net mineral trade surplus is a very favourable \$13 billion.



Up to this time successful mining had been confined to eastern and southern Australia but, with the discovery of alluvial gold near Coolgardie in 1892 and the gold lodes of Kalgoorlie soon after, profitable mining became established on the western side of the continent. The importance of gold mining in the west has continued up to the present time and in 1986 just over 70% of Australian gold production came from Western Australia.



During the early decades of the 20th century the only significant mineral finds were tungsten on King Island (Bass Strait) in 1904, and lead-zinc-silver and copper at Mount Isa (Qld) in 1923. Lead, zinc and silver were the backbone of the mineral industry for most of the first half of this century. Mineral processing expanded during this period and technological innovations resulted in improved efficiency in both mining and processing. Notable were the development of differential flotation (basically still used world-wide) for the separation of lead and zinc sulphides from Broken Hill ores and, later, electrolytic refining of zinc sulphides to pure metal. The Australian steel industry was also established, with the construction of steelworks in New South Wales at Newcastle in 1915 and at Port Kembla by 1932.

The last forty years

By the late 1940s low reserves and the apparent lack of many minerals in Australia was a cause of major concern. However, from then on there was an upsurge in exploration which led to the discovery of a range of mineral resources (as indicated on the map 'Major Mineral Discoveries') and their subsequent development. Strong overseas demand for minerals needed for post-war industrial growth, combined with an increased understanding of the geology of the continent, stimulated exploration.

Simultaneously, advances in exploration technology have enabled geoscientific principles to be systematically applied to the search for mineral deposits. Whereas earlier discoveries were often made by accident or at best by studying exposed outcrops and ore samples, deeply buried deposits with little or no surface expression and deposits in remote regions that had hitherto escaped notice were now detectable.

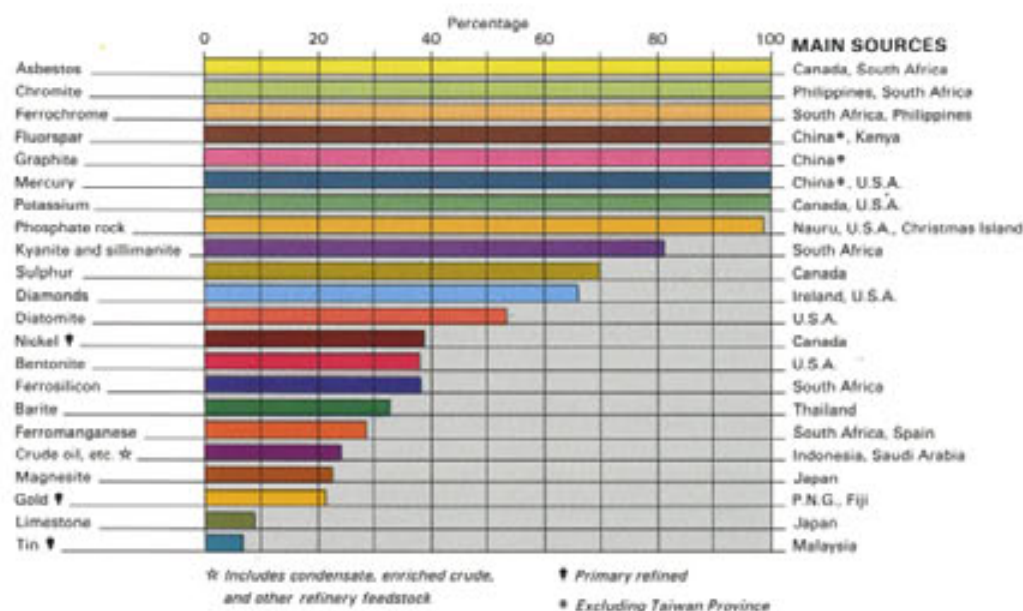
The post-war minerals boom experienced by Australia really began with uranium mining in the early

1950s. In the 1960s enormous open-cut iron ore mines began production in the Pilbara region of Western Australia; established coal mines in New South Wales were expanded and new mines developed, both in New South Wales and Queensland; large scale manganese production began at Groote Eylandt in the Northern Territory; oil and gas fields were developed in Bass Strait, at Moonee and Roma in Queensland, at Moomba in South Australia, and at Barrow Island in Western Australia; nickel mining and processing were established in Western Australia; the mining and export of bauxite became a major industry; and vast uranium resources were discovered in the Northern Territory.

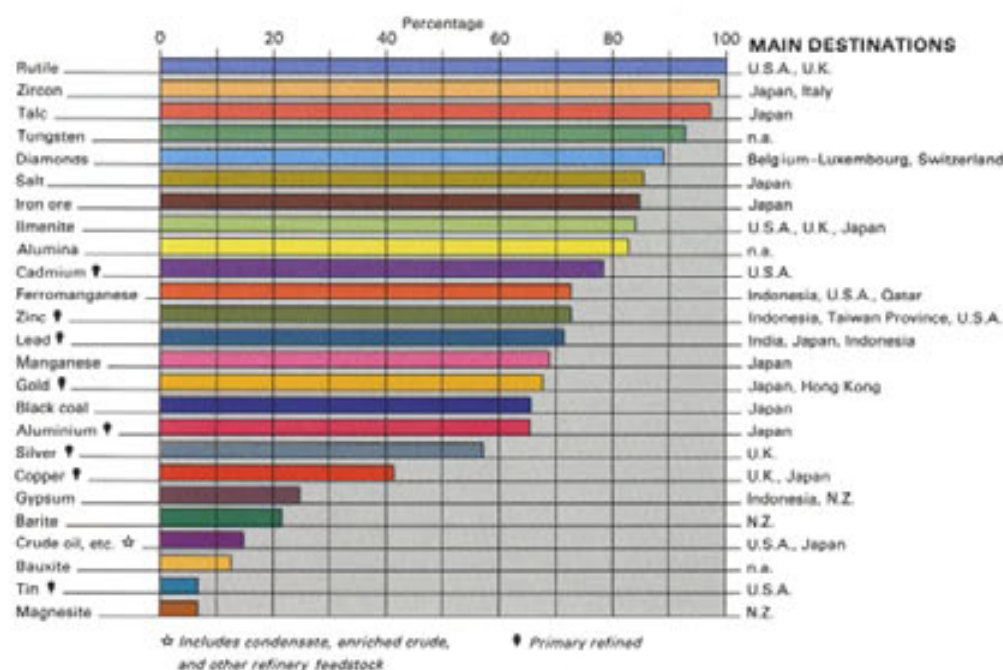
Three main factors have altered the face of Australia's mineral industry since 1965:

- Iron ore and aluminium have displaced the traditional base metals—copper, lead and zinc—which, along with silver and coal, had up to then formed the basis of the industry.
- There has been expansion of long established industries such as tin, black coal and mineral sands and the development of new ones such as nickel.
- Export markets have been considerably widened, particularly in Japan but also elsewhere in South-East Asia and Europe—as illustrated by the diagram (right) showing the percentage of mineral production exported in 1986 and the main destinations for the various minerals.

The most recent impacts on the Australian mineral industry have come from the development of petroleum and uranium resources following the energy crises of the 1970s; the resurgence of gold mining from 1980 onwards in response to greatly increased world prices; and the establishment of diamond mining. On the other hand, low world prices over the last few years for some minerals, such as nickel and tin, have resulted in declining production levels and the closure of marginal mines.



Percentage of mineral consumption imported, 1986



Percentage of mineral production exported, 1986



One of six daily ore trains on its 425 km journey from Newman to Port Hedland (W.A.) Around 20 trains, each carrying up to 21 000 t of iron ore in 210 wagons, travel between the Pilbara region mines and ports each day.

Contribution to Australia's economy

The total ex-mine value of mineral production has risen from \$540 million in 1965 to almost \$20 000 million in 1986. The overall expansion of the mining industry is clearly indicated by the fact that in 1965 mining contributed less to the Gross Domestic Product than either the pastoral or the agricultural sectors yet by 1985 was greater than both of these combined.

Today Australia's mineral industry largely satisfies all domestic mineral and fuel requirements. As late as 1960 Australia lacked self-sufficiency in many important minerals and mineral trade was barely in balance. Now the value of mineral exports is almost ten times that of mineral imports and most mineral deficiencies have been eliminated (see page 27). The deficiency in crude oil has been significantly reduced although petroleum, at around two-thirds of the value of Australia's mineral imports, continues to be the most costly imported item. The diagram 'Percentage of mineral consumption imported, 1986' on page 37 indicates the extent to which Australia still relies on imported minerals.

Recent growth in the mineral

industry has been heavily export-oriented and its contribution to foreign exchange earnings best measures its impact on the Australian economy. As shown by the pie diagrams on page 39 the mineral industry has in recent years grown to be the largest single export earner, accounting for almost half of the total value of exports in 1986. Black coal, Australia's largest single export item, together with iron ore and bauxite, alumina and aluminium account for two-thirds of the value of mineral exports. Australia is the world's largest exporter of a number of minerals including black coal, alumina, lead, ilmenite, rutile and zircon as shown in Table 4.

Despite being endowed with abundant mineral resources Australia is a relatively minor consumer

of most mineral products as illustrated by the diagram 'Percentage of mineral production exported, 1986' on page 37. Only a small proportion of mine production is fully processed within Australia; much is exported overseas in semi-processed form. In recent years, however, steeply rising fuel prices have adversely affected the economics of mineral processing in the energy-importing industrial nations of the Northern Hemisphere. As a result many treatment plants traditionally located in industrial areas close to markets are now being built near primary energy sources.

Australia, with abundant coal resources, has benefited from this trend to relocate facilities and now has considerable investment in mineral processing—perhaps best illustrated by aluminium, the production of which is extremely energy-intensive. An increasing proportion of Australia's alumina is being processed domestically and aluminium exports have been rising sharply in recent years.

Table 2. Overview of Australia's mineral industry

	1984	1985	1986
Mineral output			
Value, ex-mine (\$M)	17 358	22 108	19 720
Value added, mining industry (\$M)	8 825	10 610	12 956
Mineral primary product exports			
Value, f.o.b. (\$M)	11 421	15 262	14 811
Mineral primary product imports			
Value (\$M)	2 066	2 029	1 542
Balance of mineral trade (\$M)	9 355	13 233	13 269
Employment, total mining	77 900	78 100	78 900

Table 3. Australian and world production of principal minerals, 1986

Mineral	Unit	Australian production	World production	Australian ranking in world
Alumina	t	9 423 000	33 500 000	1
Aluminium	t	882 000	15 724 000 (a)	4
Bauxite	t	32 384 000	91 143 000	1
Coal (saleable)	t	139 000 000	3 195 000 000	7
Copper (b)	t	248 000	6 461 000 (a)	7
Copper, refined (c)	t	184 000	7 523 000 (a)	10
Diamonds	carat	29 232 000	89 160 000	1
Gold (b)	kg	75 079	1 280 800 (a)	4
Iron ore	t	94 000 000	903 000 000	4
Lead (b)	t	448 000	2 330 000 (a)	1
Lead bullion	t	188 000	n.a.	n.a.
Lead, refined (c)	t	171 000	3 990 000 (a)	8
Manganese ore	t	1 649 000	24 260 000	5
Nickel (b)	t	77 000	790 000	3
Nickel, refined (d)	t	42 000	753 000	4
Rutile	t	216 000	430 000	1
Silver (b)	t	1 023	13 425	5
Tungsten	t	1 600	16 243 (a)	4
Tin (b)	t	8 515	138 900 (a)	6
Tin, refined	t	1 399	148 700 (a)	11
Uranium	t	4 000	28 000 (a)	4
Zinc (b)	t	712 000	5 017 000 (a)	2
Zinc, refined (c)	t	308 000	4 840 000 (a)	4
Zircon	t	452 000	801 000	1

(a) Western world
(b) Metallic content of all minerals produced
(c) Primary and secondary
(d) Includes nickel oxide

Table 4. Principal Australian mineral exports, 1986

Mineral	Unit	Quantity	Value \$M	World export ranking
Alumina	t	7 687 000	1 427	1
Aluminium	t	579 544	975	3
Black coal	t	92 792 000	5 364	1
Copper	t	140 133	248	9
Gold	kg	58 735	941	3
Ilmenite	t	1 034 209	49	1
Iron ore	t	79 678 000	1 938	2
Lead	t	412 213	361	1
Manganese	t	1 145 000	n.a.	4
Nickel	t	n.a.	439	2
Rutile	t	229 665	116	1
Tin	t	7 494	58	8
Tungsten	t	2 526	14	3
Uranium	t	4 166	373	2
Zinc	t	661 823	489	2
Zircon	t	445 690	75	1



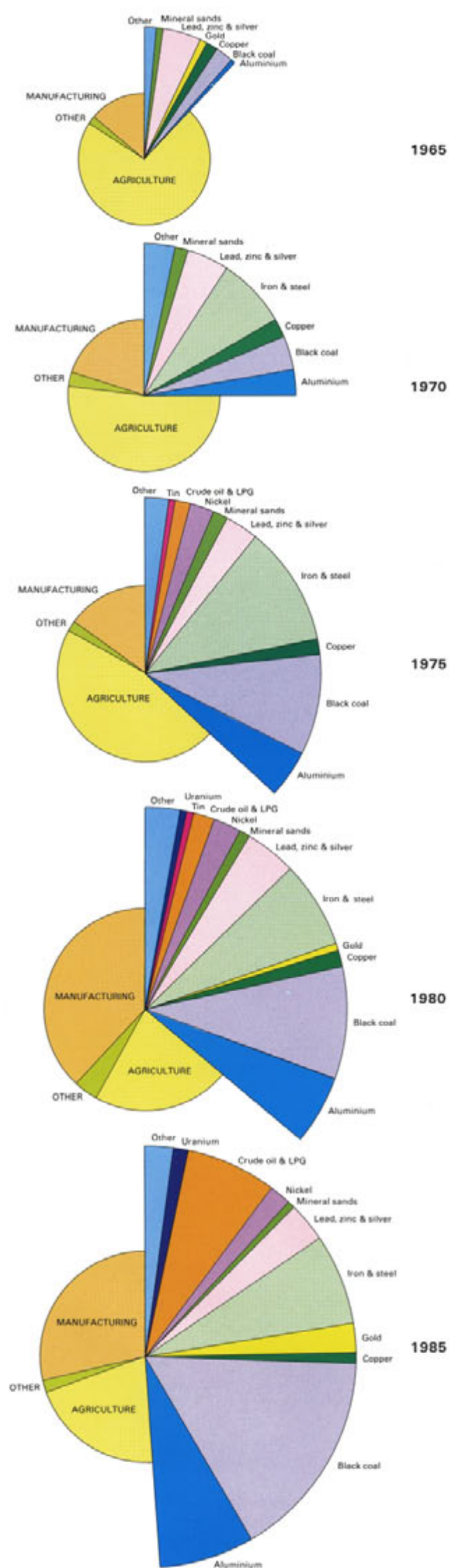
The new township of Olympic Dam (S.A.), built to serve the copper-uranium-gold mine being developed nearby

As a result of the recent minerals boom the mineral industry has resumed its former role of opening up the country with new railway lines, roads, ports and towns—some in extremely remote areas. Within a decade the mining industry was responsible for the building of 24 permanent townships, 12 ports, more than 20 airfields and the laying of nearly 2000 km of new railway track.

In the 1960s, for every \$1 million spent on iron, coal and nickel mine development, \$1.8 million were spent on associated infrastructure. More recently, provision of such facilities has still accounted for about 50% of capital expenditure on mining projects.

Australia's major mineral resources

Mineral	Unit	Economic demonstrated resources, 1986	Percentage of world resources
Bauxite	t	2 854 000 000	12
Black coal	t	34 000 000 000	5
Brown coal	t	41 900 000 000	18
Copper	t	16 000 000	3
Diamonds	carat	386 000 000	n.a.
Gold	t	1 026	1
Iron ore	t	15 850 000 000	8
Lead	t	15 760 000	11
Manganese	t	192 000 000	2
Nickel	t	1 100 000	1
Rutile	t	8 960 000	7
Silver	t	32 460	10
Tin	t	249 000	8
Tungsten	t	56 000	2
Uranium	t	462 000	28
Zinc	t	24 920 000	8
Zircon	t	12 940 000	28



Contribution of the mineral industry to Australia's export earnings, 1965-85 (at constant prices)

Table 5. Quantity and ex-mine value of Australian mineral production, 1986

	Unit	Quantity	Value (\$'000)
Major metals			
Aluminium (bauxite)	t	32 384 000	n.a.
Copper ore and concentrate	t	887 562	360 956 (e)
Copper content	t	231 737	(a)
Copper in mine products	t	248 368	(a)
Copper-tin concentrate	t	586	n.a.
Copper content	t	132	(a)
Tin content	t	7	(a)
Iron ore and concentrate	t	94 015 000	2 227 364 (b)
Iron oxide	t	38 888 (b)	2 326 (b)
Lead ore and concentrate	t	788 539	282 949 (e)
Lead content	t	396 136	(a)
Lead in mine products	t	447 673	(a)
Nickel ore	t	2 116 543	25 434
Nickel concentrate	t	402 398	283 374
Nickel in mine products	t	76 739	(a)
Tin concentrate	t	17 261	105 706
Tin content	t	8 515	(a)
Zinc ore and concentrate	t	1 337 180	322 664 (e)
Zinc content	t	843 334	(a)
Zinc in mine products	t	711 958	(a)
Gold			
Gold bullion	kg	105 172	1 274 082
Gold in mine products	kg	75 079	(a)
Gold ore and concentrate	t	10 258 (c)	11 844
Other metals			
Antimony ore and concentrate	t	909	1 489
Antimony-gold concentrate	t	75	48
Antimony in mine products	t	1 131	(a)
Bismuth concentrate	t	1 489	n.a.
Bismuth content	—	n.a.	(a)
Cadmium in mine products	t	2 079	(a)
Cobalt in mine products	t	2 914	(a)
Lithium concentrate	t	12 703	3 994
Manganese ore	t	1 649 000	88 381
Molybdenite concentrate	t	22	21 (e)
Molybdenum content	t	8	(a)
Silver ore and concentrate	t	3 842	7 694
Silver in mine products	kg	1 022 761	(a)
Tantalite-columbite concentrate	kg	140 172	4 662
Tungsten			
Scheelite concentrate	t	1 899	10 930 (e)
Tungsten content	t	1 142	(a)
Wolframite concentrate	t	835	3 712
Tungsten content	t	458	(a)
Fuels			
Black coal (raw)	t	170 067 000	5 302 444 (e)
Brown coal	t	37 604 000	238 821
Petroleum, total value	—	—	6 419 952 (e)
Crude oil and condensate	ML	29 764	5 024 645
Natural gas	million m ³	14 869 (d)	847 331 (d)
Liquefied petroleum gas	thousand m ³	3 929	547 977
Uranium oxide	t	4 899	407 299
Gemstones			
Diamonds	carat	29 232 453	256 983
Opals	—	n.a.	56 790
Sapphires	—	n.a.	13 022
Other	—	n.a.	499
Used mainly in			
Building and construction			
Clay, total value (f)	—	—	47 066
Brick clay and shale	t	6 918 000	27 482
Cement clay and shale	t	459 969	1 587
Construction materials	t	144 863 000	894 557
Gypsum	t	1 671 000	8 578
Limestone	t	10 747 000 (g)	57 322 (g)
Used mainly in			
Chemicals and fertilisers			
Phosphate rock	t	33 859	1 225
Salt	t	6 130 000	117 755 (h)
Sulphur in mine products	t	453 012	(a)
Other minerals			
Barite	t	5 819	239
Carbon dioxide	—	n.a.	580
Clay			
Bentonite and Bentonitic clay	t	39 933	1 325
Kaolin and ball clay	t	185 617	10 530 (g)
Other clay	t	1 776 000	3 022 (g)
Diatomite	t	9 048	1 697
Dolomite	t	719 864	3 481
Felspar	t	10 006	96
Garnet concentrate	t	9 724	340
Magnetite	t	41 441	1 827
Mica	t	24	2
Minerals sands			
Ilmenite concentrate	t	1 238 000	70 594
Leucocoxene concentrate	t	14 143	5 315
Monazite concentrate	t	14 822	9 503
Rutile concentrate	t	215 774	109 724
Xenotime concentrate	t	41	236
Zircon concentrate	t	451 824	72 438
Peat	t	7 265	501
Pyrophyllite (incl. chlorite)	t	8 588	476
Silica (for glass, chemicals, etc.)	t	2 091 000	22 969
Sillimanite and Kyanite	t	901	129
Talc	t	179 467	1 119 (g)
Vermiculite	t	657	13
Minerals not specified above	—	—	390
Total value (i)			19 719 710

(a) Included in value of mineral in which contained

(b) Excludes Tasmania

(c) Excludes South Australia

(d) Includes ethane

(e) Estimated

(f) Also includes value of clays listed under 'Other minerals'

(g) Excludes Western Australia

(h) Excludes Victoria

(i) Includes estimates for values of minerals not separately available

Major metals

Aluminium

Australia is the world's largest producer of bauxite, the largest producer and exporter of alumina, and the fourth largest producer and third largest exporter of primary aluminium.

Bauxite is refined to produce alumina (aluminium oxide) which in turn is smelted under extremely high temperature to extract aluminium metal. Over the past two decades the production of bauxite, alumina and aluminium has been one of the country's fastest growing mineral industries—see the two diagrams on page 41.

Australia's economic resources of bauxite, estimated to be around 5000 Mt, represent about 20% of the world's reserves and are second only to Guinea in size. As recently as the early 1950s, however, it was believed that Australia lacked significant bauxite resources but around this time three major deposits were found—at **Gove** (N.T.) in 1952, at **Weipa** (Qld) in 1955 and at **Jarrahdale** in the Darling Range east of Perth (although the existence of aluminous laterites in the latter area had been known for

many years). Other large deposits were subsequently discovered at **Mitchell Plateau** and **Cape Bougainville** in the Kimberley region of Western Australia, at **Aurukun** south of Weipa, and elsewhere in the Darling Range.

Mining of bauxite began at both **Weipa** and **Jarrahdale** in 1963 and at **Gove** in 1971. Today these mines together with others opened more recently at **Del-Park**, **Huntly**, **Willowdale** and **Mount Saddleback** in the Darling Range account for virtually all of Australia's bauxite output. Production rose rapidly from less than 2 Mt in 1966 to the current level of over 30 Mt per annum (see diagram on page 41), or 35% of total world output.

As the major bauxite deposits occur in coastal regions most of the alumina refineries were able to be built close to the mines and to deep-

water ports, thus minimising land transport of large tonnages of bauxite and alumina. The refinery at **Gladstone** in central coastal Queensland is the only one not located close to its source of bauxite; it was sited to take advantage of nearby low cost coalfields and a deep-water harbour.

Nearly 85% of the bauxite is refined domestically; the remainder, amounting to about 5 Mt per annum, is exported from **Weipa** and **Gove**. Australia's six alumina refineries, which have a combined annual capacity of 9 Mt (see Table 6), account for 25% of total world production. With an annual capacity of 2.7 Mt the refinery at Gladstone is the world's largest.

Currently more than 7 Mt of alumina, representing about 80% of production, is exported annually, mainly to the U.S.A. and Europe although increasing amounts are being sent to Asia and the Middle East. The remainder is shipped from Kwinana, Bunbury and Gladstone to the various aluminium smelters in south-eastern Australia or consumed locally by the **Gladstone** smelter.

Because the processing operations demand extremely high usage of electricity Australia's six aluminium smelters have been built close to major energy sources, notably the large power stations associated with coalfields in Victoria (Point Henry near **Geelong**, **Portland**), the Hunter Valley near **New South Wales** (**Kurri Kurri**, **Tomago**) and central Queensland (Boyne Island near **Gladstone**). The first aluminium smelter and refinery, at **Bell Bay**, was sited there to take advantage of Tasmania's generous supply of hydro-electricity.

The opening of additional aluminium smelters during 1982 and 1983, improved operating efficiencies and the expansion of existing smelters have all contributed to the dramatic increase of over 100% in primary aluminium production between 1982 and 1986 to 0.9 Mt (as shown on the production and export of aluminium diagram on page 41). The rapid rise in primary aluminium exports closely mirrors output. Approximately 65% of production is exported, with an increasing share going to the Japanese and South-East Asian markets.

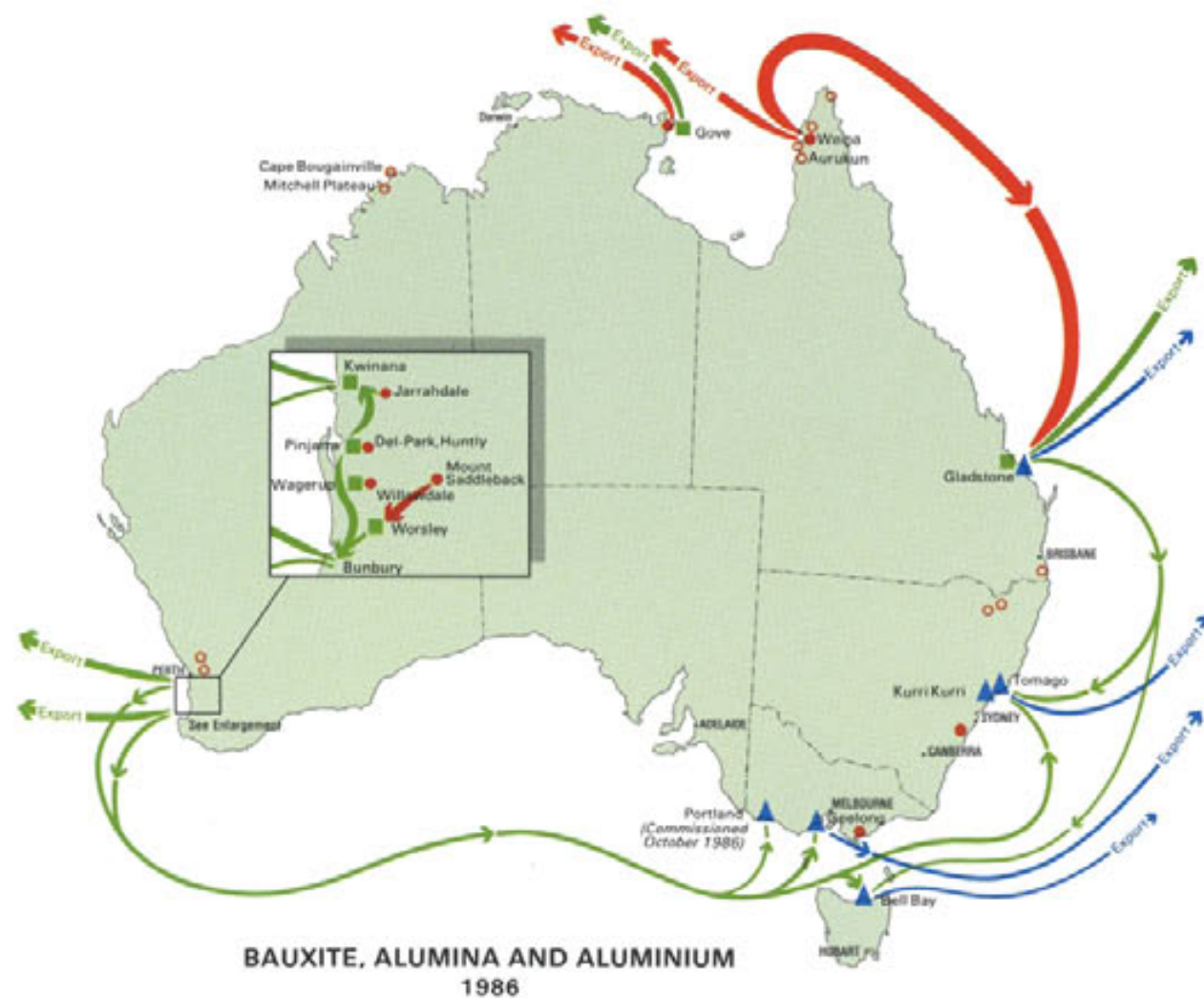
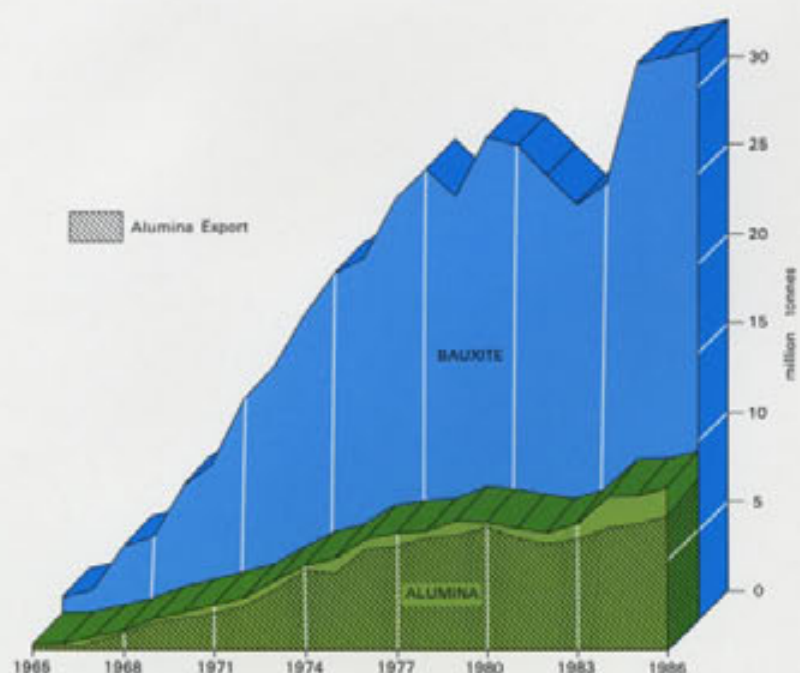


Table 6. Australia's aluminium industry

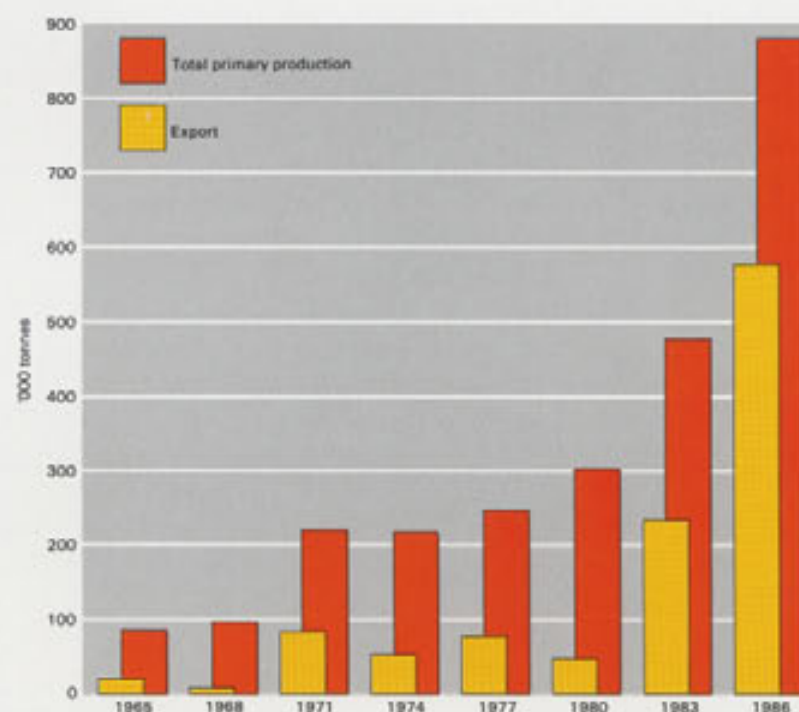
Plant	State	First commissioned	Capacity, 1986 (tonnes)	
			Alumina refinery	Aluminium smelter
Bell Bay	Tas.	1955	*	117 000
Kwinana	W.A.	1963	1 400 000	
Geelong	Vic.	1963		165 000
Gladstone	Qld	1967	2 700 000	
Kurri Kurri	N.S.W.	1969		150 000
Gove	N.T.	1972	1 000 000	
Pinjarra	W.A.	1972	2 400 000	
Gladstone	Qld	1982		208 000
Tomago	N.S.W.	1983		230 000
Wagerup	W.A.	1984	500 000	
Worsley	W.A.	1984	1 000 000	
Portland	Vic.	1986		150 000
Australia			9 000 000	1 020 000

* Alumina production ceased in 1975





Australia: production of bauxite and alumina and export of alumina, 1965–86



Australia: production and export of aluminium, 1965–86



Bauxite mining at Weipa (Old)
Following removal of vegetation and shallow overburden the aluminium-rich ore is scooped up (left) and transported to the nearby port of Weipa (far left). The stockpiled bauxite is washed, screened and graded before shipment to the Gladstone alumina refinery or overseas.

The world's largest alumina refinery, near Gladstone (Old)
Sited to take advantage of nearby large economic energy sources and a deep-water harbour, the Gladstone refinery (above) produces about 2.7 Mt of alumina annually from around twice that tonnage of Weipa bauxite.

Copper

Australia ranks as the tenth largest producer of copper but accounts for only 3% of world mine production. Nevertheless, copper is an important export-earning mineral for Australia, the world's ninth largest exporter.

Copper mining began in 1842, at Kapunda in South Australia. In the second half of the 19th century Australia was a leading world producer, exporting copper ore from rich fields now worked out or uneconomic such as Moonta and Burra (S.A.), and Cloncurry and Mount Morgan (Qld). In the early 1900s copper production declined until the high grade copper ore bodies were discovered at **Mount Isa** in 1923. Though worked for emergency purposes during the Second World War full scale production did not begin here until 1953. Mount Isa now produces about two-thirds of Australia's annual output of around 250 000 t of contained copper—see Table 7.

Other significant producers of copper ores and concentrates are **Cobar** and **Woodlawn** (N.S.W.), **Mount Lyell** (Tas.), and **Warrego** near Tennant Creek (N.T.). Low prices for copper in the late 1970s, reflecting increased penetration of the metal's traditional markets by aluminium, steel and plastic, led to the closure of marginal operations, among them **Kanmantoo** (S.A.) and **Gunpowder** (Qld). The mines at **Mount Gunson** (S.A.) and **Teutonic Bore** (W.A.) ceased operations in 1986 when reserves of copper ore were exhausted.

A major new mine with an initial annual output of 30 000 t of contained copper is being developed at **Olympic Dam** (S.A.). The mine should be in production by mid 1988 and by its fourth year of operation output of copper is expected to increase to 55 000 t annually. Evaluation of a large copper deposit with a potential annual output of 35 000 to 50 000 t of contained copper and significant amounts of precious metals is now well advanced at **Goonumbla** near **Parkes** (N.S.W.). Both opencut and underground mining are proposed.

Copper is also an important by-product of some other mining operations, notably lead and zinc mining at **Broken Hill** (N.S.W.) and **Rosebery** and **Que River** (Tas.), and nickel mining in the **Kambalda** area of Western Australia.

Much of the mine output is converted into copper metal in Aust-

ralia; nearly 80% of the concentrates are processed to blister copper (97–98% copper), so called because of its blistered appearance as it cools, and refined copper (99.9% copper). In 1986 production of primary refined copper amounted to almost 164 000 t—see Table 7.

Copper concentrates produced at **Mount Isa** are smelted on site then railed to the **Townsville** refinery, Australia's largest, which has an annual capacity of 165 000 t. About half of the copper produced at Townsville is exported.

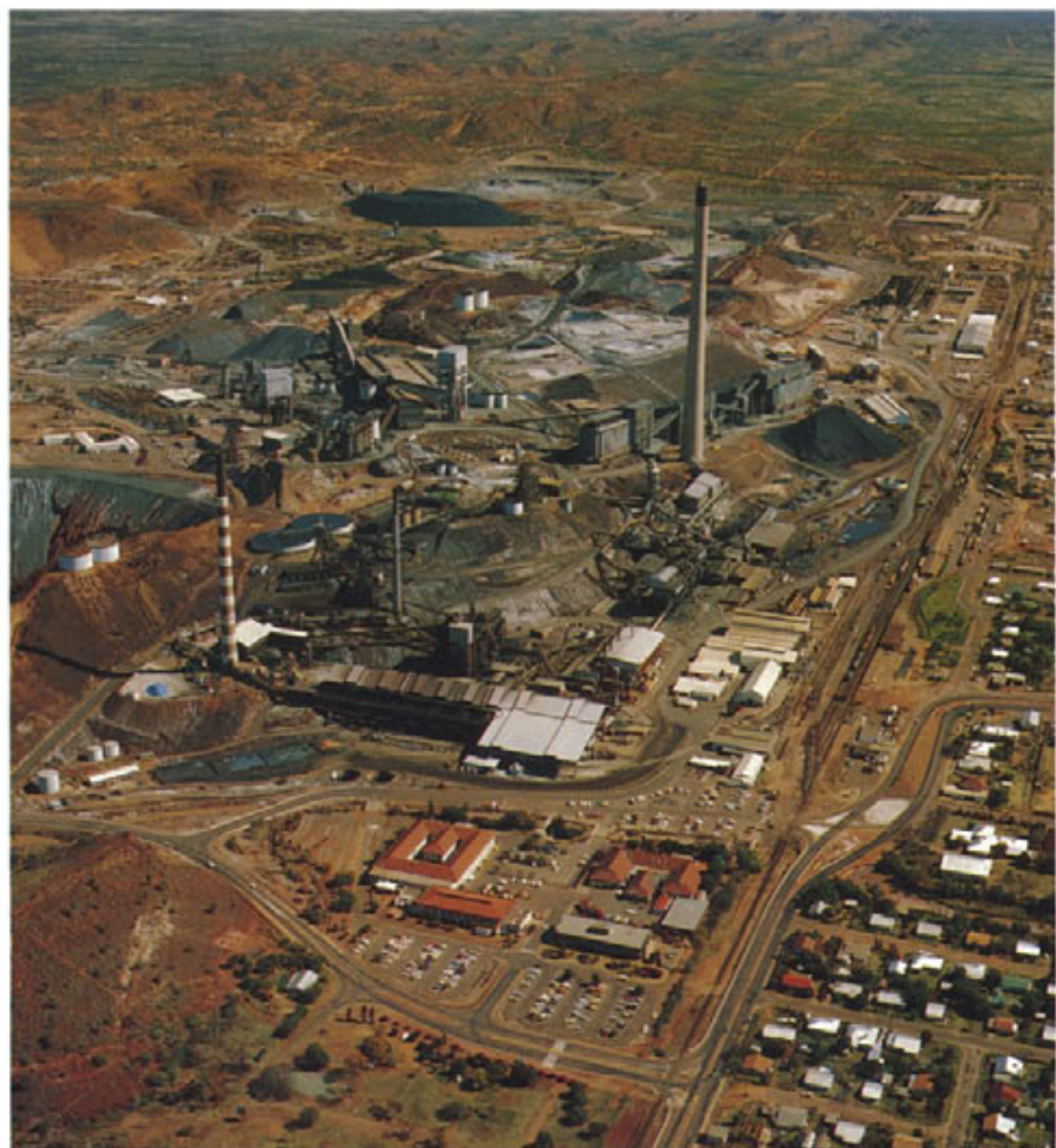
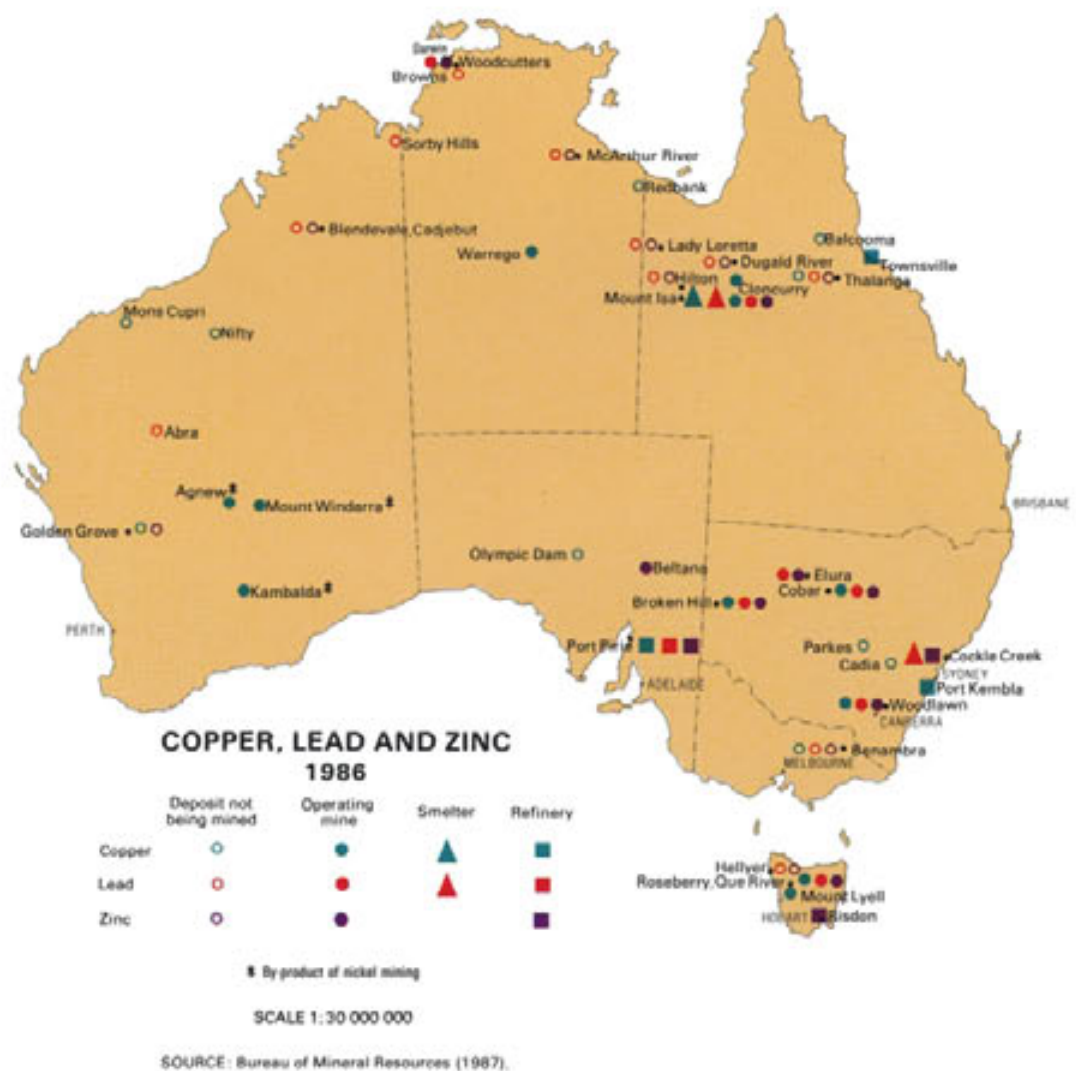
The other main centre of copper processing is the integrated smelting and refining works at **Port Kembla** (N.S.W.), originally sited there in 1907 to take advantage of abundant coal supplies and available port and industrial service facilities. Today the plant has an annual capacity of 40 000 t of refined copper and treats concentrates from **Cobar** and **Woodlawn**. The refinery is Australia's major producer of secondary refined copper—from purchased scrap, residues and drosses. Most production is sold domestically.

A small refinery with an annual capacity of 4000 t was commissioned at **Port Pirie** in 1984. It processes copper matte derived from the copper dressing of lead bullion at the nearby lead smelter/refinery.

A flash smelter formerly operated at **Warrego** but following its closure in 1981 all copper concentrates were transported by road to **Mount Morgan** for smelting. Warrego concentrates, together with concentrates from Mount Chalmers east of Rockhampton, were the major source of feed for the Mount Morgan smelter after mining ceased there in 1981. Mount Chalmers closed in 1982 due to exhaustion of ore reserves and copper concentrates produced at Warrego following the closure of Mount Morgan smelter in 1984 were exported. A low grade copper concentrate produced at Warrego is leached on site to produce a copper cement product which is sent to Burra (S.A.) for conversion to copper oxide for use in the manufacture of agricultural fertilisers.

Table 7. Copper production, 1984–86

	1984	1985	1986
	thousand tonnes		
Mine production of copper	236	260	250
Production of primary blister copper	180	168	170
Production of primary refined copper	171	164	164
Production of secondary refined copper	26	31	23
Exports of copper ore and concentrate	202	270	233
Exports of copper in copper ore and concentrate	59	78	66
Exports of refined copper	75	71	67



Surface operations at Mount Isa mine (Old). Mount Isa is the world's largest single producing lead-silver mine and a major producer of copper

and zinc. All of the ore is mined underground. The former lead-silver open-cut mine is to the left of the striped chimney; the copper

smelter is immediately to the right. The lead smelter is in front of the tallest chimney. The headframes for the copper and the silver-

lead-zinc mines are located close to one another, behind the two tall chimneys.

Lead and zinc

Australia contains about 9% of the world's economic demonstrated resources of lead and 7% of the world's zinc. It is the Western world's largest mine producer and exporter of lead, and the second largest mine producer and exporter of zinc (after Canada).

Since the discovery in 1883 of the **Broken Hill** lead-zinc-silver orebody, perhaps the richest the world has ever known, Australia has been a major producer of lead and zinc ore. This position was reinforced by the discovery in 1923 and subsequent exploitation of the large orebody at **Mount Isa**, now the site of the biggest single producing lead-silver mine in the world.

Together the mines at **Broken Hill** and **Mount Isa** account for about 75% of total lead output and over 50% of zinc output. Most of the remainder comes from **Elura**, **Cobar** and **Woodlawn** (N.S.W.), **Rosebery** and **Que River** (Tas.), and **Woodcutters** (N.T.). Zinc is also produced at **Beltana** (S.A.), where a zinc silicate deposit is mined intermittently. At **Teutonic Bore** (W.A.) zinc was mined in association with copper until the orebody was exhausted in 1986.

Several major development proposals for new lead-zinc mines are now well advanced. The **Hilton** region, just to the north of Mount Isa, is emerging as one of the world's great silver-lead-zinc areas. By the mid 1990s the production rate at Hilton is scheduled to be 2.5 Mt of ore per year which will compensate for a corresponding decline in production at Mount Isa as ore reserves there are depleted. Other deposits being developed or for which development proposals are nearing completion include **Lady Loretta** north-west of Mount Isa, **Benambra** in north-eastern Victoria, **Hellyer** near Que River (Tas.) and **Cadjebut** near Fitzroy Crossing (W.A.).

Lead-zinc ores yield a range of mine products, differing mainly in their relative proportions of lead and zinc and associated by-products. The three main concentrate types are lead (-silver), zinc (-cadmium), and lead-zinc or 'mixed' concentrates.

Lead and zinc processing are among Australia's longest established mineral industries, having formed the basis of much of the country's industrialisation in the early part of the 20th century. Today there are lead smelters at **Mount Isa** and at **Cockle Creek** near Newcastle (N.S.W.), an integrated lead smelter/refinery at **Port Pirie**, and zinc refineries at **Port Pirie**, **Cockle Creek** and **Risdon** (Tas.).

The smelter at **Mount Isa** has an annual capacity of 180 000 t of lead and processes most locally produced lead concentrates. The lead

bullion and lead concentrates not treated by the smelter are railed to **Townsville** for shipment overseas.

Lead smelting and refining commenced at **Port Pirie**, the nearest port to **Broken Hill**, in 1897. Now, with an annual production capacity of 235 000 t of refined lead, the **Port Pirie** lead smelter/refinery is the world's largest. Early attempts to integrate zinc refining were unsuccessful but in 1967 an electrolytic refinery with an annual capacity of 45 000 t was installed to recover zinc remaining in the residue after lead smelting and from stockpiled slag, both of which contain about 17% zinc.

Lead and zinc concentrates from **Broken Hill**, **Cobar** and **Woodlawn** are treated at **Cockle Creek** using the Imperial Smelting Process (which enables the zinc content of both lead and mixed lead-zinc concentrates to be recovered) to produce lead bullion, all of which is exported, and refined zinc. The rated capacity of the plant is 28 000 t of lead bullion and 80 000 t of refined zinc per annum though plans are in hand to increase total zinc capacity of the operation in stages, as economic conditions permit, over the coming years.

The largest of Australia's three zinc refineries, and the second largest in the world, at **Risdon** near Hobart, has an annual capacity of 214 000 t of high grade electrolytic zinc. The refinery was originally established in 1916 to process zinc-rich ores from the Tasmanian west coast but now treats zinc concentrates from most Australian lead-zinc mines.

Australia is the largest exporter of lead, accounting for nearly 30% of world exports of lead ores and concentrates, lead bullion and refined lead. The bulk of the lead bullion from **Mount Isa** is exported to the U.K. for refining; the remainder goes to Japan for toll refining and marketing in Asia. About two-thirds of Australia's refined lead production is exported, mainly to India and other Asian countries.

Unlike lead, where 80% of the concentrate produced is processed in Australia, less than half the zinc concentrate produced is processed locally. Over half of the zinc ore and concentrate is exported to Japan, with much of the remainder going to Western Europe and Korea. Refined zinc is exported mainly to various Asian countries and the U.S.A.



Table 8. Lead and zinc production, 1984-86

	1984	1985	1986
	thousand tonnes		
Lead			
Mine production of lead	441	498	449
Production of lead bullion	179	183	188
Production of primary refined lead	199	200	156
Exports of lead ore and concentrate	151	181	218
Exports of lead bullion (lead content)	189	175	185
Exports of refined lead	147	154	111
Zinc			
Mine production of zinc	677	759	712
Production of primary refined zinc	302	289	303
Production of secondary refined zinc	5	5	5
Exports of zinc ore and concentrate	840	836	876
Exports of refined zinc	221	215	217

The **Cadjebut** lead-zinc mine, north-west Western Australia. The **Cadjebut** deposit is one of several discovered recently after many years of exploration and drilling in the Kimberley area. Although small, the deposit is high grade and easily mined via a shallow decline. The concentrates, which are free of many impurities, are trucked to Wyndham for shipment to Australian or overseas smelters.

Iron and steel

Australia's high grade iron ore resources are amongst the world's largest. The U.S.S.R. and Canada have larger low grade resources but only Brazil has larger high grade resources. With about 10% of world production, Australia is the fourth largest producer of iron ore after the U.S.S.R., China and Brazil and the second largest exporter of iron ore after Brazil.

Iron ore has been mined from the **Middleback Ranges** of South Australia for the domestic iron and steel industry for around 70 years. However, the establishment of a large scale export industry did not begin until the mid 1960s when, following the delineation of vast resources of high grade ore in the Pilbara region of Western Australia and smaller deposits elsewhere, the long-standing Commonwealth embargo on exports of iron ore was lifted. Whereas reserves with mining potential were estimated at only 374 Mt in 1959, total economic demonstrated resources are now known to be of the order of 15 000 Mt, about 7% of the world's total.

The rapid development of deposits and associated growth of production and exports in the late 1960s and early 1970s were underpinned by the large and increasing iron ore requirements of the Japanese steel industry, the major export market. Production of iron ore rose from 7 Mt in 1965 to 51 Mt in 1970 and to almost 100 Mt in 1975. In line with a world-wide recession in the steel industry in subsequent years, pro-

duction declined to just over 70 Mt in 1983 but has since increased to around 95 Mt—see diagram 'Production and export of iron ore, 1965–86'.

About 90% of Australia's total production of iron ore is won from four major mines in the Pilbara region (**East Deepdale, Mount Tom Price, Newman and Paraburdoo**). Other production comes from smaller mines in the Pilbara, the **Middleback Ranges, Yampi Sound (W.A.)** and **Savage River (Tas.)**. Until 1983 iron ore was also mined at **Koolyanobbing**, west of Kalgoorlie, but ceased following closure of the Kwinana blast furnace, which it mainly supplied. Some ore from Koolyanobbing was used at Newcastle and Port Kembla, with the last shipments from stockpiled ore at Kwinana taking place in 1983.

Ore from the relatively low grade **Savage River** deposit is crushed and concentrated at the mine before being pumped as slurry through an 85 km-long pipeline to **Port Latta** where it is converted into pellets. In 1986 the shipment of pellets from Port Latta totalled 2.1 Mt, of which

1.5 Mt were exported to Japan and over 0.5 Mt went to domestic steel-works. Iron ore fines from the Middleback Ranges are pelletised at Whyalla and form the main feedstock for pig iron production there.

The bulk of Australia's iron ore production is exported (see Table 9 and the diagram below), largely from the Pilbara region as fines and lump ore. Japan accounts for around 60% of exports and Europe nearly 20%. The balance goes mainly to major new export markets opened up in recent years in China, South Korea and Taiwan Province.

Several mines are currently being developed or expanded in the Pilbara region. The **Channar** deposit, near **Paraburdoo**, is being opened up to supply the Chinese market. The **Nimingarra** deposit is being developed to allow an extension of mining in the **Shay Gap** area for a further 20 years. In the **Newman** area further mine expansion is taking place and at nearby **Yandicoogina** ore is being tested for potential use. Mining of the **McCameys Monster** deposit is planned to help meet a contract to supply iron ore to Romania.

Australia's major iron and steel making centres are at **Port Kembla, Newcastle and Whyalla**. Together they consume nearly 10 Mt of iron ore annually. In 1986 there were five operating blast furnaces with a total annual capacity of 5.7 Mt of pig iron. Although some of the pig iron produced is used in foundries for

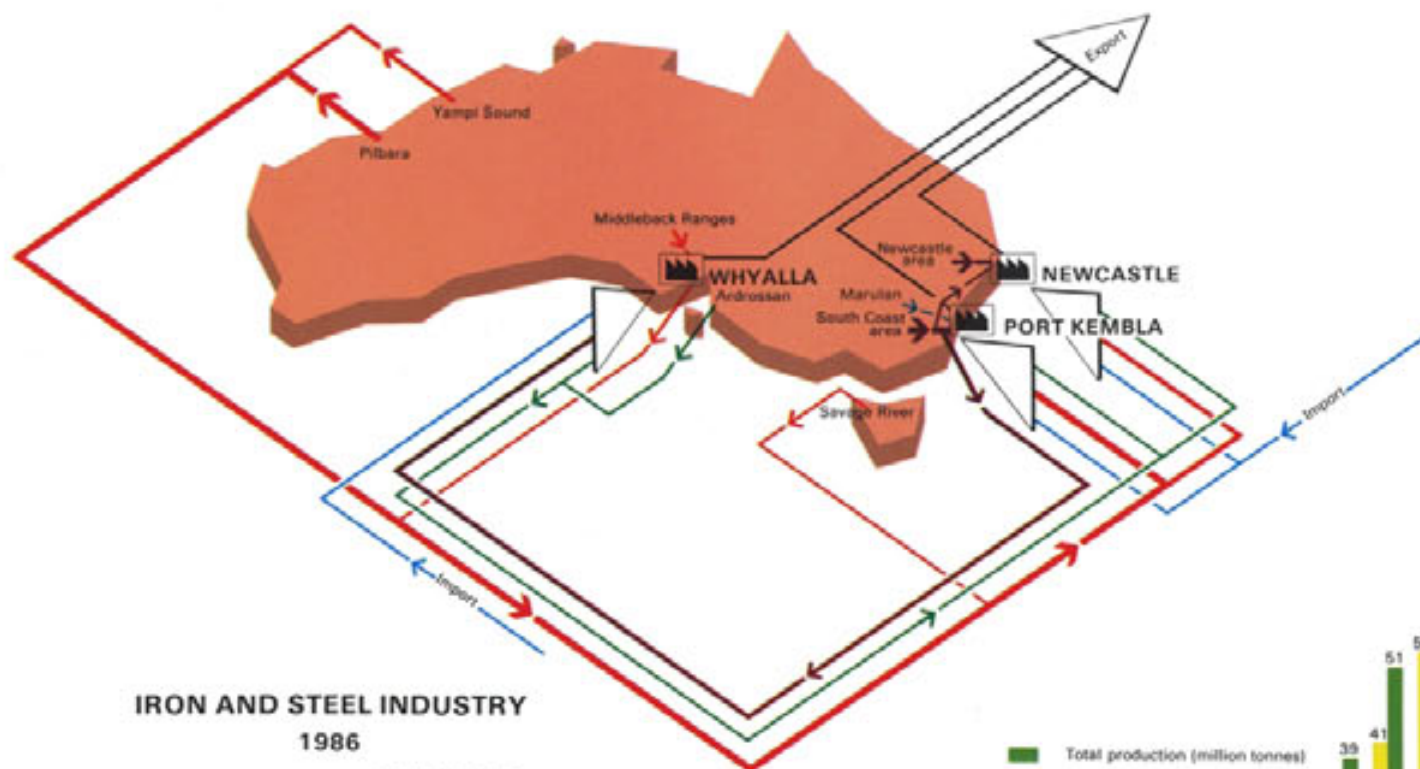
making cast iron most of it is used together with scrap for making steel. There are seven basic oxygen furnaces in operation with a combined annual capacity of 6.8 million ingot tonnes of raw steel (Port Kembla 3.8 Mt, Newcastle 1.9 Mt and Whyalla 1.1 Mt).

The raw steel is worked into many different forms. Port Kembla specialises in flat steel products whereas Newcastle concentrates on rod and bar products. Rolling mills at Whyalla produce long products, such as universal beams and columns for the construction industry, and rails and steel sleepers. Special steels, including stainless and alloy steels, are made in electric furnaces, the largest of which is at Newcastle. Tinplate is produced solely at Port Kembla.

Currently over 1 Mt of iron and steel products (including raw steel) are exported annually. In common with many Western economies the outlook for the Australian iron and steel industry would appear to be one of slow but steady growth. Recent extensive plant modernisation has resulted in greater competitiveness on the world market and raised the possibility of increased exports.

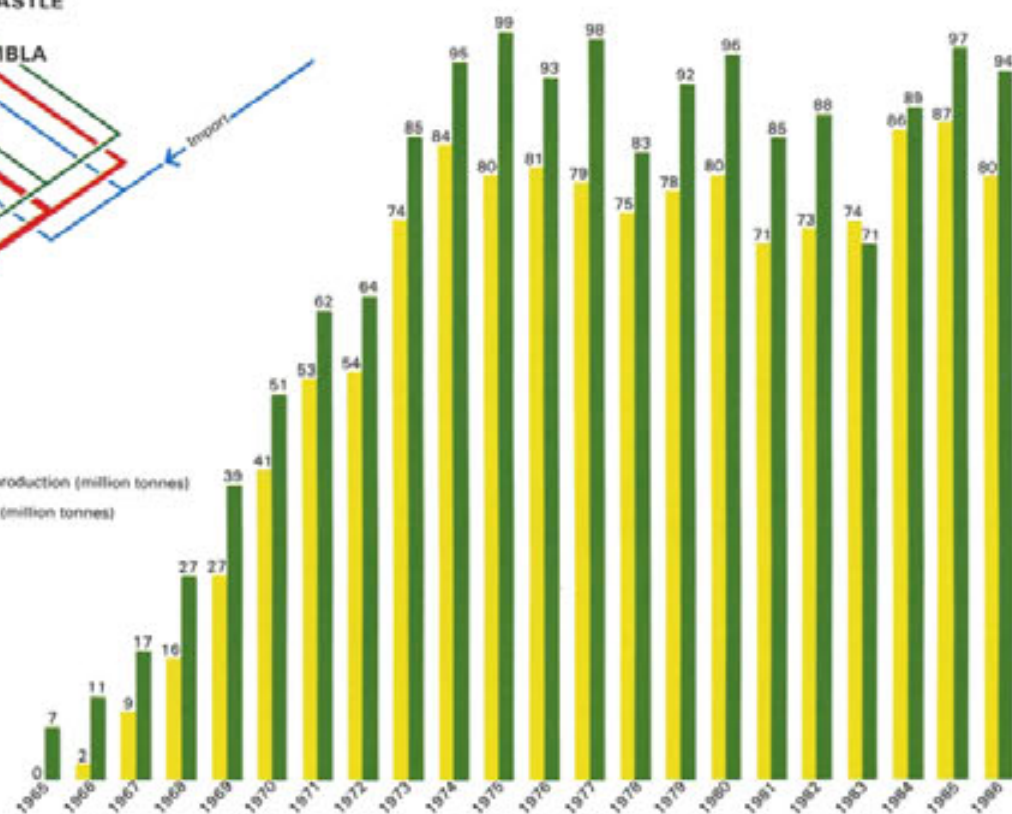
Table 9. Iron and steel production, 1984–86

	1984	1985	1986
	thousand tonnes		
Iron ore			
Mine production for iron and steel making	89 046	97 447	94 015
Production of iron ore pellets	3 489	3 725	3 338
Exports including iron ore pellets	85 480	86 914	79 678
Pig iron			
Production	5 329	5 607	5 889
Exports	71	26	26
Raw steel			
Production	6 303	6 578	6 703
Exports	294	583	481



Legend for bar chart:

- Total production (million tonnes)
- Export (million tonnes)



Australia: production and export of iron ore, 1965–86

SOURCES: Bureau of Mineral Resources (1987) and Department of Transport (1987)

Nickel

Australia is the third largest producer of mined nickel, after the U.S.S.R. and Canada, and ranks among the top five producers of refined nickel. After Canada, Australia is the largest exporter of processed nickel.

In 1965 Australia's nickel resources were considered to be negligible. However, the discovery of high grade nickel at **Kambalda** (W.A.) in 1966 triggered a period of intense exploration and a series of major discoveries—the 'nickel boom' of the late 1960s—which led to the establishment of Australia as a leading nickel producer. By 1970 the main nickel sulphide belt in Western Australia had been defined, extending from **Mount Keith** in the north to **Wannaway** in the south. In north Queensland a large lateritic nickel deposit was identified at **Greenvale**.

Nickel production rose rapidly—from concentrates containing 2500 t of nickel in 1967 to a peak of almost 85 000 t of contained nickel in 1977. Then output fell steeply in the late 1970s as some mines closed because of a severely depressed nickel market and depletion of reserves. Fluctuating prices notwithstanding, several new mines were opened in Western Australia including **Agnew** (mining suspended in 1986) and **Carnilya Hill**, and the mine at **Mount Windarra** was reopened. The 1977 production record was exceeded in 1982 (87 600 t of contained nickel) but output has since dropped because of a poor market price for nickel and the consequent closure of several mines around Kambalda.

Today the industry is still based on the mines in the **Kambalda** area and the **Greenvale** mine. With

about 10% of Australia's economic demonstrated resources of 1.1 Mt of nickel, Greenvale accounts for about a quarter of total production but is expected to be mined out in about five years.

A high degree of nickel processing is undertaken in Australia. Refineries at **Kwinana** (W.A.) and **Yabulu** near Townsville (Qld) were sited close to service and port facilities to take advantage of the large export potential in nickel metal. In addition a smelter producing nickel matte was commissioned near **Kalgoorlie** in 1972.

On average 50 000 t of high grade nickel matte in granulated form is produced each year at the **Kalgoorlie** smelter and railed to **Kwinana** for export or refining. The Kwinana refinery has the capacity to produce

about 30 000 t per annum of refined nickel, with copper sulphide, nickel-cobalt sulphide and fertiliser-grade ammonium sulphate as by-products. The refined nickel, in the form of a powder, is mostly pressed into briquettes and sintered before sale.

The **Yabulu** refinery produces sintered nickel oxide and a mixed nickel-cobalt oxide, the nickel content of which is in excess of 20 000 t annually when the plant is operating at full capacity.

The bulk of Australian nickel production is exported, principally to Japan, North America and Europe. More than 50% of exports, which in 1986 amounted to almost 320 000 t, are in the form of sintered nickel oxide or refined nickel; most of the remainder is nickel matte.



Tin

Tin has been mined in Australia for over 100 years. For nearly a decade, (around 1883), Australia led the world in tin production, a particularly important source at that time being **Mount Bischoff** (Tas.). Today, however, the main tin producing countries are Malaysia, Brazil, Indonesia, Thailand and China although Australia still remains an important producer and exporter. Mine production of tin amounted to almost 8500 t in 1986.

Almost 70% of Australia's tin production now comes from **Renison Bell** (Tas.), a deposit first worked in the 1890s and today one of the world's largest underground tin mines. The remainder is mostly from **Greenbushes** (W.A.) and mines in the **Herberton** and **Mount Garnet** areas of north Queensland. The mines at **Cleveland** (Tas.) and **Ardlethan** (N.S.W.), both significant producers for around 20 years, closed in mid 1986 following exhaustion of reserves.

Evaluation of the **Collingwood** tin deposit in north Queensland continued during 1986, though in general the search for and development of new deposits have been suppressed by sustained low tin prices.

Around 80% of Australian mine output is exported as tin concentrate to two Malaysian smelters; most of the remainder is processed and consumed domestically.

The **Sydney** high grade tin smelter and refinery, with an annual capacity of about 7000 t of tin metal, is the main domestic producer of primary refined tin. Recently the plant has operated at only 25% capacity, reflecting the closure of the **Ardlethan** hardrock mine and decreased alluvial production elsewhere in eastern Australia, the main sources of concentrates for the smelter.

An electric arc smelter and refining kettle at **Greenbushes** produced just over 500 t of refined tin in 1986. Tin produced at this plant is suitable mainly for alloys because of its antimony content.

Much of Australia's consumption of primary refined tin, which amounts to around 2700 t annually, is in the form of tinplate. The sole tinplate mill, at Port Kembla, has an installed capacity of 500 000 t of tinplate per annum.



Australia's only nickel smelter, near **Kalgoorlie** (W.A.) Concentrates from surrounding nickel mines are smelted at the **Kalgoorlie** nickel smelter. Each year the smelter produces around 73 000 t of granulated nickel matte which is railed to **Kwinana** for refining or export.



Pouring molten tin at **Greenbushes** (W.A.) In 1986 over 500 t of antimonial tin metal were produced at **Greenbushes**.

Gold

Australia is currently the world's fifth largest gold producer, after the Republic of South Africa, U.S.S.R., U.S.A. and Canada, and exports around 80% of its annual output. The next few years are likely to see Australia move into fourth place, with recent projections indicating that the remarkable growth in Australian gold production which began in the early 1980s will continue in the foreseeable future.

Gold mining in Australia dates from the middle of last century. Indeed, the fledgling Australian mining industry was transformed with the discovery of gold near Bathurst in 1851 and subsequent major gold rushes elsewhere in New South Wales, and in Victoria, Queensland and Western Australia. These rushes drew thousands of immigrants and trebled the population to over 1 million within 10 years. Between 1855 and 1860 Australia displaced the U.S.A. as the world's leading gold producer and in the decade to 1860 produced 40% of the world's gold. Over this period gold accounted for 90% of the value of Australian mineral production. In 1903 annual output peaked at 119 t, an amount not since equalled though likely to be eclipsed before 1990.

The economic importance of gold to Australia declined from the early 1900s onwards, with the industry at its lowest ebb in the mid 1970s. However, greatly increased gold prices in 1980 following international unrest led to a resurgence in gold mining. This was reflected in the reopening of a number of old mines, including **Mount Magnet**, **Lancefield** (near **Laverton**) and some of the 'Golden Mile' mines at **Kalgoorlie**; in the development of new projects; and in heightened exploration activity.

For the new mines traditional selective mining techniques have generally given way to bulk handling and open-cut mining methods, making large lower grade deposits increasingly viable. A further stimulus has been the introduction of modern ore-processing technology which has raised gold recovery

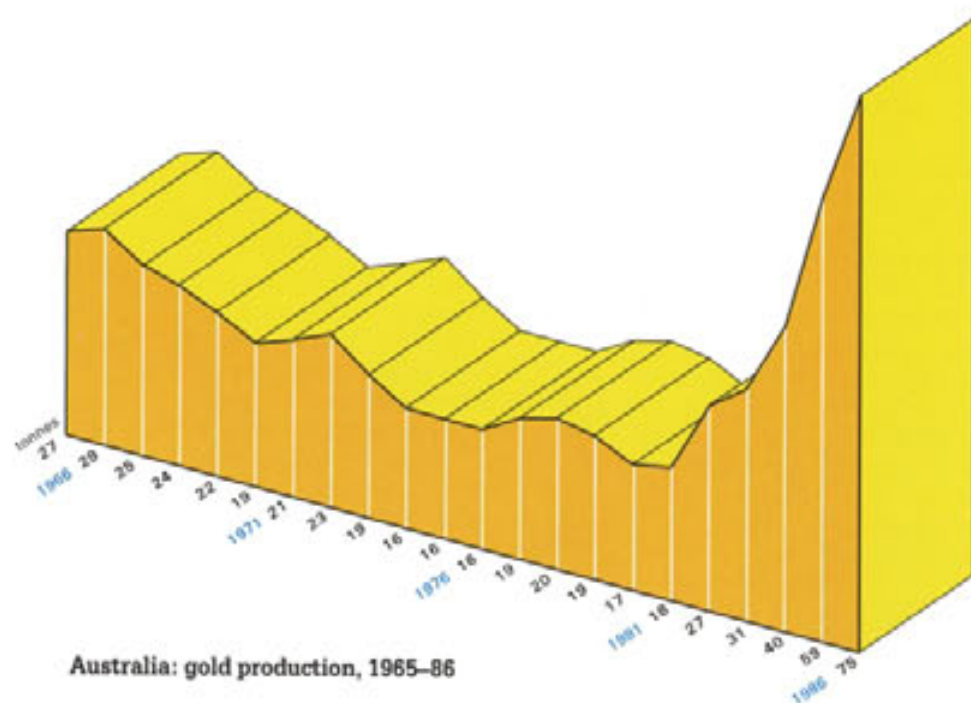
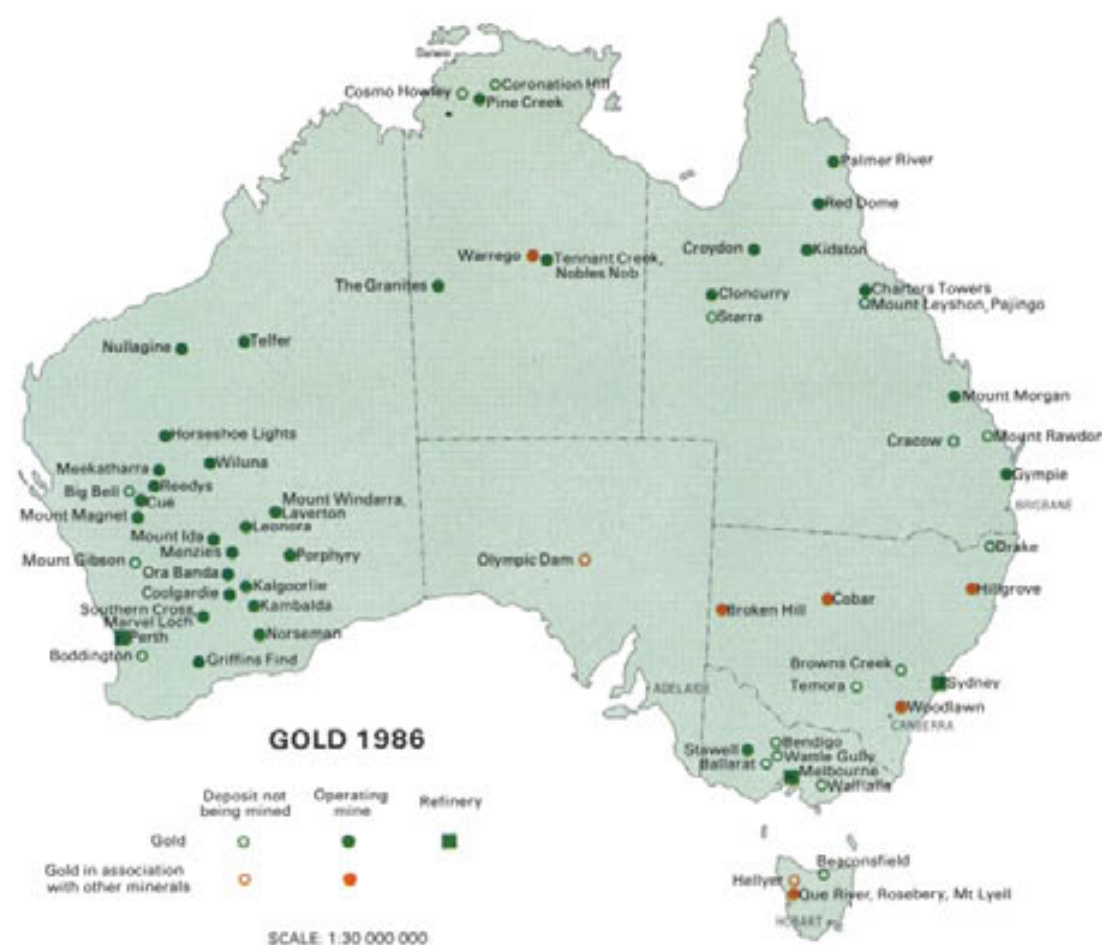
levels. In many areas the retreatment of old tailings dumps has also been taking place.

Australian gold production more than doubled between 1980 and 1984 to 40 t before almost trebling over the next three years to around 110 t in 1987. This enormous increase has resulted mainly from the commissioning of new mines and expanded output from established mines in response to the continuing favourable world price for Australian gold.

Western Australia remains the largest gold producing state, accounting for just over 70% of the national total in 1986—see diagram to the left. Output is dominated by **Telfer** (Australia's second largest producer in 1986), **Norseman**, **Kambalda** and mines in the **Kalgoorlie** area.

Queensland has recently overtaken the Northern Territory as the second largest gold producing state. The **Kidston** mine—in 1986 Australia's largest producer of gold, with a yield of nearly 7.5 t—is primarily responsible for Queensland's position. Treatment of tailings at **Mount Morgan** has produced about 1.5 t of gold annually in recent years. The **Mount Leyshon** and **Red Dome** mines were commissioned during 1986 and gold is also extracted from numerous smaller mines.

Northern Territory gold comes from mines in the **Tennant Creek** area, from **Pine Creek** and **The Granites** mine (which opened in 1986). In New South Wales gold is mainly a by-product of base metal mining at **Broken Hill** and **Woodlawn** and of antimony mining at **Hillgrove**.



The **Defiance** and **Orchin** gold mines near **Kambalda** (W.A.) Recent expansion and redesign of these open-cut mines (right) has allowed deeper mining. Together with other gold operations in the area, they produced nearly 4 t of gold in 1986-87.

Prospecting for gold near **Seymour** (Vic.) The high price of gold in recent years and the ready availability of electronic metal detectors has brought about a marked resurgence in gold prospecting.



Victorian gold production revived in the 1980s with the reopening of the **Wattle Gully** mine (since closed again). **Stawell** is currently Victoria's dominant gold mine and in 1986 produced nearly 85% of the state total of just over 1 t. Gold from Tasmania is a by-product of copper mining at **Mount Lyell** and of lead-zinc-silver mining at **Rosebery** and **Que River**.

In most states a significant number of gold deposits are being evaluated and developed. For example, in Queensland there are the **Pajingo**, **Starra** (south-east of Mount Isa) and **Cracow** deposits and in New South Wales the **Browns Creek** (just south-west of Orange) and **Temora** deposits. In Victoria a number of small mines are being reopened including **Gaffneys Creek** (east of Healesville) and at **Harrietville** (south-east of Beechworth). There is also considerable exploration activity focused on the former gold mining centres of **Ballarat**, **Bendigo** and **Walhalla**. In Tasmania the old **Beaconsfield** mine is being rehabilitated. Although almost no gold is produced in South Australia the **Olympic Dam** copper-uranium-silver-gold deposit, currently under development, is an important potential source.

Exploration in Western Australia has continued at a high level resulting in the discovery of numerous economic deposits, the more notable being **Boddington**, **Big Bell** and **Mount Gibson**. The mine being developed at Boddington, where production commenced in 1987, is destined to rapidly become one of Australia's largest gold producers, with production estimated at about 9 t a year when fully operational. In the Northern Territory the **Cosmo Howley** (south-east of Darwin) and **Coronation Hill** deposits are both being developed.

Since the Second World War there

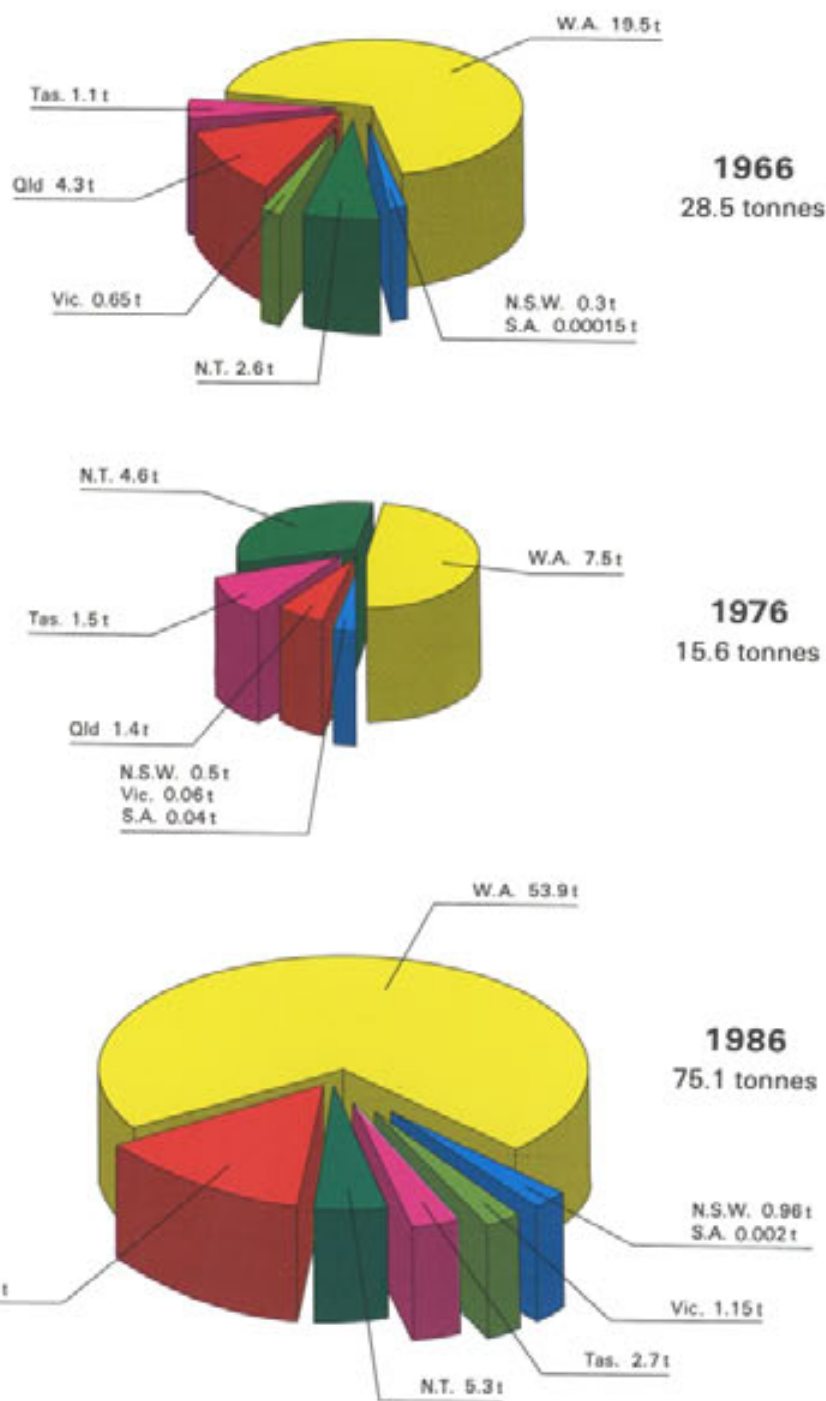
have been, surprisingly perhaps, only five completely new gold finds in areas where gold was never previously thought to occur. These are **Telfer** and **Boddington** in Western Australia, **Olympic Dam** in South Australia, and **Starra** (south of Cloncurry) and **Pajingo** in Queensland. All other currently known deposits or mines are in, or are extensions of, gold-bearing zones first discovered and mined last century or early this century.

The **Perth Mint** produces the bulk of Australia's refined gold. It is one of only three refineries in Australia which presently meet the metal specifications of the London Gold Market. Plans are underway to raise the refining capacity of the Perth Mint, with the construction of new facilities in Perth and a smaller refinery in Kalgoorlie.

Australia is only a small consumer of gold and in 1986 exported nearly 59 t of gold, about 40 t going to Japan. Other important destinations were Hong Kong, U.K., Singapore and West Germany.

The properties that have given gold its special value throughout history are its rarity, high density, colour, lustre and chemical inertness. These qualities have favoured gold as a medium of exchange and investment, as a standard for monetary systems and for jewellery. Since the advent of the electronic age gold has also emerged as an essential industrial mineral while continuing to retain its traditional status.

The strong international market for gold partly reflects the move by many countries, particularly Japan, to produce official and commemorative gold coins. Also contributing to demand is the fact that many countries now permit individuals to hold gold in the form of bullion.



Gold production by state



The legendary 'Golden Mile' at Kalgoorlie (W.A.)
The 'Golden Mile' identifies the famed string of gold lodes—first exploited in 1893—stretching between Kalgoorlie and Boulder. Measuring some 4 km by 1.2 km and extending at least 1.5 km in depth, this gold orebody is one of the world's richest. Over the next few years the landscape is likely to change dramatically with vast open-cut mines replacing underground mines.

Other metals



Antimony-gold ore mining at Hillgrove (N.S.W.)
Hillgrove (above) is the only producer of antimony ore and concentrate in Australia. Following separation of the co-product gold, antimony concentrates are produced from the ore for export.



Exposed manganese orebody, Groote Eylandt (N.T.)
Groote Eylandt contains one of the world's largest manganese deposits. Much of the orebody consists of natural pellets or 'pisolites' (lower right). These pisolites have resulted from current and wave action on manganese oxides precipitated from seawater under special temperature and chemical conditions in shallow tidal areas during the Cretaceous. Subsequently the pisolites have been agglomerated by erosion and cementation (right).



Antimony

Antimony metal is not produced in Australia though about 30 000 t of antimonial lead, containing nearly 1000 t of antimony, are produced each year as a by-product of lead refining at **Port Pirie**. A small amount of antimony concentrate, all of which is exported, is produced at **Hillgrove** in the New England area of north-eastern New South Wales.

Bismuth

In recent years Australia has been the world's largest mine producer of bismuth, accounting for some 25% of world output. Bismuth production is almost entirely a by-product of copper-gold ore treatment at the **Warrego** mine (N.T.) and amounts to an estimated 700 t per annum.

The bismuth concentrates are treated in a first-stage bismuth plant which produces copper sulphate, gold bullion and bismuth-rich residues. The residues are stockpiled, as is bismuth recovered from lead refining at **Port Pirie**. Occasionally some of the Warrego residue is upgraded and sold.

Cadmium

Cadmium is found in small quantities in most base metal concentrates produced in Australia. Recovery as a by-product from zinc refining at **Risdon** and **Cockle Creek** accounts for the bulk of Australia's production of about 1000 t of refined cadmium annually. Minor amounts of cadmium are also recovered as a by-product of lead refining at **Port Pirie**.

Cobalt

With an annual output of around 3000 t Australia is the world's fourth largest mine producer of cobalt, a major by-product of nickel mining at **Greenvale** (Qld) and **Kambalda** (W.A.). However, there is no domestic production of cobalt metal, all requirements being met by imports.

All of the nickel-cobalt sulphide (13–20% cobalt) produced at the **Yabulu** (Qld) and **Kwinana** nickel refineries is exported to Japan and Canada for further treatment. Most of the minor by-product cobalt oxide recovered from the refining of **Broken Hill** zinc concentrates at **Risdon** is also exported.

Manganese

Australia is a major producer of manganese ore, with production in recent years having averaged about 1.75 Mt.

During the 1940s manganese from small deposits in several states was used in the production of ferroalloys at Newcastle to ensure a supply to Australian steelworks during the

Second World War. In 1960 a major deposit was discovered on **Groote Eylandt** in the Gulf of Carpentaria and an opencut mine, town and port facilities were subsequently established. Today Groote Eylandt is the only producer of manganese ore in Australia although small quantities of manganese dioxide are recovered during zinc refining operations at **Risdon**.

Much of the manganese consumed domestically is used in the production of manganese alloys at **Bell Bay**. The plant, commissioned in 1960, now has the capacity to produce up to 190 000 t per annum of alloys (mainly ferromanganese, used in steel making to improve the hardness, toughness and tensile strength of the finished product, and silicomanganese). The Bell Bay site was chosen because of the availability of hydro-electric power and port facilities, and its convenient location between the steelworks in New South Wales and South Australia.

Australia is a leading exporter of manganese, shipping 75% of its ore production to steel plants in South-East Asia (notably Japan) and Europe. Much of the ferromanganese and silicomanganese produced at Bell Bay is also exported.

Platinum and palladium

Platinum and palladium are contained in nickel concentrate produced in Western Australia. Some is recovered overseas during refining of nickel matte produced at the **Kalgoorlie** nickel smelter, and some in Australia during the treatment of copper sulphide residue from the **Kwinana** nickel refinery at the **Port Kembla** copper refinery.

Silver

Australia is the world's fifth largest mine producer of silver, almost all of which is a by-product of base metal mining and smelting. By far the largest mine producers of silver are **Mount Isa** and **Broken Hill**. Of a total mine production of just over 1 million kg in 1986, 74% was from lead concentrates, 10% from zinc concentrates and 12% from copper concentrates. Only 1.4% was a by-product of gold mining, mainly at **Kidston** (Qld) and mines throughout Western Australia.

Production of refined silver is in excess of 300 000 kg annually. Most is recovered at the **Port Pirie** lead refinery, though some silver is also recovered at the copper refinery at **Port Kembla** and from the refining of gold bullion and scrap at the **Perth Mint**.

The silver content of lead bullion produced at **Mount Isa** and **Cockle Creek** is not recovered in Australia. A considerable quantity of silver is also contained in exported base metal concentrates.

Tantalum and lithium

Australia is a substantial producer of tantalum, a co-product of tin mining. **Greenbushes** (W.A.) is Australia's largest producer of tantalum, a metal used in the manufacture of electronic components and corrosion-resistant alloys. Smaller amounts of tantalum are mined at **Moolyella** (W.A.) and **Bynoe Harbour** (N.T.).

In 1983 production of lithium began at Greenbushes from one of the world's highest grade and largest known deposits of spodumene, a major source of lithium. The deposit occurs on the margin of the tin-tantalum orebody. By 1986 production of high grade spodumene concentrate, which is mostly exported, amounted to 12 700 t.

Tungsten and molybdenum

Australia is one of the Western world's major producers of tungsten, ranking fourth after South Korea, Canada and Bolivia. This position has been maintained even though continuing weak demand and low prices over the last few years have resulted in production falling to about half of its 1980 peak of over 3500 t.

Tungsten occurs principally in two ore minerals—wolframite and scheelite. Both have been mined to a greater or lesser extent in Australia since tungsten first gained commercial importance in the early 1900s. Much production in the past has been in association with tin min-

ing, particularly in Tasmania and Queensland.

The bulk of Australian tungsten now comes from two deposits—**King Island** in Bass Strait (scheelite), one of the largest tungsten mines in the world, and **Mount Carbine** in Queensland (wolframite 75%, scheelite 25%). Following recent closures of a number of mines, the only other significant producing mine is **Kara** in Tasmania.

Almost all production is exported in the form of concentrates, mainly to West Germany, U.S.A. and U.S.S.R. Small amounts of concentrates are processed domestically and used mainly in the manufacture of tungsten carbide-tipped tools.

In the early 1900s Australia was the world's leading producer of molybdenum but now produces only minor amounts, all as a by-product of tungsten mining at **King Island**.

Vanadium

Australia's demonstrated resources of vanadium total almost 10 Mt, or approximately 15% of reported world resources, but almost all are at present classified as sub-economic. Vanadium is not currently mined in Australia though a small quantity was produced at Cloates near **Wundowie** (W.A.) in 1980 and 1981. Its main use is to strengthen and toughen steel.

Most of Australia's vanadium resources are contained in oil shale deposits in the **Julia Creek** area of north-western Queensland. Substantial resources are also contained in titaniferous magnetite deposits in Western Australia including **Barramie**, **Wundowie** and **Jameson Range**.



Tungsten mining on King Island, Bass Strait (Tas.)

Although tungsten has been mined in various parts of Australia since late last century, most production in recent years has come from the King Island scheelite deposit (above). Annual output now averages around 1200 t of scheelite concentrates and 12 t of molybdenum concentrates.



Open-pit tin-tantalum mining at Greenbushes (W.A.)

Tin has been mined at Greenbushes since 1888 though commercial production of tantalum did not begin until the 1920s. Since 1983 lithium has also been produced at Greenbushes. The combined output of tin-tantalum and lithium ore has averaged 1.5 Mt in recent years.

From mine to metal

Most minerals undergo several stages of processing between mine and market or point of manufacture. Each step involves successively smaller tonnages and higher grade or purer end-product.

Primary processing, or concentration, generally involves only physical processes. The ore is first crushed and ground to release the mineral particles from the waste rock and then concentrated by utilising physical or chemical differences to separate the mineral ore and the unwanted material.

With generally large tonnages of ore to be processed the concentration plants are usually

located as close as possible to the mines, a far more economical arrangement than transporting the ore elsewhere for treatment.

Secondary processing, which involves smelting and/or refining, is usually carried out away from the mine. The importance of proximity to energy, water and other raw materials (such as coke and limestone in the case of iron and steel plants) and to industrial and transportation facilities are paramount in determining the location of secondary plants.

Smelting breaks the chemical bonds in the concentrated ore compound, thereby reducing

the mineral to metal. For example, galena (lead sulphide) is roasted and smelted to separate lead from sulphur. Iron ore, largely hematite (iron oxide), is smelted to separate iron from oxygen. The very high temperatures required to break the chemical bonds mean that processing costs are much higher than at the primary stage. Oxide bonds are more difficult to break than sulphide bonds hence the treatment of oxide ores, such as bauxite, requires a greater amount of energy.

Refining removes the small amounts of other metals which may have chemically followed the main metal in the smelting process. Refining is also a costly process, requiring precise control to produce the desired

highly pure mineral.

Concentration and refining both involve the removal of impurities. For most metals concentration refers to the initial ore upgrading while refining refers to the final metal purification. In aluminium processing, however, ore upgrading is actually refining because all impurities are removed at this stage, leaving only alumina (aluminium oxide). The process, both chemically complex and energy intensive, is part of the secondary processing stage. Consequently, alumina refineries are usually located in industrial or port areas with ready access to large quantities of power.

In contrast, many industrial or non-metallic minerals are frequently

used for their physical properties alone and processing generally does not go beyond beneficiation. Indeed, for many purposes these minerals require only crushing and sizing.

Although many deposits in Australia are found inland the coast is directly accessible with no major obstacles in the form of physical or political boundaries. Thus ore can be concentrated at the mine and then transported overland to the coast for further processing and/or shipment from specialised ports. Sea transport is used not only for exporting minerals but also for much domestic mineral traffic, especially the more bulky, lower value commodities.



Testing the depth of froth in a nickel flotation cell at the Kambalda nickel concentrator (W.A.)

Fuels

Black coal

Australia's economic demonstrated resources of black coal (54 500 Mt in 1986) represent about 6% of the world's total.

Australia is a significant producer and the leading exporter of black coal, with production now amounting to over one-third of the value of all minerals produced. In recent years coal has overtaken wool as the country's most valuable export commodity and now represents 15% of the total value of exports.

Based on production in 1986 the world's largest black coal producers are China (805 Mt), U.S.A. (738 Mt) and U.S.S.R. (585 Mt), with two-thirds of total output between them. Poland (192 Mt), South Africa (177 Mt) and India (165 Mt) form the next largest group, followed by Australia (139 Mt).

Australia is the world's largest exporter of black coal, accounting for almost 28% of internationally traded coal in 1986. Such a high ranking on the export scale occurs because 90% of world production is consumed domestically; Australia alone exports more coal than it consumes.

In 1800 coal provided Australia's first mineral export. Coal mining was well established in New South Wales by the early 19th century and in Queensland by the 1870s. For the first half of the 20th century Australia maintained a minor export trade in coal though production was increasingly directed towards the domestic market for use in power generation and in the steel and cement industries.

Since 1965 exports of black coal have expanded steadily, increasing more than twelve-fold to almost 93 Mt in 1986. Domestic consumption also rose substantially over the same period, from 25 Mt to 43 Mt. As with iron ore the initial impetus for export growth was the rapid post-war expansion of the Japanese steel industry, which demanded high quality coking coal. The 1970s were marked by further expansion of coking coal, in particular into European markets and the new steel industries in South Korea and Taiwan Province.

Along with a recession in the world steel industry the oil crises of the 1970s focused renewed interest on coal as a fuel. Thus, in the middle and late 1970s the emphasis in new mine development in Australia shifted from coking to steaming coal; coking coal is used in steel-making whereas the lower grade steaming coal is used for generating electricity. Steaming coal accounted for 47% of Australian coal exports in 1986.

The largest producers of black coal in Australia are New South Wales (66.4 Mt of saleable coal in 1986) and Queensland (66.1 Mt)—see Table 10. Tasmania, South Australia and Western Australia account for the remaining 6.6 Mt.

Coal mining has traditionally been by underground methods though recent developments have been in large scale opencut mining, enabling modern equipment to operate at depths far greater than previously possible. About 90% of Queensland's coal is mined by opencut methods, most coming from a series of export-oriented mines

along the western margin of the **BOWEN BASIN**, extending from **Collinsville** and **Goonyella** in the north to the **Blackwater** area and **Moura** in the south. In 1986 a record 51.5 Mt of black coal was exported from Queensland.

About 9 Mt of steaming coal from **Callide**, **Tarong**, the **West Moreton** area and several mines in the **BOWEN BASIN** is used annually for domestic electricity generation. Over 0.3 Mt of the **Collinsville** coal is actually railed more than 1200 km to **Mount Isa** for use in the nearby **Mica Creek** power station. In addition metal treatment plants consume over 1.5 Mt a year, of which 1.2 Mt is used in alumina refining.

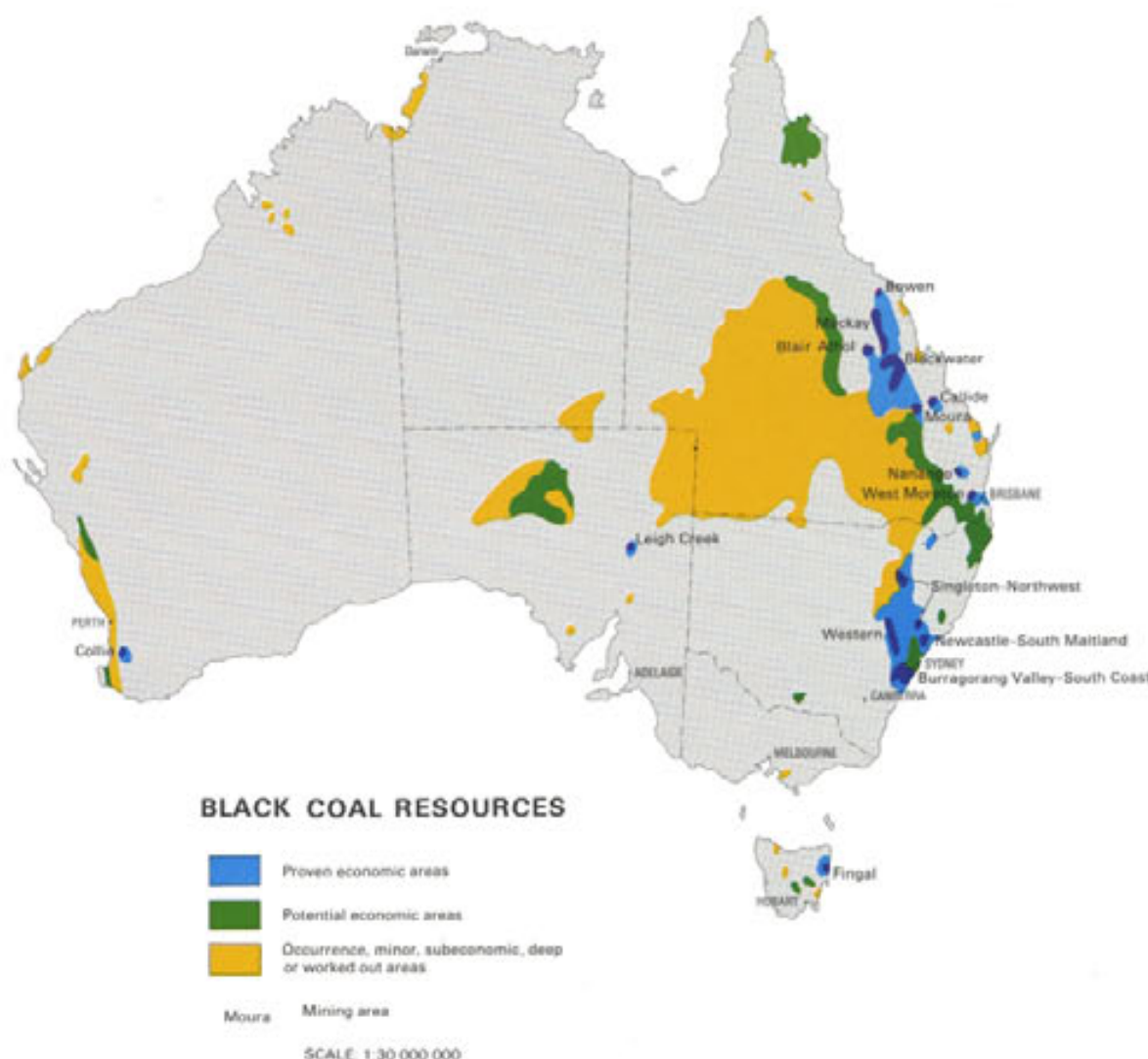
New South Wales production is from opencut and underground mines in the **SYDNEY** and **GUNNEDAH BASINS**. In 1986 almost 19 Mt was used for electricity generation with a further 6 Mt going to the domestic iron and steel industry and over 1 Mt to other industries, notably cement manufacture. The remainder, amounting to 40.5 Mt, was exported.

In South Australia about 2 Mt of black coal is produced annually at **Leigh Creek** for power generation at **Port Augusta**. All coal consumed at the **Whyalla** steelworks (over 1 Mt a year) is imported from New South Wales and to a lesser extent Queensland.

Coal production in Western Australia, all from **Collie**, amounts to over 3 Mt per year. Most is used for electricity generation. Tasmanian coal production (about 0.5 Mt per annum from mines at **Fingal**) is mainly used by the local cement and paper manufacturing industries.

Development of the enormous **BOWEN BASIN** coalfields, in sparsely populated areas of central Queensland, has necessitated huge capital investment. With the coal deposits remote from industrial centres and seaports, transport facilities have been a major infrastructure cost. Whereas railway development in New South Wales has largely involved upgrading the existing network, in Queensland hundreds of kilometres of new line have had to be built between mines and new coal loaders at **Hay Point**, **Dalrymple Bay**, **Gladstone** and **Abbot Point**.

The main port for shipment of coal from New South Wales is **Newcastle**, which has three loading



SOURCE: Derived from map 'Coal Resources', Division of National Mapping, 1986.



Mining the 30-metre thick black coal seam at Blair Athol, central Queensland
Over 5 million tonnes of steaming coal is produced annually by strip mining at Blair Athol. Most of the coal is railed nearly 300 km to Dalrymple Bay for export. The shallow overburden is removed by a 46 m³ capacity dragline to expose the unusually thick coal seam.

facilities for coal mined in the Hunter Valley (**Newcastle-Lake Macquarie**, **Cessnock** and **Singleton-Muswellbrook**) and at **Ulan** and **Gunnedah**. The Sydney and Port Kembla loaders handle coal from the **South Coast** area, the **Lithgow** area, **Tahmoor** and **Burratorang Valley**.

Japan remains the largest export destination for Australian black coal although its share has fallen from 99% in 1969 to just under 46% in 1986. This drop is largely the result of Australia actively diversifying into new export markets, notably in Europe, South Korea and Taiwan Province.

MINING AREA



Black coal production by mining area and destination, 1985-86

Source: Joint Coal Board (1986) and Queensland Coal Board (1986).

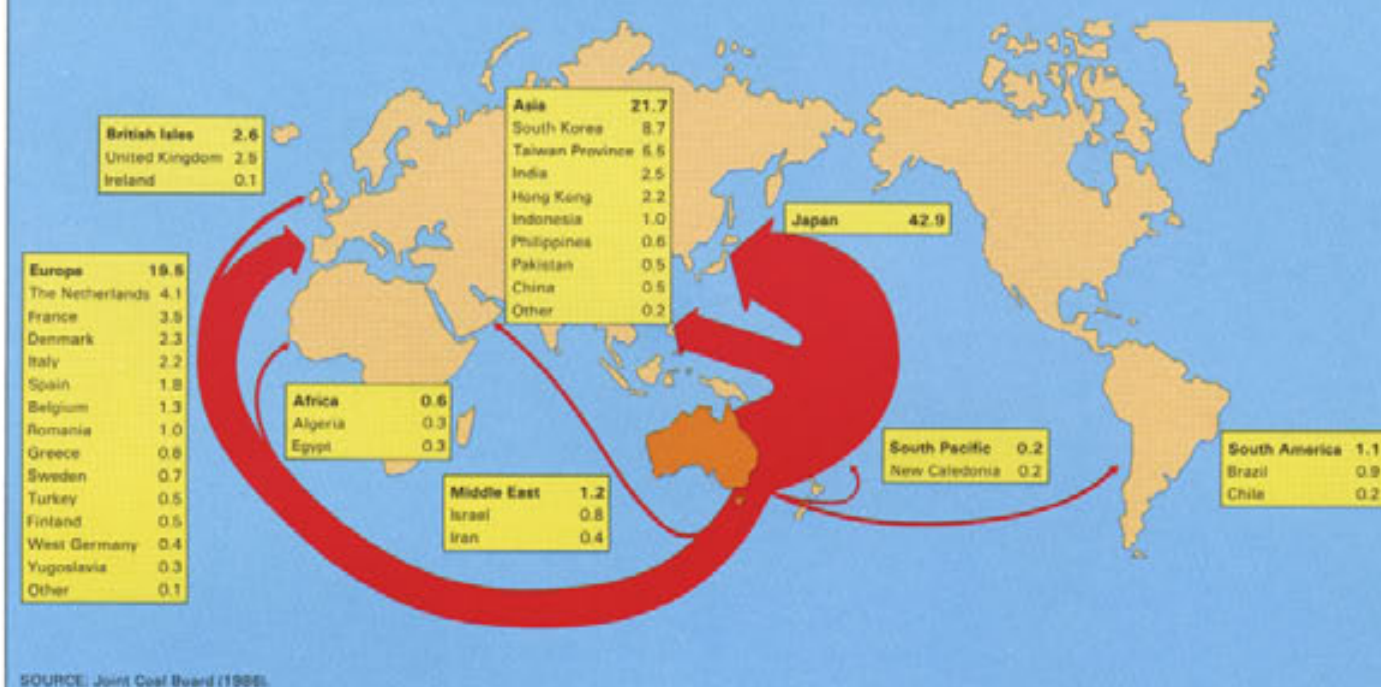
AUSTRALIA'S BLACK COAL EXPORTS, 1985-86
(million tonnes)

Table 10. Production of saleable black coal, 1984-86

	1984	1985	1986
	thousand tonnes		
Queensland	50 777	60 976	66 134
New South Wales	57 430	62 259	66 412
Tasmania	282	334	350
South Australia	1 325	2 041	2 368
Western Australia	3 686	3 769	3 831
Total	113 500	129 379	139 095

Source: Joint Coal Board (1986).

Latrobe Valley (Vic.)
 The three major Latrobe Valley mines, at Yal-lourn, Morwell and Loy Yang, together produce around 40 Mt of brown coal annually. The associated power stations have a total generating capacity of over 4000 megawatts and supply more than 80% of Victoria's electricity needs.



Brown coal

Brown coal, or lignite, has a high moisture content and a heating value which is only about a quarter that of black coal. Nevertheless, brown coal can be mined economically on a large scale by opencut methods where it is found in thick seams near the surface.

Over 98% of Australia's economic demonstrated resources of brown coal, now estimated at 46 500 Mt, are in Victoria, currently the only Australian producer. Much smaller deposits occur in Tasmania, South Australia and Western Australia.

Most production is from the Latrobe Valley in the Gippsland area east of Melbourne, where thick seams (one of which reaches 165 m in thickness) have fuelled Victoria's electric power industry for the past 50 years. Output from the two major producing centres, at Yal-lourn-Morwell and Loy Yang, was estimated to be over 36 Mt in 1986. Smaller, private brown coal mining operations at Anglesea and Bacchus Marsh produced around 1.2 Mt in 1986, mainly for electricity generation for the Point Henry aluminium smelter at Geelong and for use in paper manufacture.

Because brown coal deteriorates rapidly when exposed to the atmosphere and may ignite spontaneously when stockpiled, it is not stored or transported over long distances. Consequently, in any one year consumption largely approximates production and the Victorian power stations utilising Gippsland brown coal are all located on site. However, in briquette form, with a large proportion of its moisture removed, brown coal can be stored and transported readily. (About 2.5 t of raw coal are required to make 1 t of briquettes.) In 1986 over 2 Mt of brown coal from Yallourn was converted into briquettes at the Morwell briquette factory for use locally in power generation, and for char manufacture and general industry.



Liquefied natural gas plant under construction at Withnell Bay, Burrup Peninsula (W.A.)

This plant is an integral part of the giant North West Shelf natural gas project, based on the shipment of 6 Mt of LNG annually to Japan for at least 20 years.

Petroleum (crude oil and natural gas)

Overall, Australia is currently about 90% self-sufficient in petroleum. Self-sufficiency in natural gas is likely to continue well into the future, given the vast known resources and projected level of domestic requirements. Australia also produces all of its requirements for light crude oil although the heavy crude oil required for fuel oil and lubricating feedstock needs to be imported.

Australia's demonstrated petroleum resources as at the end of 1986 are summarised in Table 11. Recent production by individual states is shown in Table 12.

The demand for light crude oil suitable for automotive consumption has been wholly met over the last few years by domestic output, principally from the Bass Strait oilfields off the coast of south-eastern Australia. However, production is expected to fall significantly after the end of the decade and, if new discoveries are not made beforehand, the current level of exports and self-sufficiency in light crude oil are unlikely to be maintained.

Before 1965 Australia depended almost entirely on imports of crude oil and petroleum products. Furthermore, natural gas was not available to any of the capital cities even though it had been used to generate electricity in Roma (Qld) since 1961.

Aided by the *Commonwealth Petroleum Search Subsidy Act*, in force from 1958 to 1974, active exploration in the 1960s resulted in the discovery of commercially viable oil and gas fields. Oil from Australia's first commercial field, discovered at **Moonie** in south-eastern Queensland in 1961, began flowing to Brisbane by pipeline in 1964 and the **Barrow Island** oilfield, off the north-west coast of Western Australia, commenced production in 1967. By 1969 pipelines linked natural gas fields in the **Roma** area to Brisbane and fields in the **Moomba** area to Adelaide. Two years later natural gas began flowing from the **Dongara** area to Perth.

The most important discoveries, however, were made in the **Bass Strait** area of the **GIPPSLAND BASIN**, where in 1964 the first well drilled intersected the **Barracouta** gas field in 46 m of water. Over the next few years significant oil and gas discoveries were made, including the large **Halibut** and **Kingfish** oilfields, and since 1969 Melbourne has been supplied with natural gas from Bass Strait.

Currently an estimated 50 000 t of crude oil and 15 million m³ of natural gas are piped ashore each day to the **Longford** gas processing and crude oil stabilisation plant. The ethane and liquefied petroleum gas (LPG) removed from natural gas at Longford are piped to the **Long**

Island Point fractionation plant on Western Port Bay for separation into propane, butane and ethane. Most of the propane and butane is exported to Japan while the ethane is sent to the Altona petrochemical complex by a submarine pipeline across Port Phillip Bay. Crude oil and condensate are also piped from Longford to Long Island Point. From here some is exported though most is shipped to refineries in other states or sent via an onshore pipeline to the refineries at **Altona** and **Geelong**.

Presently around 78% of domestically produced oil comes from the Bass Strait fields. However, more recent finds in the area have generally been much smaller than the early discoveries.

In the early 1960s impressive gas strikes were made in the **COOPER BASIN** in far north-eastern South Australia (**Moomba** area). Pipelines were built to connect gas fields in the area to Adelaide (1969) and to Sydney (1976). A branch line from the Moomba-Sydney pipeline to Canberra was completed in 1981.

The **COOPER** and **EROMANGA BASINS** are now the second largest producers of petroleum liquids in Australia, after Bass Strait. Oil and gas liquids from the Moomba area are transported by pipeline to **Port Bonython** on Spencer Gulf, where a fractionation plant has been established to separate LPG from crude oil and condensate. Commercial production of oil from the Jackson field in south-western Queensland commenced in 1981. A pipeline completed in 1984 now connects various fields in the **Jackson** area to Moonie, and on to Brisbane where the crude is refined.

In 1971 and 1972, after several years of exploration drilling, large natural gas fields were discovered along the North West Shelf off the Western Australian coast. These now include the **North Rankin**, **Goodwyn**, **Angel**, **Gorgon** and **West Tryal Rocks** fields in the **CARNARVON BASIN** and the **Scott Reef** and **Brecknock** fields in the **BROWSE BASIN**. As at the end of 1986 economically recoverable sales gas resources were estimated at 438 billion m³ and subeconomic resources at a further 1083 billion m³. In addition there are appreciable resources of condensate and LPG.

Because of the remoteness of the North West Shelf fields and the technical difficulties inherent in developing offshore resources in water as deep as that encountered in this area, production did not commence until 1984, when gas from North Rankin was first delivered to Perth via a 1600 km pipeline. The second phase of the North West Shelf Project, the largest single resource development in Australia's history, is scheduled to come on stream in late 1989 and is based on the export of up to 6 Mt a year of liquefied natural gas (LNG) from the North Rankin and Goodwyn fields to Japan for up to 25 years. By late 1987 expenditure on the LPG phase had already surpassed \$2 billion.

The presence of substantial reserves of natural gas in the AMADEUS BASIN of the Northern Territory was proved in the mid 1960s but the remoteness of the area hindered development for many years. It was not until 1984 that Palm Valley began supplying gas by pipeline to Alice Springs. Since early 1987 natural gas has also flowed north to Darwin along a 1500 km pipeline from the Palm Valley and nearby Mereenie fields, initially to fuel the new Channel Island power station. Around the same time Mereenie oil began flowing by pipeline to Alice Springs for processing.

There have been several other notable petroleum developments and discoveries in Australia recently. Australia's most distant offshore oilfield—Jabiru, in the Timor Sea 600 km west of Darwin—began producing and exporting oil towards the end of 1986; planning is proceeding for development of the nearby Challis field. The small offshore Harriet oilfield, north-east of Barrow Island, began producing in early 1986; the South Pepper and North Herald oilfields, south-west of Barrow Island, are currently being developed.

On the opposite side of the continent the construction of a pipeline carrying natural gas from the Denison Trough gas fields in the BOWEN-SURAT BASINS to the alumina refinery at Gladstone has been approved.

Exploration has also indicated gas reserves with potential for future development in the Petrel and Tern fields in Joseph Bonaparte Gulf off the northern Australian coast.

Australia's eight oil refineries are all located in or close to the five largest capital cities. They have a combined daily primary processing capacity of between 110 500 and 118 300 m³, the actual capacity at any particular time depending on the type of crude oil being processed. About a quarter of the oil (mostly heavy crude) consumed by domestic refineries is imported from overseas.



Table 11. Australia's petroleum resources, 1986*

Basin	Crude oil (million m ³)	Natural gas (billion m ³)	Condensate (million m ³)	LPG (million m ³)
Economic				
Amadeus/Bonaparte	10	187	3	12
Bowen	—	1	—	—
Canning	1	—	—	—
Carnarvon	24	438	84	28
Cooper	4	85	7	14
Eromanga	11	2	—	—
Gippsland	192	186	22	45
Perth	—	2	—	—
Surat	—	1	—	—
Sub-total	242	902	116	99
Subeconomic				
Adavale	—	1	—	—
Amadeus	—	10	—	1
Bass	1	8	8	5
Bonaparte	1	44	7	3
Bowen	—	5	—	—
Browse	—	683	45	—
Carnarvon	6	400	4	2
Cooper	—	15	2	2
Gippsland	11	21	—	—
Perth	1	—	—	—
Sub-total	20	1 187	66	13
Total	262	2 089	182	112

* Demonstrated recoverable resources as at December 1986

Table 12. Field production of petroleum products, 1984-86

State	Crude oil (thousand tonnes)			Natural gas* (million m ³)			Condensate (thousand tonnes)			LPG† (thousand m ³)		
	1984	1985	1986	1984	1985	1986	1984	1985	1986	1984	1985	1986
Queensland	618	1 171	1 386	449	490	512	19	36	44	—	51	76
Victoria	19 586	22 022	17 882	5 703	5 276	5 638	636	545	559	3091	3110	2859
South Australia	796	994	1 187	5 022	5 281	5 365	339	578	590	299	969	995
Western Australia	984	984	1 305	1 414	2 393	3 147	64	207	320	2	1	—
Northern Territory	20	106	414	13	30	46	—	—	—	—	—	—
Total	22 004	25 277	22 174	12 601	13 470	14 708	1058	1366	1513	3392	4132	3931

* Sales gas and gas used in field and plant operations

† Includes field and plant use

Economic demonstrated resources are resources judged to be economically extractable. The quantity and quality are computed partly from specific measurements and partly from extrapolation for a reasonable distance on geological evidence.

Subeconomic demonstrated resources are similar to economic demonstrated resources in terms of certainty of occurrence. Though they are considered to be potentially economic in the foreseeable future they are judged to be subeconomic at present.

Petroleum occurs naturally as a gas (natural gas), a liquid (crude oil) or a solid (bitumen). It is composed of chemical compounds of hydrogen and carbon (hydrocarbons).

Crude oil is petroleum that exists as a liquid in natural underground reservoirs and remains liquid in atmospheric conditions. The chief product from crude oil, when it is refined, is petrol. Other products include diesel fuel, aviation turbine fuel, oils, greases, and raw materials for plastics, detergents, paints, weed killers, etc.

Natural gas exists as a gas or in solution in crude oil in natural underground reservoirs. It consists mainly of methane and ethane, together with some LPG, condensate, nitrogen and carbon dioxide. In addition to being a valuable domestic and industrial fuel, natural gas is used as a feedstock in the petrochemical industry.

Liquefied petroleum gas (LPG) is a mixture of heavy hydrocarbon gases and consists mainly of propane and butane. LPG is either naturally occurring (that is, derived by separation during field production of crude oil or natural gas) or a by-product of oil refining. LPG can be easily compressed into its liquid form for storage and transport to markets. LPG is widely used in Australia and it is also exported.

Condensate is a liquid consisting mainly of pentanes and heavier hydrocarbons. It exists as a part of the natural gas in the reservoir but is liquid at surface temperatures and pressures.

Liquefied natural gas (LNG). For natural gas to be readily transportable to overseas markets it is necessary to reduce its volume, as is the case with LPG. However, the liquefying of natural gas is a difficult and expensive operation involving lowering its temperature to -240°C in large scale refrigeration plants. The first installation of its kind in Australia for this purpose is being built at Withnell Bay near Dampier (W.A.) to supply LNG from the North West Shelf fields to Japan.

Oil shale

Australia's demonstrated resources of oil shale amount to over 57 billion tonnes, from which 3.8 billion m³ of shale oil is recoverable. Most of these resources are contained in narrow but deep Tertiary basins near the coast in eastern Queensland and include the large **Condor**, **Yaamba**, **Rundle**, **Stuart**, **Nagoorin** and **Lowmead** deposits between Bowen and Bundaberg.

Inferred resources of shale oil are very much greater and amount to 40.6 billion m³. Together with the large demonstrated **Julia Creek** deposit they are contained in a thin but extensive marine formation of Cretaceous age that extends south from the Gulf of Carpentaria and underlies much of north-western Queensland.

Shale oil was last produced in Australia in 1952, at Glen Davis west of Sydney. Presently all Australian resources of shale oil are classified as subeconomic; however, research and development into extraction technology are continuing.

Uranium

Australia contains nearly 30% of the Western world's 'low cost' resources of uranium. These resources, estimated at around 460 000 t in 1986, occur mainly in the Alligator Rivers area of the Northern Territory and at **Olympic Dam** in South Australia.

As a producer of uranium Australia, with 4150 t in 1986, ranks fourth behind Canada (11 700 t), U.S.A. (5200 t) and South Africa (4600 t), which together accounted for nearly two-thirds of Western world production (37 110 t). Australian production in 1986 was from only two mines.

The earliest exploited uranium deposits in Australia, at Radium Hill and Mount Painter (S.A.), were worked for radium from about 1910 to 1931. Stimulated by military requirements the Commonwealth Government encouraged exploration, resulting in the discovery of Rum Jungle (N.T.) in 1949, Mary Kathleen (Qld) in 1954 and the small South Alligator River deposits.

Government-owned Rum Jungle, 40 km south of Darwin, became Australia's first major uranium mine, producing from 1954 to 1971; Radium Hill was mined again from

1949 to 1961. Mary Kathleen was mined from 1956 to 1963 and several mines were worked in the South Alligator River valley. All production was exported.

The withdrawal of the U.S.A. and U.K. from the market in the 1960s led to declining production and exploration in Australia. The easing of export controls in 1967, however, and a growing need overseas for uranium for nuclear power generation resulted in renewed exploration and major discoveries in the early 1970s.

Ranger, **Nabarlek**, **Koongarra** and **Jabiluka** were discovered, confirming the existence of a world-scale uranium province in the Alligator Rivers region. New discoveries were also made—at **Yeelirrie** and **Lake Way** (W.A.), **Beverley** and **Honeymoon** (S.A.), and **Ben Lomond**, **Westmoreland** and **Maureen** (west of Tully) in north Queensland. In 1975 an enormous deposit of copper and uranium (with gold and silver) was found at **Olympic Dam** in central South Australia.

Mary Kathleen reopened in 1976 and closed finally in 1982, upon fulfillment of sales contracts. Of the newer discoveries only **Ranger** and **Nabarlek** have so far been mined though development of the **Olympic Dam** deposit is well advanced and production is expected to commence in the latter half of 1988.

The entire Nabarlek orebody was mined out in 1979 and on-site processing of the stockpiled ore is expected to be completed by 1990. Exports from Nabarlek commenced in 1980. The nearby Ranger mine, which began operating in 1981, is now the Western world's second largest uranium mine, with resources sufficient for a mine life of 30–40 years at the current production rate of 3000 t per year.

Uranium ore is mined and milled to produce uranium oxide, or 'yellowcake', which requires further treatment to upgrade it into a usable fuel for nuclear power stations, the principal use of uranium. Australian processing of uranium ore is confined to the production of yellowcake, all of which is exported under Government-controlled contracts to Japan, South Korea, U.S.A., West Germany, Sweden, Belgium and the U.K.

Australia has no nuclear power stations and domestic consumption of uranium is limited to minor quantities used in medical, industrial and scientific applications.

Industrial minerals

Industrial minerals generally comprise the non-metallic, non-fuel minerals. While many industrial minerals and rocks are used for the chemical elements they contain, for example phosphate rock and salt, others are used for their physical properties—as fillers in plastics and extenders in paints or as abrasives, weighting agents and absorbents. Thus industrial minerals and rocks are used in a wide range of products and industrial processes.

On the map 'Minerals other than Fuels' and in the following text industrial minerals are grouped according to their principal uses:

- gemstones;
- building and construction minerals;
- chemical and fertiliser minerals; and
- other industrial minerals, including clays and mineral sands.

Strict product specifications notwithstanding, industrial minerals often have low unit ex-mine values because they tend to be relatively common and are generally mined in simple, shallow, low cost surface operations. For some commodities (such as construction sand and aggregate) there is little scope for adding commercial value to the minerals as they can be used virtually unprocessed except for washing, crushing and screening.

The low unit values limit the distance over which products can be economically moved to market. Therefore the distribution of limestone, dolomite and some clay mining operations, for example, reflects not only geological factors (natural occurrence) but also economic factors such as market proximity and transport costs.

Some industrial commodities require beneficiation and other forms of chemical and/or physical modification, such as fine-grinding, all of which can substantially increase product values.

The high cost of transporting bulky, low value commodities has restricted export opportunities for many industrial minerals. Salt and gypsum, however, are notable exceptions because they are produced very near to the coast. Conversely, Australia imports a large proportion of its requirements of industrial minerals such as mica, feldspar, fluorspar and barite. Even though deposits of these minerals occur in Australia they are often too remote from markets to make them competitive with imports.



The Ranger open-cut uranium mine (N.T.)



Gemstones

Australia is a major world source of raw gems, in particular diamonds, opals and sapphires. Lower value stones produced in smaller quantities include nephrite jade, chrysoprase, rhodonite, zircon, garnet, agate and amethyst.

Diamonds

Following the development of the **Argyle** deposit in the Kimberley region of Western Australia in the early 1980s, Australia has become the world's largest producer of diamonds. Output from this deposit alone now exceeds the annual diamond production of any other country. Production at Argyle consists of about 5% gem, 40% cheap gem and 55% industrial grade diamonds.

Alluvial diamonds were mined on a small scale in New South Wales as far back as the 1870s, mainly as by-products of gold or tin mining. An upsurge in exploration in the late 1960s led to the discovery of diamonds elsewhere in Australia. Nevertheless, it was not until 1979 that a commercially significant deposit of alluvial diamonds, at Smoke Creek in the Kimberleys, and the upstream lamproite source rock, the Argyle AK-1 pipe, were found.

Proven resources at Argyle are 54 Mt at a grade of 6.4 carats per tonne; probable reserves amount to a further 14 Mt at 6.1 carats per tonne. Mining of the easily extracted alluvial material started in 1983 and opencut mining of the pipe itself commenced in December 1985.

Production rose rapidly from 6.2 million carats in 1983 to almost 30 million carats valued at \$257 million in 1986. Resources are sufficient for about 20 years of mining at the current rate of production.

At 3 parts per million Argyle is the highest grade pipe in the world though 95% of the stones fall into the lower value cheap-gem and industrial categories. At full production Argyle will add over 20% to the world's diamond supply but, because of the low proportion of gem-quality stones, in value the mine will add only about 4%. Australia has only a small domestic market for diamonds and all Argyle production is exported.

Opals

Australia has been the world's leading producer of precious opals since

the 1930s and currently supplies an estimated 95% of the world market, including all of the world's black opal. The estimated value of opal production has been steadily increasing in recent years and in 1986 amounted to over \$56 million.

The first recorded discoveries were in Queensland in 1872 but most production is now from three South Australian centres—**Andamooka, Coober Pedy** and **Mintabie**.

Lightning Ridge in north-western New South Wales, though accounting for only a small percentage of total production, is famous as the world's only source of black opal. Most boulder opal comes from Queensland, where opal occurs patchily in the west of the state in a broad zone extending from **Kynuna** and **Opalton** to **Yowah**.

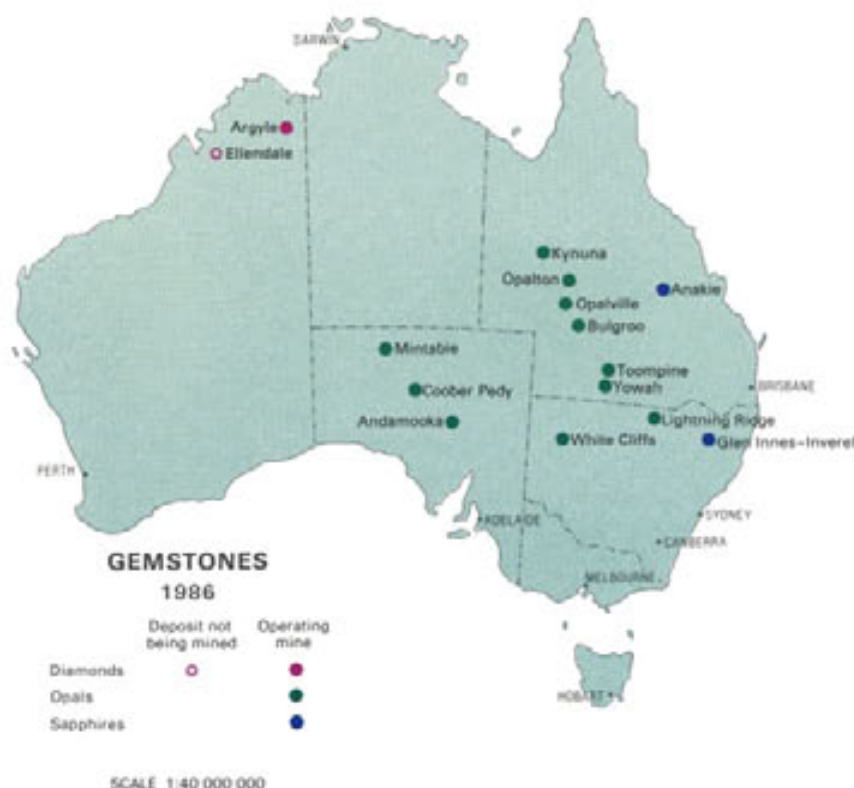
Opal is won by underground or opencut mining, or by retreating old dumps. Methods are extremely variable as miners use their own particular combinations of equipment and initiative.

The bulk of Australian opal is sold in Hong Kong, Japan and the U.S.A. with minimal processing. The exception is black opal from Lightning Ridge which, because of its opacity in uncut form, must be cut and polished so that the quality and hence the value can be determined.

Sapphires

Australia is the world's largest supplier of sapphires, satisfying over 70% of the world market for uncut stones. In 1986 the estimated value of sapphire production was \$13 million.

Sapphires were first discovered in Australia in the New England district of north-eastern New South Wales in 1851. Commercial production began in Queensland in the 1890s and had commenced in New South Wales by 1920. The **Anakie** (Qld) and **Glen Innes-Inverell** (N.S.W.) areas are still the major fields, employing small scale mining methods similar to those used on the opal fields. Uncut stones are exported, mainly to Thailand.



Argyle diamond mine, Kimberley region (W.A.)

Using highly automated mining and recovery techniques, the Argyle mine (left) is now the world's largest producer of diamonds. In 1986 production amounted to over 29 million carats. Comfortable air-conditioned, motel-style accommodation (above left) is provided adjacent to the mine. Because of the remoteness of the area and the harsh climatic conditions, the miners commute from Perth on a two week on/two week off basis.



Opencut opal mining at Mintabie (S.A.)

After blasting, bulldozers progressively rake over and remove the silcrete surface and the softer underlying sandstone into fan-shaped heaps. Horizontal and vertical seams of opal—varying from milky white to almost black—are exposed as the trenches are cut, often to a depth of more than 25 metres.



Building and construction minerals

Asbestos

Asbestos is the general name for a group of six fibrous minerals of which chrysotile (white asbestos) is the most important. Chrysotile accounts for about 95% of world asbestos production, due primarily to its resistance to heat and its high flexibility and tensile strength. Up to 1983 chrysotile was mined at **Woodsreef** near Barraba (N.S.W.) but all domestic asbestos requirements are now met by imports.

Gypsum

Gypsum is the naturally occurring dihydrate form of calcium sulphate. Current annual production of gypsum amounts to around 1.7 Mt of which about one quarter is exported.

Its ability to readily give up water when heated and to absorb it again at normal temperatures makes gypsum particularly suitable for manufacturing plaster, its most common industrial use. Gypsum has other important uses—as a retarder in cement and as a soil conditioner.

In Australia the as-mined material generally contains 90–98% gypsum. Principal centres of production are **Lake MacDonnell** and **Kangaroo Island** (S.A.), and **Useless Loop** and **Lake Cowan** (W.A.). Other areas of production include **Lake Brown**, **Lake Seabrook**, **Lake Hillman** and **Cowcowing Lakes** (W.A.); **Morgan**, **Blanchetown**, **Cooke Plains**, **Lake Fowler** and **Stenhouse Bay** (S.A.); **Nowingi** and **Cowangie** (Vic.); and **Paka** (N.S.W.).

Gypsum is also a by-product of processing phosphate rock to phosphoric acid in the manufacture of fertiliser.

Limestone

Limestone (or marble, its metamorphosed equivalent) is the basic raw material for a number of important industrial commodities, notably cement and lime. Together with salt, limestone is also used in the manufacture of sodium carbonate (soda ash), a widely used industrial chemical. Large quantities of raw limestone are used as a metallurgical flux, especially in the iron and steel industry, and in various agricultural applications.

About two-thirds of Australia's annual production of around 10 Mt of limestone is used to manufacture cement. Limestone is mined in all states though New South Wales is the largest producer (3.4 Mt in 1986), principally from **Marulan South** and from mines in the **Kandos-Portland** area west of Sydney.

In general, limestone deposits are worked mainly near major cities and industrial centres to minimise transport costs, for example **Calcium** near Townsville and **Mount Larcom** near Gladstone in Queensland; **Marulan South** near the Port Kembla iron and steel works and the cement works at Berrima and Maldon; **Angaston**, **Rapid Bay** and **Klein Point** near Adelaide; and **Wanneroo** near Perth.

Exports of raw limestone are insignificant though exports of cement (which accounts for about two-thirds of total limestone output) average around 200 000 t per annum. About 1 Mt of limestone is imported annually from Japan as backloaded raw material for the domestic iron and steel industry.

Chemical and fertiliser minerals

Phosphate

Australia's phosphate requirements, used almost exclusively for the manufacture of superphosphate fertiliser, are met entirely by imports.

Very large phosphate deposits were discovered in 1966 in the Georgina Basin in north-western Queensland. One of the largest of these, the **Phosphate Hill** deposit, was brought into production in 1975, producing a so-called 'direct-shipping-grade' rock by open-cut selective mining. However, Australian superphosphate manufacturers resisted using it because their plants were geared to imported rock with different characteristics. This factor plus a poor export outlook led to the cessation of mining in 1982, after several years of only intermittent production.

The mine at Phosphate Hill has been on care-and-maintenance since 1983 and subsequent production represents sales from existing stockpiles. Investigations are continuing into the feasibility of producing phosphoric acid and a high grade fertiliser product utilising phosphate rock from Phosphate Hill and by-product sulphuric acid which would be derived from waste smelter gas at Mount Isa.

Salt

Australia's salt industry expanded rapidly in the late 1960s and early 1970s to meet a growing demand by chemical industries for a source of sodium and chlorine. Australia is now the second largest exporter of crude salt, after Mexico.

Salt is recovered as a precipitate, formed by solar evaporation of seawater or underground brines. Salt

is also mined dry, as so-called rock salt, although mining of this type does not occur in Australia.

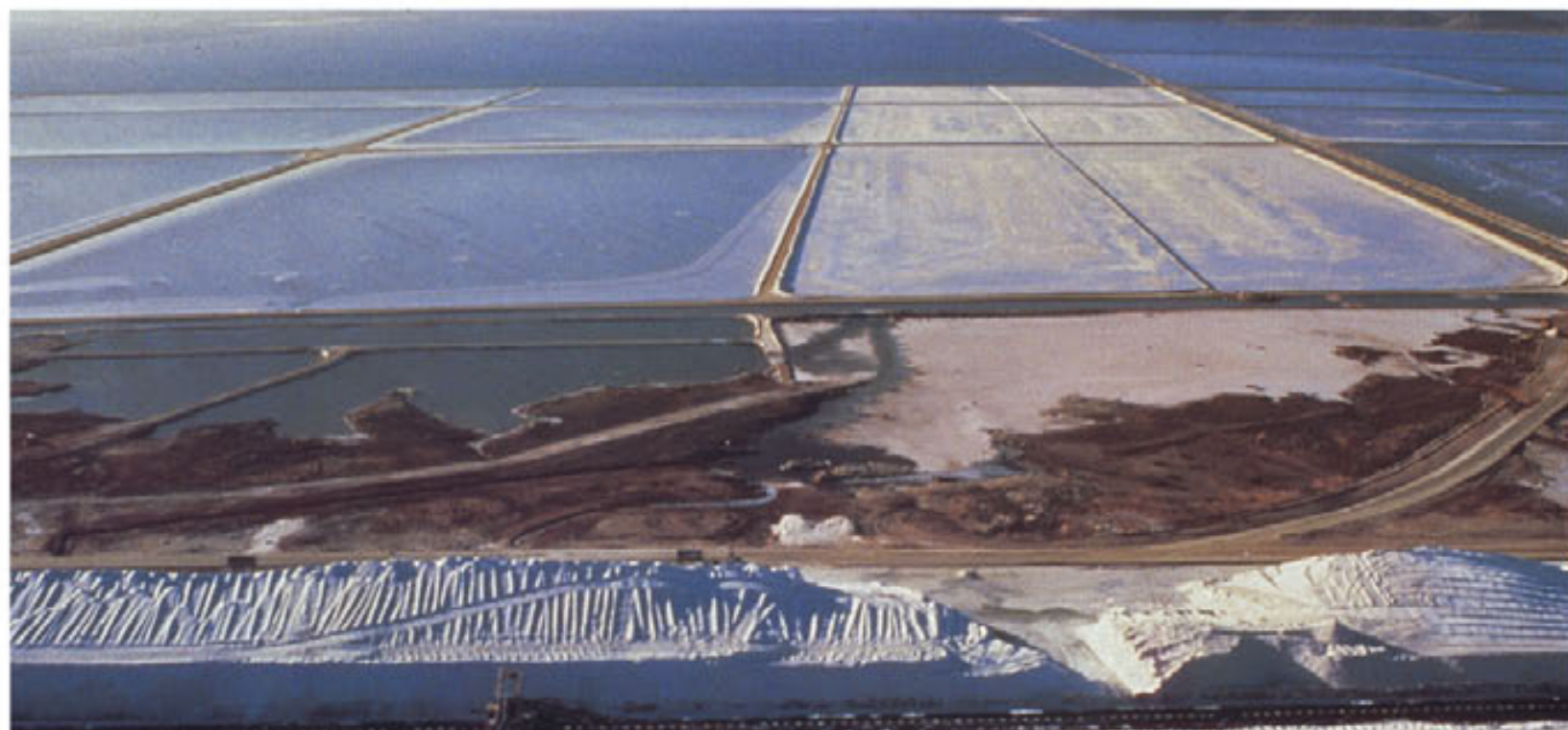
About 80% of Australian salt production comes from four large export-oriented operations based on solar evaporation of seawater at **Useless Loop**, **Lake Macleod**, **Dampier** and **Port Hedland** in north-west Western Australia. Total production in 1986 amounted to just over 6 Mt.

Australia's own salt requirements are supplied mainly by similar though smaller operations at **Dry Creek** (S.A.) and **Geelong** (Vic.), and at **Bajool** (Qld) where production is based on solar evaporation of both underground brines and seawater. About 75% of domestic salt is consumed by the chemical industry; the balance is used in other industrial applications, in food processing and by households.

Sulphur

Australia has no known deposits of elemental sulphur ('brimstone') and is dependent to a large extent on overseas supplies. However, about 35% of domestic sulphur requirements are met by sulphuric acid recovered as a by-product at smelters processing indigenous metallic sulphides: from lead concentrates at **Port Pirie**; from zinc concentrates at **Risdon**; and from lead and zinc concentrates at **Cockle Creek**. Total annual production of sulphuric acid amounts to nearly 2 Mt, most of which is consumed in the manufacture of superphosphate.

Sulphur is also recovered as ammonium sulphate from nickel refining at **Kwinana**. In addition small amounts of elemental sulphur are recovered during oil refining at some Australian refineries.



Crystalliser ponds and stockpiled salt at the Dampier field (W.A.) Seawater is pumped into large solar evaporating ponds (just visible in the background) and then transferred into the adjacent crystalliser ponds where the salt is precipitated. During the hot summer months about 1 Mt of moisture evaporates each day. After harvesting, the salt is hauled by road trains to nearby stockpiles for washing and drying. In total the Dampier salt field, Australia's largest, covers 9000 hectares and produces around 2 Mt of salt annually.

Deposits of the most commonly used materials for building and construction—sand, gravel and stone—are not shown on the map 'Minerals other than Fuels' nor discussed here because, although widespread, they are usually worked only in the vicinity of the very large population centres.

Other minerals

Mineral sands

Australia is the world's principal source of mineral sands, accounting for over 50% of world production of zircon, 50% of Western world production of rutile and 25% of Western world production of ilmenite in 1986. Australia also produces significant amounts of monazite and leucoxene—see Table 13.

Mineral sands were first mined in Australia in the 1930s, at Byron Bay in far north-eastern New South Wales. By the late 1940s rutile and zircon mining had extended into Queensland and further south in New South Wales. Soon after the start of ilmenite mining near Bunbury in south-west Western Australia in the 1950s, Australia became the world's leading producer of mineral sands. Australian companies have also led in the development of improved technology for mining and processing mineral sands, and now export processing equipment such as electromagnetic and electrical separators.

Up to 1974 mineral sands production along the east coast accounted for more than 95% of Australia's total annual output of rutile. By 1978, this had fallen to 65%, largely as a result of production at Eneabba, 270 km north of Perth, where mining started in 1974. Production of rutile is now divided about equally between the east coast (North Stradbroke Island near Brisbane and the Newcastle-Forster and Taree-Kempsey areas) and the west coast.

Western Australian mineral sands are rich in ilmenite and production from deposits in the Capel area and at Eneabba account for more than 80% of Australia's annual output of around 1.25 Mt of ilmenite. These deposits also provide about 70% of all zircon concentrates produced, virtually all of the monazite concentrates and all of the leucoxene concentrates. In addition the Capel deposits are an important source of xenotime, which contains the rare-

earth element yttrium.

Since 1981 mineral sands production has declined on the east coast because of lower ore grades and environmental constraints on mining. However, the recent discovery at Byfield near Rockhampton (Qld) of one of the largest mineral sands deposits in the world could lead to a resurgence of mining on the east coast. Metallurgical testing of a large mineral sand deposit near Horsham (Vic.) is being carried out to assess its potential.

Most Australian mineral sands production is exported as concentrates. Only ilmenite is currently processed further in Australia—at Capel, where it is upgraded at three plants to produce about 160 000 t of synthetic rutile (92% TiO₂) annually, and at Narngulu near Geraldton, where a 112 500 t per year synthetic rutile plant has been completed.

Construction of a plant to produce 450 t of high purity zirconia powders and 250 t of zirconium chemicals per year has commenced at Rockingham near Perth. It is expected to be in operation by late 1988.

About 130 000 t a year of ilmenite concentrate from the Capel area is used for pigment production at nearby Bunbury and at Burnie (Tas.). The high chromium content of east coast ilmenite precludes its use for this purpose, though a plant with a capacity of 250 000 t a year has been built near Brisbane to extract relatively low chrome ilmenite, suitable for upgrading to synthetic rutile, from stockpiled high chrome ilmenite.



Mineral sands and their uses

Many different products are derived from mineral sands.

Ilmenite is a mixture of iron and titanium oxides (54–60% TiO₂). It is used in the steel industry for furnace linings, as a fluxing agent, for sand blasting, for pigment production by the sulphate process or by direct chlorination. Ilmenite is also beneficiated to synthetic rutile in a complex process which removes the iron.

Leucoxene is altered ilmenite containing about 87% TiO₂ and is mined in association with ilmenite in the Capel area of south-west Western Australia.

Monazite is a major source of rare-earth elements such as cerium, thorium and lanthanum used in high strength micro-alloyed steel, ductile iron, and super and pyrophoric alloys; as catalysts in petroleum cracking; in glass for television tube face plates, eye glasses and camera lenses; in electronics as phosphors for colour television tubes, x-ray intensifiers and computer components; and in the generation of nuclear energy.

Rutile. The major uses of rutile are in the production of titanium dioxide pigment for the paint, paper and plastics industries; as a flux coating for welding rods; and in the manufacture of titanium metal, which has important uses in aerospace applications.

Zircon is used in making refractory bricks and furnace linings, especially in glass and steel-making plants. It is also used extensively in the ceramics industry as a foundry medium and is the primary source of zirconium, a metal used mainly in nuclear reactors.

Table 13. Mineral sands production, 1984–86

	1984	1985	1986
	thousand tonnes		
Ilmenite concentrate	1 493	1 419	1 238
Leucoxene concentrate	32	14	14
Monazite concentrate	16	19	15
Rutile concentrate	170	212	216
Zircon concentrate	458	501	452

Floating dredge and wet concentrator recovering mineral sands, North Stradbroke Island (Qld)
Sand dredged from the front of the man-made pond is piped to the floating concentrator. Here the heavier mineral sands are extracted by separators before being sent by barge to the dry separation plant near Brisbane for final separation into rutile, zircon and ilmenite. The residual sand from the wet concentrator is returned to the rear of the pond for progressive revegetation.

Barite

Barite (barium sulphate) is a high density mineral used extensively as a weighting agent in drilling muds to help confine high oil and gas pressures. Australia's main production is from an underground mine at **Oraparinna** (S.A.). Other producing centres include **Truro** and **Mount Mulga** (S.A.) and **Kempfield** (N.S.W.).

Clays

Clays are a complex group of minerals with different modes of geological occurrence, and different mineral composition and end-uses.

Bentonite is composed mainly of the clay mineral montmorillonite, a hydrous aluminium silicate. Bentonite clays are broadly classed as swelling or non-swelling. When mixed with water the naturally swelling clays expand to form a gel-like mass; the swelling capacity of the other group of bentonites can be increased through treatment with soda ash.

Bentonite has a wide range of uses, particularly as a bonding agent in moulding sand for foundry use, as a sealant to minimise seepage in dams, earthworks and drilling muds, and in stockfeeds. Bentonite production amounted to almost 40 000 t in 1986, mostly from the **Miles** area (Qld).

Fullers earth is the collective term applied to clay and other fine-grained earthy material noted mainly for its absorbent properties. Originally used for cleaning and thickening ('fulling') wool for cloth making, more modern uses include decolourising and purifying mineral, vegetable and animal oils. Australian production is small by world standards and currently all comes from the **Lake Narraminy** (W.A.) deposit, which has demonstrated reserves of 10 Mt.

Kaolin is a clay consisting principally of kaolinite, distinguished by its softness, whiteness and low absorption properties. The paper industry is the largest consumer of kaolin though the fibreglass, paint, plastics, adhesive, rubber and ceramics industries are also significant users. Production in 1986 totalled 186 000 t.

Kaolin is mined in the **Mudgee** and **Gulgong** areas (N.S.W.), at **Coorabin** (N.S.W.) and at **Tongonah** (Tas.). Mining of the large deposit of kaolin which occurs in association with bauxite at Weipa (Qld) commenced in the latter part of 1986. The kaolin, which is of paper-coating quality, is at present all exported to Japan. A similar grade of kaolin is also being mined at **Pittong** near Ballarat (Vic.) and shipped to the U.K. Kaolin from the tantalum-lithium mine at **Greenbushes** (W.A.) is also exported to Japan.

Fireclay and brick, stoneware, tile and pipe clays are produced throughout Australia, with mines characteristically located close to major centres of consumption.

Fireclay is a term used to describe

those refractory clays which do not burn white; it therefore excludes kaolin. Fireclays are classified as low, medium, high or super duty depending on their resistance to high temperatures; they are also characterised by low coefficients of expansion and some degree of thermal insulation. They are used in the manufacture of refractory products such as firebricks and various other shapes, ramming and airgun mixes, castable materials, retorts and crucibles.

Brick, stoneware, tile and pipe clays include a wide variety of bulky, low value clays and other fine-grained earths, and the names given to them reflect their end-uses rather than their mineral structure. All the products derived from these clays are fired, and often based on a blend of clays to obtain a mix with the required physical properties.

Construction materials such as low grade red-burning clays and shales used to make common building bricks and higher grade clays used for making face bricks are generally quarried in and around major consuming centres throughout Australia. For this reason they have not been shown on the map 'Minerals other than Fuels'.

Diatomite

Diatomite or 'diatomaceous earth' is a siliceous rock composed mainly of the skeletal remains of aquatic organisms called diatoms. Its main uses are as an insulator, as a filter medium for swimming pools and food and drink processing, and as a filler. Annual production is less than 10 000 t and comes mainly from a deposit near **Barraba** (N.S.W.), with lesser amounts from **Black Duck Creek** (Qld) and **Lillicur** (Vic.). About half of Australia's diatomite requirements are imported.

Dolomite and magnesite

In Australia the only magnesium minerals of commercial importance are dolomite and magnesite, which are used mainly as raw materials for magnesia-containing products such as refractories, fluxes, fillers, cements and fertilisers.

Almost all dolomite produced is consumed domestically, about 85% of it as flux in the iron and steel industry. Production in 1986 exceeded 700 000 t, the bulk of which came from **Ardrossan** (S.A.).

Australian production of crude magnesite is small by world standards and has fallen in recent years to just over 40 000 t in 1986. Production is mainly from mines at **Fifield** and **Thuddungra** (N.S.W.), and **Copley** (S.A.). Over 10 000 t of dead-burned magnesite and magnesium oxide are imported each year to overcome a shortfall in domestic production. Magnesium metal is not produced in Australia and all requirements are imported.

In 1985, what is believed to be the world's largest deposit of magne-

site, containing an estimated 250 Mt, was discovered at Kunwarara, just north of Rockhampton (Qld). Current development plans envisage output of 100 000 t of magnesite per year, with production of magnesium metal commencing around 1992.

Felspar

Felspars are the most abundant mineral constituents of igneous rocks and are used as a source of alumina and alkalis in glass and ceramics. Small amounts of felspar are produced at **Londonderry** and **Wialki** (W.A.), and in the **Cockburn area** near Broken Hill (N.S.W.).

Mica

Mica is a complex hydrated aluminium silicate mineral which can be split into very thin, tough and transparent flakes with outstanding dielectric and insulating properties. Australian production comes mainly from the **Williamstown** deposit near Adelaide though output has been low and declining in recent years. Most domestic requirements are now met by imports.

Peat

Peat is the first stage in the formation of coal. It is a spongy material made up of partly decomposed organic matter, minerals and water. Because of its water retaining qualities peat is used extensively as a soil conditioner and as a mulch. In some countries it is an important energy source.

Australian production of peat is small (about 10 000 t annually) and most is consumed domestically. The main producing centres are **Lake Muir** (W.A.), **Wingecaribee Swamp** near Bowral and **Killarney Swamp** near Bombala (N.S.W.), and the **Bronte** area of central Tasmania.

Silica and garnet

Silica and garnet are weathering-resistant minerals that occur in beach sands. Silica is abundant along the east and west coasts of Australia and by far the greatest proportion of that produced (over 2 Mt in 1986) is for glass manufacture from deposits in and near the capital cities.

Silica for metallurgical applications (as either an alloying or a fluxing agent) is preferred in lump form, generally as quartz or quartzite. Such deposits are mined at **Marrangaroo** near Lithgow (N.S.W.) for use as a flux at the Port Kembla steelworks; at **Beaconsfield** (Tas.) and **Iron Knob** near Whyalla (S.A.) for manufacturing ferro-silicon and silicomanganese at **Bell Bay** (Tas.); and near **Mount Isa** for use locally as a flux. About 100 000 t of silica sand per year from **Douglas Lake** (W.A.) is used as metallurgical flux at the nearby Kalgoorlie nickel smel-

ter.

Hardrock silica is also used in the production of elemental silicon. Australia's first silicon smelter, with an annual capacity of 9000 t of metallurgical grade silicon, was commissioned at **Electrona** near Hobart in 1987. Silica treated at the plant is mined near **Smithton** in north-western Tasmania. A second silicon plant, at **Bunbury**, is scheduled to commence production in 1989 and will treat silica to be mined at **Moora**. Silicon is used as an alloying material, particularly with aluminium, and in the electronics and chemical industries.

Over 500 000 t of silica sand is exported annually to Japan from **Cape Flattery** in north Queensland. A further 250 000 t is exported from deposits mined in the **Perth** area.

Garnet is an important natural abrasive and in world terms Australia has become a significant producer in recent years. Almost 10 000 t of garnet concentrate was produced in 1986, mainly from the large **Port Gregory** deposit north of Geraldton (W.A.).

Sillimanite

Sillimanite is an aluminium silicate mineral used in a broad range of acid-refractory products, especially mortars and castables. Production is small and comes from **Williamstown** (S.A.), along with kaolinised sillimanite, kaolin and mica.

Talc and pyrophyllite

Though not related chemically talc and pyrophyllite have similar physical properties, in particular a high degree of lubricity or 'slip' and a high fusion point.

Talc is used mainly in ceramics, paints, rubber, plastics, cosmetics, insecticides and agricultural dusts. Most Australian production (nearly 180 000 t in 1986) is exported, principally to Japan. The main producing centres are **Three Springs** and **Mount Seabrook** (W.A.); **Mount Fitton**, **Gumeracha** and **Lyndoch** (S.A.); and near **Mudgee** (N.S.W.).

Because of its high fusion point pyrophyllite is used mainly in refractory applications and in whiteware ceramics. Production averages around 8000 t annually, mainly from the **Pambula** area of southern New South Wales.

Vermiculite

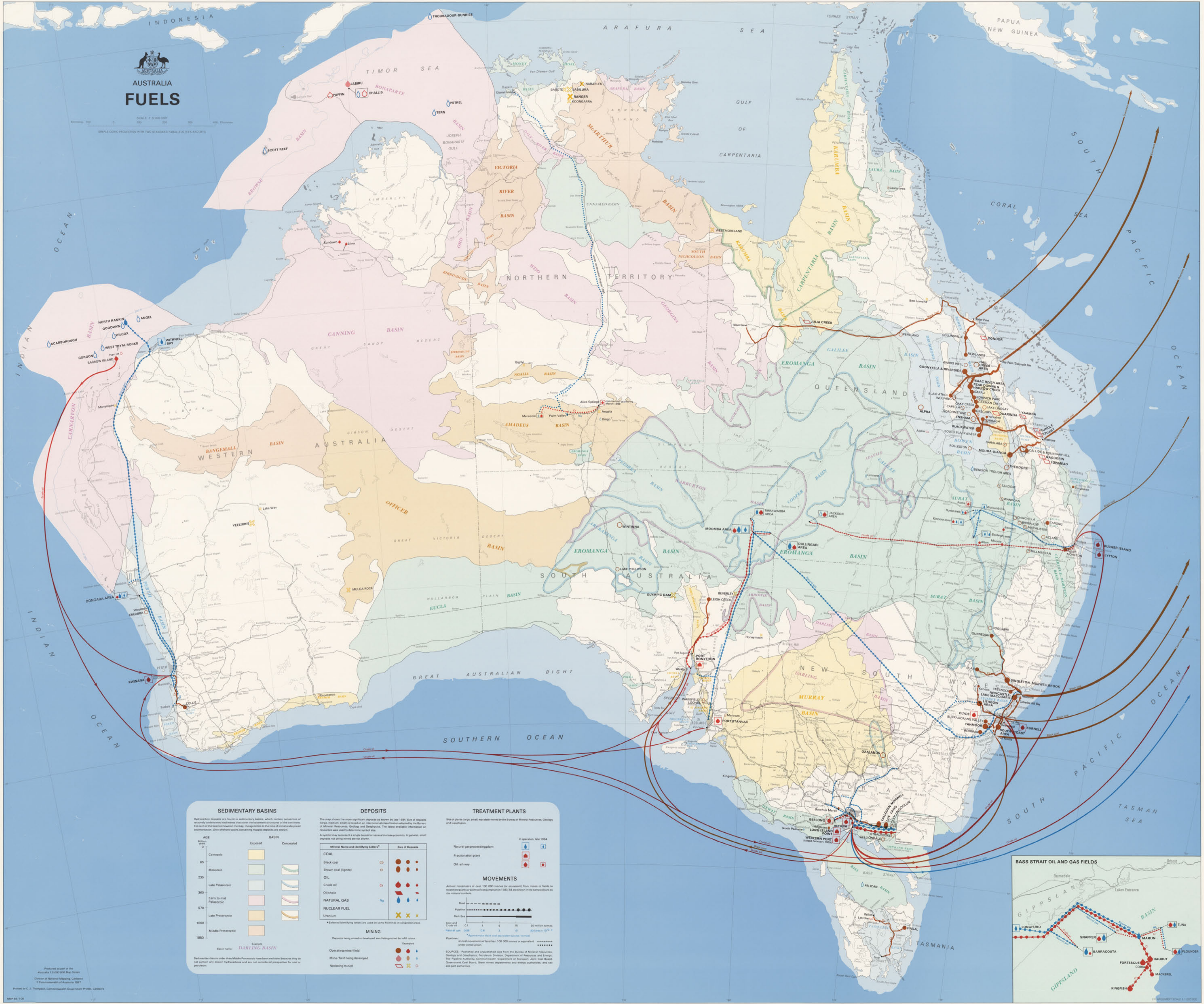
Vermiculite resembles mica but its commercial value lies in its ability to expand into worm-like particles with a bulk of 8 to 12 times that of the as-mined material when heated quickly to about 1000°C. Its main uses in Australia are with plaster in acoustic and fireproof sprays and as an insulating material. As production from the sole producer, at **Young River** near Esperance (W.A.), is both small and sporadic most domestic needs are imported.

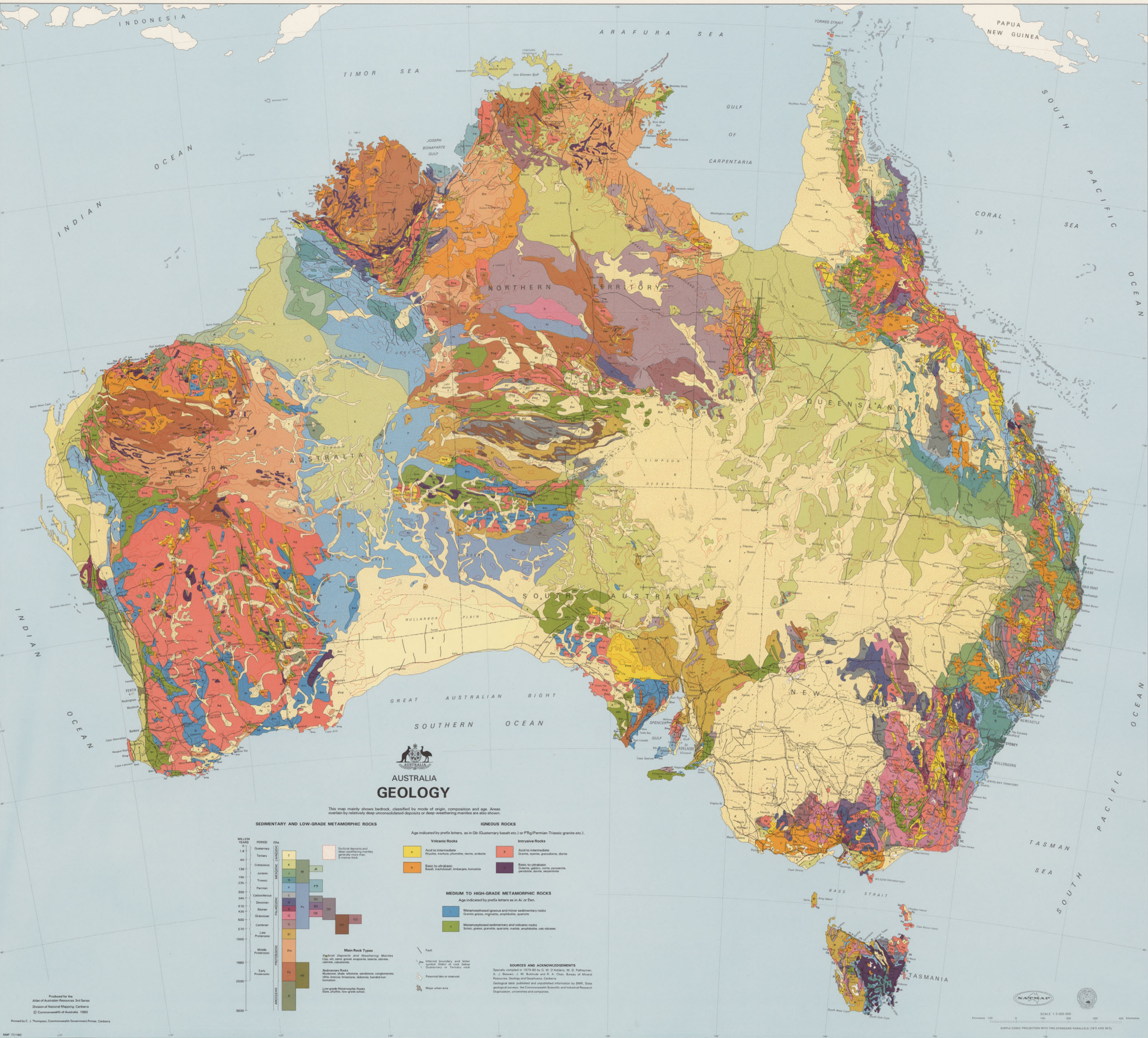
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- Australian Overseas Information Service:** front endpaper, pages 12 (*1*), 15 (*right*), 18 (*centre left & lower right*), 21 (*lower right & lower left*), 26, 35, 46 (*right*), 48 (*top*), 49 (*top*), 54 (*lower left*) and back endpaper.
- BHP Petroleum:** page 52.
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- Bureau of Mineral Resources, Geology and Geophysics:** Ian Crick page 30; **Peter J. Davies** page 23 (*lower right*); **Morrie Duggan** page 22 (*right*); **John Kennard** page 16 (*left*); **Kevin McCue** page 8 (*right*); **Mike Owen** page 17; **Roger Pratt** page 48 (*lower*); **Colin Simpson** page 10 (*computer image*); **John Shergold** page 16 (*right*); **A. J. Stewart** page 12 (*3 & 4*); **Malcolm R. Walter** page 15 (*top left*); **Gavin Young** page 18.
- J. H. Cleghorn:** page 29.
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- Jim Frazier:** pages 15 (*lower left*) and 19.
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- Methuen:** **Mary E. White** page 21 (*centre right*).
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- Western Mining Corporation Holdings Ltd:** pages 37, 38, 45 (*left*), 46 (*left*) and 49 (*lower*).

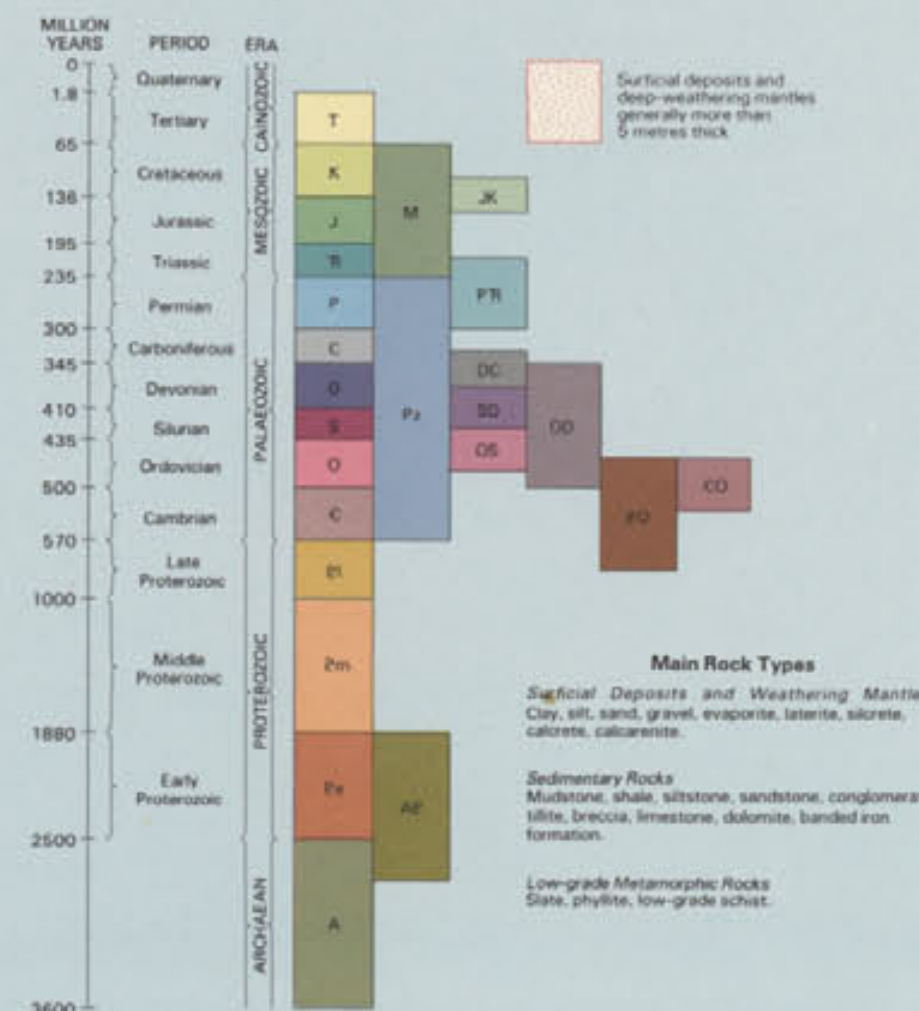




**AUSTRALIA
GEOLOGY**

This map mainly shows bedrock, classified by mode of origin, composition and age. Areas overlain by relatively deep unconsolidated deposits or deep-weathering mantles are also shown.

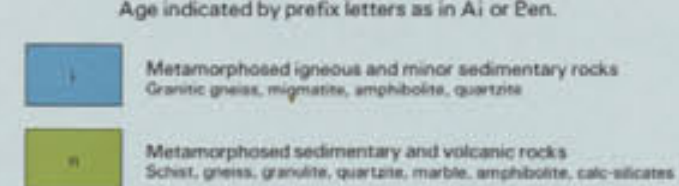
SEDIMENTARY AND LOW-GRADE METAMORPHIC ROCKS



IGNEOUS ROCKS



MEDIUM TO HIGH-GRADE METAMORPHIC ROCKS



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