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Australia's mineral resources and their global status

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Australia's known resources of a wide range of mineral commodities are considerable in comparison with rates of production. Australia has the world's largest economic demonstrated resources of bauxite, lead, zinc, silver, ilmenite, rutile, zircon, tantalum, and uranium. In addition, Australia is ranked in the top three countries in the world for economic demonstrated resources of brown coal, copper, cobalt, gold, iron ore, manganese ore, nickel, gem/near-gem and industrial diamond.

Despite a high rate of discovery of significant new mineral deposits, particularly since the 1950s, there is considerable potential for discovery of further mineral deposits in Australia. This is indicated by the abundance of high-quality known resources and the range of prospective geological settings. Increasingly, future discoveries are likely to be in regions where there has been little exploration to date because of their remoteness or the presence of concealing regolith or sedimentary cover.

The few widely used mineral commodities for which Australia has low levels of demonstrated resources include chromium, platinum group metals, trona, and some components of fertilisers, such as potassium salts, and elemental sulphur.

Given the acceptance of widespread multiple or sequential land use, which accommodates responsible exploration and mining, Australia is very well placed to maintain its position as one of the world's major suppliers of a wide range of mineral commodities.

Introduction

This paper reviews Australia's mineral resources, with emphasis on the major export commodities. It discusses Australia's mineral resource stocks and their global importance, mineral commodities likely to be important in the 21st century, and the requirements for sustaining mineral production to meet world demand.

Australia has been a mining nation since coal was the first won in the Newcastle district in the 1790s. The minerals industry has played a major role in opening up remote parts of the continent, and it was a major contributor to the economic growth of Australia in the second half of the 19th century, mainly through gold production. The first half of the 20th century, however, was a lean time for exploration and discovery, and the minerals industry played a more subdued role in the nation's economy.

There has been tremendous growth in the minerals industry and numerous discoveries of world-class ore deposits since the early 1950s. Before then, Australia's known economic mineral resources were either non-existent or insignificant for a variety of mineral commodities of which we are now a major world supplier. Examples include bauxite, iron ore, uranium, nickel, and diamonds. There are now at least 70 different styles of mineral deposits of economic or potential economic significance known in Australia. These have distinct features and formed in different geological settings.

The important position that the minerals sector has assumed in the Australian economy is apparent from Australian Bureau of Statistics (ABS) surveys, which indicate that the minerals sector provided export earnings of about $A31 billion in 1996–97 (processed and unprocessed exports), amounting to about 30% of Australia's total exports of goods and services and over 40% of merchandise exports (ABS 1997a). The minerals and petroleum industry combined contributed approximately 7% to Australia's gross domestic product (GDP) in 1996–97 (ABS 1997b) (ABARE 1997a). During 1996, the minerals industry employed over 80 000 people directly and more than 230 000 in downstream activities (metal and mineral product manufacturing), amounting in total to 3.5% of the work force (ABS 1997c).

During the recovery of mineral commodities required to sustain the world's population there are impacts on the environment at the immediate mine sites. Most underground or small open-pit mines, such as many gold, base-metal and uranium mines, have very limited areas of impact. Large-scale open-pit coal, bauxite, iron ore and mineral sand mines can, for a time, occupy areas up to several tens of square kilometres before rehabilitation. Even so, only about 0.02% of the Australian landmass is directly affected by mining (Woodside & O'Neill 1993). More land is indirectly required for mining activities: mine-related infrastructure and settlements have been estimated to occupy approximately 0.4% of Australia's landmass (Woodside & O'Neill 1993).

Because mineral resource development involves such a very small area at any given time, it is a very high-productivity land use. In 1996–97, Australian mine production (ABARE 1997b) provided export earnings of roughly A$20 million per square kilometre directly affected by mining. If all the areas indirectly required for mining activity are taken into account, the return from mining is approximately A$0.75 million per square kilometre.

Australia's mineral resources in a global context

Progressive improvement in the geoscientific knowledge base over the last 50 years has been a major factor leading to high levels of exploration, and the consequent discovery of an enviable breadth and quality of mineral resources. BRS estimates that about 150 important mineral deposits were discovered in the 17 years before 1967, an average of about 9 a year. The number of important deposits discovered over the 30 years between the beginning of 1967 and the end of 1996 was 488, an annual average of 16. Over the last decade there has been an average of 18 important discoveries each year.

Australia's main mines and known mineral deposits are shown in Figure 1. With some notable exceptions, these cluster in regions of outcropping basement rocks in areas that are not deeply weathered or covered by sedimentary basins. Exceptions include coal deposits and some lead–zinc deposits developed in basins, bauxite and some nickel deposits in highly weathered lateritic areas, and the Olympic Dam deposit, which is deeply buried beneath younger sedimentary strata.

The Mineral Resources and Energy Branch[2] of the Bureau of Resource Sciences (BRS) prepares formal estimates of Australian resources of the major mineral commodities, continuing the annual series established by the former Bureau of Mineral Resources in 1975. Table 1 presents BRS's compilation of Australia's economic demonstrated resources (EDR)[3], subeconomic demonstrated[4] and inferred resources[5] of minerals and fuels to the end of 1996, (BRS 1997).

[1] Mineral Resources and Energy Branch, Bureau of Resource Sciences, PO Box E11, Queen Victoria Terrace, Canberra ACT 2600, Australia.

[2] Since this paper was finished, the Mineral Resources and Energy Branch of BRS has been transferred to the Australian Geological Survey Organisation (GPO Box 378, Canberra, ACT 2601).

[3] Economic demonstrated resources are specific bodies of mineral-bearing material whose location, quantity, and quality are known from specific measurements or estimated from geological evidence and for which, at the time of determination, profitable extraction or production under defined investment assumptions has been established, analytically demonstrated or assumed with reasonable certainty.

[4] As for EDR, but not able to be profitably extracted at the time of determination.

[5] Inferred resources are resources for which quantitative estimates are based largely on broad knowledge of the geological character of the deposit and for which there are few if any samples or measurements. The estimates are based on an assumed continuity or repetition, of which there is geological evidence.

LEGEND

- Mine being developed
- Mine
- Deposit
- Smelter
- Refinery
- Export port
- Coal producing area
- Individual operating coal mine
- Large coal deposit

KEY TO MINERALS

Al	Aluminium
Cu	Copper
Fe	Iron
Pb	Lead
Ni	Nickel
Sn	Tin
Zn	Zinc
Au	Gold
Mn	Manganese
Ag	Silver
W	Tungsten
D	Diamonds
Op	Opals
Gs	Other Gemstones
Sa	Sapphires
A	Asbestos
Gp	Gypsum
Ck	Kaolin
Ls	Limestone
Mag	Magnesite
MS	Mineral Sands
P	Phosphate Rock
RE	Rare Earth
Ta	Tantalum
Li	Lithium
Na	Salt
Si	Silica
T	Talc
U	Uranium

AUSTRALIAN MINING & MINERAL OPERA[TIONS] AND SIGNIFICANT MINERAL DEPOSITS

KILOMETRES 100 0 100 200 300 400 500 KILOMETRES

Adapted from a map produced by
the Australian Surveying & Land Information Group (
and the Minerals Council of Australia (MCA)

December 1997

Bureau of Resource Sciences
A U S T

COAL DEPOSITS, EASTERN AUSTRALIA

Mines producing 1 million tonnes of saleable coal 1994/95
- ■ Underground mine

QUEENSLAND
Black coal
BLAIR ATHOL AREA
- Blair Athol

BOWEN BASIN AREA
- Blackwater
- Collinsville
- Curragh
- German Creek
- ■ German Creek
- Goonyella/Riverside
- ■ Gordonstone
- Gregory
- Jellinbah East
- Moura
- Newlands
- Norwich Park
- ■ Oaky Creek
- Oaky Creek
- Peak Downs
- Saraji
- South Blackwater
- ■ South Blackwater

CALLIDE BASIN AREA
- Boundary Hill
- Callide

IPSWICH BASIN AREA
- Ebenezer
- Jeebropilly

TARONG BASIN AREA
- Meandu

NEW SOUTH WALES
Black coal
HUNTER COALFIELD
- Bayswater No 2
- Drayton
- Howick
- Hunter Valley
- Lemington
- Mount Thorley
- Muswellbrook
- Ravensworth-Narama
- Saxonvale-Bulga
- ■ South-Bulga
- Warkworth No 1

NEWCASTLE COALFIELD
- ■ Cooranbong
- ■ Munmorah
- ■ Myuna
- ■ Newstan
- ■ Pelton/Ellalong
- ■ West Wallsend
- ■ Wyee

SOUTHERN COALFIELD
- ■ Appin
- ■ Cordeaux
- ■ South Bulli
- ■ Tahmoor
- ■ Tower
- ■ West Cliff

WESTERN COALFIELD
- ■ Angus Place
- ■ Baal Bone
- ■ Clarence
- ■ Ulan
- Ulan

VICTORIA
Brown coal
- Anglesea

LATROBE VALLEY
- Loy Yang
- Hazelwood
- Yallourn

ADDITIONAL GOLD DEPOSITS

OTHER MAJOR MINES IN EASTERN GOLDFIELDS, WESTERN AUSTRALIA
- Bannockburn
- Bardoc – Davyhurst
- Barnicoat
- Binduli
- Darlot
- Grosmont – Norris
- Gullewa
- Jubilee
- Kundana
- Lady Bountiful Extended
- Mount McClure
- Mount Monger
- Tarmoola
- Nimary
- Palm Springs

OTHER MINES IN THE PINE CREEK AREA NORTHERN TERRITORY
- Brocks Creek
- Fountain Head
- Mount Bonnie
- Yam Creek

ADDITIONAL NICKEL DEPOSITS

OTHER MAJOR DEPOSITS IN EASTERN GOLDFIELDS, WESTERN AUSTRALIA
- Bulong
- Silver Swan
- Maggie Hays
- Cawse

World resources are also included in Table 1. These are mainly taken from Mineral Commodity Summaries, 1997, (U.S. Geological Survey 1997), updated where BRS has more recent data.

As indicated in Table 1, Australia has the world's largest EDR of bauxite, lead, mineral sands (ilmenite, rutile and zircon), silver, tantalum, uranium, and zinc. In addition, Australia's EDR are within the top three worldwide for brown coal, cobalt, copper, gold, iron ore, manganese ore, nickel, and industrial and gem/near gem diamond. Australia ranks fourth for EDR of lithium and rare-earth oxides and sixth for black coal. In addition, Australia has almost all the world's opal resources and a significant share of world sapphire resources.

Australia is a world leader in the production of bauxite, natural industrial diamond, gem and near-gem diamond, lead, lithium, ilmenite, rutile, zircon, tantalum, zinc and opal, and a significant world producer and exporter of black coal, gold, iron ore, manganese ore, nickel, lithium, silver, copper and sapphire (Table 2).

Table 3 summarises global information for major mineral commodities, listing countries with largest resources, uses and possible substitute commodities. This compilation draws on US Geological Survey (1997) and BRS data.

Mineral commodities for which Australia has substantial resource stocks

Bauxite. Bauxite, which contains aluminium oxides and various impurities (notably iron oxides and silica), is the raw material for production of alumina (Al_2O_3) and aluminium metal. Starting from a low base in the late 1960s, Australia became the world's largest producer and exporter of bauxite and alumina by 1980.

In Australia's known regions of laterite development, bauxite concentrations are widespread. It is mined from open cut operations at Weipa in Queensland, Gove in the Northern Territory, and the Darling Range in southwest Western Australia. There are also extensive deposits in the Mitchell Plateau and Cape Bougainville regions of northwest Western Australia, but these are currently not economic.

Demonstrated resources of bauxite in Australia are estimated at more than 8300 Mt, of which at least 3000 Mt are classified as EDR, the highest in the world. In addition, there are at least a further 1500 Mt in the inferred resource category (BRS 1997). Estimates of bauxite resources worldwide are 55 000–75 000 Mt (US Geological Survey 1997).

Table 1. Australia's identified resources of major minerals, 1996, and world economic demonstrated resources, 1996. (Sources: BRS 1997; US Geological Survey 1997)

		Australian identified resources			*World economic* demonstrated resources*	*Australian share of world economic resources*	
		Demonstrated		*Inferred*			
Commodity		*Economic*	*Subeconomic*	*Undifferentiated*		*Percentage*	*Ranking* (h)
Bauxite	(Mt)	3024	5329	1598	23000 (a)	13	1
Black coal (recoverable)	(Gt)	49	6	very large	705	7	6
Brown coal (recoverable)	(Gt)	41	3	166	312	14	3
Chromium	(kt Cr)	-	263.3	1623.8	3700000	< 1	na
Cobalt	(kt Co)	414.1	302.1	491.9	4000	10	3
Copper	(Mt Cu)	23.6	17	14.2	310	8	3
Diamonds:							
gem & near-gem	(10^6 c)	85	223.5	34.4	300 (b)	28	2 (g)
industrial	(10^6 c)	90	240.2	51.2	570 (a)	16	3
Gold	(t Au)	4454	1263	1887	46000	10	3
Iron ore	(Gt)	17.8	14.2	17.4	151	12	2
Lead	(Mt Pb)	18.7	14.2	21.9	69	27	1
Lithium	(kt Li)	166	82	7	2800 (f)	8 (e)	4
Magnesite	(Mt $MgCO_3$)	179.9	328	110	8600	2	4
Manganese ore	(Mt)	118.0	194.1	166.6	1885 (a)	6	3
Mineral sands:							
ilmenite	(Mt)	135.0	68.8	89.2	586 (a)	23	1
rutile	(Mt)	14.9	34.5	25.2	41.99 (a)	36	1
zircon	(Mt)	21.4	25.1	20.8	60.95 (a)	35	1
Molybdenum	(kt Mo)	-	7.9	859.5	5500	< 1	na
Nickel	(Mt Ni)	6.4	5.6	6.6	51	13	3
Phosphate rock	(Mt)	103	2758	1947	11000	1	7
PGM (Pt,Pd,Os,Ir,Ru, Rh)	(t metal)	19.1	45.2	87.9	56000	< 1	low
Rare earths							
REO & Y_2O_3	(Mt)	1	14.2	4.2	100	1	4
Silver	(kt Ag)	43.3	24.4	23.2	280	15	1
Tantalum	(kt Ta)	8.1	5.7	64.8	19	30	1
Tin	(kt Sn)	119.5	214.0	308.3	7000	2	9
Tungsten	(kt W)	0.9	62.1	180.1	2100	< 1	low
Uranium (c)	(kt U)	622	93	180	2208 (d)	28	1
Zinc	(Mt Zn)	39.9	24.3	20.8	140	29	1

Abbreviations: t = tonne; c = carat; m^3 = cubic metre; L = litre; kt = 10^3t; Mt = 10^6t; Gt = 10^9 t; GL = 10^9L; na = not applicable

* Based largely on Mineral Commodity Summaries for 1996 (US Geological Survey, February 1997)

(a) Adjusted by BRS.

(b) 1994 data.

(c) BRS scheme for classifying uranium resources.

(d) Source OECD/NEA and IAEA (1997).

(e) Based on contained manganese content.

(f) Excludes Russia, China, Portugal, Namibia.

(g) BRS estimate.

(h) Ranking as at 1 February 1996.

Australian bauxite deposits are almost exclusively blanket type with pisolitic texture, either free-flowing, as at Weipa, or partly consolidated with a hard crust, as in the Darling Range. They are extensive and associated with Tertiary laterites, which overlie Tertiary sediments at Weipa, Mesozoic sediments at Gove, and Archaean gneisses in the Darling Range. Recoverable Al_2O_3 ranges from 55% for Weipa bauxite to 30% in some of the Darling Range deposits. Reactive silica ranges from 0.3 to 5.3%.

Over 80% of Australia's bauxite production is processed to alumina at refineries near the Darling Range, currently the world's leading producing region of bauxite and alumina, and at Gove and Gladstone. About 80% of the processed alumina is exported and the remainder is smelted to aluminium metal in Queensland, New South Wales, Victoria and Tasmania.

Iron Ore. Until the mid 1960s Australia's identified iron ore resources were limited, mainly occurring in the Middleback Ranges of South Australia. Since the discovery of new resources in the Pilbara region of Western Australia and the lifting of the export embargo, Australia's EDR of iron ore have grown dramatically. They fell sharply in 1977 as a result of some higher phosphorus resources being downgraded to subeconomic, but substantial increases in 1991 followed successful exploration. EDR were estimated at 17 800 Mt in 1996.

It is difficult to compare iron ore resources on an international basis because they are traditionally reported as tonnes of ore, ignoring the wide range of grades considered to be economic in different mines and different countries. Using a combination of U.S. Geological Survey and BRS resource estimates, Australia is ranked third in the world in terms of tonnes of ore, with 11.8% of the total ore EDR. In terms of contained iron, Australia is ranked second, but its share of world EDR becomes about 17%. Russia is the premier iron ore nation with approximately 23% of ore EDR and 18% of contained iron EDR. The Ukraine has the second largest proportion of world EDR.

Approximately 90% of Australia's EDR occurs in the Pilbara region, particularly in the Hamersley Basin. The bulk of EDR is in iron enrichments in banded iron formations (BIF) and Tertiary palaeochannel deposits. Typical examples of iron enrichment in BIFs are the hematite deposits of the Brockman Iron Formation at Mount Whaleback and Mount Tom Price and the hematite–goethite deposits of the Marra Mamba Iron Formation. Pisolitic limonite palaeochannel deposits are exemplified by the mesa

Table 2. Australian and world production of major minerals 1996, and Australian resource to production ratios. (Sources: ABARE 1997a, 1997b; US Geological Survey 1997)

		1996 mine production		*Australian share of world mine production*		*Australian resource (EDR) to production ratio*
Commodity		*Australia* [a]	*World* [b]	*Percentage*	*Ranking* [i]	*Years (rounded)*
Bauxite	(Mt)	43.1	122.6	35	1	70
Black coal (recoverable)	(Gt)	0.25 [d]	3.71 [e]	5	6	200
Brown coal (recoverable)	(Gt)	0.0536	0.84	5	7	800
Chromium	(kt Cr)	-	12000	na	na	na
Cobalt	(kt Co)	0.9	24.1	4	7	500
Copper	(Mt Cu)	0.5	10.7	5	6	50
Diamonds						
gem & near gem	(10^6 c)	18.9	54	33	1	4
industrial	(10^6 c)	23.1	58	46	1	4
Gold	(t Au)	289	2300	12	3	15
Iron ore	(Gt)	0.147	1.01	14	4	120
Lead	(Mt Pb)	0.52	2.815	18	1	40
Lithium	(kt Li)	3.07	6.4 [c]	27	2	50
Magnesite	(Mt $MgCO_3$)	0.31	9.2 [c]	3	9	600
Manganese ore	(Mt)	2.1	21.5	14 [h]	3 [h]	60
Mineral sands						
Ilmenite	(Mt)	2.0	6.6 [c]	24	1	70
Rutile	(Mt)	0.18	0.3 [c]	45	1	80
Zircon	(Mt)	0.46	0.89 [c]	46	1	50
Molybdenum	(kt Mo)	-	126	na	na	na
Nickel	(Mt Ni)	0.11	1.04	11	3	60
Phosphate rock	(Mt)	0.001 [f]	131	<1	low	na
PGM (Pt,Pd,Os,Ir,Ru, Rh)	(t metal)	0.7	260 [g]	<1	low	30
Rare earths						
REO & Y_2O_3	(Mt)	-	0.08	na	na	na
Silver	(kt Ag)	1.0	14.8	7	5	40
Tantalum	(kt Ta)	0.3	0.431	70	1	30
Tin	(kt Sn)	8.8	190	4	6	15
Tungsten	(kt W)	-	30	na	low	na
Uranium	(kt U)	4.975	36.028	14	2	130
Zinc	(Mt Zn)	1.07	7.229	15	2	40

Abbreviations: t = tonne; c = carat; kt = 10^3 t; Mt = 10^6t; Gt = 10^9t; na = not applicable

(a) ABARE (1997a,b)

(b) BRS estimates adapted from Mineral Commodity Summaries for 1996 (US Geological Survey, 1997) and other sources.

(c) Excludes USA.

(d) Raw coal.

(e) Saleable coal.

(f) BRS estimate.

(g) Platinum and palladium only.

(h) Based on contained Mn content.

(i) Ranking as at 1 February 1997.

Table 3. World mineral commodities by major resource countries; uses and substitutes[a].

Commodity	*Country ranking of EDR*	*Uses & Substitutes*
Bauxite	**Australia [1]**, Guinea [2], Brazil [3], Jamaica [4].	Principal ore for alumina and aluminium production. Other possible sources are clay, alunite & oil shales. Magnesium can substitute for aluminium in some applications.
Chromium	Rep. of South Africa [1], Kazakhstan [2], Zimbabwe[3]. Australia has no EDR	Stainless steel is the major end-use for chromite.There is no technically or economically acceptable substitute for chromite ore in the production of stainless steel, ferrochromium, chromium chemicals or chromite refractories.
Coal	USA [1], FSU[b] [2], China [3], **Australia [6]**.	Electricity generation, coal-gas generation, making coke for use in blast furnaces (iron production); also as a source of industrial and domestic heat. Tars and certain plastics are by-products of coke/gas production.
Cobalt	Zaire [1], Cuba [2], **Australia [3]**, Zambia [4].	Special alloys, magnets, ceramics, catalysts and paints. Nickel may substitute in some applications, but with potential loss of product performance; barium/strontium ferrite are potential substitutes in magnets.
Copper	Chile [1], USA [2], **Australia [3]**.	Electrical equipment, car radiators and refrigerators. Aluminium may substitute in various products; titanium, steel, optical fibre and plastics are substitutes in certain applications.
Diamond: gem/near-gem	Botswana [?1][c] **Australia [?2],** Russia [?3], South Africa[?4].	Jewellery. In some jewellery, substitutes may include cubic zirconia.
Diamond: industrial	Zaire [1], Botswana [2], **Australia [3]**.	Abrasives, in cutting tools, wire-drawing dies, boring and milling tools. Substitutes are synthetic diamonds, which make up more than 80% of industrial diamonds used. Alternative, less-hard materials include cubic boron nitride.
Gold	Rep. of S. Africa. [1], USA [2], **Australia [3]**.	Jewellery and electrical/electronic applications. Substitutes can be palladium, platinum and silver. Regarded as an inherent store of value and used as a hedge against inflation.
Iron ore	Russia [1], **Australia [2]**, USA[3], Brazil [4].	Only source of primary iron, the least expensive and most widely used metal. Iron and steel compete with more expensive materials having a property advantage like plastics/aluminium or with cheaper non-metallic products like concrete.
Lead	**Australia [1]**, USA [2], China [3].	Lead-acid batteries; other uses include shielding in medical radiography, building/construction as flashing, weights, and glass additive. Substitutes are plastics, aluminium, tin, and steel in certain applications.
Lithium	Chile [1]; USA[2], Canada [3], **Australia [4]**.	Special glasses, dinnerware, porcelain enamels, electrical ceramics, aluminium smelting, lubricants, batteries, medicines. Substitutes include borates and certain feldspars.
Magnesite	China[1], Russia [2], North Korea [3], **Australia [4]**.	Calcined magnesia and sintered magnesia for high-quality refractory bricks, neutralising acid wastes, water treatment, fertiliser. Magnesium metal/light alloys.
Manganese ore	Rep.of S.Africa[1], Ukraine [2], **Australia [3]**.	Stainless and special steels and silico- and ferromanganese alloys, chemicals, batteries, and ceramics. No satisfactory substitutes for its major applications.
Mineral sands:	**Australia [1]**,?Norway[2], China [3], Canada[?].	Ilmenite and rutile are titanium oxide minerals. Pure white titanium oxide pigments for paper and paint manufacture and ceramics. Titanium metal is light yet strong, and corrosion
ilmenite	**Australia [1]**, Brazil [2],	resistant; used in aerospace, jet engines, aircraft and prosthetic and medical equipment.
rutile	Rep.of S.Africa [?] USA [?]	Substitutes are anatase deposits (Brazil), Ti-rich magnetites, titaniferous slag.
zircon	**Australia [1]**, Rep. of S Africa [2], USA [3].	Ceramics, foundry bricks, furnace linings, refractories, and abrasives. Substitutes include baddleyite (ZrO_2). Chromite and olivine are substitutes in some foundry applications.
Nickel	Cuba[1], Russia[2], **Australia[3]**, Canada[4]	Stainless steel and other special alloys, batteries, and coinage, and as a catalyst. Substitutes include cobalt, copper, titanium and platinum, and aluminium, steel and plastics for some uses
Phosphate Rock	Morocco & W.Sahara [1], Rep of S. Africa [2], USA[3], **Australia[7]**	Fertiliser, as essential nutrient in agriculture (no satisfactory substitute); also in detergents and water treatment. Phosphoric acid used in treatment of iron rust.
Platinum-group metals	Rep.of S Africa [1], Russia [2], Canada [3] USA[4].	Platinum-group metals (palladium, platinum, osmium, iridium, ruthenium, rhodium) are used mainly in catalytic applications; high melting point and corrosion-resistant applications; dies; electrical, electronic, dental and medical uses; jewellery. Substitutes include silver and gold.
Rare-earth oxides	China[1], FSU[b] [2], USA[3], **Australia [4]**, India[5].	Found principally in monazite in Australia; used in magnets, specialised steel alloys, as catalysts, colorants in glassware, TV screens, batteries, and electronic devices. Substitute source minerals include bastnaesite, xenotime, phosphorites, apatite, and spent solutions from uranium extraction.
Silver	**Australia [1]**, Canada [2], Mexico [3], USA[4], Peru[5].	Jewellery, photographic paper and films, plating on tableware, mirrors, dental applications, and coinage. Substitutes include stainless steel, aluminium and rhodium, tantalum and gold in certain applications.
Tantalum	**Australia [1]**, Nigeria [2], Zaire [3], Canada [4].	So-called superalloys, capacitors, corrosion-resistant equipment and high-temperature applications. Substitutes include aluminium in electronic capacitors, titanium, zirconium and platinum in corrosion-resistant equipment, and tungsten in high-temperature applications.
Tin	China[1], Brazil[2], Malaysia[3], Thailand[4], **Australia[9]**.	Tin plate for food packaging, solder for use in electonics, and in bearing alloys. Substitutes include glass, aluminium, and plastics for containers and cans.
Tungsten	China [1], Canada[2], Russia[3],USA[4].	Light-globe filaments; may not be easily substituted. Tungsten carbide inserts are a major component of cutting tools. Substitute cutting materials include ceramic and ceramic–metallic composites.
Uranium	**Australia[1]**, Kazakstan[2], Canada[3], South Africa[4].	Fission material in nuclear power reactors. Thorium is a possible substitute.
Zinc	**Australia [1]**, Canada[2], USA[3].	Galvanised zinc coatings for iron and steel, diecast alloy products, pigment, and as zinc oxide in rubber manufacture. Substitutes include plastics, aluminium and magnesium in diecasting.

[a] Source: Mineral Commodity Summaries, 1997; US Geological Survey (February, 1997); Australia's Identified Mineral Resources, 1996 (BRS 1997).

[b] FSU—Former Soviet Union (USSR).

[c] Estimates by BRS designated by question marks.

deposits of the Robe River area.

Australia currently produces about 14% of world output and is the world's second largest exporter of iron ore after Brazil, its main customers being Japan, China and South Korea. Between 1976 and 1996 inclusive, Australia produced approximately 2193 Mt of iron ore, principally from the Hamersley Basin in the Pilbara region of Western Australia. There is relatively minor production also from the Middleback Ranges and the Savage River magnetite mine in northwestern Tasmania.

For the foreseeable future, Australia's iron ore industry will continue to be based on iron-enriched BIF and palaeochannel resources. In the future, there may be scope for the recovery of iron from unenriched BIFs in the Hamersley Basin. The tonnages of these are vast and their grade is about 30% Fe, which is similar to that mined in some countries.

Manganese ore. In 1996, Australia's EDR of manganese ore were 118 Mt. Based on contained manganese, Australia has about 8% of world EDR and ranks third after South Africa (52%) and the Ukraine (19%).

Australia produced 10% of world manganese ore output in 1996 and was the second largest exporter after Gabon, having displaced South Africa for the first time in 1993. The principal mine and resources are on Groote Eylandt, Northern Territory, and there is smaller scale production from mines in the Woodie Woodie area, in the Pilbara region of Western Australia.

Australia's resources of manganese ore support a significant export industry and significant domestic ferromanganese, silicomanganese and manganese dioxide processing. Manganese alloys are produced for domestic use and export at Bell Bay, Tasmania. In all, over 80% of annual ore production is exported.

Mineral sands: titanium minerals and zircon. Australia has extensive mineral sand deposits, in which the minerals of economic interest are ilmenite, rutile, zircon and monazite. Based on BRS and US Bureau of Mines data, Australia's EDR are estimated at 135 Mt of ilmenite, 14.9 Mt of rutile, and 21.4 Mt of zircon. These constitute 23% of world EDR of ilmenite, 36% of rutile, and 35% of zircon, the highest in the world for all three minerals. Western Australian deposits have about 50% of Australia's rutile and zircon and over 70% of the ilmenite, while deposits in the east host the remainder. Monazite is discussed below, under ***rare earths***.

Of Australia's total EDR of rutile and zircon, about 30% and 34%, respectively, are unavailable for mining, being mainly in national parks in Queensland and New South Wales.

Australia is the world's largest producer and exporter of alluvial ilmenite, rutile and zircon and its mineral sands industry is currently expanding on expectation of forecast growth in demand for titanium dioxide pigment, the principal end-use for ilmenite and rutile, and on the strong growth in demand for zircon by the ceramics industry. In anticipation of forecast increased prices, current operators have returned to full production and a new operation is underway at the Beenup mine in southwest Western Australia. Several deposits near Ivanhoe in southwest New South Wales and east of Ouyen in northwest Victoria, and the Goodicum ilmenite deposit near Monto in Queensland are currently under investigation.

In addition to developments in mining, there has been strong development in value-added products, in particular, synthetic rutile and titanium dioxide pigment. Australia is the world's largest producer of synthetic rutile. Over half the ilmenite mined in Western Australia is upgraded to synthetic rutile in four plants located in the State. Two zirconia plants operate in Western Australia, producing zirconium chemicals and high purity zirconia.

Australia's consumption of mineral sands is very small and the bulk of production is exported. About 2000 t/yr of rutile is used in coatings for welding rod electrodes and about 10–15 000 t/yr of zircon is used in the form of 'sand' and 'flour' at foundries, and in refractory and ceramic products.

Subeconomic resources of about 50 Mt of contained titanium occur in hard rock titaniferous magnetite deposits, mainly in Western Australia.

Black coal. In 1996, Australia's recoverable EDR of black coal were 49 000 Mt, about 7% of the world's recoverable EDR. This ranked Australia sixth behind the USA, former USSR, China, India, and South Africa. Relative to most coal from other countries, Australian black coals have the advantages of low sulphur (generally 0.3–0.8% S, which means less potential acid rain production) and high energy content (less greenhouse gas production per unit of energy).

Of Australia's in-situ black coal EDR, 44% is in the Sydney Basin of eastern New South Wales and 34% in the Bowen Basin of central Queensland. Relatively small, but locally important, EDR of black coal occur in South Australia, Western Australia and Tasmania. Some 40% of Australian in-situ black coal EDR is amenable to open-cut mining.

Australian black coal resources are mined for both domestic and export markets. In 1996, Australia was the sixth highest producer of saleable black coal in the world, producing approximately 5% of total output. In 1994–95, 72% of Australia's raw black coal production came from open-cut operations. Coking coal contributed 55% of export tonnages. Thermal coal exports are expected to continue to rise as new mines are established and expansions occur at existing mines to meet projected higher demand, particularly from Asian countries.

The greatest potential threat to the Australian export coal industry's future lies in the development of responses by countries to the greenhouse issue. However, there are opportunities for wider use of Australia's valued low-sulphur coal and clean coal technologies.

Brown coal. Australia has very large resources of brown coal in the Latrobe Valley in the southeast corner of the continent, where industrial development and electrical power requirements are concentrated. Brown coal is not commonly exported, principally because of its lower calorific value, and is used mainly for domestic power generation in Victoria.

In 1996 Australia's EDR of brown coal were 41 000 Mt, about 14% of the world's recoverable EDR. This ranked Australia third behind the former USSR and Germany. Australia's substantial resources of brown coal are mainly in the Latrobe Valley of east Gippsland, which has 94% of EDR. In 1996, Australia produced about 53 Mt of brown coal, approximately 5% of world output, making it the seventh largest producer. For the foreseeable future, Victoria will remain the only brown coal producer in Australia.

Shale oil. Australia has vast resources of shale oil, mainly under shallow cover in eastern and central-western Queensland. The demonstrated resources are currently all classified as subeconomic, but this situation will be assessed in the light of the results of a demonstration plant under construction at the Stuart project near Gladstone in eastern Queensland. Stage 1 of the Stuart shale oil project will be the construction of a 4500 barrels/day research and development facility, which is to provide information for optimum operation of a full commercial module, to be followed by a full commercial plant comprising five more processing units.

Uranium. The OECD Nuclear Energy Agency (OECD/NEA) international scheme for uranium resources classification is somewhat different from that used by BRS for other mineral commodities, particularly in that it specifies cost categories. The low-cost resources category of this scheme—Reasonably Assured Resources (RAR) at less than US$80/kg U—is considered here to be 'EDR' because, while the uranium price has been well below US$80/kg U for some time, most of Australia's resources in this category could be recovered economically at prevailing prices.

Australia has the world's largest 'EDR' of uranium, approximately 28%. Other countries which have reported large resources of low-cost RAR include Kazakhstan (20%), Canada (17%), South Africa (9%), Brazil (7%) and Namibia (7%) (OECD/NEA & IAEA 1998). The Russian Federation and Uzbekistan also have large low-cost uranium resources, which, as yet, are not fully categorised into the OECD/NEA scheme. Australia's 'EDR' have increased from 8200 t U in 1967 to 622 000 t U in 1996. Most of its resources are in a group of deposits discovered between 1969 and 1975 (McKay et al. 1995). The continued growth of low-cost resources during the 1980s and 1990s was the result of ongoing reassessment and the delineation of additional resources at these deposits.

Olympic Dam in South Australia is one of the world's largest deposits of uranium, and accounts for more than 60% of Australia's low-cost resources. Unconformity-related uranium deposits in the Alligator Rivers region of the Northern Territory (Ranger, Jabiluka, Koongarra), and in the Rudall River area of Western Australia (Kintyre), constitute more than 20% of Australia's resources. The remaining resources are in calcrete deposits in Western Australia (Yeelirrie, Lake Way) and a number of sandstone deposits, including Westmoreland (Queensland), Beverley and Honeymoon (South Australia).

World uranium production declined progressively from the late 1980s to 1994 in response to massive oversupply, but production has started to pick up again and prices have increased. Uranium oxide is currently produced domestically at two mining/milling operations, Ranger and Olympic Dam. Australia's total production for 1996 was a record 4975 t U, making it the second largest uranium producer with 14% of world production. Canada maintained its leading position in 1996 with 32% of world production, while Niger with 9% was the third largest producer (Nukem 1997).

Since its election in March 1996, the Australian Liberal/National Party Coalition Government has made a number of changes to Commonwealth Government policies relating to uranium mining, including removal of the former Government's 'three mines' policy and relaxation of the guidelines for foreign investment in Australian uranium mines. These changes, together with an improved outlook for the uranium market, have resulted in proposals to develop new mines at Jabiluka (Northern Territory), Kintyre (Western Australia), Beverley and Honeymoon (South Australia).

Furthermore, production from Ranger has been increased and Olympic Dam is planning to almost treble production by the end of 1999. The Jabiluka deposit is set to be developed as an underground mine and it is proposed to process the ore at the Ranger mill. Beverley and Honeymoon are being considered for in situ leaching operations.

With these developments, Australia's annual production is likely to increase from its present level of 4975 t U (for 1996) to approximately 11 190 t U by the year 2000.

Gold. Australia's high standard of living in the late 19th century was very much a function of wealth generated during the first gold rushes, when mining was widespread. From 1851 to 1900, the main production was from Victoria (1885 t), Queensland (371 t), New South Wales (355 t) and Western Australia (165 t).

Following an extended period when gold output stagnated as a result of years of depressed prices, Australia's latest gold rush started in earnest in 1980, in response to rapid price increases and development of low-cost carbon processing technologies. EDR rose from 342 t in 1982 to a record 4454 t in 1996.

Australia now has about 9.5% of world EDR (as estimated from BRS and U.S. Geological Survey statistics), the third largest EDR of all countries, behind South Africa and the USA. Some 61% of EDR is in Western Australia. Queensland, New South Wales and the Northern Territory have similar EDR, together amounting to 25% of the total. The remaining EDR occur in Tasmania, Victoria, and South Australia.

From a base annual production of 15–20 t through the 1970s, gold increased to 289 t in 1996, mirroring the strong growth in resources. This means that Australia now ranks third in production—up from sixth in 1986—and currently accounts for about 12% of world output.

Gold is produced in all States and the Northern Territory, overwhelmingly from hard rock deposits. Western Australia dominates production, accounting for well over half the total. The main mines are in the Archaean Yilgarn Block and these are essentially gold-only deposits. Important discoveries in recent years include Boddington, Plutonic, Bronzewing, Kanowna Belle and Yilgarn Star. Telfer, in Proterozoic rocks in the eastern Pilbara region, is also a major mine.

Continuing additions to gold resources, which are more than compensating for ongoing high levels of production, are attributed to exploration successes resulting from substantial expenditure on gold exploration. In 1995–96 ABS statistics show that 57% of all mineral exploration expenditure was directed at the search for gold. Some 450 companies have had direct exploration or production interests in gold in Australia in recent times.

Copper. Copper was one of the earliest commodities mined in Australia, following discoveries in the 1840s at Kapunda and Burra in South Australia, with Australia becoming one of the world's leading producers of copper in the mid to late 1800s.

Australia's EDR of copper in 1996 were estimated at 23.6 Mt, the third largest in the world. The main resources are in the Mount Isa and Ernest Henry deposits in Queensland, Olympic Dam in South Australia, Northparkes in New South Wales and the Mount Lyell deposit in Tasmania. Production at Mount Isa has increased since the opening of the Deep Copper mine in 1994.

The eastern part of the Mount Isa Block is emerging as a significant copper–gold province with the operation of the Selwyn, Osborne, Ernest Henry, and the Eloise mines. Another emerging copper–gold province is in central New South Wales, where the large Northparkes mine is operating, the substantial Cadia deposit is under construction, and additional resources near the Girilambone mine are being evaluated. Other significant copper resources are in Palaeozoic volcanogenic massive sulphide deposits in eastern Australia (although these have generally lower copper:lead+zinc ratios than many deposits of this style in other countries), deposits in the Cobar region of central-western New South Wales, and the Archaean Scuddles deposit in Western Australia. Significant copper resources also occur at the Nifty copper mine in Western Australia and at the Mammoth mine near Mount Isa.

Mine production of copper in 1996 was 0.5 Mt, sixth largest in the world. A major expansion is planned to increase production at Olympic Dam to 200 000 t per year of copper metal by the year 2000.

Lead, zinc and silver. Australia has been a major exporter of lead, zinc and silver since mining began at Broken Hill, in western New South Wales, over a century ago.

In 1996, Australia's EDR for lead, zinc and silver were 18.7 Mt, 39.9 Mt and 43 300 t respectively, the world's largest for each of these metals.

Major recent additions to identified resources have been in the Mount Isa Block of northwestern Queensland, where mining and concentrate production are underway at the unusually silver-rich deposit at Cannington. A decision has been made by Pasminco to mine the large Century deposit, northwest of Mount Isa, with production beginning in late 1999. The Dugald River zinc-rich deposit northeast of Mount Isa continues to be evaluated.

Development work is proceeding at the George Fisher lead–zinc mine (Queensland), which is accessed underground from the Hilton mine. At Mount Isa, Mount Isa Mines Ltd reduced their ore reserves of zinc–lead–silver by 6.6 Mt as a consequence of production and downgrading of resources after reappraisal of the mining plan.

At Rosebery (Tasmania) work is focusing on upgrading confidence in inferred resources of 5.5 Mt in the deeper parts of the mine.

Final feasibility and underground reconnaissance studies of the Blendevale deposit in northwest Western Australia began in April 1996. The $20 million study is addressing the mining of 1.5 Mt of ore per year to produce concentrates containing about 100 000 t of zinc and 29 000 t of lead.

Exploration continues for base metals in the Pilbara region of Western Australia, where two new small to medium sized deposits have been delineated at Sulphur Springs and Salt Creek. Added to the known deposits at Mons Cupri and Whim Creek, these enhance the prospectivity of the region.

Australia's 1996 mine production of zinc, lead, and silver was 1.07 Mt, 0.52 Mt and 1013 t, respectively, ranking it first in the world for lead, second for zinc, and fifth for silver. Production is mainly from the very large stratiform deposits at Mount Isa and Cannington in Queensland, McArthur River in the Northern Territory, and Broken Hill, NSW.

Development of the ISAMILL fine-grinding technology for liberating fine-grained ore minerals was a key factor in enabling mining to proceed at McArthur River in 1995, some 40 years after discovery of the deposit. There is production also from the Elura deposit, NSW, and the volcanogenic massive sulphide deposits at Hellyer and Rosebery in Tasmania, and Scuddles in Western Australia.

About 80% of Australia's mine production of lead is processed to either lead bullion or refined metal, whereas less than 50% of zinc mine production is refined locally. Most of the silver mined is exported in other metals (e.g. lead bullion) or other metal concentrates. Silver production at the Kidston gold mine should be maintained into the next century by the new Eldridge gold–silver resource. The primary lead refinery located at Port Pirie, South Australia, is the largest in the world; lead is also smelted at Mount Isa and at Cockle Creek, New South Wales. Zinc is refined at Port Pirie, Cockle Creek, and at Risdon in Tasmania, which is one of the largest zinc refineries in the world.

Nickel. Australia's nickel EDR have grown dramatically since the 1966 discovery of nickel at Kambalda, Western Australia, from virtually nil to 6.4 Mt in 1996. A 70% increase in 1996 over 1995 in EDR reflects successful exploration and reclassification of some resources, following improved nickel prices. Australia's share of EDR now stands at 13%, third largest in the world after Cuba and Russia, having for the first time displaced Canada for that position.

About two thirds of the EDR are in sulphide deposits in Western Australia, where there was a mini-nickel boom in late 1995 and 1996. Australia's sulphide deposits occur in komatiitic dunites and peridotites. Nickel deposits hosted by dunites include the major low-grade disseminated resources at Mount Keith, Yakabindie and Honeymoon Well. Nickel resources hosted by peridotites and adjacent to sulphidic sedimentary/tuffaceous strata include the deposits of the Kambalda field and at Leinster.

Nickeliferous laterite makes up 37% of Australia's EDR. Most of these laterite resources are located in the Archaean Yilgarn Block of Western Australia, where the main deposits, Murrin Murrin, Cawse and Bulong, are under development. Minor lateritic resources occur in central north Queensland.

Australia produced about 110 000 t of nickel in 1996, about 11% of the world's annual mine output of nickel, and was ranked third behind Russia and Canada. Most nickel mined in Australia is processed to smelted and refined forms domestically, making it a substantial value-adding industry. Smelting operations are located at Kalgoorlie, and refineries at Kwinana, Western Australia, and Yabulu, Queensland. The industry also produces significant copper, cobalt and platinum-group metals as by-products.

Major expansion and revitalisation are based on the expectation of market growth, and have been spurred on by the discovery of high-grade nickel mineralisation at Silver Swan, northeast of Kalgoorlie, which commenced production in mid 1997. Three projects in Western Australia, Murrin Murrin, Cawse and Bulong lateritic deposits, with production of 9000–45 000 t of nickel per year, are scheduled to come on stream in late 1998. A variety of processing plants will be used at these new projects, including pressure acid leaching, ammonia leaching and bacterial leaching. Other projects at Yakabindie, Maggie Hays and Honeymoon Well are at an advanced stage of planning.

Cobalt. In Australia, cobalt is principally recovered as a by-product of nickel operations. Australian economic demonstrated resources are estimated at about 414 000 t, 10% of world resources and third largest in the world after Zaire and Cuba. Cobalt resources increased by 150% in 1996, as a result of reassessment and additions from nickel and copper deposits in Western Australia and Queensland. Production has decreased since 1992, with the closing of the cobalt-rich Greenvale lateritic nickel deposit in Queensland. Planned by-product output at the Ernest Henry copper–gold deposit near Cloncurry should significantly bolster cobalt production. Production is also planned at the Yakabindie nickel sulphide deposit and the Murrin Murrin lateritic nickel deposit in Western Australia.

Tantalum and lithium. The Greenbushes pegmatite in southwestern Western Australia contains most of Australia's EDR of tantalum (8057 t Ta) and is the source of most of the tantalum production, which is exported for use in high-strength alloys with high-temperature and corrosion-resistance properties. Australia has the world's highest EDR of tantalum, with about 30% of the world total, and Greenbushes is the world's largest tantalum deposit. Other important resources occur in Western Australia, at the Wodgina project in the Pilbara district.

Greenbushes also contains Australia's only EDR of ***lithium,*** and is the country's only lithium producer. Australia is estimated to have approximately 8% of world EDR, fourth after Chile, USA and Canada. Its production in 1996 was the second highest in the world after Chile, with about 27% of world output (excluding the USA, where production data are withheld), followed by Canada. Spodumene (lithium-bearing) concentrate from Greenbushes is mainly exported for use in container glass and ceramics. A plant is being built at Greenbushes to produce lithium carbonate for use in ceramics, specialty glass, aluminium smelting, and continuous casting of steel.

Magnesite. World primary magnesium consumption growth has risen to around 15–20% per year in recent years, its superior weight saving properties (33% lighter than aluminium) making it increasingly attractive, particularly for use in automotive applications. Demand for magnesite and magnesia products has also grown. Australia has 2% of world EDR of magnesite and ranks fourth. Other sources of magnesium include magnesium-rich salt deposits and brines. These are widespread worldwide, but the cost of extraction and access to markets means that none is economically viable in Australia.

Australia is well positioned to take advantage of increases in demand for high-grade magnesite resources. Significant production of magnesite has occurred in Australia since 1990 and annual production has increased strongly to about 300 000 t of beneficiated high-grade magnesite in 1996. This has been mainly from the 1.2 billion tonne deposit at Kunwarara in central eastern Queensland, where magnesite ore is being processed to dead-burned magnesite and electrofused magnesia. In addition, there has been significant magnesite production from Thuddungra in southeastern New South Wales. Large deposits of magnesite also occur near Savage River in northwest Tasmania and at Huandot near Woodcutters, in the Northern Territory.

In 1997, Queensland Metals Corporation (QMC) and Normandy Mining Ltd, through a 50/50 joint venture company, Australian Magnesium Investment Pty Ltd, announced plans to build a magnesium smelter with a 90 000 t per annum capacity at Gladstone, which will use a process developed by CSIRO.

Although Australia accounted for only 2% of the world's

EDR of magnesite ore in 1996, the Kunwarara deposit is still the world's largest known resource of cryptocrystalline, nodular magnesite.

Diamond. Until the 1970s, Australia had been considered poorly endowed with diamond, because only very small quantities had been won from time to time from placer deposits, mostly near Copeton in New South Wales. This changed in the 1970s with the discovery of diamonds at several places in the Kimberley region of northwestern Western Australia. Diamonds were found in numerous lamproite pipes at Ellendale and, later, in the Argyle lamproite and other diatremes, and in alluvial deposits in the Smoke Creek and Limestone Creek drainage systems near Argyle.

The AK1 lamproite pipe at the Argyle deposit contains virtually all of Australia's diamond EDR, and a significant percentage of world EDR of industrial diamonds. In 1996, Australia's diamond EDR were estimated at 175 million carats, one of the highest of any country. Australia currently ranks near the top in gem/near gem EDR with over 25% of the world's EDR, based on previous world estimates. Australia had 16% of world industrial diamond in 1996 to rank third behind Zaire and Botswana. Australia's EDR of both categories of diamond are falling as a result of production at Argyle, where there is large-scale open-pit mining. A feasibility study of an underground operation below the open pit has been completed and other options are also being assessed.

Argyle has been a substantial producer since 1983 and produces virtually all Australia's diamond. Its relatively low proportion of gem quality stones (about 2.5% gem, 52.5% near gem, and 45% industrial grade stones) means that Australia's total value of production is less than for several other diamond producing countries, including South Africa and Russia. The presence of rare, high-value dark-pink diamonds at Argyle partly compensates for the low percentage of gem quality stones. In 1996, Australia was the largest producer in the world of both natural industrial diamond and gem/near-gem diamond, with a combined production of 42 million metric carats.

The small Bow River alluvial diamond mine, 30 km northeast of Argyle, closed in 1996. Relatively small resources of alluvial diamond, derived from the Argyle deposit, are being worked at the nearby Argyle Alluvials operation. Minor production commenced at Copeton in northeastern NSW during 1997.

Diamondiferous kimberlite pipes in the Merlin cluster, eastern Northern Territory, are being developed and other pipes at Coanjula to the south of Merlin are under evaluation. The small known resources of diamond in the Ellendale area and other pipes west of Argyle are presently subeconomic.

Opal. Opal is an amorphous hydrated form of silica, in which a variable proportion of water is chemically bonded within the structure. Opal's characteristic play of colours is caused by regular layers of silica spheres diffracting light. The opal formed as a result of silica mobilisation in the Tertiary Period, during extensive weathering of Cretaceous sediments in the Great Artesian Basin and older rocks around its margin. Impermeable clay lenses, cavities and fossils formed favourable sites for precipitation of opaline silica.

Australia is the world's leading producer of opal, which is used solely for jewellery, accounting for some 95% of world natural opal production. The resources in the known opal fields in South Australia, New South Wales and Queensland, although not quantified, are very substantial and should sustain the industry at current production rates for at least 50 years.

Sapphire. Until 1988, Australia supplied up to 70% by volume of the world's sapphire, mainly small dark-blue stones from alluvial mines in the Inverell–Glen Innes area of northern New South Wales and the Anakie–Rubyvale area of central Queensland. For the past 20 years or so most of the output has been sold to Thai dealers for heat treatment and faceting for jewelry. Since 1987, there has been a major increase in production from Thailand, Nigeria and China and most recently from Sri Lanka and Tanzania, and Australia's market share has decreased to approximately one-quarter of world supply. With the shallow, richer alluvial deposits being worked out, future resources will be increasingly in deeper, lower grade alluvials in known gemfields and in poorly consolidated volcaniclastic source rocks.

Mineral commodities for which Australia has significant resource stocks

Tin. In the past decade, tin has been of relatively minor importance in the Australian mineral industry, largely because of the collapse of the tin price in 1985, a lack of high-grade deposits and the low cost of production of ore in other major tin-producing countries. In 1996, Australia's EDR of tin were 119 490 t, less than 2% of world EDR. China, Brazil, Malaysia, Thailand, and Indonesia dominate world EDR, whereas China, Indonesia, Brazil and Bolivia are the major producers of tin.

Australia's EDR for tin are dominated by the world-class carbonate-replacement deposit at Renison Bell in Tasmania. Definition of resources underlying current underground operations at this mine is largely responsible for the increase in EDR over recent years. The decision to proceed with development of the deep resources has increased the expected mine life from 5 to 12 years, during which time it is expected that Renison Bell will continue to be the major producer of tin concentrates in Australia.

In north Queensland there has been minor production recently from some of the numerous alluvial deposits in the historical tin mining region around Mount Garnet. In Western Australia there is a significant resource of tin at the Greenbushes mine, where it is produced as a by-product of tantalite mining. The Greenbushes operation is the sole smelter of tin in Australia.

Tin demand has suffered and prices fallen because of substitution by aluminium and steel for tin-plated cans for beverages and food. Since 1993, there have been small improvements in both the level and stability of tin prices, but further rises will be necessary before Australia's EDR of tin increase substantially.

Tungsten. Australia was an important western world tungsten producer until the mid to late 1980s. The King Island (Tasmania) and Mount Carbine (Queensland) deposits were formerly among the ten largest known western world tungsten orebodies. Most mines closed because of depressed prices driven by oversupply. Small quantities of tungsten, in scheelite concentrate, continue to be produced at the Kara mine near Burnie, Tasmania, as a by-product of magnetite mining for coal washeries.

Currently China and Russia dominate world tungsten, both in production and EDR. Australia's EDR of tungsten are very small, but demonstrated and inferred subeconomic resources are still quite large and amount to about 11% of the world total. They occur at Mount Mulgine northeast of Perth, Western Australia, on King Island, and at Mount Cleveland in Tasmania, Torrington in New South Wales, Mount Carbine and Wolfram Camp in Queensland, and Molyhill in the Northern Territory.

Phosphate. Phosphate is one of the main nutrients essential for plant life. As Australian soils are generally nutrient poor, fertilisers are used extensively in agriculture to enhance productivity. The Australian mainland has produced little phosphate in the past because of a hitherto lack of an economic resource.

The recent proving of the commercial feasibility of the previously uneconomic phosphate resources at Phosphate Hill, 70 km south of Duchess, in northwest Queensland, has taken Australia from having virtually no economic phosphate resources to a country with sufficient EDR to rank seventh in the world. Australia's EDR of phosphate are about 1% of the world's total economic resources of 11 000 Mt.

Australia's EDR of phosphate total 103Mt of phosphate rock at an average grade of 23.4% P_2O_5, all located at Phosphate Hill. The Phosphate Hill deposits form part of a much larger resource totalling some 2000 Mt of phosphate rock, the bulk of which is classified as economically paramarginal. The phosphate occurs as sedimentary phosphate rock beds (phosphorites) within the Cambrian Georgina Basin.

In late 1996, WMC announced that the company would proceed with the development of mining and processing facilities at Phosphate Hill to produce 1 Mt/yr of high-analysis ammonium phosphate fertilisers at a cost of $650 million. Production is expected to commence in late 1999. Sulphur dioxide gases from MIM's copper operation at Mount Isa will be captured and converted to acid for use in the phosphate processing operation.

Rock phosphate is exported from Christmas Island, an Australian Indian Ocean territory. In Western Australia, a subeconomic resource of phosphate occurs in the regolith of a carbonatite at Mount Weld, southeast of Laverton.

Rare earths. Australia has the world's largest EDR of alluvial monazite in mineral sand deposits, the second most important source of rare-earth oxides after the giant cerium-bearing bastnaesite deposits of China and the USA. Monazite contains cerium and yttrium as well as thorium. No monazite is produced in Australia, but a plant to extract rare earths from monazite is proposed for Pinjarra, Western Australia, with the capacity to produce 1500 t/yr of rare-earth nitrates.

Several alkaline rock deposits in Western Australia, at Brockman, Cummins Range and Mount Weld, are potential sources of rare earths. Mount Weld is a carbonatite pipe with particularly high grades of Ce and Nd developed in the regolith; the resource amounts to 1.3 Mt at 23.6% total rare earths.

Other resources of rare earths include the Olympic Dam copper–uranium–gold deposit in South Australia, and uranium tailings from Mary Kathleen in northwestern Queensland, and Mount Painter in South Australia.

Silica. Australia has considerable, but unquantified, resources of silica, mainly as quartz sand. Australian output of silica (excluding construction sand and aggregate) is in the order of 3.0 Mt/yr. Of this, about 2.5 Mt/yr is exported as sand, mostly to Japan and principally from Cape Flattery in northern Queensland. Large quantities are also exported to Japan from two new deposits in Western Australia located near Kemerton and Mindijup, northeast of Albany. Silica for domestic use is also largely quartz sand, which is used mostly for manufacturing glass; lesser amounts are used for foundry sand, filter sand and other industrial purposes. About 250 000 t/yr of hardrock silica (quartzite) is quarried for steel industry flux or for manufacturing ferrosilicon and silica manganese alloys.

Mineral commodities for which Australia has limited resource stocks

There are several mineral commodities for which there are minor or no EDR. Notable amongst these are chromium, molybdenum, platinum-group metals, potassium (a major nutrient used in fertilisers), and sodium salts.

Potash. Potash is exploited from certain types of salt deposits. Australia has no known economic potash resources and imports potassium chloride and sulphate from Canada and USA.

Sulphur. Sulphur is required mainly to make sulphuric acid for use in phosphatic fertiliser manufacture, metallurgical operations and in general chemicals. There are no commercial deposits of elemental sulphur or sulphur-bearing sour gas known in Australia, and about three-quarters of demand is met by imports, mainly from Canada. Australian refineries recover some sulphur from imported petroleum and there is some acid production from metallurgical plants treating sulphide ores.

Sodium carbonate and sulphate. Trona and other sodium carbonate minerals are widely used, particularly in glass, the chemical industry, soaps and detergents, water treatment, pulp and paper. Sodium sulphate is also used in detergents, pulp and paper, and glass.

Australia does not have EDR of these sodium minerals. There are some sodium carbonate brines in the Denison Basin of Queensland, but these cannot be recovered economically. Pseudomorphs after trona and other sodium carbonate minerals occur in the Officer Basin of South Australia, but it appears that all the original sodium salts have been dissolved out of the strata.

Chromium. Australia has no EDR of chromite. There are subeconomic resources in Western Australia, in layered intrusives at Panton and Lamboo in the Kimberleys, and Coobina in the Pilbara; in chromiferous laterites at Range Well in the northern Yilgarn region, and in New South Wales in polymetallic laterite at Syerston near Fifield. These are minor in world terms.

Almost all chromite used in Australia is imported for refractory and foundry uses, and most chrome alloy and chemical product needs are also imported.

Molybdenum. Australia has no EDR of molybdenum. Subeconomic resources, which are minor by world standards, occur mainly in Queensland, partly in association with uranium and partly with scheelite. The potential for future molybdenum production in Australia is expected to depend on the economics of recovering the metal as a by-product of mining other commodities.

Platinum-group metals. Platinum-group metals produced in Australia are a by-product of nickel operations and amount to only about 2% of world output. The EDR are contained in nickel deposits. Of the total EDR, about 26% is platinum, 47% palladium, and 27% other PGM.

There are significant inferred resources of platinum-group metals in intrusives in Western Australia, at Munni Munni and Mount Scholl in the Pilbara, at Panton in the Kimberley district, and in and beneath lateritic deposits at Range Well in the northern Yilgarn. Platinum-group metals also occur in the polymetallic lateritic deposits at Syerston and Fifield in New South Wales, and in association with uranium and gold at Coronation Hill and elsewhere in the Kakadu region of the Northern Territory. Exploration and mining are not permitted within Kakadu National Park.

Mineral commodities of the future

Using trends for this century as a broad guide, it has been forecast that every commodity mined today is still likely to have uses through the coming century (Skinner 1993). Although ceramics, glasses, polymers, composites, laminates and other materials will displace some metals from some present uses, the same metals are likely to find new roles and niches.

There will probably be relatively large increases in demand for light, strong materials, incorporating magnesium, titanium, zirconium, tantalum and carbon fibre. Platinum-group metals are likely to be required increasingly in a range of catalytic applications. Demand is also likely to increase for some speciality mineral commodities, including some rare earths and pure silica, for use in high-technology applications. Shale oil deposits are likely to be exploited increasingly as a source of oil in response to petroleum shortages.

As discussed in the previous section, Australia is fortunate in having large stocks of the source materials for most of these commodities, with the exception of the platinum-group metals.

Sustaining mineral production

The world's socioeconomic system is fundamentally dependent on the availability of mineral resources, which are required for housing, agriculture, power, communication, transport and lifestyle, and the demand is increasing for most mineral and energy commodities. This demand is not something which can be switched off—it is being driven as much by a burgeoning world population and the growing aspirations of people in the developing nations of the Asia–Pacific region and elsewhere as by high usage of resources in developed nations.

As the world population grows, there is increasing pressure on availability of land for supplying mineral commodities, food, water, housing and infrastructure, and for disposing of waste. There are also simultaneous pressures to protect the environment, commonly by setting aside considerable areas as reserves where most human activity, including exploration and mining, is prohibited or severely restrained.

Sustainable development requires social, environmental and development objectives to be in balance. The basic requirements for sustaining mineral production to meet global demand are:

1. adequate stocks of the mineral commodities that will be required in the future; and
2. ongoing access to land for exploration and mining of additional resources to replace those being worked now.

Skinner (1993) has documented how, with the world population increasing rapidly, access to land for specific competing or complementary uses is becoming an increasingly important consideration. The area available for supplying mineral commodities, food, water, housing and infrastructure, and for disposal of waste is decreasing rapidly.

Australia is almost unique amongst all the developed countries in that its economic growth and development have been sustained for much of the past 150 years by its primary industries, particularly in recent decades by the minerals and energy sector for a significant proportion of its GDP and export revenue. Up until now, there have been few signs that, compared with other western world economies, Australia's reliance over such a long period on the minerals sector, in conjunction with the manufacturing and services sector, is a cause for concern.

How long will Australia's mineral resources last?

Predictions of how long mineral resources will last are difficult because the magnitude and distribution of undiscovered mineral resources is never fully known, and we can only make meaningful predictions of demand for particular mineral commodities for a short time into the future. Even allowing for these uncertainties, no significant shortages of Australia's main mineral commodities are indicated in the foreseeable future.

The trend over time in the level of EDR for individual commodities has been used as a guide to longevity of mineral resources. The stable or increasing long-term EDR trends for all major commodities in Australia (Fig. 2) are similar to global trends reported by the U.S. Geological Survey (1996). Identified resources (IR), or our total stock of known resources (including the subeconomic), have also been rising over this period and are currently more than twice the level of EDR (BRS 1997). This means that the rate of replenishment of resources through mineral discoveries, both in Australia and globally, has at least kept pace with the rate of depletion of resources by mine production. But such trends, in isolation, do not provide a reliable indication of how long this situation will persist.

Trends in the ratio of EDR to annual production indicate the length of time that mining of the current economic resources could continue at current production rates. Data for major Australian mineral commodities are included in Table 2. Many commodities have high ratios: those more than about 40 years include bauxite, black coal, iron ore, magnesium, manganese, mineral sands, nickel and uranium. Because the addition of new resources through exploration and discovery is at least keeping pace with resource loss from production, this ratio should provide a minimum estimate of resource longevity. This is clearly indicated for gold, for which Australia's EDR to production ratio has remained at around 10–15 for the past 15 years or more.

Exploration is the lifeblood of the minerals industry. Analyses by the Bureau of Resource Sciences (Williams 1994) have shown a broad correlation between exploration expenditure for particular mineral commodities and the magnitude of additional resources discovered in the ensuing few years. Additionally, precompetitive geoscientific exploration data provided by governments leads to increased levels and intensity of private exploration expenditure in the areas covered. Overall, trends in exploration expenditure can provide an early indication of future trends in mineral resource stocks. Australia has been maintaining a healthy level of exploration expenditure, despite an increasing interest in exploration by domestic companies overseas, particularly in South America.

It was concluded by a select group of mineral economists and resource specialists in the mid-1980s that known world resources for most commodities are sufficient to last a further 100 years, with the possible exception of some energy materials (McLaren & Skinner, 1987). Nothing has arisen in the past decade to cast doubt on this assessment. There is a widely held view, emphasised by Skinner (1993), that it will be the environmental and social consequences of minerals use, rather than the size of the resource base, that will constrain the use of resources in the 21st century.

How can it be that mineral resource stocks are not being rapidly depleted, bearing in mind that the rate at which new deposits are forming is much slower than the rate of mining of minerals? After all, concerns about 'non-renewability' have led to predictions that the world is rapidly running out of many mineral commodities. Such predictions achieved prominence after a study by the Club of Rome (Meadows et al. 1972).

While mineral resources are not 'renewable' in the same sense as agricultural and fish resources, this does not mean that Australia's or the world's mineral resources will be exhausted in the foreseeable future, because:

- technical advances and lower costs mean that mineral resources can be recovered economically in progressively lower concentrations and from greater depths;
- the resources able to be recovered economically are a function of commodity prices. Perceived shortages would inevitably lead to price increases, which would mean that previously subeconomic identified resources would become economic;
- the identified resource base is large and there is considerable potential for discovery of additional resources, especially in regions and countries which have remained poorly explored;
- exploration is being made more effective by continuing improvement of the geoscientific knowledge base, including discovery techniques and technologies; and
- there is increasing recycling, substitution and efficiency of use of mineral commodities.

Importance of land access

The resource base for the mineral commodities required in the future is healthy, as far as we can judge. This is one key element of a sustainable minerals supply. The other key part of the sustainability equation is ongoing new discoveries at a rate needed to replace production. Sustaining high rates of mineral production to meet demand, with consequent revenue from the minerals sector, requires continuing access to large areas of land for exploration and to localised areas for mining.

The minerals industry now generally accepts that there should be some special areas where resource development should not occur. But continuing the trend to set aside large areas of other land for conservation, to the exclusion of other activities, is clearly not sustainable in the medium to long term. Wherever feasible, land-use decisions need to permit multiple and/or sequential use of land in a manner which integrates resource development with social and environmental objectives.

Exploration requires access to large areas of land because it is difficult to discover mineral deposits, which are small and distributed sparsely and irregularly, although not randomly, across Australia. Furthermore, many deposits will have no obvious surface expression, so discovering a significant mineral deposit is somewhat analogous to finding 'a needle in a hay stack'. The overall discovery rate in Australia is roughly one potential mine for every thousand exploration programs (Lacey 1973).

It is not possible to say with any authority that a given area has been fully explored or is barren of any economic mineral resources. Decision-makers have not commonly appreciated that the assessment of the mineral potential of any area needs continual revision to take account of new knowledge, models and

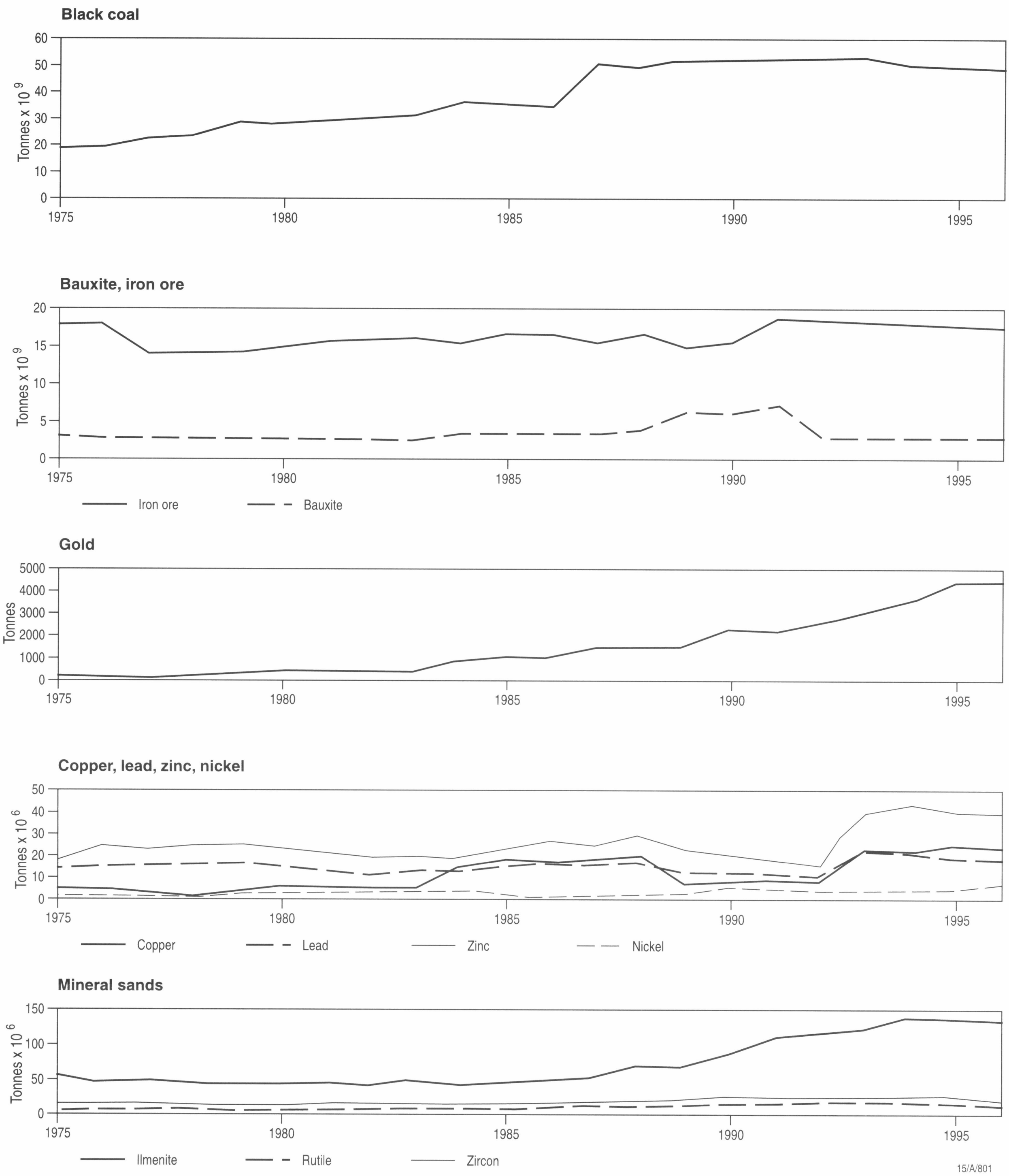

Figure 2. Trends in economic demonstrated resources (EDR) for major commodities since 1975. (Adapted from BRS 1997)

technology. As new information and understanding will increase or decrease the potential for particular styles of mineralisation, the minerals industry is anxious to be able to continue low impact exploration to gather geoscientific data in all but the most environmentally and culturally sensitive areas.

The industry has expressed concern about a marked increase in the area of land where exploration and mining are either prohibited or uncertain because of native title claims or possible extensions to the national conservation reserve system. It has acknowledged that proposed mines in potentially sensitive areas should be considered on a case-by-case basis and mining permitted only where detailed assessments show it would be very unlikely to have lasting adverse impacts on environmental, social and cultural values beyond the immediate mine site.

Furthermore, the minerals industry has expressed concern about sovereign risk, following several government decisions in the early 1990s which precluded mining in particular areas on environmental and cultural grounds; for example, Coronation Hill (Au–platinum-group metals, Northern Territory); Shoalwater Bay (mineral sands, Queensland); and Lake Cowal (Au, New South Wales). The urban sprawl above coal resources in the Campbelltown–Picton–Tahmoor area south of Sydney is an example of another type of constraint on land access for mining.

Responsible resource development is a temporary and localised land use which can coexist with a range other activities and be part of a sequence of uses for a particular parcel of land.

There are many examples of mined land being successfully rehabilitated and used for recreation, conservation or agriculture (BRS 1997a). With careful planning, resource development can also achieve environmental, recreational and other objectives.

The Bureau of Resource Sciences monitors and analyses trends in resource access and security through its TRACS decision-support tool (East et al. 1996).

Where are Australia's undiscovered mineral resources?

Most new mineral resources in Australia are likely to be found under the three-quarters of the continent that is covered by a veneer of deeply weathered material or sedimentary strata, particularly in extensions of known mineral provinces, and in regions that have been too expensive in the past for substantial mining operations because of their remoteness and difficult logistics. Exploration for concealed deposits is increasing in remote regions of central, northern and southern Australia, aided by advances in technology and understanding which assist target selection and also minimise the impact of exploration on the landscape, notably:

- detailed geophysical surveys and multi-spectral imagery, which help in the mapping of rock types beneath surface cover, and identify anomalies potentially related to the presence of mineralisation; and
- a greater understanding of the application of geochemical exploration in deeply weathered terrains.

Concluding remarks

Relative to current rates of production, Australia's known mineral resource base is very considerable. Its stock of economic mineral resources is of unequalled magnitude and quality across a broad range of important world traded commodities.

The presence of large, rich mineral deposits and the variety of prospective geological settings imply that Australia has considerable potential for discovery of new mineral deposits of a range of styles. Most future discoveries are likely to be in regions that have received little attention to date because they are remote or because geological units that could be considered prospective are limited in outcrop or concealed. Exploration is being aided by the latest technology and a sound and improving geoscientific knowledge base.

There is a small number of mineral commodities for which Australia currently has few or no demonstrated economic resources, including chromite, platinum-group metals, potassium salts, and sodium carbonate (trona).

If a trend to prohibit rather than regulate mining in areas with any significant environmental or socio-cultural values does not diminish, quarantining of mineral resources will soon begin to compromise the sustainable supply of mineral commodities.

Given widespread multiple or sequential land use, which accommodates responsible exploration and mining, Australia is very well placed to maintain its position as one of the world's leading suppliers of a wide range of mineral commodities. Even allowing for uncertainties in future demand and rates of discovery of new resources, no shortages of Australia's principal mineral commodities are indicated for the foreseeable future.

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