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# Known, absent and potential mineral deposit types in Australia

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## SUMMARY

Australia is in the top six global producers for a wide range of mineral commodities of abundant metals (Fe, Mn, Al, Ti), base metals (Ni, Cu, Zn, Pb), precious metals (Au, Ag), scarce metals (REE, Li, Sb), energy metals (U, Th) and industrial/ precious minerals (salt, diamonds, zircon). Australia also has a wide range of uranium deposit types but their future is controlled by government policy. There are very few mineral deposit types that are not present or minor in the Australian continent. These include PGE deposits in large layered intrusions and Witwatersrand-type gold deposits, Carlin-type gold deposits, low-sulfidation-type epithermal Au-Ag deposits, Zambian-type copper deposits and MVT deposits. For most of these, appropriate depositional environments are extremely rare or absent. The future of the Australian mineral industry will continue to depend on a combination of brownfield exploration in known mineral districts and greenfields exploration, increasingly under deeper cover, for deposit classes within these mineral districts. Craton margins that are intruded by basic and/or felsic magmas are particularly attractive tectonic targets. They will continue to be fertile exploration environments for IOCG deposits and intrusion-hosted Ni-Cu deposits, and submarine gold-rich porphyry-to-VMS systems may have been neglected as exploration targets in the past. The future potential for pegmatite-hosted lithium deposits is high.

**Key words:** Australia, mineral deposits, exploration targets

## INTRODUCTION

This concise review, adapted from Groves et al. (2017), covers the major mineral deposits in Australia, reviews important absentee deposit types and briefly comments on the potential for new deposit types and mineral provinces in Australia within ongoing exploration programs. The mineral deposit types are grouped hierarchically in terms of resource elements listed from abundant metals (Fe, Mn, Al, Ti, Cr) through base metals (Ni, Cu, Zn, Pb), to precious metals (Au, Ag, PGE) and scarce elements (REE, Li, Sn, W, Sb) to energy metals (U, Th) and industrial (salt, phosphate) and precious minerals (diamond, zircon). Important deposits are shown in Figure 1. The summary of Australian mineral deposit types with the most important mineral provinces and major examples of deposits is presented in Table 1 of Groves et al. (2017) and is not repeated here. The reader is referred to general references such as Solomon and Groves (2000), other papers in the Australian Ore Deposit monograph and Geoscience Australia and State Survey websites for primary data and deposit descriptions.

## ABUNDANT AND BASE METAL MINERAL DEPOSITS IN AUSTRALIA

Australia is a major global producer of iron ore with extensive resources and reserves, mostly from enriched late Archean- to early Paleoproterozoic-banded iron formations (BIFs). The major province is the Paleoproterozoic Hamersley Basin in Western Australia (WA), with numerous giant deposits such as Mt Whaleback and Mt Tom Price, and various others in the Newman and Paraburdoo districts. The Cretaceous Groote Eylandt manganese ores are examples of the global oolitic and pisolitic orthoquartzite-clay-Mn oxide association that includes the giant deposits of Nikopol in Ukraine and Chiatura in Georgia. Paleoproterozoic Mn deposits are mined at Woodie Woodie in the Hamersley Basin and from Bootu Creek in the Tomkinson Creek Province near Tennant Creek. Australia is the premier bauxite producer globally, with widespread deposits in WA, Queensland and the NT, where there has been temporally extensive and complex tropical to arid deep weathering. Precursor rocks range in age from Archean in the Darling Ranges of WA, through Proterozoic for the Mitchell Plateau, to Cretaceous for the deposits on the west coast of Cape York Peninsula, where the largest deposits are at Weipa and Gove. Australia is also the premier producer in terms of titanium and zircon from heavy mineral sands in modern beaches or beach placers in paleo-shorelines. Major deposits occur along the south-western coastline of WA at localities such as Eneabba and Capel. Deposits also occur along the eastern coastline of Australia from north of Sydney to Fraser Island, including those mined on Stradbroke Island, with inland examples in the Murray Basin. Chromite deposits are rather rare in Australia, mainly because of the lack of large layered intrusions of Bushveld proportions, although thin chromite seams are mined from Coobina in the Marymia Dome of WA.

Australia is a relatively small but significant nickel producer on a world scale. Most deposits are Neoarchean komatiite-hosted deposits of Ni-Cu with minor platinum group elements (PGEs) in the greenstone belts of the Eastern Goldfields of the Yilgarn Craton. These form the premier group of this deposit type globally, with large deposits widely spread in the terrane and major concentrations in the Kambalda, Forrestania and Mt Keith-Leinster nickel districts. There are enormous resources of lateritic nickel – currently largely uneconomic – in the highly weathered Yilgarn terranes. Intrusion-hosted deposits at Nova in the Fraser Range of the Albany-Fraser Orogen and Nebo-Babel in the Musgrave Province represent potential future mines. Internationally, Australia is a relatively small copper producer despite some very large examples of various deposit styles. These include the giant IOCG (iron oxide-copper-gold) deposit at Olympic Dam and smaller examples that include Prominent Hill, Carrapateena and Ernest Henry, all of Mesoproterozoic age. Giant SEDEX deposits of similar age are typified by the Mt Isa deposit in the Cloncurry-Mt Isa Province of Queensland. There are also porphyry Cu-Au

deposits associated with late Ordovician high-K volcanic rocks at Northparkes and Cadia in the Lachlan Orogen of New South Wales (NSW). The oldest porphyry Au-Cu-Mo deposit known globally is the giant Boddington deposit in a Neoarchean greenstone belt in south-western WA. Historically, VMS deposits have contributed to copper production, with the Mesoarchean deposits at Golden Grove in the Murchison Province of WA being the largest current producer. The recent VMS discoveries of DeGrussa and Monty in the Paleoproterozoic Bryah Basin in WA are probably the most copper-rich VMS deposits on Earth (over 5% Cu average grade with intersections up to 32% Cu). Mt Lyell in western Tasmania was a major producer. Finally, small deposits with affinities to the Zambian Copperbelt deposits are mined from the Paterson Province of WA, with the most significant being the Nifty deposit. Australia is a major zinc producer on the world scene. This relates to Australia's premier position in terms of Meso-Paleoproterozoic SEDEX deposits globally. The SEDEX deposits are sited predominantly in the McArthur Basin of the NT and the Mt Isa Province of north Queensland. McArthur River (HYC) is the major deposit in the former, with new discoveries at Myrtle and Teena. Century is the major deposit in the northern Mt Isa Province, with Mt Isa, Hilton and Dugald River being significant deposits in the south. Cannington, a Broken-Hill-type deposit on the south-eastern margin of the Mt Isa Province, is a significant Ag-Pb-Zn producer, although nowhere near as large as the Broken Hill deposit in NSW that helped shape Australia's mining future. Lesser zinc production comes from VMS deposits such as the Archean Golden Grove deposit in WA and the Cambrian Rosebery, Que River and Hellyer deposits in Tasmania. Australia is similarly a significant lead producer on a global scale. Lead and zinc generally occur together, so it is not surprising that the major producers are SEDEX deposits such as McArthur River and Broken-Hill-type deposits such as Cannington, with Broken Hill a major past producer. Of mainly academic significance are the Mississippi-Valley-type deposits of the Canning Basin in WA that include Cadjebut, Blendevale and Twelve Mile Bore, and the deep Admiral Bay deposit discovered during oil exploration.

## AUSTRALIAN PRECIOUS AND SCARCE METAL MINERAL DEPOSITS

Australia has been a major gold producer since the mid-19$^{th}$ century. The main deposit type has been orogenic gold with major provinces in Neoarchean greenstone belts of the Yilgarn Craton and the Paleozoic turbidite-slate belts of the Lachlan Orogen in Victoria. Other significant provinces include those of the Proterozoic Pine Creek Orogen in the NT and numerous provinces scattered along the Paleozoic Tasman Fold Belt in NSW and Queensland. Currently, the major producers are in the Archean Yilgarn Craton of WA where the telluride-bearing Golden Mile Au deposit at Kalgoorlie still dominates, although there are numerous major producers including Norseman, Kambalda-St Ives, Paddington, Lawlers, Agnew, Jundee, Sunrise-Cleo, Granny Smith and Wallaby. Although the giant Ordovician-Devonian Ballarat and Bendigo goldfields dominated production in the Victorian gold province, Fosterville is now the largest gold producer there. The Neoproterozoic Telfer gold deposit in the Paterson Province of WA may be a rare world-class example of an intrusion-related gold deposit. Gold is also produced from the relatively gold-rich Ordovician porphyry Cu-Au deposits at Cadia and Northparkes and from various VMS deposits including Rosebery (Cambrian) in Tasmania, Golden Grove (Archean) in the Yilgarn and DeGrussa (Paleoproterozoic) north of the Yilgarn. Boddington was originally mined for low-grade gold in lateritic bauxite but is now a giant hard-rock Archean porphyry Au-Cu-Mo mine. The Kidston gold-rich breccia deposit may also be affiliated with porphyry systems. Australia's role as a silver producer has decreased since the silver-rich Broken Hill deposit has drastically reduced production. The Broken-Hill-type deposit at Cannington in the Mt Isa Province is currently Australia's major silver producer, with by-product output from other SEDEX deposits, the IOCG deposits on the margin of the Gawler Craton and VMS deposits, particularly Rosebery in western Tasmania. Globally, Australia is a relatively minor producer of PGEs. There are thin, reef-like deposits in small, layered intrusions at Munni Munni in the Archean Pilbara Craton and PGEs have been recovered from alluvial deposits sourced from early Paleozoic Alaskan-type serpentinite lenses at Fifield in the Lachlan Orogen of NSW, and Os-Ir minerals were recovered from alluvial deposits at Adamsfield in western Tasmania.

Although dwarfed by China, Australia is a significant producer of rare-earth elements (REE). As for Ti, Zr and Th, there is significant production from beach placer deposits. There are also large REE concentrations in the Mt Weld carbonatite and at the Olympic Dam iron oxide copper-gold deposit. Most of the world's lithium resources are in evaporites and brines in South and North America. In terms of pegmatite-hosted deposits, however, Australia has the premier examples. The giant Neoarchean rare-metal Sn-Ta pegmatites at Greenbushes in south-western WA are now mined for spodumene, and significant lithium minerals are mined from Archean pegmatite swarms in the Pilbara Craton of WA, including those of the Pilgangoora district, and in the Yilgarn Craton. Historically, Australia boasted the two largest primary tin deposits in the world at Mt Bischoff and Renison Bell in western Tasmania. Cleveland was a smaller deposit of similar style. Currently, Australia is a relatively minor tin producer on the global market. Renison Bell still operates, Mt Bischoff has had recent minor production, and smaller greisen and quartz vein deposits are being evaluated at Mt Lindsay and Queen Hill in western Tasmania and Baal Gammon in the Herberton district of Queensland. Tungsten was also mined from numerous quartz vein deposits; for example, in north-eastern Tasmania, normally in the roof zones of fractionated granitic cupolas. Most current resources are in Neoproterozoic skarns at O'Callaghan's in the Paterson Province of WA and the Devonian Dolphin skarn deposit on King Island. When the Greenbushes mine was in full operation, the country was a leading producer of tantalum-niobium globally. However, production has declined significantly although tantalum is still produced from Archean pegmatites at Wodgina in the Pilbara Craton, and there are significant resources of niobium-tantalum in the large Paleoproterozoic Mt Weld REE-bearing carbonatite in the NE Yilgarn Craton, both in WA. Australia is a minor producer of antimony, with production mainly from small quartz Au-Sb-W veins at Costerfield in the Lachlan Orogen of Victoria and Hillgrove in NSW.

## AUSTRALIAN ENERGY METAL AND NON-METAL MINERAL RESOURCES

Australia has major uranium resources and is a significant producer globally despite government restrictions. Traditionally, uranium mining has been dominated by giant unconformity-related deposits, such as Ranger and Narbalek, in the Paleoproterozoic Pine Creek Orogen of the NT, with future resources including those at Jabiluka. More recently,

the Mesoproterozoic IOCG deposit at Olympic Dam has become a significant producer. Supergene uranium concentrations in paleochannels are sources from both the Frome Embayment in SA, and the Yilgarn Craton of WA, including the calcrete-uranium deposit at Yeelirrie. Although there are minor vein-type deposits of thorium, significant production is essentially limited to beach placers from WA, including Eneabba and Capel, and from Queensland, including Stradbroke Island. Australia is the premier producer of zircon from beach placers where ilmenite and rutile coexist with the zircon. Australia is a comparatively minor producer of phosphates. Historically, now-depleted guano deposits on islands such as Christmas Island were major producers. Phosphate is mined from Middle Cambrian marine phosphorites at Phosphate Hill, Duchess on the south-eastern margin of the Georgina Basin, south of Mt Isa. Although not strictly a mineral deposit, solar salt is a major commodity produced in Australia from evaporation ponds along the coastlines of WA and SA. The salt is essentially NaCl and contains none of the more valuable potassium or lithium salts. There are potentially mineable sylvite (KCl)-bearing evaporation beds in the Boree Salt Member in the Bowen Basin of Queensland, and at Chandler in the Amadeus Basin. Australia is the premier provider globally of diamonds in terms of carats produced rather than total monetary value. Kimberlites, the traditional hosts to diamonds, are widespread in Australia, but it is the lamproite pipes in the Halls Creek and King Leopold Mobile Zones of the Kimberley that host the major diamond deposits, with the Mesoproterozoic lamproite pipe at Argyle in the Halls Creek Mobile Zone, with rare coloured – particularly pink – diamonds, that dominates production. Australia is also a significant producer of industrial minerals such as magnesite, silica and talc.

## MINERAL DEPOSIT TYPES ABSENT FROM AUSTRALIA

Although the Pilbara Craton and the Kaapvaal Craton of South Africa have been correlated as Vaalbara (Nelson et al., 1999), their metallogeny is totally different, apart from the similar Neoarchean to Paleoproterozoic iron ore provinces. South Africa is highly endowed with gold through the Witwatersrand deposits, and PGEs, Cr, Ti and V through the layered intrusion of the Bushveld Complex. These strongly suggest a metal-enriched lithosphere under this part of southern Africa, with giant Cr and PGE deposits also developed in the Great Dyke of Zimbabwe. In contrast, the Pilbara has only relatively small layered intrusions and small occurrences that might be of a Witwatersrand-style of Mesoarchean age at Nullagine. Although widespread gold nugget occurrences, at least some from a Neoproterozoic sedimentary source rock, have recently been recorded in the Pilbara, they show no close resemblance to Witwatersrand-type deposits in terms of host rocks or gold occurrence. The Neoarchean Windimurra intrusion in the Murchison Province of the Yilgarn Craton is of similar size to the Bushveld Complex but has not been similarly uplifted to expose its lower units, although it does have Ti-V deposits in its upper magnetite units. Although Australia has thousands of kilometres of craton margins, large layered intrusion-hosted Ni-Cu-PGE deposits similar to Sudbury, Norilsk and Voisey's Bay are extremely rare. The exception until very recently has been Nebo-Babel in the Musgrave Province of central Australia, with Nova a recent discovery in the Albany-Fraser Orogen. Similarly, most Australian craton edges did not experience the emplacement of magmas from enriched lithosphere to produce A-type to alkaline magmatism, such as the eastern margin of the Gawler Craton with the resultant major IOCG province that includes Olympic Dam. These craton margins are nowhere overlain by shallow-marine, carbonate-bearing sedimentary sequences intruded by lithosphere-derived magmas, which might explain the absence of Carlin-type gold deposits in Australia. Mississippi-Valley-type deposits do occur in the Canning Basin (for example, Cadjebut), but are rare considering the widespread Paleozoic limestone sequences in Australia, particularly in the Kimberley region of WA and western Tasmania. Similarly, Irish-type deposits appear to be absent, and low-sulfidation epithermal gold-silver deposits are very rare except for deposits at Pajingo and Cracow in Queensland.

## CONCLUSIONS

In terms of abundant metals, Australia has large resources of all but chromium for the coming decades. It is likely that extensions to known deposits or similar deposits will continue to be discovered by brownfield exploration. As near-coastal beach placers are depleted, inland deposits in the Murray and Eucla Basins are likely to be developed. In terms of base metal deposits, there have been few major discoveries in recent years in traditional regions as provinces become well-explored with respect to direct detection via geophysical techniques. The value of exploration of potential new provinces has recently been highlighted by the discovery of the Nova Ni-Cu deposit in the Proterozoic Albany-Fraser Orogen along the south-eastern margin of the Yilgarn Craton. Craton margins are particularly prospective for other Ni-Cu deposits and IOCG deposits wherever there is evidence of basic or felsic volcanism. Recent discovery of Cu-Au deposits in the Paterson Province adjacent to the margin of the Pilbara Craton by Rio Tinto attest to this. There is also the recently discovered DeGrussa Cu-rich VMS deposit in the largely ignored Paleoproterozoic Bryah Basin of the Capricorn Orogen north of the Yilgarn Craton. Overall, production from VMS deposits has declined dramatically along with exploration as most traditional provinces are considered well-explored. However, the discovery of the relatively sulfide-poor Henty gold deposit in the Mt Read VMS province in western Tasmania, plus the clear recognition of a new class of gold-rich submarine VMS-porphyry-high-sulfidation epithermal deposits (Dubé et al., 2012) raise the possibility of the existence of deposits with insignificant electrical and electromagnetic response. Classic sediment-hosted copper deposits of the Central African Copperbelt type seem to be lacking in Australia and yet the right geological conditions exist in the Neoproterozoic Adelaide Geosyncline of SA and the Yeneena Basin of WA. Rifted basins with clastic sedimentary rocks, red beds, evaporites and black shales of favourable age are present, but only minor copper occurrences have been revealed to date. In terms of precious metal deposits, the traditional orogenic gold provinces of WA and Victoria are well explored, but discoveries continue to be made in the Yilgarn Craton despite limited greenfields exploration. As for the base metals, at least some of these new discoveries are in non-traditional terranes, such as the boundary between the Yilgarn Craton and Albany-Fraser Orogen in the case of the Tropicana deposit, and the Yamarna Greenstone Belt remote from the traditional Eastern Goldfields in the case of the Gruyere deposit. For non-metals, increased lithium exploration will occur as the demand for lithium ion (Li-ion) batteries accelerates. Both the Archean Pilbara and Yilgarn Cratons are host to numerous pegmatite swarms that hold potential for future lithium mining.

It is likely that mineral exploration in Australia will be dominated by brownfield exploration around existing mines in known mineral districts, but that greenfields exploration under deeper cover will increase as brownfield resources decline. The recent discovery of Telfer-like gold mineralization under about 400 m of cover at Havieron, east of Telfer, by Greatland Gold represents bold and innovative exploration. It is important from an exploration perspective that several of the recent greenfields discoveries, including the Nova Cu-Ni and Tropicana gold deposits and Rio Tinto copper discovery, all in WA, lie on craton margins, as do several world-class IOCG deposits following the discovery of Olympic Dam in South Australia.

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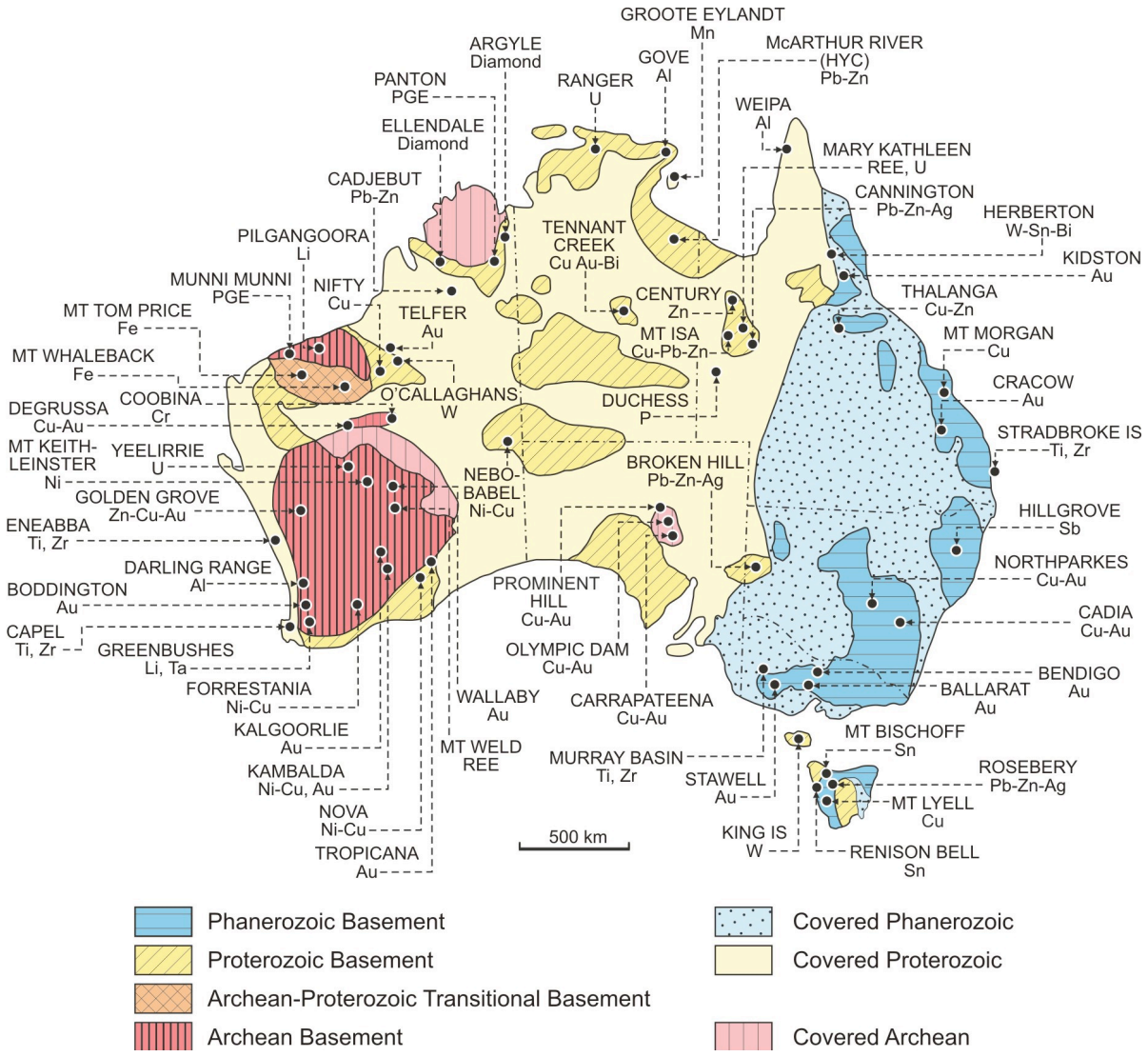


**Figure 1. Map of Australia illustrating extent of Archean, Proterozoic and Phanerozoic basement. Many of the largest mineral deposits are shown including some that have been discovered recently. Adapted from Solomon and Groves, 2000 (Figure 1.6).**