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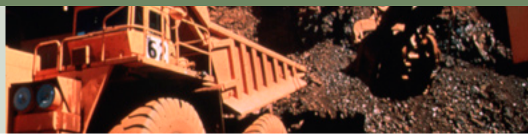
Catching *the nickel boom*

New synthesis will aid nickel explorers



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In August 2006, a tonne of nickel was worth a record $US34 750 on the world market, a 7.7-fold increase from 2001—an astounding performance driven mainly by the urbanisation and industrialisation of China. At that price, global stockpiles of nickel have virtually disappeared, while exploration expenditure and activity are at all-time highs as Australia's nickel industry experiences a 'boom phase' of unparalleled opportunities.

To support Australian explorers, Geoscience Australia has just published *Nickel sulfide deposits in Australia: characteristics, resources and potential*, a comprehensive synthesis in which we review the geological settings and resources of Australia's nickel sulphide deposits at a national scale and place them in a global context for the first time. The paper summarises the key factors that determine the fertility of nickel-bearing magmatic systems, with a predictive focus that should be of considerable interest to companies exploring for nickel deposits.

Evolution of Australia's nickel sulphide industry and global status

The discovery of massive nickel–copper sulphides at Kambalda near Lake Lefroy in the Eastern Goldfields of Western Australia on the 28 January 1966 heralded the beginning of the nickel industry in Australia. The sulphides at Kambalda assayed 8.3% Ni and 0.5% Cu over 2.7 metres, and were hosted by unusual ultramafic igneous rocks called komatiites—rocks rich in magnesium, iron and the mineral olivine. Exploration since 1966 has defined a total resource (total production plus remaining reserves and resources) of nickel metal from sulphide ores of approximately 12.9 Mt, and five world-class deposits (each containing at least 1 Mt of nickel metal). In 2006–07, production from nickel sulphide and laterite deposits will reach 212 000 tonnes of nickel and earn around A$4.2 billion in export revenue (ABARE 2006), making Australia the world's third largest producer of nickel after Russia and Canada.

More than 90% of the nation's total known resources of nickel metal from sulphide deposits were defined during the relatively short period from 1966 to 1973, and production from many komatiite-hosted deposits in the Eastern Goldfields began within two years of discovery. Australia is particularly well endowed with world-class komatiite-associated deposits at Mt Keith (3.4 Mt), Perseverance (2.5 Mt), Yakabindie (1.7 Mt), Kambalda region (1.4 Mt), and Honeymoon Well (1 Mt), along with smaller high-grade deposits (assaying 5–9% Ni) at Cosmos, Prospero, Long, Silver Swan and Victor. In contrast, the nickel resources in Australia's tholeiitic mafic–ultramafic intrusions (containing more siliceous igneous rocks than komatiites) are substantially smaller than those in the major foreign deposits.

Exploration for nickel sulphides has been very active since 2001 in most Precambrian provinces of Australia. Record numbers of exploration companies are active in Western Australia (more than 170 in 2006), accounting for more than 90% of the nation's Ni–Cu exploration budget of A$168.1 million (ABS 2006). The main areas of interest include Archaean greenstone belts in the Yilgarn Craton (near Kambalda, Leonora, Leinster and Southern Cross), the northern margins of that craton, the western part of the Pilbara Craton, and the Proterozoic Musgrave, Kimberley, Albany–Fraser and Hamersley provinces. Recent exploration successes include:

- increased resources at previously known deposits (many deposits near Kambalda, Carnilya Hill, Flying Fox T Zero to T5, Radio Hill, Sally Malay)
- delineation of deep and covered mineralised komatiite sequences (Cosmos Deeps, Prospero, Wedgetail, Flying Fox T5)
- new mineralised Precambrian mafic±ultramafic intrusions (Nebo–Babel, Copernicus, Billy Ray)
- new styles of mineralisation and/or new provinces (Collurabbie, Sinclair, Koolyanobbing North, Beasley, and Avebury in western Tasmania).

Classification of Australia's nickel sulphide deposits

Australia's nickel sulphide deposits are associated with ultramafic and/or mafic igneous rocks in three major geotectonic settings:

- Archaean komatiites emplaced in rift zones of granite–greenstone belts
- Precambrian tholeiitic mafic–ultramafic intrusions emplaced in rift zones of Archaean cratons or Proterozoic orogens
- hydrothermal-remobilised occurrences with no apparent age or tectonic constraints.

Most deposits can be classified (table 1) into two orthomagmatic associations that reflect the dominant chemical affinities of the host magma (komatiitic or tholeiitic) and a third association that encompasses hydrothermal-remobilised mineralising systems. The largest and most economically important deposits are associated with Archaean komatiitic rocks in the greenstone belts of the Yilgarn Craton of Western Australia. These deposits account for approximately 82% of the nation's nickel production; minor contributions come from tholeiitic mafic–ultramafic intrusions (~3%) and laterite (~15%) sources.

The world's komatiite-associated Ni–Cu deposits are of specific Archaean and Proterozoic age, with the largest formed at ~2700 Ma and ~1900 Ma (figure 1). In contrast, basal Ni–Cu sulphide deposits do not appear to be age dependent. Large deposits/mining camps associated with continental flood basalt (Noril'sk) and astrobleme (Sudbury) events appear to have a very restricted representation in the geological record. The

Figure 1. Time-nickel sulphide metallogenic event plot showing approximate ages and relative sizes of nickel sulphide deposits and nickel sulphide camps/provinces in the world.

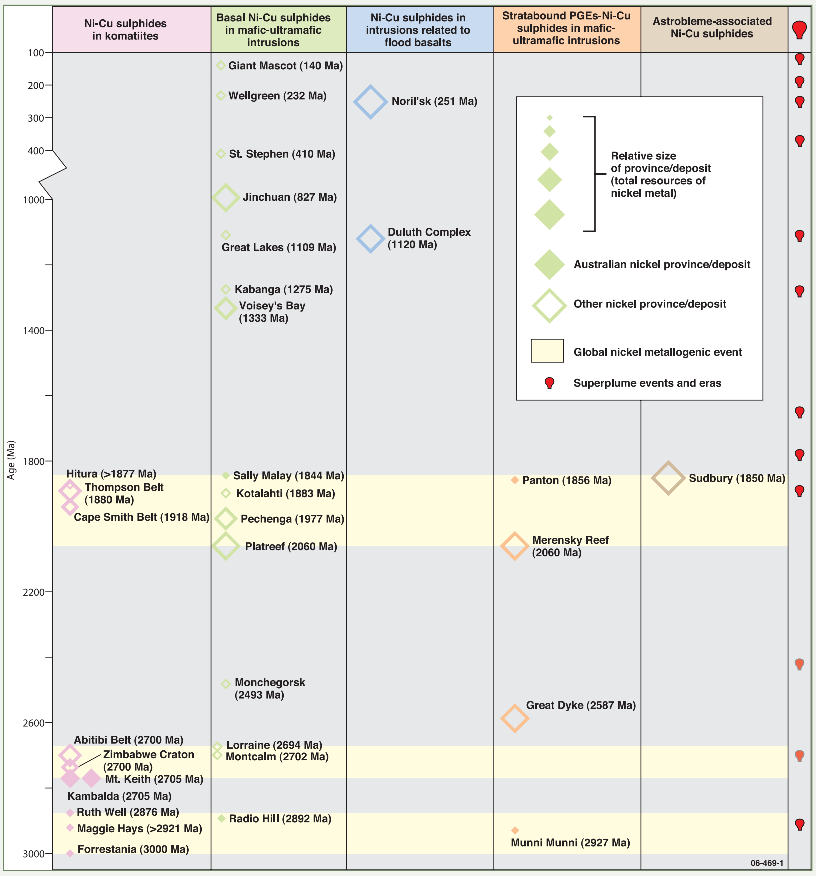
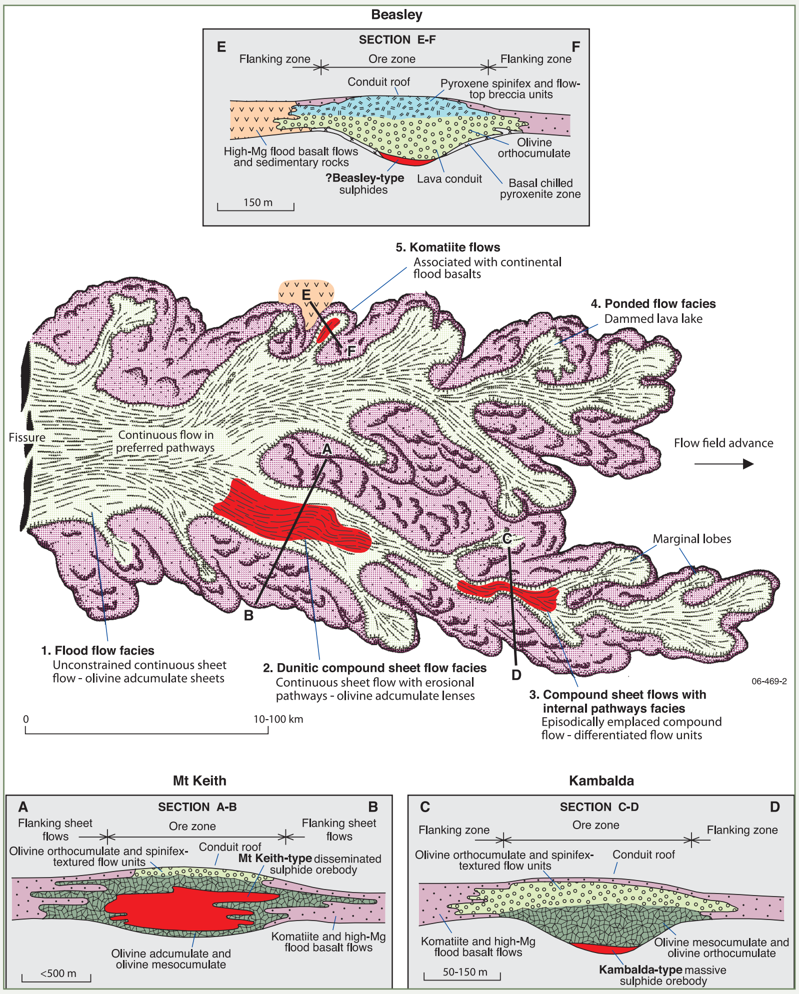


Table 1. Classification of Australia's nickel sulphide deposits

Association	Deposits/prospects	Age (Ma)	Metal association	Ni:Cu
1. Komatiitic				
1A. Massive and/or matrix sulphides at base of olivine cumulate (peridotite) sequences in preferred lava pathways	*Kambalda, WA* Maggie Hays, WA Cosmos, WA	~2900–2700	Ni-Cu±Au±PGE±Co	7-20
1B. Disseminated sulphides in central parts of thick olivine cumulate (dunite) sequences in preferred lava pathways	*Mt Keith, WA* Black Swan, WA Honeymoon Well, WA	~2900–2700	Ni-Cu±PGE±Co	>20
Other komatiitic deposits				
• Sulphides at basal contact of olivine cumulate sequences associated with comagmatic flood basalts	*Beasley, WA*	?2770	Ni-Cu-PGE	NA
• PGE-enriched sulphides associated with komatiitic and tholeiitic mafic-ultramafic rocks	*Collurabbie, WA* ?Daltons, WA	?2900–2700	PGE-Ni-Cu	<2
2. Tholeiitic				
2A. Massive and disseminated sulphides in feeder conduit and/or depressions along basal contacts of mafic±ultramafic intrusions	*Radio Hill, WA* Sally Malay, WA Mt Sholl, WA Nebo-Babel, WA	~2925–2700, ~1850,~1080	Ni-Cu-Co±PGE	0.5-7
2B. Stratabound disseminated sulphides near ultramafic-gabbroic zone contacts of mafic-ultramafic intrusions	*Munni Munni, WA* Weld Range, WA Windimurra, WA	~2925–2800, ?1850	PGE-Cu-Ni	<2
2C. Stratabound chromitite layers near ultramafic-gabbroic zone contacts of ultramafic-mafic intrusions	*Panton, WA* Eastmans Bore, WA Salt Creek-Plumridge, WA	~1850, ~1300	PGE-Ni-Cu-Au-Cr	5
2D. Discordant bronzitite breccia pipes in mafic-ultramafic intrusions	*Carr Boyd Rocks, WA*	?2700	Ni-Cu	3
3. Hydrothermal-remobilised				
3A. Hydrothermal-remobilised—ultramafic host or ?skarn	*Avebury, Tas*	?360	Ni	Ni>>Cu
3B. Hydrothermal-remobilised—metasedimentary rock host	*Sherlock Bay, WA* Cruickshank, WA	~2925–2700	Ni-Cu	5
Other hydrothermal-remobilised deposits				
• Hydrothermal-remobilised—felsic±mafic±ultramafic rock hosts	*Elizabeth Hill, WA* ?Andover, WA	<2870	Ag-Pb-Ni-Cu±PGE	NA
• Remobilised-metamorphic—metagabbro host	*Corkwood, WA* Bow River, WA	~1865	Ni-Cu-Co	3
• Hydrothermal arsenical-auriferous-bearing quartz-carbonate veins	*Mt Martin, WA* Bamboo, WA	NA	Ni-As-Au	Ni>>Cu

Type examples of deposits/prospects are indicated in italics.
NA – not available

Figure 2. Komatiitic mineralising systems. Schematic section through an inflationary komatiite flow field that developed through sustained eruption of komatiite. The spatial relationships between various komatiite facies and types of nickel mineralisation are shown for the Mt Keith (section A–B), Kambalda (C–D), and Beasley (E–F) type deposits. Modified after Dowling & Hill (1998).



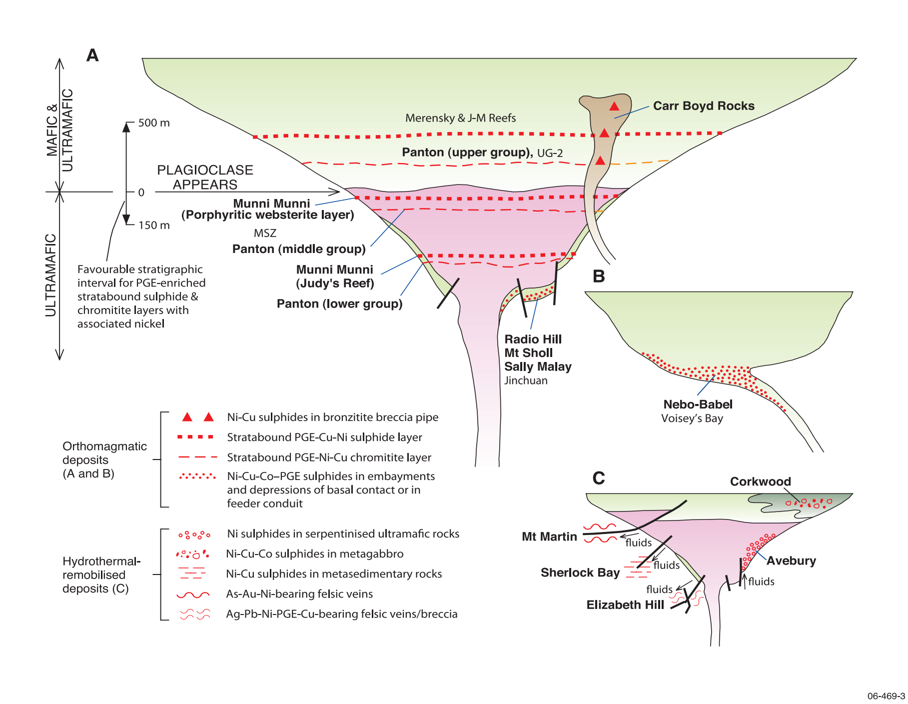
ages of Australia's major deposits correlate with at least three major global-scale nickel metallogenic events at ~3000 Ma (3000 Ma to 2875 Ma), ~2700 Ma (2705 Ma to 2690 Ma) and ~1900 Ma (2060 Ma to 1840 Ma). These events correspond with major periods of juvenile crustal growth and the development of large volumes of primitive komatiitic and tholeiitic magmas. They are thought to have been caused by mantle overturn events associated with mantle plumes or larger superplumes (figure 1).

Fertile versus barren magmatic systems, and prospectivity

Analysis of the world's major komatiite provinces reveals that the most fertile komatiite sequences are generally of late Archaean (~2700 Ma) or Palaeoproterozoic (~1900 Ma) age, have dominantly Al-undepleted chemical affinities (Al_2O_3/TiO_2 = 15 to 25), and form compound sheet flows with internal pathways and dunitic compound sheet flow facies. The preferred pathways (figure 2) assist in focusing large volumes of primitive magma flow (i.e. high-magma flux environments) and facilitate interaction of the magma with a potential sulphur-bearing substrate. The identification of magmatic facies in komatiitic systems is therefore important for assessing economic prospectivity. There is considerable potential for further discovery of komatiite-hosted deposits in Archaean granite–greenstone terranes, including large and smaller high-grade deposits (5–9% Ni), that may be enriched (2–5 g/t) in platinum-group elements (PGE), especially where the host ultramafic sequences are poorly exposed under shallow cover or younger basinal sequences.

In contrast to komatiitic-mineralising systems, the broad criteria for assessing the nickel prospectivity of tholeiitic mafic±ultramafic intrusions and their provinces are less clear. However, a significant exploration advantage for investigating basal Ni–Cu–Co sulphide deposits (such as at Sally Malay, Radio Hill and Nebo–Babel) is that they can occur in small- to medium-sized, sulphur-saturated mafic bodies of various ages. Most Precambrian provinces in Australia and, in particular,

Figure 3. Tholeiitic and hydrothermal mineralising systems. Schematic distribution of orthomagmatic and hydrothermal-remobilised nickel sulphide deposits associated with tholeiitic mafic±ultramafic intrusion.



A. Stratabound, basal, and discordant Ni–Cu–Co and PGE–Ni–Cu deposits in mafic–ultramafic intrusion. Australian deposits (shown in normal type) are Munni Munni, Radio Hill, Mt Sholl (west Pilbara Craton); Carr Boyd Rocks (Yilgarn Craton); and Panton and Sally Malay (Halls Creek Orogen). Foreign deposits (italics) are Merensky Reef and UG–2 Chromitite (Bushveld Complex, South Africa); J–M Reef (Stillwater Complex, USA); MSZ (Main Sulphide Zone–Great Dyke, Zimbabwe); and Jinchuan Intrusion (China).

B. Massive Ni–Cu–Co sulphide deposits in the feeder conduit of mafic-dominated intrusion: Nebo–Babel (Musgrave Province, WA) and Voisey's Bay (Canada).

C. Hydrothermal-remobilised Ni–Cu–±Ag±PGE and other metal deposits hosted by: serpentinised ultramafic (Avebury), deformed mafic (Corkwood), metasedimentary (Sherlock Bay, Mt Martin), and igneous (Elizabeth Hill) rocks.

Proterozoic orogenic belts, contain an abundance of these intrusions that have not been fully investigated. The Musgrave Province, Halls Creek Orogen, Albany–Fraser Orogen, Arunta Block, and western parts of the Yilgarn, Pilbara and Gawler cratons are considered the more prospective provinces. The major exploration challenges for finding basal Ni–Cu–Co sulphide deposits are to determine the predeformational geometries and younging directions of the intrusions, and to locate under cover, favourable environments (e.g., structural irregularities and depressions in basal contacts and feeder conduits) that concentrate the economically important massive sulphides (figure 3).

Hydrothermal-remobilised nickel sulphide deposits have diverse geological settings and metal associations that reflect the different compositions of the source rocks and fluids. Typically, most hydrothermal deposits are small tonnage and of low economic importance. The unusual Avebury deposit in western Tasmania has increased awareness of hydrothermal-type targets in Phanerozoic provinces that were previously considered to have low prospectivity.

Australia has large areas of Archaean to Phanerozoic continental flood basalts, but no 'Noril'sk-type' Ni–Cu–PGE deposits associated with these rocks have yet been discovered. Hence, there is also some potential for these underexplored deposits in large igneous provinces, such as the late Archaean Fortescue Group basalts of the Pilbara Craton, Palaeoproterozoic Hart Dolerite–Carson Volcanics of the Kimberley Basin, and Mesoproterozoic Warakurna dolerites/intrusions and Cambrian Kalkarindji basalts of western and northern Australia.

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Related websites/articles

Nickel sulfide deposits in Australia: characteristics, resources and potential will appear in Ore Geology Reviews, volume 29, No. 3–4, October 2006
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AusGeo News 79
Nickel sulphide metallogenic provinces: resources and potential
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Resources
Australia's nickel endowment (PDF)
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