On the 16th of May 2007, the price of nickel metal rose to an all-time record of US$54,200 per tonne, surpassing the previous highest price of $US23,900/t reached in 1988. The nickel price has been surging in response to strong demands, constrained supplies and low metal stockpiles, all reflecting robust worldwide economic growth and especially China’s huge need for raw materials.

Economic quantities of such metals as nickel, platinum, and palladium are concentrated in mafic-ultramafic igneous rocks. These particular rocks are a focus for minerals exploration in Australia which has witnessed significant nickel discoveries in past exploration booms. To assist the mining industry during these buoyant times, Geoscience Australia has released a new 1:4 000 000 scale colour map ‘A Synthesis of Australian Proterozoic Mafic-Ultramafic Magmatic Events. Part 2: Northern Territory and South Australia’. For the first time on a single map, the continental extent and age relationships of Proterozoic mafic and ultramafic rocks, and associated mineral deposits are shown throughout the Northern Territory and South Australia.

The major objective of this presentation is to promote the applications of this map, which should be of interest to those companies exploring for nickel, platinum-group elements, chromium, titanium, and vanadium, as well as to those interested in the geological evolution of the Australian continent.

Background image: Glacially striated, polished, massive sulphide outcrop on top of the Ovoid deposit showing ‘loop textures’ of chalcopyrite (greenish) and pentlandite (scattered blockier white crystals) surrounding pyrrhotite (brown), Voisey’s Bay nickel-copper deposit, Labrador, Canada (photographer Steve Tilley – CVRD-Inco; photograph taken August 2004).
Outline of presentation.
Basic Concepts: Formation of Tholeiitic Ni-Cu±PGE Sulphide Deposits

4. Surface Setting:
Depleted basalts → vectors for sulphide separation at depth

3. Sub-Volcanic Setting:
Suphides scavenge Ni, Cu, PGEs in high-level contaminated sills (Noril’sk)

2. Intrusive Setting:
Late S saturation of magma in chamber → stratabound PGE layer (Merensky Reef, Munni Munni); early S saturation → massive Ni-Cu sulphides at basal contact & feeder conduit (Voisey’s Bay, Sally Malay)

1. Mantle Setting:
Fertile magmas derived from melting of mantle plume

Schematic diagram showing the basic concepts for the formation of magmatic Ni-Cu±PGE sulphide deposits associated with tholeiitic mafic-dominated magmas. (1) The formation of these deposits commences with fertile mafic magmas derived from the partial melting of hot mantle plumes deep within the Earth. The fertile basaltic magmas are relatively rich in metals but poor in sulphur. (2) The migrating magmas rise upwards and generally form magma chambers in the middle and upper levels of the crust. The basaltic magmas may interact with the surrounding crustal rocks and become contaminated with sulphur. If sulphur saturation occurs, droplets of sulphide liquid will form and scavenge the chalcophile metals platinum (Pt), palladium (Pd), nickel (Ni), and copper (Cu) from the magmas. If these sulphide droplets become sufficiently concentrated, a magmatic sulphide deposit is formed. The timing of the sulphide saturation event can determine the style and stratigraphic level of mineralisation. Massive Ni-Cu±PGE sulphides in the feeder conduit and/or in structural embayments-depressions along the basal contacts of the magma chamber (e.g., Voisey’s Bay, Radio Hill) generally form from early sulphide saturation processes (e.g., crustal contamination). In contrast, stratabound PGE-enriched layers that occur at higher stratigraphic levels near major compositional contacts between mafic-ultramafic sequences (Merensky Reef, Munni Munni) form from relatively late sulphide saturation processes (e.g., magma mixing) in the chamber. Other elements, such as titanium (Ti), vanadium (V), and cobalt (Co) may be concentrated in the magma through crystal fractionation processes and form stratabound deposits in the more evolved upper parts of the intrusion. (3) At higher levels in the crust, voluminous basalitic sill and dyke magmatic systems can attain sulphide saturation by crustal contamination processes (Noril’sk-Talnakh). (4) Comagmatic lavas at surface will be depleted in those elements which are enriched in the sulphide deposits. Recognition of these metal-depleted basalts can therefore provide evidence of mineralising systems deeper in the crust.

Timeframe and strategies for the ‘Characterisation and Metallogenesis of Proterozoic Mafic-UltraMafic (‘MUM’) Magmatic Events’ Project.
Methodology of ‘MUM’

• **Magmatic Event Criteria:** Published, reliable (>75% U-Pb zirc/badd) age of mafic or ultramafic rock

• **Solid Geology Base Maps:** Important to assess total volume of magmatic system (Solid Geology of South Australia by Cowley (2006), & solid geology coverages of NT provinces)

• **Characterisation:** Province, Formation, Age, Rock Types, Bulk Composition, Setting, Mode of Occurrence, Thickness, Country Rocks, Deposit Types. Datasets linked by STRATNO (ARC GIS 9.2)

Methods used in the ‘Characterisation and Metallogenesis of Proterozoic Mafic-Ultramafic Magmatic Events’ Project: criteria for defining magmatic event, different solid geology base maps used, and attribution of data.

Distribution of Archean and Proterozoic mafic-ultramafic rocks and associated deposits and mineral occurrences (with no formal resources) in the Northern Territory and South Australia.
Nickel endowment (total resources of nickel metal associated with sulphide ores) of provinces in Australia. Endowment is dominated by the Archean komatiite-hosted deposits in the Eastern Goldfields and to a lesser extent the Youanmi Provinces of the Yilgarn Craton, with relatively minor contributions from the Pilbara Craton (Mt Sholl, Munni Munni, Radio Hill, Ruth Well, and Sherlock Bay deposits), Halls Creek Orogen (Sally Malay, Panton, and Copernicus deposits), Pine Creek Orogen (Area 55, Browns, Mt Fitch deposits), Musgrave Orogen (Nebo-Babel deposit), and western Tasmania (Avebury deposit).
New Magmatic Events colour map from Geoscience Australia – ‘A synthesis of Australian Proterozoic mafic-ultramafic magmatic events. Part 2: Northern Territory and South Australia’.

* The map can be downloaded free from Geoscience Australia at: http://www.ga.gov.au/map/index.jsp#geology
Summary of the nineteen Major Magmatic Events (informal names) defined in this study. The smiling green face symbols indicate the two Magmatic Events (ME) to be discussed in more detail in this presentation.
ME 15: **Mordor Event ~1130 Ma**

**Provinces:** Aileron Province-Arunta Region

**Examples:** Mordor Igneous Complex (1133±5 Ma)

**Form:** Composite plug-like alkaline-ultramafic body; spatially associated with major faults

**Rock Types:** Syenite, monzonite, shonkinite, wehrlite, clinopyroxenite, pyroxenite, lherzolite, dunite

**Size:** Small outcropping bodies 6 by 6 km, 1.2 km thick

**Mineralisation:** Stratabound PGE-Au-Cu-Ni (only example in NT-SA)

**Status:** Prospect

**Potential analogues:** Merensky Reef (2060 Ma); Alaskan-Urals

Salient points of the ME 15: Mordor Event ~1130 Ma.
Geological map of the Mordor Igneous Complex, Arunta Region, central Australia (modified after Langworthy & Black, 1978). The complex is an unusual composite plug-like alkaline-ultramafic body that has created considerable exploration interest for PGEs, Au, Ni, Cu, Cr, diamonds, vermiculitic phlogopite, U, and rare-earth elements (Hoatson et al., 2005). It can be broadly subdivided into a western zone of homogeneous syenite and an eastern zone comprising a highly fractionated comagmatic suite of alkaline felsic and mafic rocks (syenite, monzonite, melamonzonite, shonkinite) spatially associated with phlogopite-bearing ultramafic rocks (wehrlite, olivine clinopyroxenite, lherzolite, dunite, pyroxenite).

The photograph in the bottom right corner shows outcropping phlogopite pyroxenite from the northwest part of the intrusion.


Total Magnetic Image of the central Arunta Region, central Australia. Modelling of the aeromagnetic data by Meixner and Hoatson (2003) showed that the steep-sided Mordor Igneous Complex corresponds to a circular region of moderate magnetic intensity comprising four separate very intense anomalies. Its emplacement, and that of the much later ~732 Ma Mud Tank Carbonatite plug-like body located 52 km to the north-northwest, may have been facilitated by the nearby Woolanga Lineament — a deep-seated northwest-trending crustal dislocation. A group of magnetic-gravity high anomalies (large yellow ellipse) north of Alice Springs have similar geophysical characteristics to the Mordor Igneous Complex. Meixner and Hoatson (2003) interpreted these ovoid-shape anomalies to be plug-like mafic-ultramafic bodies (Joppita Bore intrusions) under shallow cover, possibly similar to the Mordor Igneous Complex.

Salient points of the ME 17: Gairdner Event ~825 Ma.
Distribution of the Proterozoic Mafic-Ultramafic Magmatic Events defined in the Gawler Craton and surrounding basins of central South Australia. The youngest event – ~825 Ma Gairdner Event – comprises a prominent northwest-trending mafic dyke swarm that covers much of the state, and various coeval basaltic lava flows in the Adelaide Geosyncline and surrounding provinces (most of these polygons are too small to see here; see slide #23 for further details).
Large Igneous Provinces (LIPS):

- Large volume pulses of coeval mafic-dominated magmas (flood basalts, dyke swarms & sills, mafic-ultramafic intrusions)
- Generally products of thermal mantle plumes & associated major flood basaltic provinces in rift environments
- Linked to regional-scale uplift, continental breakup & Ni-Cu-PGE mineralisation events

Exploration Criteria:

- Continental-scale flood basalt provinces
- Controlling faults, magma plumbing systems, feeder conduits
- Depletion of chalcophile metal elements coincident with geochemical signatures (Th/Nb, La/Sm) of crustal contamination

Summary of the major features of Large Igneous Provinces (LIPS) and criteria used for exploring these greenfields environments.
Distribution of Phanerozoic Large Igneous Provinces (modified after Coffin & Eldholm, 2001).

Interpreted spatial distribution of Large Igneous Provinces (LIPs) in Western Australia-Northern Territory-South Australia defined in this study. These magmatic provinces are characterised by large volumes of coeval magmatism (generally of mafic composition) that covered extensive areas at various times during the Proterozoic and early Phanerozoic. The magmatism is generally associated with mantle-plume activities and takes the form of continental flood basalts, giant swarms of dolerite dykes and sills that may be feeders to the basalts, and massive and layered mafic and mafic-ultramafic intrusions.

The Kalkarindji LIP is modified after Glass and Phillips (2006), the Warakurna LIP is modified after Wingate et al. (2004), and the Marnda Moorn LIP is modified after Wingate and Pidgeon (2005).


Schematic section of typical mineralised Noril’sk-Talnakh-type intrusions and associated volcanic and sedimentary rocks, Russia. Massive and disseminated sulphide deposits associated with these shallow-level ‘gabbro-dolerite’ intrusions contain large resources of nickel, copper, and platinum-group elements.

Photographs: massive Ni-Cu sulphide ores (left), mining operations at Noril’sk (centre), and remobilised chalcopyrite-rich ores (right).

Modified section and photographs from Lightfoot (2005) in Data Metallogenica.
Composite chemostratigraphic trends for the flood basalt sequences at Noril’sk, Russia. The Nadezhdinsky basalts (red symbols) played a significant part in the mineralising systems at Noril’sk-Talnakh. These particular basalts are markedly depleted in nickel and platinum relative to the other basalt formations in the ~3-km-thick volcanic pile (top and bottom left plots). Their constant MgO contents (~6%; top right plot) indicate that the chalcophile metal depletion trends are not due to variations in magma compositions (i.e., due to more evolved magmas), but are related to magma mixing processes involving the Nadezhdinsky basalts and associated Morongovsky basalts (orange symbols), and the formation of the comagmatic mineralised gabbro-dolerite intrusions. The relative high Th/Nb ratios of the Nadezhdinsky basalts (bottom right plot) are also consistent with the parental magmas assimilating considerable amounts of continental crust.

Geochemical data from Lightfoot & Keays (2005) and Data Metallogenica.
Schematic section (left) showing the distribution of the major ore types in the Noril’sk-Talnakh nickel-copper-PGE sulphide deposits, Russia. These deposits could be interpreted as forming in an open and voluminous magmatic system, such as an intrusive version of a lava channel (right photograph).

Modified section and photograph from Lightfoot (2005) in Data Metallogenica.
Exploration Challenges

Identify:
(1) PGE & chalcophile metal depletion trends coincident with crustal contamination signatures
(2) Rifts, localised feeders, & thermal erosion features

痕跡元素 geochemical features of various basalts and dolerite dykes belonging to the ~825 Ma Gairdner Event superimposed on the geochemical fields of the Noril’sk flood basalts (see slide #20). The coeval mafic components of the Gairdner Event have similar Th/Nb ratios (Drexel et al., 1993; Zhao et al., 1994; Wingate et al., 2004) to the crustally contaminated basalts from Noril’sk, however, nickel abundances (centred near 100 ppm) show no obvious metal depletion trends.

Geochemical data for mafic volcanics from Noril’sk from: Lightfoot & Keays (2005) and Data Metallogenica.

Geochemical data for dykes and mafic volcanics of the ~825 Ma Gairdner Event from:


Schematic map showing the mafic components of the ~825 Ma Gairdner Event and interpreted rift zone and plume head in South Australia and the Northern Territory (Zhao et al., 1994). Various basaltic units are represented in the Bitter Springs Formation (Amadeus Basin), Wooltana Volcanics and Beda Volcanics (Adelaide Geosyncline, Gawler Craton), and dolerite dykes are associated with the Amata Dyke (Musgrave Orogen) and Gairdner Dyke Swarm (Gawler Craton, Coompana Block, Officer Basin, Musgrave Orogen).

First vertical derivative (FVD) magnetics image (provided by Martin Gole – AusQuest Limited, 2006) showing a possible feeder vent and a very long thermal erosion channel etched into the uppermost surface of the Antrim Plateau Basalts (~520 Ma Kalkarindji Event – ME 19).
Plot of nickel sulphide deposits versus time showing approximate ages and relative sizes of nickel sulphide deposits, camps, and provinces. Most significant deposits in the world can be broadly classified into komatiitic, tholeiitic (basal and stratabound), and astrobleme associations. Basal nickel-copper sulphide deposits occur throughout the geological time record, whereas the komatiite association is restricted to the ~1920 Ma–1880 Ma period and also more prominently, for Australian deposits, in the Archean around ~2700 Ma and ~3000–2900 Ma. The concentration of different types of nickel deposits forming during a particular geological period defines three major global nickel metallogenic events at ~2060 Ma to 1840 Ma, ~2705 Ma to 2690 Ma, and ~3000 Ma to 2875 Ma. Several of the major Magmatic Events (ME) defined in this study (indicated by yellow text at right) appear to correlate in time with global superplume events. The geological periods of the major superplume events are from Abbott and Isley (2002).

Conclusions from ‘NT-SA Study’

- **Protracted period of tholeiitic mafic magmatism** (flood basalts, dyke swarms, sills, intrusions) **from 2460 Ma to 520 Ma**; high frequency from 1860 Ma to 1590 Ma (11 of 19 events)

- **Magmatic Events** (particularly Palaeoproterozoic) can be correlated across the continent therefore high potential for large-volume magmatic systems

- **Apparent deficit of significant mineralisation discovered**, but Magmatic Events in NT-SA have mineralised correlatives elsewhere in the continent (1070 Ma Giles Event in WA & SA-NT) & high % of Prot intrusions under shallow cover & untested

- **Large volume, continent-wide igneous provinces** (>1 x 10^6 km^2) prominent in ‘younger’ Proterozoic (1070 Ma, 825 Ma, 520 Ma)

- **Exploration opportunities** (esp. intrusions under cover & LIPs): 825 Ma Gairdner Event (contam. & metal ?depleted volcs-dykes) 1070 Ma Warakurna Event (Nebo-Babel-type mafic intrusions) 1130 Ma Mordor Event (alkaline-ultramafic intrusions)

Concluding messages and contacts.