INTRODUCTION TO NICKEL SULPHIDE EXPLORATION

Jon Hronsky
Western Mining Services (Australia)
June 2007
This presentation provides a succinct introduction to nickel sulphide geology -- a complex field with many uncertainties that remain to be resolved.

Our intent is to communicate the **KEY IDEAS** that form the basic framework for understanding these deposits and for developing successful strategies to discover them.

Generic, widely-applicable concepts are emphasized; comprehensive exploration strategies based on these Key Ideas must include detection technologies (e.g. direct geochemical or geophysical ore targeting) applicable to local geologic environments.
• The concepts described in this presentation relate only to those nickel sulphide deposits that have formed from magmatic processes. These represent the overwhelming majority of nickel sulphide deposits discovered to date.

• The concepts described do not apply to mineralization that is related to hydrothermal processes (e.g. the Avebury deposit in Western Tasmania).

• A few nickel sulphide deposits have formed in atypical geodynamic settings associated with convergent margin processes (e.g. Aguablanca in Spain) – most, but not all, of the concepts described below are relevant to these deposits as well.
- Basic NiS Ore-forming Processes
- Classification of Nickel Sulphide Deposits
- Province Scale Controls and Targeting
- District Scale Controls and Targeting
- Deposit Scale Controls and Targeting
- Summary
Basic NiS Ore-forming Processes
• KEY IDEA: The fundamental mineralization process involves segregation of an immiscible sulphide magma from a silicate magma.
  – Sulphide and silicate liquids are immiscible over a wide range of conditions.
  – A sulphide liquid will separate from a magma when it becomes saturated in sulphur (under reducing conditions).
  – Ni, Cu, and PGEs have a very strong tendency to partition into the sulphide liquid (their partition coefficients are often called “D” factors; the larger the “D” factor the more readily it partitions into the sulphide phase).
  – Physical accumulation of this sulphide liquid leads to ore formation.
Preferred partition coefficients for Ni, Cu, Co, Pt and Pd between sulphide liquid and komatiite melt (from Naldrett, 1989; Peach et al., 1990; Fleet et al., 1991)

<table>
<thead>
<tr>
<th></th>
<th>Ni</th>
<th>Cu</th>
<th>Co</th>
<th>Pt</th>
<th>Pd</th>
</tr>
</thead>
<tbody>
<tr>
<td>27% MgO</td>
<td>100</td>
<td>250</td>
<td>40</td>
<td>$10^3$-$10^4$</td>
<td>$10^3$-$10^4$</td>
</tr>
<tr>
<td>19% MgO</td>
<td>175</td>
<td>250</td>
<td>58</td>
<td>$10^3$-$10^4$</td>
<td>$10^3$-$10^4$</td>
</tr>
</tbody>
</table>
KEY IDEA: Sulphide saturation of a magma can be induced by simply adding sulphur, but this is not the only way.

- It can also occur through:
  - decreasing FeO content
  - increasing fO₂
  - reducing Temperature
  - increasing Pressure

- Complex assimilation, fractionation and contamination processes in high energy magma chambers are likely to provide opportunities for sulphide saturation.
• **KEY IDEA:** Primary magmatic sulphides have a distinctive sulphide assemblage – variations from this inevitably reflect post-ore processes.

• The bulk composition of a sulphide liquid is determined by the activities of FeO, O and S in the silicate magma.

• Because most natural magmas have relatively restricted ranges of FeO content and Fe$^{2+}$/Fe$^{3+}$ ratio (which controls magma oxidation state), the composition of magmatic sulphides is also restricted.

• Consequently, crystallised magmatic sulphide liquids of all types will be dominantly comprised of Pyrrhotite, with subordinate Pentlandite, Chalcopyrite and Pyrite.
• **KEY IDEA:** The concentration of ore metals in the sulphide fraction is known as “tenor” – four main processes are thought to control tenor.

1. The fractionation state (i.e. MgO content) of the host silicate magma at the time of sulphide saturation

2. The R Factor

3. The fractionation history of the sulphide liquids themselves

4. Post-magmatic processes
Tenor Variation with Magma Fractionation State

Source: Naldrett and MacDonald (1980)
R Factor controls ore tenor

\[ Y_{sul} = X_{sul} \cdot D \left( 1 + R \right) / \left( R + D \right) \]

- \( R \) = mass ratio of silicate/sulphide melt
- \( D \) = sulphide/silicate partition coefficient
- \( X_{sul} \) = initial metal content-silicate magma
- \( Y_{sul} \) = final metal content-sulphide melt

**KEY IDEA:** Large dynamic systems, where sulphide melt equilibrates with large volumes of silicate magma, produce the highest-tenor mineralization.
Schematic of Sulphide Liquid Fractionation

Key Idea: If the residual Cu-PGE liquid can be segregated, it can form a very high tenor and high value ore.
A real example of sulphide fractionation: The Kharalekh orebody at Noril’sk

>1.5 Chalcopyrite Ores

1.5 - 2.2 Cubanite Ores

2.5 - 3.0 Chalcopyrite - pyrrhotite Ores with hexagonal & monoclinic pyrrhotite

3.0 - 4.5 Chalcopyrite - pyrrhotite Ores with hexagonal & monoclinic pyrrhotite

4.5 - 5.5 Pyrrhotite Ores with monoclinic pyrrhotite

>5.5 Pyrrhotite Ores with monoclinic pyrrhotite

Margin of Intrusion

Mineralogical geochemical streams

Noril’sk - Kharayelakh Fault

( Modified by Naldrett et al 1996 after Stekhin, 1994)
• **KEY IDEA:** Most nickel sulphide deposits have been overprinted by significant post-ore deformation and alteration which can be very significant economically.

  – Deformation can mechanically remobilize sulphide-rich ores; tenor variations may occur related to hydrothermal redistribution of metal and addition of sulphur.

  – Remobilised vein ore can be formed - typically enriched in Cu, Pd, Pt and Au relative to Ni, Os and Ir.

  – Alteration can help upgrade disseminated ores.
An example of Post-ore Deformation: Rocky’s Reward NiS Deposit – Western Australia
KEY IDEA: Nickel sulphide deposits form as part of a lithosphere-scale magma plumbing system. In order to target them, we need to understand the entire system.
• KEY IDEA: Nickel sulphide deposits form in magma conduit zones (either volcanic or intrusive) that have been the foci of anomalous magma flux.
Classification of Nickel Sulphide Deposits
• KEY IDEA: The two most important practical ways to classify nickel sulphide deposits are to do so based on their sulphide content and to do so based on the fractionation state (MgO content) of their parental magma.
## Sulphide-content based Classification

<table>
<thead>
<tr>
<th></th>
<th>Type 1</th>
<th>Type 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sulphide Content</strong></td>
<td>Massive-matrix-heavy disseminated; typically &gt; 40 modal %</td>
<td>Disseminated; typically &lt;10 modal %</td>
</tr>
<tr>
<td><strong>Sulphide Accumulation Process</strong></td>
<td>Physical emplacement of a discrete sulphide magma phase – may be modified by gravitational settling</td>
<td>Broadly coeval accumulation of droplets of sulphide liquid and silicate gangue minerals such as olivine and orthopyroxene</td>
</tr>
<tr>
<td><strong>Exploration Implications</strong></td>
<td>May be small targets, commonly associated with a broader Type 2 envelope; susceptible to post-ore deformation; good EM targets</td>
<td>May be large targets and have a strong geochem response if exposed at surface; IP useful only if not dunite-hosted</td>
</tr>
</tbody>
</table>
Schematic Example:
Type 1 and Type 2 Ore Formation in Komatiite Lava Channels
## Parental Magma-based Classification

<table>
<thead>
<tr>
<th></th>
<th>High MgO</th>
<th>Low MgO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parental Magma</strong></td>
<td>Ranges from 30% MgO for Kambalda-style Archean komatiites to about 18% for Raglan-style Proterozoic komatiites</td>
<td>Ranges from about 12% MgO for Noril’sk-style Picrites to about 8% MgO for Voisey’s Bay-style troctolites</td>
</tr>
<tr>
<td><strong>Typical Ore Host Rocks</strong></td>
<td>Peridotites to Dunites; typically most magnesian part of host complex</td>
<td>Variable but commonly gabbro-norites; may not be most magnesian rocks in complex</td>
</tr>
<tr>
<td><strong>Type 1 Ores</strong></td>
<td>Emplaced via gravitational settling at base of magma channels; High Ni/Cu</td>
<td>Emplaced late into host magma conduits; not necessarily stratabound and/or basal contact associated; Low Ni/Cu – bigger systems may host Cu-PGE rich fractionated ores</td>
</tr>
<tr>
<td><strong>Type 2 Ores</strong></td>
<td>Typical grade range 0.5-0.7% Ni</td>
<td>Typical grade range 0.2-0.4% Ni, 0.2-0.4% Cu</td>
</tr>
<tr>
<td><strong>Geodynamic Setting</strong></td>
<td>Dominant NiS ore-style in Archean; not known after Paleoproterozoic; require thin lithosphere at time of emplacement</td>
<td>Occur throughout geological time but not very important in Archean; may occur in anorogenic or even compressional settings</td>
</tr>
</tbody>
</table>
Province Scale Controls and Targeting
• KEY IDEA: Nickel sulphide deposits are associated with the regional scale foci of Large Igneous Provinces (LIPs).
  
  – A Large Igneous Province (LIP) is an anomalously voluminous and aerially extensive region of mantle-derived magmatic rocks emplaced rapidly (<1Ma – few Ma).
  
  – Magmas are dominantly picritic to basaltic, but komatiites are important in Archean and Paleoproterozoic.
  
  – An LIP requires active mantle upwelling (i.e. mantle plumes).
LIP example: The Siberian Traps Province

Noril’sk
lavas
&
tuffs

limit of province
Other Well Known Modern LIPs

Condie, 1999
• KEY IDEA: Although modern LIPs are relatively easy to recognize, the much larger number of older LIPs are far more difficult to identify for several reasons:
  – Fragmentary preservation via later rifting and plate movements
  – Erosion removal of volcanic sequence
  – Heterogeneous later cover sequences
  – Orogenic reworking
• KEY IDEA: The locations of LIP focal zones (target regions for NiS) are controlled by the structure of the underlying sub-continental lithospheric mantle.

  – There is a strong association with the margins of discrete lithospheric-mantle domains, particularly those that have been resilient to overprinting tectonic deformation.

  – These lithospheric domains typically formed in the Archean, although the overlying supracrustal sequence may be younger.
Example of control by the margin of a lithospheric domain: Thompson Nickel Belt

Figure 3.1 Geological setting of the Thompson Nickel Belt (TNB) at the margin of the Superior craton, adjoining the internal (Reindeer) zone of the Trans-Hudson Orogen. The TNB is the most highly deformed and metamorphosed, and probably the oldest of the four known Paleoproterozoic supracrustal belts. The ages are approximate and discussed in the text. Under the Palaeozoic cover, the belts are drawn from aeromagnetic patterns and exploration drilling information where available, but the northern and southern ends of the TNB are not constrained. A possible flat-lying basin is drawn with a speculative boundary that follows an area of low gravity. The age and origin of the sedimentary rocks in the Muddy Bay area are also unknown.
• KEY IDEA: NiS deposits occur at lithospheric boundary zones because the geometry of the base of the lithosphere controls the degree of melting of mantle plumes.

  – If a plume ascends under thick (>200 km) continental lithosphere, only minor low-degree partial melting will occur (e.g. intracratonic alkalic magmatism).

  – Ascending plumes will be channelled around thick lithospheric keels, rising higher at their margins.

  – Plume melting will also be dramatically enhanced at these positions because of greater adiabatic decompression.
Example of Plume focusing by a mantle lithospheric keel:

Modern Magmatism and the Tanzanian Craton

Taken from (Nyblade et al., 1996) Geology
District Scale Controls and Targeting
KEY IDEA: Nickel sulphide deposits tend to be closely associated with major deep-tapping structures that provide optimum conduits for magma flux from mantle.
Role of Deep Structures: LithoProbe section through Voisey’s Bay

VB = Voisey’s Bay
• **KEY IDEA:** Nickel sulphide camps are associated with localized zones of concentrated lava/intrusion emplacement typified by greater volumes and greater differentiation of magmatic products.

• **KEY IDEA:** These camp-scale zones are localized by the intersection of cross-structures with major mantle-tapping structures.
Kambalda Example (Beresford et al, 2002)

**Interpretation of the geochemical Distribution within the Kambalda Dome**

<table>
<thead>
<tr>
<th>Pd (ppb)</th>
<th>MgO (wt%)</th>
<th>Th/Nb</th>
<th>Do/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;200</td>
<td>&lt;4</td>
<td>&lt;1.5</td>
<td>Chondritic</td>
</tr>
<tr>
<td>&lt;4</td>
<td>&lt;30</td>
<td>&gt;1.5</td>
<td>Chondritic</td>
</tr>
<tr>
<td>&gt;4</td>
<td>&gt;30</td>
<td>&lt;1.5</td>
<td>Chondritic</td>
</tr>
</tbody>
</table>

- Lobate Flows
- Mineralised Flows
- Coronet
- Victor
- Vent?
Noril'sk Example: Note structural control on the foci of differentiated intrusions (turquoise)
• Why haven’t we mentioned the role of a sulphur-bearing wallrock when this is a key genetic ingredient in most published NiS ore genetic models?

• The reason is that it is not a particularly relevant or useful exploration targeting parameter, except in certain specific localized situations.
  – Significant NiS deposits occur without any proximal S-bearing wallrocks.
  – Barren associations of mafic/ultramafic magmas with S-bearing wallrocks are common.
Deposit Scale Controls and Targeting
• KEY IDEA: NiS orebodies are closely associated with magmatic conduit zones, either volcanic or intrusive, and the identification of such zones is a priority for exploration.

• KEY IDEA: In general, the largest and most dynamic conduit zones are most prospective.
Conduit Zones: High MgO (Archean Komatiite) examples

Barnes (2006)
• KEY IDEA: There are important exploration related differences between High MgO and Low MgO deposits at the deposit-scale.

  – Type 1 High MgO deposits are always at or very close to the basal contact of their host unit. Type 1 Low MgO deposits may be at the basal contact, but may also be emplaced at the upper contact internal to the unit or immediately flanking it.

  – There is a common association between strong magnetic anomalies and ore zones in High MgO deposits (related to serpentinization of host peridotites), but no such predictable association in Low MgO deposits.

  – Host magmatic units are characterized by low-aspect ratio geometries in the High MgO case and much higher aspect ratios in the Low MgO case.
• KEY IDEA: Low-MgO associated NiS deposits are commonly hosted by intrusions with highly anomalous and complex geometries, often broadly pipe-like. The Russian term “Chonolith” is used to describe these bodies.
Examples of Chonoliths from the Noril’sk Camp

Zen’ko and Czamanske 1994
Chonoliths -- more examples

Kabanga (Wolfgang Maier)

Kabanga North

Kabanga Main

Kabanga (Wolfgang Maier)

Babel-Nebo (Hronsky, 2003)

Nkomati (Li et al, 2002)
KEY IDEA: Type 1 Ore Shoots in High-MgO systems tend to plunge sub-parallel to the trend of their host primary magmatic channel, although later deformation can induce superimposed second-order plunges.

Digger Rocks Komatiite-hosted deposit, WA (Source: Western Areas Website)
KEY IDEA: Type 1 ore shoots in Low –MgO systems tend to be structurally controlled with mineralization concentrated in dilatant sites.

Voisey’s Bay Example (Geol. Surv. NF and Lab, 2000)
Key Ideas Relevant To Localized Detection Strategies

- **KEY IDEA:** Geochemical exploration (i.e. based on surface sampling) for nickel sulphide deposits emphasizes co-incident Ni-Cu-PGE anomalism because these deposits commonly occur in settings with high background nickel.

- **KEY IDEA:** Type 1 Nickel sulphide deposits are highly conductive and are good targets for detection using electromagnetic surveying.
## General Comments on Direct Detection Technologies

<table>
<thead>
<tr>
<th>Terrane Type</th>
<th>Type 1 Deposit (massive-matrix sulphide)</th>
<th>Type 2 Deposit (disseminated sulphide)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Residual Terrane</strong></td>
<td>Airborne and ground EM highly effective if few barren conductive units (e.g. black shales), however in many ore environments these are common. Surface geochemical sampling likely to be effective but may need to be tightly spaced. Historically, prospecting favourable contacts for sulphides/gossans has been very effective.</td>
<td>Surface geochemical sampling very effective because of large footprint. IP is problematic in serpentinitised ultramafics because of magnetite false-anomaly effect. In High-MgO systems, magnetics important in mapping prospective channels.</td>
</tr>
<tr>
<td><strong>Covered Terrane</strong></td>
<td>As above comments for airborne and ground EM. Important role for down-hole EM in increasing effectiveness of target drill testing.</td>
<td>As above comments for application of IP. Large target size means drill-testing relevant magnetic anomalies is a reasonably effective method in High-MgO systems.</td>
</tr>
</tbody>
</table>

**IMPORTANT NOTE:** The effective application of direct detection technology is highly dependent on the particular local situation!
• The identification of the Key Ideas that form the basic framework for understanding nickel sulphide deposits is an important step in developing successful discovery strategies.

• These Key Ideas are best identified and articulated with reference to the appropriate scale:
  • Basic NiS ore forming processes
  • Province scale targeting
  • District/camp scale targeting
  • Deposit scale targeting
Western Mining Services LLC
7343 South Alton Way, Suite 100
Centennial, Colorado 80112 USA
T: +1 (303) 210-6315
F: +1 (303) 770-0948
barton.suchomel@wesminllc.com

Western Mining Services (Australia) Pty Ltd
Suite 26, 17 Prowse St.
West Perth, WA 6005 Australia
T: +61 (0)8 9322 4601
F: +61 (0)8 9322 4602
jon.hronskey@wesminllc.com

Web Site: www.wesminllc.com