

## Advances in Ni-Cu-PGE Sulphide Deposit Models and Implications for Exploration Technologies

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### ABSTRACT

*It is commonly possible to identify groups of orebodies within one cluster or camp of temporally and spatially constrained deposits that have common empirical traits, and to then develop successful exploration technologies based on these similarities. Models developed for exploration for contact, footwall, and offset styles of mineralization at Sudbury are examples at the camp scale, whereas the models for massive sulphide and disseminated sulphide deposit types associated with the ultramafic rocks of the Yilgarn represent examples where the models have been applied on the scale of greenstone belts. Exploration at the edges of economically mineralized systems is often rewarding as the detailed quantitative data can be used to inform robust predictive models, and the exploration risk is commensurately lower. Inherent in this approach is the bias towards exploring with known technologies and models that do not consider previously unrecognized geologic settings. The risk of missing a new style of mineralization in a mature camp or mine environment or in a new geological environment is thus heightened. In greenfields exploration, data sets are often unavailable or incomplete, and successful exploration requires holistic geological models that embrace the common characteristics of nickel systems and maximize value from empirical geoscience observations that form the basis for project selection and then targeting of exploration using advanced geochemical and geophysical technologies. The petrologic characteristics of the host rocks can effectively be used to rank exploration approaches in prospective environments; for example, the petrological associations and geochemical signatures of the associated mafic and ultramafic rocks provide an indication of whether the magma is from a productive source and has equilibrated with sulphide. At the deposit scale, linkages between the abundance of metal in the sulphides within the rock and the geological context offer ways to inform geological models, and they can focus efforts to define drill targets and to better delineate orebodies. This paper summarizes the state of present understanding of the key requirements for the formation of large nickel sulphide systems. It also reviews recent advances in our understanding of these systems and illustrates how geological models are increasingly informed by an array of geochemical and geophysical data.*

### INTRODUCTION AND OBJECTIVES

Ni-Cu-PGE sulphide ores typically form by the equilibration of immiscible magmatic sulphide and silicate magma (Naldrett, 2004). The extent to which the sulphides are enriched in Ni, Cu, and platinum group elements (PGE) is then a measure of not only the composition of the parental magma, but it is a function of the inherent efficiency of the chemical and physical processes of equilibration between the two melts (Naldrett, 2004). Without a common set of empirical characteristics together with technologies based on geochemistry and geophysics, we are challenged to recognize metallotects with the potential to host economic concentrations of Ni sulphide mineralisation; exploration expenditures on drilling and delineation depend on the right choices.

Several features are common to igneous systems that contain Ni sulphide mineralisation; these have been referred to as 'key

features' (e.g., Keays and Lightfoot, 1994), and they are commonly used in evaluation of exploration opportunities. Some of the principal observations that relate to many, but importantly not all, major Ni sulphide deposits include such features as available source of metals (mafic and ultramafic magmas), a source of S to saturate the magma (e.g., sulphidic black shales), gravitational segregation of dense immiscible sulphide liquid, and concentration of the sulphides into physical traps at the base of intrusions, within conduits, or in rock bodies emplaced in transpressional shears. Geochemical characteristics attendant with these traits include a within-plate magma signature (with the obvious exception of Sudbury, which is a crustal melt sheet; see below), depletion of the silicate melt in Ni, Cu, and PGE due to the removal of sulphide melts (into which these elements strongly partition), and contamination of the magma by assimilation of continental crust. The geophysical signatures of Ni systems can (but don't always) include magnetic high signatures, gravity highs, and/or either conductivity (due to the

presence of massive sulphide) or chargeability (due to disseminated sulphides). In order to apply geophysical approaches in greenfields settings, the right target environment must be selected, and this demands a combination of basic geoscience information such as geological observations, petrologic and geochemical data, and structural studies.

The salient goal of this paper is to critically evaluate the foundation for the application of the geophysical approaches discussed in King (this volume), and places special emphasis on three principal areas: 1) The spatial location(s) of the orebodies relative to the host rock body, and the morphology and structure of the latter. 2) The empirical petrological associations that are commonly exhibited by massive sulphides in the presence of chaotic assemblages of igneous rocks with varying textures and inclusions. 3) Establishing the geochemical fingerprint of igneous systems that contain magmatic Ni-Cu-PGE sulphides, and then using these fingerprints to advance brownfields and more mature exploration projects.

### COMMON GEOLOGIC TRAITS OF MAJOR NICKEL CAMPS

There are numerous studies that illustrate the common characteristics of clusters of nickel sulphide orebodies that comprise deposits or groups of deposits within so-called 'nickel camps' or 'significant clusters'. This section of the paper examines in different levels of detail some of the key characteristics of the world's eight most important camps: Noril'sk (Russia), Sudbury (Ontario), Voisey's Bay (Labrador), Pechenga (Russia), Thompson (Manitoba), Raglan (Quebec), Kambalda and the Yilgarn komatiites (Western Australia), Jinchuan (China), along with smaller deposits in China (Hong Qi Ling in Jilin Province and Karatungka in the Xinjiang Autonomous Region).

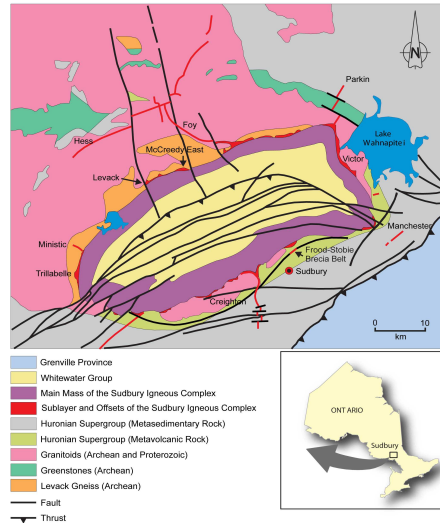
#### Sudbury, Ontario, Canada

Sudbury competes with Noril'sk as one of the two principal producers of nickel and for ranking as the world's largest nickel deposit. Sudbury is one of the largest mining camps, and some of the mines have been in near continuous operation for over 100 years. The Sudbury Igneous Complex (SIC) is a 1.85 Ga elliptical rock body that is located on the boundary between the Superior Craton and the Proterozoic Huronian Belt to the South (Figure 1). The SIC is subdivided into a lower sequence of noritic rocks, a central sequence of gabbroic rocks, and an upper sequence of granophyre (Naldrett and Hewins, 1984; Figure 2a). The SIC is widely accepted to be the product of a meteorite impact event (Grieve, 1994; Grieve et al., 1991; Figure 2a), and the process that gave rise to the ores has now been reconciled with this genetic model (Lightfoot et al., 1997a, b, 2001b; Keays and Lightfoot, 2004; Lightfoot and Farrow, 2002). Nickel

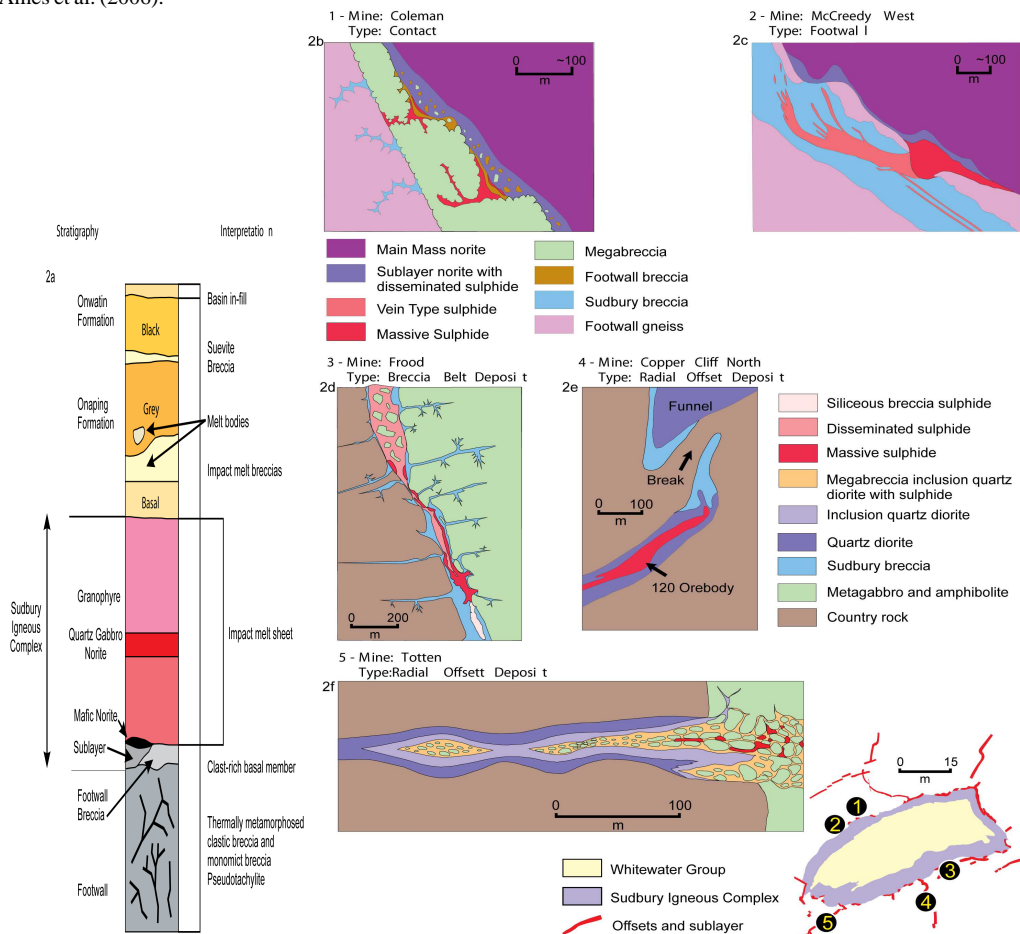
sulphide mineralisation is located proximal to the base of the SIC in three principal environments (Figure 2b-f):

1. The Sublayer, a discontinuous unit of inclusion-rich igneous-textured norite and metamorphic-textured granite located in depressions at the base of the SIC. The mineralisation in the noritic Sublayer is typically disseminated or forms the matrix to a breccia; leucocratic footwall breccias often contain lenses of massive and disseminated sulphides (Figure 2b-c; Morrison, 1984; Morrison et al., 1994). Mineralisation occurs in both small embayments (~500 m wide, 500 m long, and ~200 m deep) and sometimes as more continuous zones within troughs (~1 km wide, ~1 km deep, and extending for over 3 km), but there is no clear relationship between the scale of these embayment features and the size of the ore deposit (e.g., historically, Creighton Mine has >200 million tonnes (Mt), whereas the Trill embayment is similar in size, but it contains an order of magnitude less mineralisation; Figure 1).
2. Mineralisation associated with radial dykes of quartz diorite and in association with quartz diorite in a concentric breccia belt that flanks the southern part of the SIC. These dykes are termed 'Offset Dykes'. Within the Offset Dykes and Froid-Stobie Breccia Belt (Figure 2d-f) the mineralisation occurs in plunging lenses of inclusion-rich quartz diorite distributed at irregular intervals along the Offset Dykes. Some Offset Dykes host economic mineralisation (e.g., the Copper Cliff deposits), whereas others contain only small amounts of weakly disseminated sulphide (e.g. the Foy and Ministic Offset Dykes; Figure 1).
3. The immediate footwall of the SIC is commonly strongly brecciated with the development of pseudotachylite vein systems; these vein systems are cross cut by a Cu-rich vein style of mineralisation that is locally referred to as "footwall mineralisation" (Figure 2c). The mineralisation forms sharp-walled veins that cross cut the Archean gneisses for distances of several hundred metres away from the original base of the SIC and as continuous zones for distances of up to 1 km; locally these veins are associated with patches of trace disseminated sulphides that carry elevated precious metal abundance levels.

At Sudbury, there are a large number of deposits which share features of one of these groups; thus ore deposit models for the Sudbury nickel deposits are influenced by the very specific and unique relationships that developed in response to a combination of meteorite-impact, crustal melting, protracted differentiation of superheated sulphide saturated silicate magmas, gravitational accumulation of the sulphides, and remobilization into dilational structures in the footwall (Morrison et al., 1994). Geological exploration models are supported by deposit-scale surface and borehole geophysical surveys that effectively image the strongly conductive sulphide mineralisation in the absence of significant spurious conductivity due to barren sulphides in the country rock (Polzer, 2000; King, this volume; King et al., 2006).



**Figure 1:** Geological of the Sudbury Igneous Complex, showing the location of the Sublayer and Offset dykes at the outer margin of the Main Mass. Modified after Ames et al. (2006).

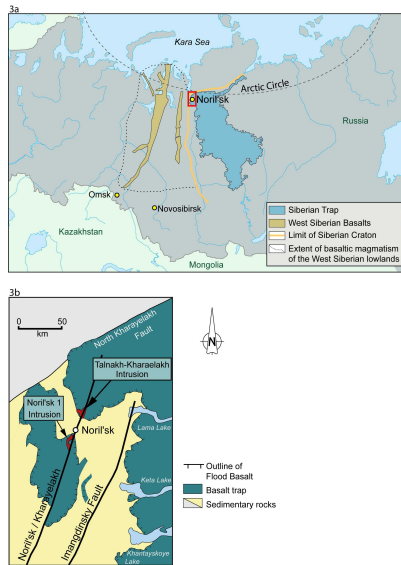


**Figure 2:** a) Stratigraphic and geological relationships in the SIC and their interpretation according to the meteorite impact hypothesis (based on Grieve, 1994 and Grieve et al., 1991). TZQG – Transition Zone Quartz Gabbro. Geology of the main types of Ni sulphide ore deposits at Sudbury. b) Contact type example from Coleman Mine; c) Contact and Footwall Type from McCreedy West Mine; d) Quartz diorite and Sudbury Breccia in the Frood-Stobie Breccia Belt at Frood Mine; e) Offset type mineralisation as represented by the development of mineralisation at primary discontinuities in the Copper Cliff Offset at Copper Cliff North Mine; f) Offset type mineralisation as represented by the Totten Deposit in the Worthington Offset. Modified from Farrow and Lightfoot (2002).

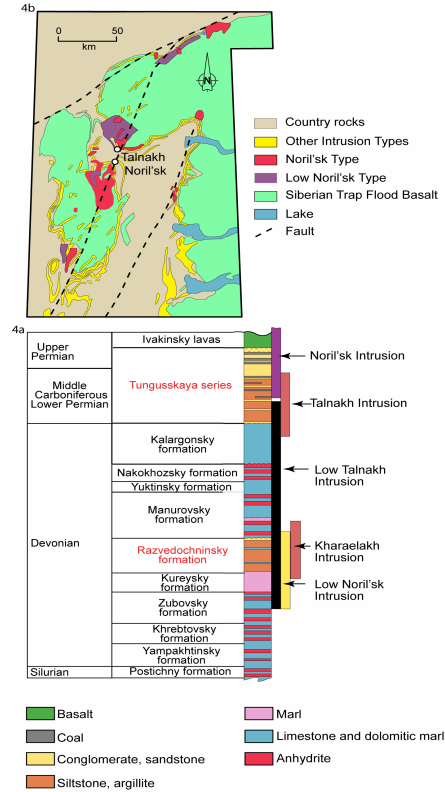
### Noril'sk, Russia

Mineralised intrusions at Noril'sk (Figure 3a-b) are within Devonian and Permian sedimentary rocks and the basal trachybasaltic and tholeiitic members of the Siberian Trap continental flood basalt (Fedorenko, 1991; Fedorenko et al., 1996; Figure 4). The three principal mineralised intrusions are Kharaelakh and Talnakh near the City of Talnakh, and Noril'sk I near Noril'sk City (Figures 4b and 5a-b). The intrusions partly replace argillites, shales and marls in preference to dolomites, limestones and evaporites, and the ~200-500 m wide metamorphic halos traditionally ascribed to flow of large volumes of magma through open system conduits are now interpreted to be due to apophyses extending from the flanking edge of the intrusion (Zotov, 1989; Figure 6). There are four principal mineralisation types associated with the Kharaelakh Intrusion (Figure 7) that are classified on the basis of spatial distributions, associations with silicate rocks, and metal contents and tenors of the sulphide:

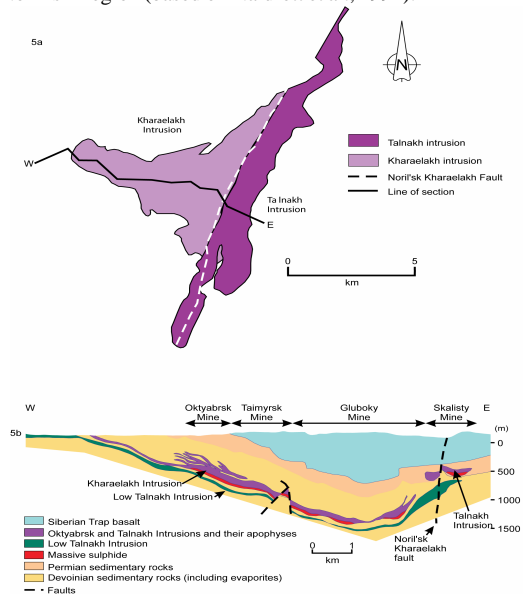
1. Massive Ni-rich ores developed at the lower contact or in the underlying sedimentary rocks (Figure 7).
2. Breccia ores at the upper exocontact (Cuprous Ores) of the Kharaelakh Intrusion or the lower exocontact of the Talnakh Intrusion (Figure 7).
3. Disseminated sulphide ores within the picritic gabbrodolerites and a group of rocks that have variable textures with inclusions and vesicles that are termed taxitic gabbrodolerites.
4. Low-sulphide platinum group element mineralisation associated with pegmatoidal rocks developed near the roof of economically mineralised intrusions (Sluzhenikin et al., 1994).



**Figure 3:** a) Distribution of Siberian Trap flood basalts in the Noril'sk Region, and the west Siberian Lowlands (after Yakubchuk and Nikishin, 2004); b) Distribution of Siberian Trap lavas at Noril'sk, and location of the Noril'sk I, Talnakh, and Kharaelakh Intrusions (after Naldrett et al., 1992)



**Figure 4:** a) Stratigraphy of the sedimentary package beneath the flood basalts of the Noril'sk Region, showing the position of the mineralised Noril'sk I, Talnakh and Kharaelakh Intrusions (after Czamanske et al., 1995); b) Distribution of principal intrusion types in the Noril'sk Region (based on Naldrett et al., 1992).



**Figure 5:** a) Map showing the location of a broadly east-west section through the Kharaelakh and Talnakh Intrusions; b) East-west section showing the stratigraphic position of the Kharaelakh and Talnakh Intrusions, and the thickness variations in the Talnakh and Low Talnakh Intrusions, and the location of thicker zones of mineralisation (after Naldrett et al., 1992)..

Ores at Noril'sk are spatially associated with the Devonian sulphate-laden sedimentary rocks, and this is commonly considered to be the source of the sulphur in the Noril'sk ores (e.g., Naldrett et al., 1992 and references therein). However, the intrusions replace shales and marls rather than evaporites, and ~1-2 m angular xenoclasts of anhydrite occur within the intrusion show no indication of partial melting or assimilation. The intrusion almost entirely "replaces" silts of the Razvedoochninsky Formation (Zotov, 1989). In places the interstices between anhydrite crystals are filled by sulphide, but the textural evidence for assimilation of the sulphate is weak (Figures 4 and 6).

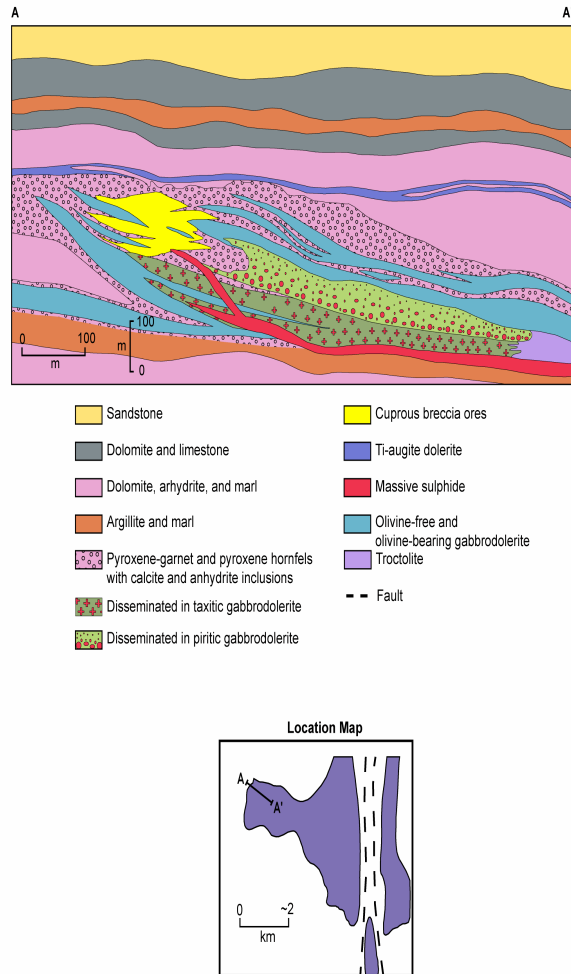


Figure 6: Detailed geological relationships in the western part of the Kharaelakh Intrusion (Lightfoot and Zotov, 2007).

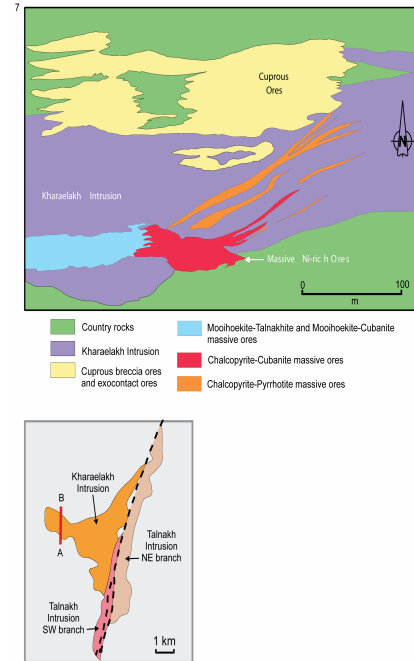


Figure 7: Distribution of principal ore types in the Kharaelakh Intrusion (after Lightfoot and Zotov, 2007).

### Kambalda, Western Australia

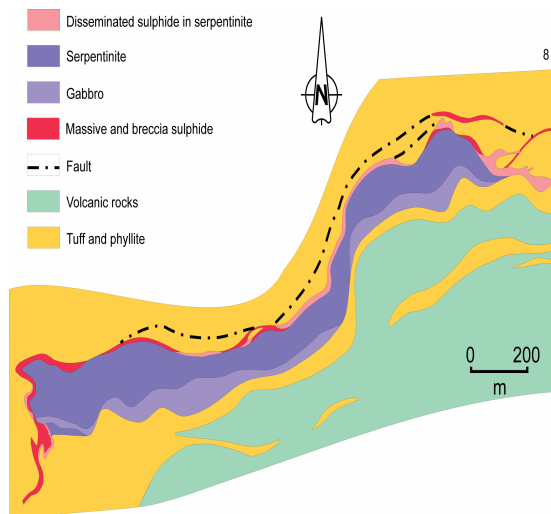
Another example of a cluster of deposits that share common geological and petrological associations is the Kambalda style of komatiite-hosted nickel sulphide deposits (e.g., Leshner and Keays, 2002). Here, the mineralisation is interpreted to have developed as 'ore shoots' in either one of two processes, flow erosion or structural remobilization. In the former, mineralisation is interpreted to have developed in trough-like depressions that cut down through the stratigraphically underlying metasedimentary and metavolcanic rocks at the base of thickened parts of komatiite flows (Leshner and Keays, 2002). In the later, mineralisation found along structural lineaments at the base of komatiite flows is interpreted as remobilised sulphide (Stone et al., 2005). Notwithstanding the details of this complex debate, the geological and petrological relationships in the stratigraphic sequence of the flows has proven an enormously useful predictive tool for the identification of new 'shoots' and extensions of mineralisation at Kambalda. There are other examples of channelized komatiite-hosted nickel sulphides in the Yilgarn (e.g., Black Swan; Dowling et al., 2004; Hill et al., 2004), and in many respects the broad similarity in empirical geological relationships forms the cornerstone of an exploration model. A second group of deposits is associated with ~1 km thick olivine accumulate rocks of the type found in the Mt. Keith ultramafic intrusion (e.g., Leshner and Keays, 2002).

An increased willingness to explore in non-traditional environments that are structurally displaced from the original ultramafic host has boosted exploration success in the Yilgarn. A classic example is the Rocky's Reward deposit that appears to be structurally detached from the Perseverance ultramafic body

(de Vitry et al., 1998). Another example is the Emily Anne Deposit in the Lake Johnson Greenstone Belt, Western Australia. As our knowledge of the increased diversity in geological and petrological associations grows within this group of komatiite-associated nickel deposits, so too do the challenges of developing reliable holistic exploration models.

**Raglan, Quebec, Canada; Thompson, Manitoba, Canada; Pechenga, Kola Peninsula, Russia**

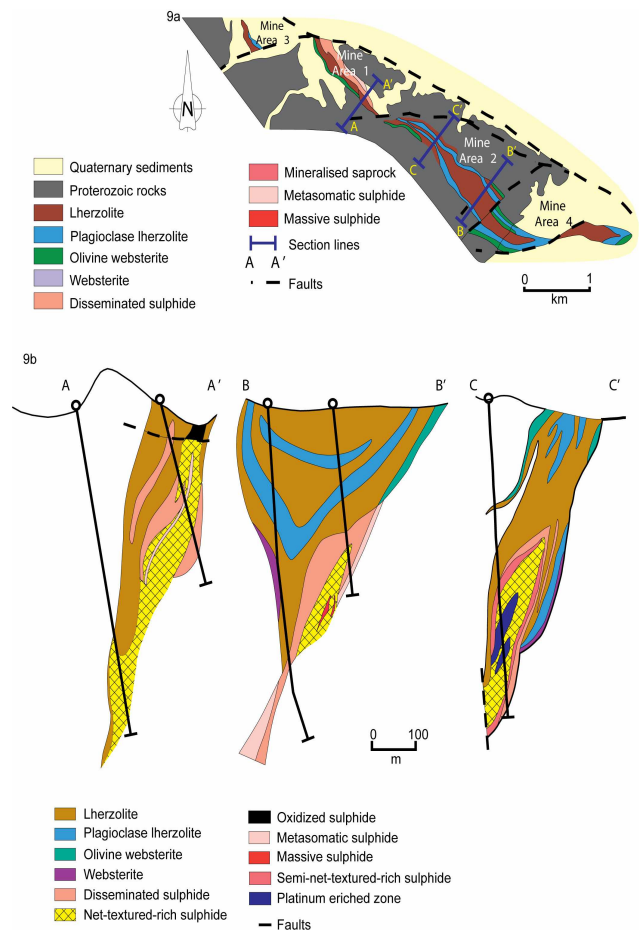
Economically significant nickel sulphide mineralisation is associated with primitive high-Mg rocks from the Raglan Belt in northern Quebec (Lisher, 2007), the Thompson Nickel Belt, northern Manitoba (Layton-Mathews et al., 2007), and the ferropicritic intrusions of the Pechenga Belt (Smolkin et al., 1997; Laverov, 1999). In each case mineralisation is broadly related to variably altered and deformed ultramafic rock bodies, but at Thompson, the relationship between primary intrusions and mineralisation is obscured by four recognized phases of deformation (Layton-Mathews et al., 2007). Geological relationships in the Pechenga deposit share some of this same structural complexity, but the economically important disseminated sulphide mineralisation is unequivocally associated with the ultramafic bodies in the Zhandovkoye Intrusion at Pechenga (Figure 8). The same is true of the disseminated and locally more massive Ni sulphide mineralisation from the Birchtree Mine in the Thompson Nickel Belt (Layton-Mathews et al., 2007). In contrast, more massive Ni-rich mineralisation tends to occur proximal to either small boudins of serpentinized ultramafic rock (e.g., the Thompson Mine in the Thompson Nickel Belt) or at the lower contact and along structures parallel to this contact as exhibited by the ores at Zapolyarny in the Pechenga Belt (Smolkin et al., 1997; Figure 8). Raglan is the least structurally complex of this group, and in many places the orebodies appear to have structurally modified associations with trough-like depressions in the stratigraphic base of the ultramafic rock sequence (Lisher et al., 2007).



**Figure 8:** Geological map of the Zapolyarny Intrusion, Pechenga Greenstone Belt (after Laverov, 1999).

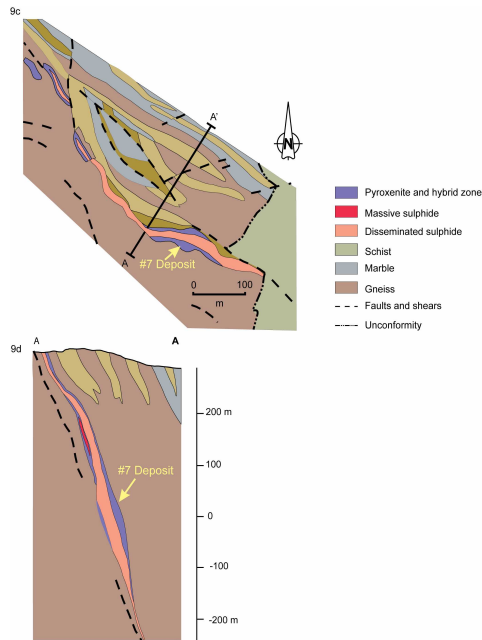
**Jinchuan, China**

Nickel sulphide deposits in China are commonly associated with small intrusions that have exceptionally high sulphide/silicate rock ratios, and can contain one or more ore zones within the structurally controlled intrusions or rock bodies. Jinchuan is China's largest nickel deposit, with historic and current resources and reserves estimated to be at least 500 Mt grading 1.2 wt.% Ni (Chai and Naldrett, 1992); it is developed in a structural zone which runs parallel to the Proterozoic-aged Longshushan Belt. Ores are principally disseminated within plagioclase lherzolite that comprises the principal rock type (Figure 9a-b). The rock body has both primary and structurally modified contacts, and when projected to surface, has an area of approximately 1.5 km<sup>2</sup>. Several other Ni deposits in China are marked by the association of large quantities of mineralisation with very small volumes of mafic-ultramafic rock; one of the most extreme examples is the Hong Qi Ling Deposit in Jilin Province (Figures 9c-d; Tang, 1993; Zhou et al., 2002).



**Figure 9:** a) Geological map of the Jinchuan rock body showing the distribution of rock types, key structures, and sections (after Tang, 1993; Tang et al., 1992; Tang and Barnes, 1998); b) Sections through three of the profiles shown in Figure 4a (after Tang, 1993)

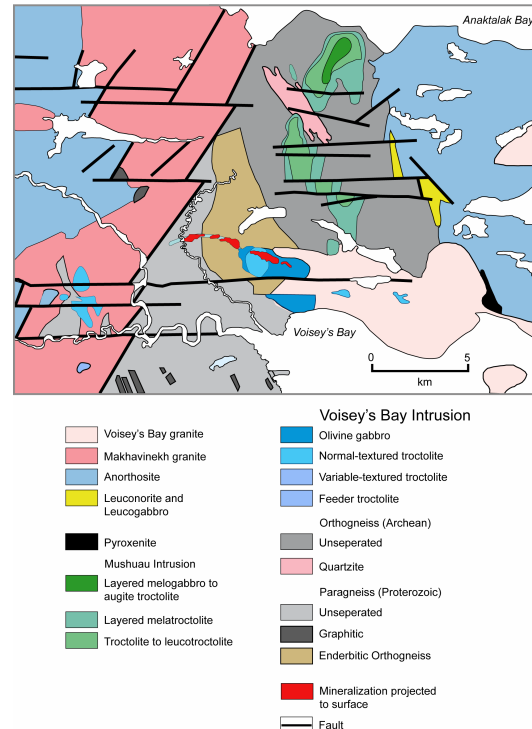




**Figure 9:** c) Geological map of the Hong Qi Ling Number 7 Deposit in Jilin Province, China (after Tang, 1993); d) Section showing the form and distribution of sulphide mineralisation in the Number 7 Deposit at Hong Qi Ling (after Tang, 1993).

### Voisey's Bay, Labrador, Canada

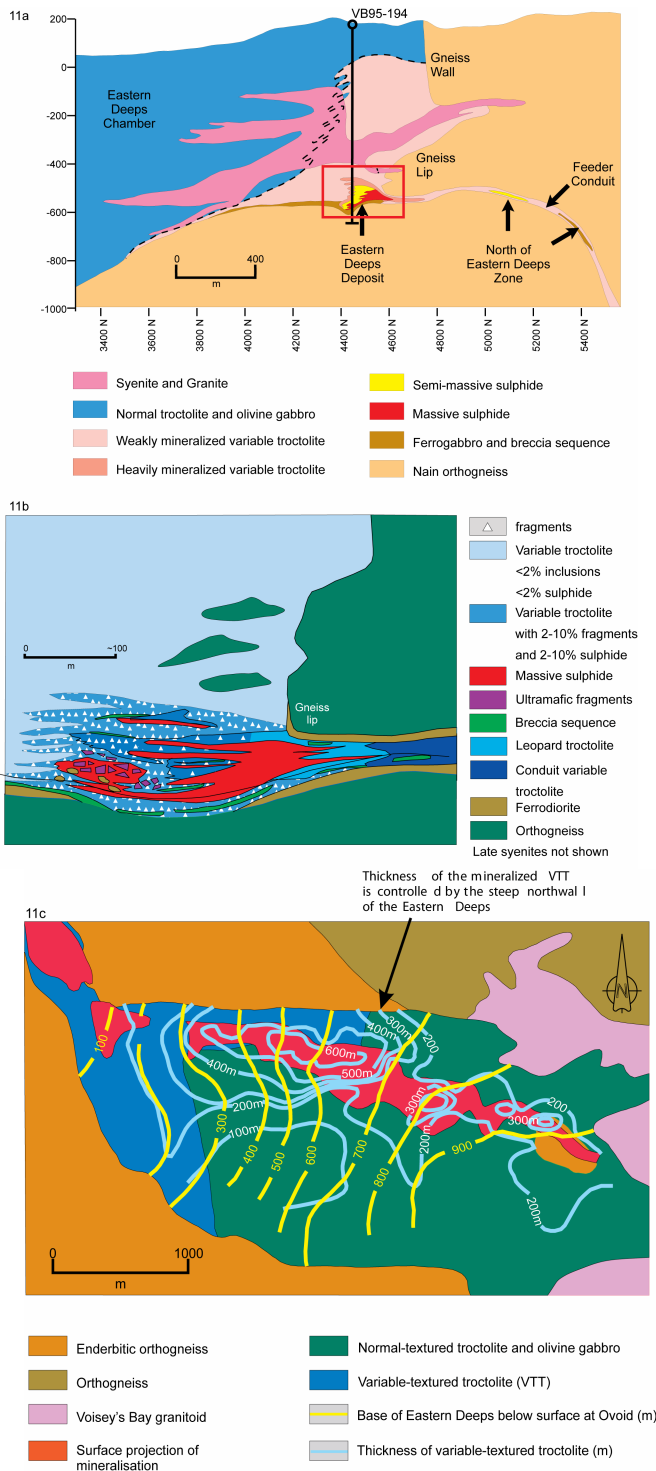
The most significant recently discovered Ni sulphide deposit is at Voisey's Bay, Labrador, Canada. The Voisey's Bay Intrusion consists of a series of 1.34 Ga olivine gabbros, troctolites, ferrogabbros, and ferrodiorites that are within the anorthositic Nain Plutonic Suite. The deposit is associated with a pair of small intrusive bodies termed the Eastern Deeps (Figure 10) and the Western Intrusion that are linked by a conduit dyke. The intrusions and the associated mineralisation are associated with west-east oriented structures (Evans-Lamswood et al., 2000) that cross-cut at right angles the broad boundary between the Proterozoic-aged Churchill paragneiss to the west and the Archean Nain Orthogneiss to the east (e.g., Lightfoot and Naldrett, 1999). Mineralisation is spatially related to recrystallized inclusions of Churchill paragneiss (Li et al., 2000) that are of a very different source when compared to the immediately adjacent paragneiss. The Ovoid Deposit is located at what is interpreted to be a dilation in the conduit dyke [an alternate interpretation is that it is at the entry point of the conduit into a now-eroded magma chamber (Lightfoot and Naldrett, 1999)]; the Eastern Deeps Deposit is located at the entry point of the conduit into the Eastern Deeps Chamber (Figure 11a), and the location of the mineralisation is principally controlled by the injection of massive sulphide and sulphide-laden magma from depth into the Eastern Deeps chamber (Figure 11b; Lightfoot and Naldrett, 1999). Other deposits like the Reid Brook Zone are associated with the same conduit, or with immediate country rock structures (Lightfoot and Naldrett, 1999)



**Figure 10:** Geological map of the Voisey's Bay deposit area (after Lightfoot and Naldrett, 1999)

### PETROLOGICAL ASSOCIATIONS IN CHAOTIC ROCK ASSEMBLAGES

A key feature of many of the large Ni-Cu sulphide systems is the association of the ores with rocks that have unusually chaotic or variable assemblages of minerals and/or inclusions of country rocks, cogenetic cumulates and/or materials of unknown source. Sudbury is the classic example; here the ores at the lower contact are associated with noritic rocks that contain both country rock inclusions and a suite of what have been previously referred to as 'exotic inclusions' (Pattison, 1979; Plate 1). The exotic and country rock inclusions yield 1.85 Ga ages that coincide with the age of the SIC (Corfu and Lightfoot, 1997). The origin of the exotic inclusions is unclear, but they may be cogenetic and originate by incomplete assimilation of melted patches of precursor mafic-ultramafic country rock (e.g., Lightfoot et al., 1997b). In almost all deposits at Sudbury, the ores occur in direct association with these inclusion-rich noritic rocks in the Sublayer, or are associated with inclusion-rich quartz diorites in the Offset Dykes and the Froid-Stobie Breccia Belt (Lightfoot and Farrow, 2002). Exploration models at Sudbury embrace the importance of inclusion-packed noritic rocks and breccias as a key requirement for assessing exploration potential. The potential that contact mineralisation has migrated into the underlying footwall breccias is commonly indexed to the extent of thermal recrystallization of the breccia matrix (e.g., Morrison, 1984; Morrison et al., 1994). Mineral zones with evidence of extreme recrystallization and partial melting are commonly the locus of orebodies that have migrated into the breccias from the contact environment.



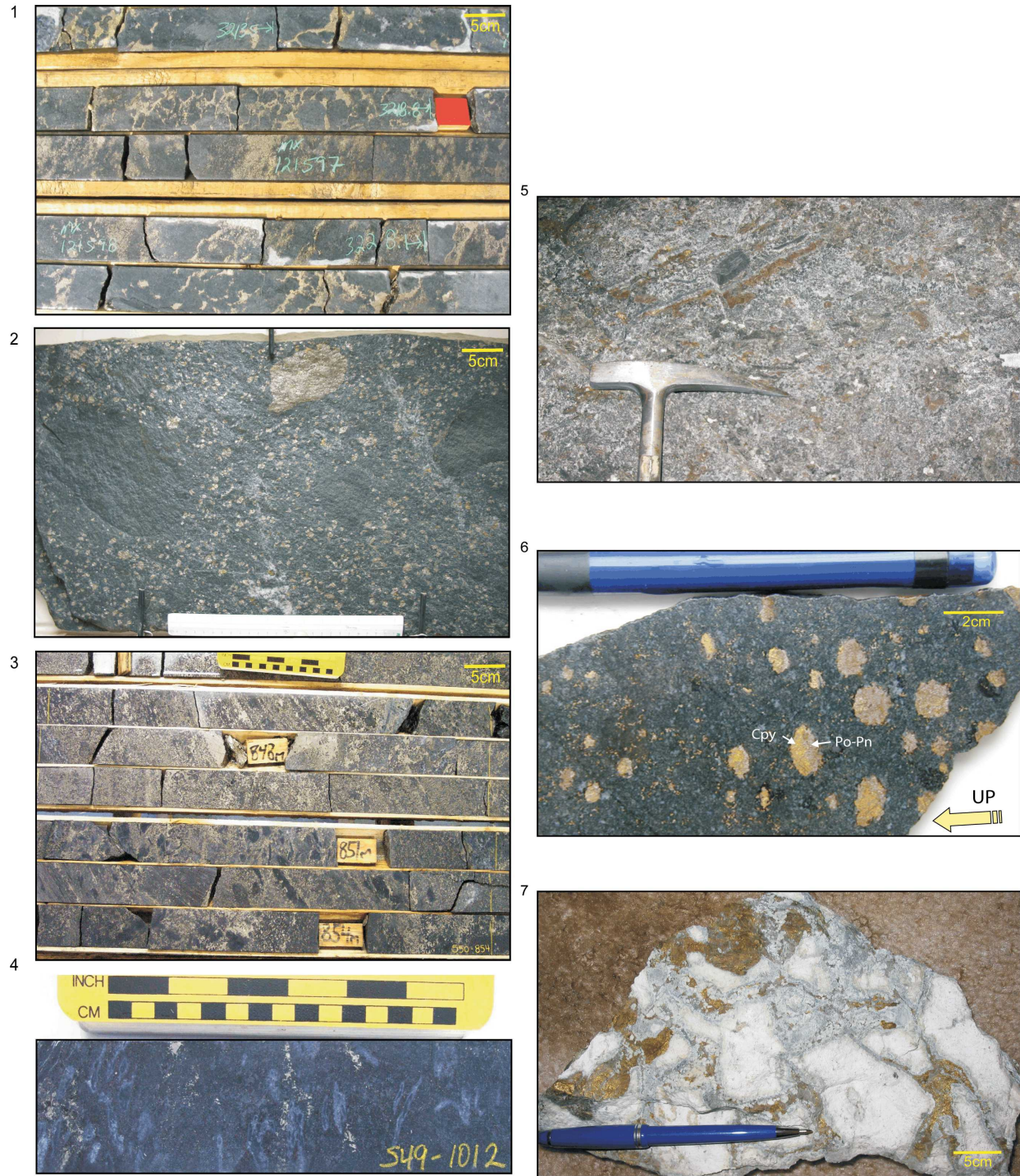
**Figure 11:** a) West-facing geological section through the Eastern Deeps Deposit at Voisey's Bay (after Lightfoot et al., 2001); b) Detailed geological relationships in the Eastern Deeps orebody (Lightfoot and Naldrett, 1999); c) Isopach map showing the thickness variations in the mineralised variable-textured troctolites of the Eastern Deeps Intrusion, and the depth to the base of the intrusion (after Lightfoot et al., 2001).

Chaotic assemblages are also developed at Voisey's Bay where an inclusion-packed magmatic breccia sequence is spatially associated with the ores, and a domain of troctolite with very variable grain size, mineralogy, and inclusion content forms a halo around the Eastern Deeps deposit and is spatially associated with the massive and heavy disseminated sulphide ores in the conduit dyke (Lightfoot and Naldrett, 1999). Figures 11a-b illustrate the spatial association of these rocks with the massive ores in the Eastern Deeps deposit. Typical examples of variable troctolite with different proportions of inclusions are shown in Plate 3. The inclusions have reacted with the Voisey's Bay magma; based on their chemical and mineralogical compositions, they originated from sulphide-rich paragneiss units of the Proterozoic-aged Tasiuyak Gneiss country rocks. Although there is compelling evidence for reaction between the inclusions and the melt (Li et al., 2000), the largest component of assimilation of country rock evident in the main intrusion results from assimilation and incorporation of Archean-aged Nain orthogneiss (Li et al., 2000). This has posed a conundrum because there is limited evidence for major assimilation of the more sulphidic country rock gneiss, and overwhelming evidence for assimilation of the typically sulphur-poor Nain orthogneiss. This has led to speculation that the formation of the ores took place by assimilation of largely country rock sedimentary sulphide within an atypical unit of the Tasiuyak Gneiss, where the observed inclusions are fragments of only partially reacted silicate sedimentary layers (Lightfoot and Zotov, 2007).

The intrusions at Talnakh and Noril'sk also show a close spatial association of variable-textured olivine gabbrodolerite rocks that contain highly resorbed inclusions containing hercynitic spinels; these form ghost textures of the original inclusions (Plate 4). These rocks are termed 'taxites', and they are a key host for the disseminated sulphides in the picritic gabbrodolerites of the differentiated Noril'sk I (Plate 5), or in picritic gabbrodolerites of the differentiated Talnakh and Kharaelakh Intrusions that carry massive sulphide ores and breccia ores. The importance of taxites has been the subject of enormous debate in the Russian literature; some views consider the taxites to be the product of migration of fluids through the magmas (e.g., Zotov, 1989), whereas others view them as primary magmatic textures formed within compositionally variable or mingling magmas (e.g. Naldrett et al., 1992 and references therein). The empirical association between massive sulphides and taxites is rarely clear. Even though Ryabov et al. (2000) show that the massive sulphide zones are partially contained within domains of taxitic gabbrodolerite, there is much evidence to suggest that the massive ores and disseminated ores were introduced in two or more separate pulses of magma (e.g. Lightfoot and Zotov, 2007). Much of the mineralization at Talnakh is in the lower exocontact (e.g., cuprous breccia ores shown in Plate 6), whereas the Kharaelakh Intrusion is marked by the development of upper exocontact ores that are locally termed the Cuprous Ores (Figure 7).

Although it is a feature found in many other small to medium-sized Ni sulphide ore deposits, not all deposits have a clear association with chaotic rock assemblages. As an exploration guide, it is important to emphasize that three of the largest deposits exhibit these features, and so chaotic rock assemblages are typically viewed as encouraging in exploration within these camps.





**PLATES 1-7:** Plate 1: Inclusion-rich Sublayer from the Creighton 402 embayment, Sudbury Igneous Complex; Plate 2: A sample of inclusion quartz diorite from Frood Mine with inclusions of recrystallized gabbro and fragments of sulphide within mineralised diorite (see also Pattison, 1979); Plate 3: Strongly mineralised breccia sequence rocks from the Eastern Deeps (after Lightfoot et al., 2001); Plate 4: Weakly mineralised breccia sequence rocks from the Eastern Deeps (after Lightfoot et al., 2001); Plate 5: Taxitic gabbrodolerite with inclusions containing hercynite spinel from Komsomolsk Mine, Talnakh Intrusion (after Lightfoot and Zotov, 2007); Plate 6: Blebby disseminated sulphide in picritic gabbrodolerite from Oktyabrsk Mine, Kharaelakh Intrusion (after Lightfoot and Zotov, 2007); Plate 7: Mineralised breccia from the lower exocontact at Komsomolsk Mine, Talnakh Intrusion. The fragments are bleached country rock shales that have been heavily metasomatized (after Lightfoot and Zotov, 2007).

### CHAMBER GEOMETRY AS A CONTROL ON ORE LOCALIZATION

A feature of many large Ni sulphide deposits is the association of their ores with the lower contact of an intrusion or flow, or the localization of mineralization within dyke-like conduits. Some of the parallels between different deposits are quite striking. For example, the conduit assemblage ores at Voisey's Bay are typically localized within the dyke at locations where there is a dilational jog or feature (Lightfoot and Naldrett, 1999). In the case of the Reid Brook Zone at Voisey's Bay, the massive ores, inclusion-rich massive ores, heavy disseminated sulphides, and mineralized olivine gabbros occur within the dyke in zones that are separated by weakly mineralized olivine gabbro and troctolite. The massive sulphides can occur outside of the dyke along sub-horizontal structures. These zones consist of massive sulphide mineralization that is compositionally similar to the massive sulphide in the dyke, but it is localized along flat-lying structures and possibly parallel structures that offered dilations for injection of sulphide magma during the emplacement of the mineralization into the conduit (Evans-Lamswood et al., 2000). The marginal rocks of the dyke are typically fine-grained magnetite-rich ferrodiorites and ferrogabbros which grade into olivine gabbros. These rocks are typically devoid of sulphides. Towards the center of the dyke are domains of mineralized olivine gabbro and troctolite that contain predominantly mafic-ultramafic inclusions; in some cases there are fragments of the marginal ferrogabbro (Lightfoot and Naldrett, 1999). The petrological and geological relationships therefore point to the sequential emplacement of magmas with different compositions, sulphide content, and inclusion content. The later influxes of magma carried magmatic sulphide liquids and deposited them at locations in the system where the conduit geometry changed in width or orientation and at the entry point of the conduit into the larger Eastern Deeps chamber (Figure 11b; Lightfoot and Naldrett, 1999). Sulphides were also injected along sub-horizontal dykes and into structural openings (Evans-Lamswood, et al., 2000).

Relationships broadly similar to the Voisey's Bay conduit occur in the Offset Dykes at Sudbury. Here, inclusion-rich mineralized quartz diorite and inclusions of massive sulphide occur in a steeply plunging shoot and series of shoots in the Copper Cliff Offset (Farrow and Lightfoot, 2002). The Worthington Offset illustrates the geological relationships most clearly in outcrop at surface (Figure 2f; Lightfoot and Farrow, 2002); the geological relationships point to the emplacement of two different units. The first marginal phase of quartz diorite is devoid of sulphide and only locally contains inclusions of country rock. The second phase of quartz diorite typically occupies the core or core-margin of the Offset and contains inclusions of the first phase of quartz diorite within a matrix of quartz diorite with disseminated sulphide and bodies of more massive inclusion-rich sulphide (Lightfoot and Farrow, 2002; Figure 2f).

Conduit-like dykes and sills are also important in other deposits. At the Jinchuan and Hong Qi Ling deposits the primary emplacement of the magma took place in a transpressional opening within a regional structural zone. The ultramafic rocks contain disseminated sulphide at Jinchuan and both massive and

disseminated sulphide at Hong Qi Ling. In both cases, the volumes of sulphide relative to silicate are far too great for in situ genesis of the ores. This indicates that the sulphides were introduced in one or more stages of emplacement from a deeper chamber (Tang, 1993). The Karatungka (Zhou et al., 2002) and Uitkompst (Maier et al., 2004) deposits are examples of magma conduits that contain massive and disseminated sulphide in the lower portion of a differentiated tube-like body. These bodies might be viewed in the same way as intrusions at Noril'sk which are interpreted to be open system magma conduits in which ore formation is related to influx of repeated batches of magma which equilibrated with sulphide liquid (Naldrett, 2004) and possibly the emplacement of sulphide magmas, sulphide-laden magmas (Lightfoot and Keays, 2005) or conduits for migration of fluids that deposited metals (Lightfoot and Zotov, 2007).

### GEOCHEMICAL PROPERTIES OF MAGMATIC SULPHIDE SYSTEMS

The vast majority of Ni sulphide deposits are formed from magmas that vary in degree of evolution from komatiitic through to basaltic, but they are spatially and temporally related to within-plate magmatic activity or early rifting of the continental crust (Naldrett, 1999; 2004). Superimposed on this is the temporal relationship of many of the largest Ni sulphide systems with Carboniferous-Permian, Proterozoic, and Archean-aged rocks linked to major within-plate or rifted continental margin magmatism that are broadly distributed around cratonic margins or within cratonic tectonic assemblages in highly deformed greenstone belts.

Some deposits defy categorization with such a model, and the deposits at Sudbury are perhaps the most extreme example. Here, the melts are thought to be generated entirely by impact-associated crustal melting (Grieve, 1994). However, the vast majority of the other deposits are genetically related to mantle-derived magmas that formed within or adjacent to rift zones. For this reason, a within-plate geochemical signature helps distinguish prospective belts from less favorable belts comprising rocks derived from oceanic, arc, or alkalic settings.

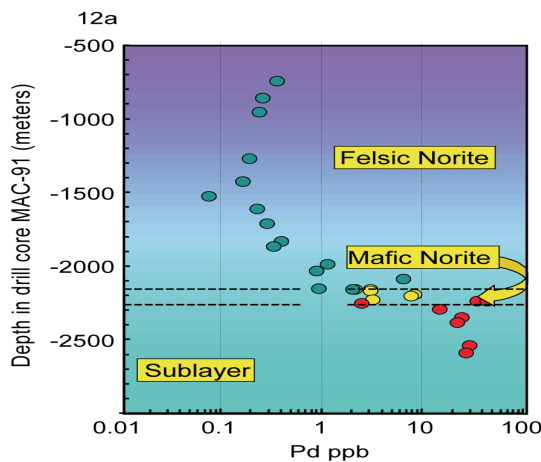
Another geochemical feature that offers immediate value in exploration is the recognition of rocks that became sulphide saturated during their migration, emplacement, and/or crystallization. Sudbury and Noril'sk are the best-characterized systems from this perspective. These two camps formed by radically different processes, yet they have some remarkable similarities in their geochemical signatures.

Sudbury ores are localized along the lower contact of the SIC, either within the Sublayer and immediate footwall, or along radial and concentric Offset Dykes. Bulk compositions of the overlying noritic rocks of the Main Mass of the SIC indicate that there are anomalously low levels of Ni, Cu, and PGE in these rocks relative to those expected in rocks with similar MgO contents (Lightfoot et al., 2001b; Keays and Lightfoot, 2004). This depletion signature is found in other sections through the SIC (Keays and Lightfoot, 2004; Lightfoot and Zotov, 2005). The observation that the thickest portions of metal-depleted norite are juxtaposed above some of the largest orebodies leads to the suggestion that the ore potential of the lower contact of



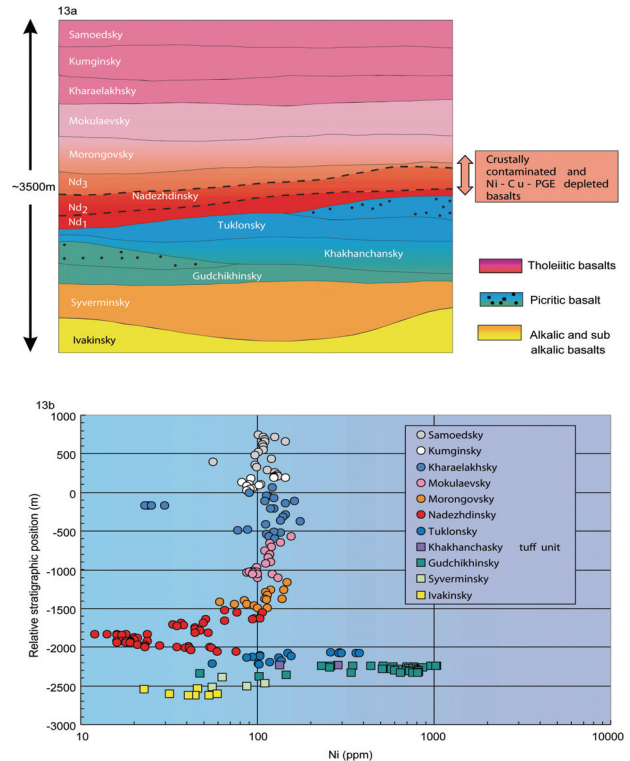
the SIC is linked broadly to the availability of metals from the overlying melt sheet. The superheated conditions of this melt promoted a very efficient saturation and segregation of immiscible sulphide to the lower contact. At Sudbury there is therefore a clear spatial relationship between the distribution of the ores and the location of the thickest portions of metal-depleted norite (Figure 12a, b).

At Noril'sk the basaltic rocks of the Siberian Trap at Noril'sk contain a voluminous unit (5,000-10,000 km<sup>3</sup>) of Ni-Cu-PGE depleted basalt termed the Nadezhdinsky Formation (Figure 13a). Isopachs of the thickness of this unit (Fedorenko, 1991), reveal that it is spatially localized over the Noril'sk Region where the mineralized Noril'sk and Talnakh Intrusions are located. Further, it is also broadly centered along a zone containing comagmatic weakly mineralized and unmineralized intrusions that are termed the Low Talnakh and Low Noril'sk Group. Lightfoot et al. (1990) first noted the very low Ni and Cu abundances of the Nadezhdinsky Formation (e.g., Figure 13b), and this observation led Naldrett et al. (1992) to propose that the voluminous Nadezhdinsky Formation basalts might be the source of the metals in the Noril'sk and Talnakh deposits. Further confirmation of this hypothesis came from detailed studies of the PGE abundance levels in the basalts rocks; Lightfoot and Keays (2005) showed that the abundance levels of PGE in the Nadezhdinsky basalts are exceptionally low, and the Pd/Pt ratios are the inverse of the ratios found in the ores. This was more compelling evidence that the signature of ore formation in the Noril'sk Region is evident in the basaltic rocks. Naldrett et al. (1992) noted that the bulk compositions of the mineralized intrusions do not match with those of the Nadezhdinsky Formation and proposed that these intrusions were the exit conduits for magmas that flowed from depth to the surface.

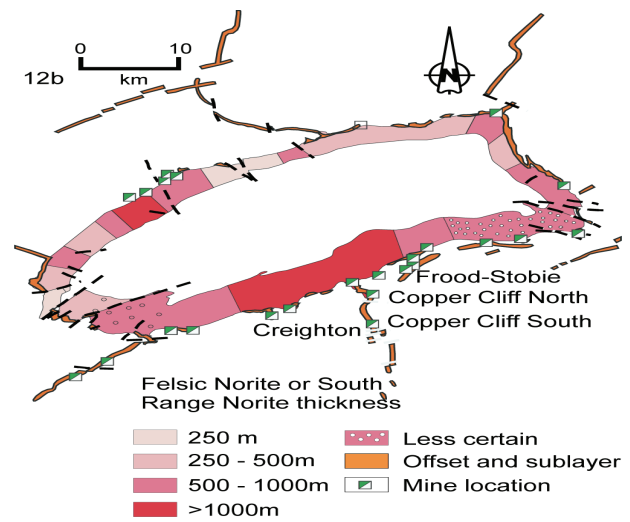


**Figure 12:** a) Pd content versus vertical stratigraphic position in Main Mass noritic rocks of drill core MAC91 located near Nickel Rim Mine (from Keays and Lightfoot, 2004); b) Schematic diagram showing the variation in the interpreted thickness of the Main Mass Felsic Norite (and equivalent South Range Norite) in different sectors of the Main Mass (after Keays and Lightfoot, 2004). Note that the thickest stratigraphy of metal-depleted noritic rocks is immediately adjacent to the giant ore deposits at Creighton, Copper, Cliff, and Frood-Stobie.

Various models have been proposed to explain the formation of the Noril'sk-Talnakh ores (e.g., Naldrett, 2004), but most of these models are based on geochemical evidence, and do not agree with the historical geological knowledge of the Noril'sk

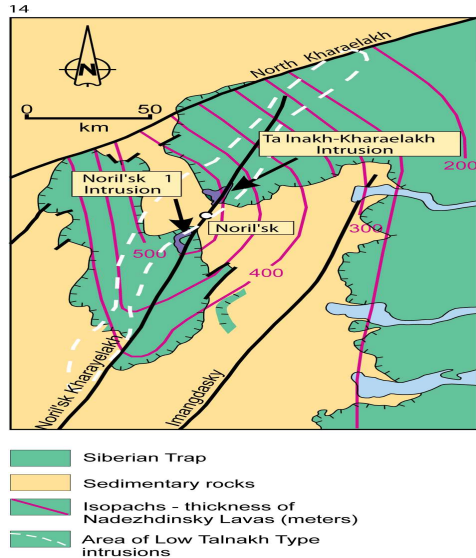


**Figure 13:** a) Stratigraphy of the basaltic rocks in the Noril'sk Region (after Lightfoot and Hawkesworth, 1997); b) Variation in Ni abundance with relative stratigraphic position in the Noril'sk Region (data sources: Lightfoot et al., 1990, 1993, 1994; Hawkesworth et al., 1995)



Region (e.g., Zotov, 1989), and so the models remain challenged and controversial (as discussed in Arndt et al., 2003). The exploration significance of these observations is compelling. There is a clear and unequivocal spatial relationship between

metal-depleted basalts and ore deposits (Figure 14), and this relationship demands better genetic models that will only come as the Russian literature is more appreciated and further research is conducted. At both Noril'sk-Talnakh and Sudbury, there is a clear relationship between the metal-depleted rocks and the presence of orebodies.

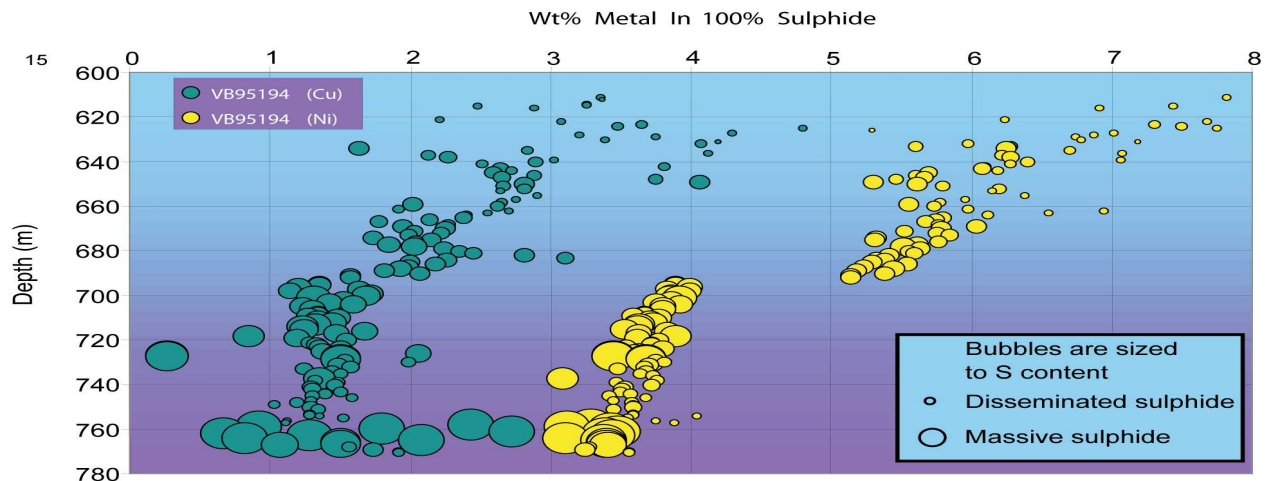


**Figure 14:** Map showing the distribution of isopachs of thickness on Nadezhdinsky Formation lavas in the Noril'sk Region (after Naldrett et al., 1992 and references therein).

A secondary feature of the silicate rocks that sourced metals at Sudbury and Noril'sk is the geochemical evidence of a large

crustal contribution to the magma (Lightfoot et al., 1990; 1997b). The role of silicate crust in stimulating sulphide saturation remains incompletely understood (Lightfoot and Hawkesworth, 1997), but the observation that some of the largest Ni sulphide systems are associated with intrusions that have contamination signatures remains an important empirical observation.

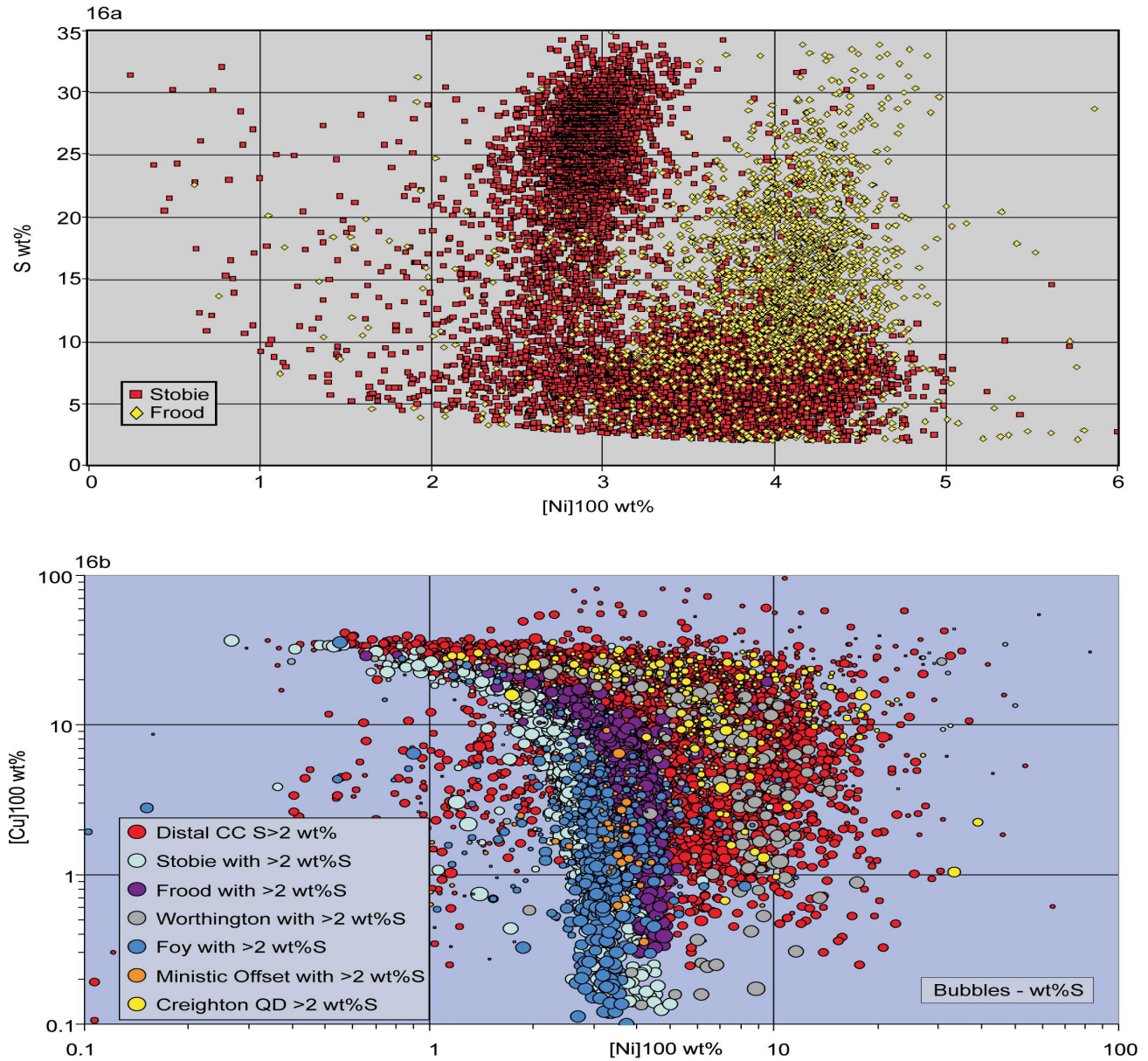
Geochemistry offers exploration value at many levels, from the regional context discussed above to the details of exploration and delineation of orebodies. The Eastern Deeps deposit at Voisey's Bay illustrates a particular example of the application of this technology. The deposit is localized at the entry point of a conduit from the north into the base of the Eastern Deeps chamber. A zone of variable-textured troctolite surrounds the massive sulphides; the detailed internal structure of the deposit has been described in Lightfoot and Naldrett (1999). Drill holes through the Eastern Deeps deposit have been subjected to very detailed assaying during exploration, and the data for one example (95VB194) are shown in Figure 15. This figure shows that the calculated metal contents in the sulphide component of the rock define two markedly different populations. Typically the higher grade massive and semi-massive ores have moderate to low metal tenors, whereas the more disseminated sulphides have very high tenors of Ni and Cu. There is a marked boundary between the two ore types which can be identified in drill core (Lightfoot et al., 2001a). The inherent value of this approach in exploration comes from its application in improving strategies of exploration and delineation drilling. In areas where there are thick intersections of low-tenor mineralization there is greater potential to discover additional resources of economic mineralization.



**Figure 15:** Variation in Ni and Cu tenor of sulphide in drill core VB95-194; bubbles are proportional in size to S concentration where a filter has been applied to exclude weakly mineralized samples for which reliable tenors can not be estimated (after Lightfoot et al., 2001a). Large bubbles are massive sulphides; smallest bubbles contain 2-5% sulphide.

The variations in metal tenor of sulphide are also significant at Sudbury. Figure 16a shows the Ni tenors calculated in sulphide where materials with low sulphide content and/or metal contents are excluded. It is clear that mineralization in some Offset Dykes such as Copper Cliff, Worthington, and Creighton is exceptionally high tenor, whereas others such as Foy and Ministic have very low metal tenor. These differences are important in the context of the expectations associated with

exploration models as well as the identification of technologies suitable for beneficiation of the ores. Froid-Stobie offers another example where major differences exist in the metal tenors of ores as a function of sulphide concentration (Figure 16b). The Froid ores have a high Ni tenor, but Stobie ores are both high and low in Ni tenor and record at least two different generations of sulphide based on petrological relationships shown in Plate 6.



**Figure 16:** a) Variation in Ni tenor of sulphide versus S concentration in assay data from the Froid and Stobie mines at Sudbury. Note the presence of two different populations of sulphide metal tenor at Stobie, but only one type at Froid; b) Variations in Ni versus Cu tenor sulphides from different Sudbury Offset dyke deposits; unpublished data: CVRD Inco Limited. Bubbles are sized to S concentration. Weakly mineralized samples for which reliable tenors cannot be estimated are not shown.



### KEY FEATURES OF LARGE NICKEL SULPHIDE SYSTEMS

A description of the details of every large Ni system is beyond the scope of this paper, but excellent accounts with a broad range of key references are given in Naldrett (1999) and Naldrett (2004). A salient point is that in most cases there are a series of common empirical traits or features that are found in each of the systems:

1. There is a tendency for the larger deposits to be associated with rocks that formed in a within-plate tectono-magmatic setting. Sudbury, however, is an exception, and there are an increasing number of deposits that are recognized as being located within arc settings. However, these are generally one or two orders of magnitude smaller than the large systems summarized above.
2. Magmatic ores that are enriched in Ni, Cu, and PGE form from magmas that were not previously S-saturated (Keays, 1995). Equilibration of the magmas with small quantities of sulphide effectively stripped out the platinum group elements.
3. The magmas must have contained significant amounts of Ni, Cu, and PGE or the magmas must have been sufficiently superheated such that protracted equilibration with magmatic sulphide efficiently removed the metals from large volumes of magma (e.g., Sudbury; Lightfoot et al., 2001b).
4. There is an empirical linkage between S-bearing country rocks and mineralized intrusions; Pechenga, Raglan, Kambalda, Thompson, Kabanga, and Noril'sk all show this association; importantly, there is no such clear spatial association at Sudbury and Jinchuan. Sulphidic black shales and marls are a ready source of S, but there is little geological evidence at Talnakh for the derivation of the sulphur from the anhydrite of the sedimentary evaporites. There remains some debate over the possible role of silicification of mafic magmas as a trigger to sulphide saturation (e.g., Lightfoot and Hawkesworth, 1997), but empirical relationships in some flood basalt sequences indicate that significant amounts of crustal contamination are not associated with metal depletion (e.g., the Deccan Trap, India; Lightfoot, 1985).
5. Efficient interaction of the magmatic sulphide with the silicate magma is required so that the sulphides attain elevated metal tenors. Sulphides must have efficiently segregated and accumulated either in situ or in deeper holding chambers. Gravitational energy provided the driving force, and so it is commonly observed that more massive Ni-Cu-rich sulphides are broadly spatially related to disseminated sulphides. For example at Voisey's Bay, the Eastern Deeps Deposit sits within a very large halo of disseminated sulphides. In contrast, the strongly mineralized large Sublayer depressions of the SIC rarely exhibit evidence of strong enrichment of disseminated sulphides within the overlying Main Mass. At Jinchuan, there are vast amounts of disseminated sulphide, but very little massive sulphide.
6. The localization of sulphides in physical depressions at the base of a flow or intrusion, within a dyke that extends out

of the Sudbury melt sheet such as the Offset Dyke deposits described in Lightfoot and Farrow (2002) provide evidence for localization due to both gravitational enrichment and injection of sulphides or sulphide-laden magmas. In contrast, other deposits like Voisey's Bay, Noril'sk, Talnakh, and Jinchuan evidently formed by the injection of either sulphide-laden magma or massive sulphide melt. The relative importance of these processes is subject to ongoing heated debate because there is a reluctance to believe that dense magmatic sulphide magmas and sulphide-laden magmas can be efficiently transported vertically over great distances. The geological relationships at Voisey's Bay and Noril'sk-Talnakh, however, provide strong evidence that this did occur.

7. Many Ni-Cu sulphide ore deposits are differentiated into Ni-rich and Cu-rich deposits. The footwall ores at Sudbury and the Ni-rich cuprous ores at Talnakh are perhaps some of the best examples of this association. Several features of magmatic sulphides have received less attention; there is commonly an association of magmatic sulphide ores with rocks that contain phlogopite mica. Some of the sulphide blebs from Noril'sk-Talnakh and Insizwa are not only differentiated into pyrrhotite-pentlandite rich bases and chalcopyrite-rich tops, but also often have a cuspsate accumulation of secondary hydrous minerals at the top of the bleb (Lightfoot et al., 1984). One interpretation is that this is simply an indication of small volumes of volatile components and compatible elements within the sulphide melt. Other explanations suggest that in large deposits large volumes of fluids (so-called transmagmatic fluids) passed through the magma conduits (Zotov et al., 1984) and this process is largely responsible for the formation of the Noril'sk ores (Zotov, 1989).
8. There is an increasing recognition that many large Ni sulphide orebodies have been modified by tectonic introduction of ductile sulphides into structural zones. These are key features of the Pechenga and Thompson deposits, and economic sulphide mineralization is present within these structures. Less well known is that some of the largest ore deposits at Sudbury (e.g., Creighton), have a significant proportion of sulphide ores hosted in structures that cut into the footwall.

### IMPLICATIONS OF GEOLOGICAL MODELS TO APPLICATIONS OF POTENTIAL FIELD DATA

Mafic-ultramafic rocks that host Ni sulphide mineralization have distinctive potential field properties which can contrast with the country rocks. Moreover, the associated disseminated and massive sulphides are typically highly conductive and commonly provide a strong conductivity contrast with the host rocks.

Magnetite is a common primary mineral or hydrothermal alteration product in mafic-ultramafic rocks. Further, such rocks have a high density that is typically greater than the adjacent rocks, by virtue of the elevated abundance of mafic minerals like olivine and pyroxene. This has led to the common utilization of airborne magnetic and ground gravity surveys in the

identification of mafic rocks (King, this volume). Gravity surveys offer a traditional means to identify dense ultramafic rock bodies where they occur in less dense country rocks. Magnetic and gravity survey data are important in Ni sulphide exploration at both the regional and property scales. However, some large Ni sulphide deposits do not possess magnetic and/or density contrasts.

In strongly deformed terrains, Ni sulphide mineralization that may have been originally associated with the lower contact of ultramafic rock bodies may have been structurally detached. Examples of this include the Semelitka Deposit, Russia that is detached from the Zapolyarny Intrusion at Pechenga (Laverov, 1999). The Thompson orebody in the Thompson Nickel Belt is associated with an exceptionally small volume of ultramafic rock, but is hosted largely within strongly deformed schist of the Pipe paragneiss unit (Layton-Mathews et al., 2007).

Small bodies of mafic-ultramafic rock can contain exceptionally large economic Ni sulphide deposits; examples include the Jinchuan Intrusion which has a projected surface outcrop area of less than 1.4 km<sup>2</sup>, yet contains a historic and present reserve and resource of over 500 Mt of mineralized ultramafic rock (Chai and Naldrett, 1992). At Sudbury, the 20-60 m wide by 14 km long Copper Cliff Offset Dyke is composed of weakly magnetic quartz diorite. This dyke contains a historic and current resource and reserve in excess of 240 Mt of mineralization. At Noril'sk, the Kharaelakh Intrusion is only 100-250 m wide, yet the enormous Oktyabrsk, Taimyrsk, and Komsomolsk deposits are all contained in an intrusion that has a volume of little more than 2-3 km<sup>2</sup> (Lightfoot and Zotov, 2007). A number of the very small producing or past-producing mines in China are associated with intrusions that are volumetrically trivial and have surface areas of less than 0.5 km<sup>2</sup> (Tang, 1993). Many of these intrusions have very high ratios of sulphide/silicate rock, but few are as extreme as the Ovoid Deposit at Voisey's Bay where, with the exception of a narrow dyke and a series of breccias at the contact, the entire body consists of massive pyrrhotite, chalcopyrite, pentlandite, and magnetite (e.g., Lightfoot and Naldrett, 1999); in other cases such as the Ovoid at Voisey's Bay the entire intrusion consists of massive sulphide. Efforts to locate these types of intrusion-bearing magnetic sulphides with higher resolution airborne geophysical methods demand careful consideration of the possible geometry of the intrusion, and interpretations that discount targets based on size should be treated with caution. Direct detection of these systems with magnetic survey methods is therefore not straightforward.

In the case of Voisey's Bay, the Eastern Deeps Deposit is hosted in troctolites and olivine gabbros, and although these have a very strong gravity signal, they are much less magnetic than the surrounding Nain Gneiss (Balch et al., 1998); it is the magnetic signature of the mineralization in the Ovoid Deposit which produces a very large magnetic high; the associated conduit olivine gabbros and troctolites themselves have a very weak magnetic signature.

Gravity data typically offer more regional constraints on the presence of buried or concealed mafic-ultramafic rock bodies or zones of anomalously dense crust where mafic-ultramafic magmatic activity may have been focused. As discussed above, the intrusions associated with nickel sulphide mineralization are often very small, so the gravity expression commonly does not

reflect the density profile of larger bodies of mafic-ultramafic rock that are developed in the root zones of magmatic activity. Direct detection of nickel sulphide systems with gravity methods is therefore challenged, although gravity data are clearly important in ranking exploration priorities on the scale of the belt.

By far the most successful method of direct detection of sulphide uses the resistive and conductive properties of magmatic sulphide orebodies. Both barren and nickeliferous sulphides are conductive and chargeable; as are carbonaceous shales and graphite, so the application is complicated in belts with such country rocks with geophysical properties that are too similar to the exploration target. Disseminated sulphides typically are unconnected, so although they can be targeted using induced polarization methods, they are rarely conductive. In contrast, massive sulphides are highly conductive, and so a range of electromagnetic survey methods has been developed to target mineralized systems by regional airborne geophysical surveying right through to exploring extensions of orebodies in existing mines using down-hole electromagnetic methods. The success of these tools is well established (see King, this volume), and it is unlikely that their position will be usurped as key tools in the exploration toolbox.

In a geological context, there is commonly a spatial association between large lenses of disseminated Ni sulphide mineralization and the presence of massive Ni sulphides. One of the best examples of this is the Eastern Deeps deposit at Voisey's Bay where the core zone of massive sulphide is surrounded by an extensive (up to 700 m thick) domain of variable-textured troctolites that show an enormous range in grain size, normative silicate mineralogy, and degree of mineralization (Li et al., 2000 and references therein). Another example is Noril'sk, where although there is a geological association between massive sulphides and mineralized rocks of the intrusion, there is geological evidence to suggest that the emplacement of these different styles of mineralization took place at different times (Lightfoot and Zotov, 2007). One consequence of this is that deposits may not be characterized by the presence of both massive and disseminated sulphide. For example, Noril'sk I intrusion contains economic disseminated sulphide mineralization but no massive sulphide.

Unfortunately, not all orebodies are surrounded by readily recognizable halos of disseminated sulphide; for example the Creighton orebodies at Sudbury are associated with two large troughs termed 'embayments' that are developed at the base of the Main Mass of the SIC. The immediately overlying noritic rocks contain disseminated sulphide in the most basal inclusion-rich noritic rocks (termed the Sublayer), but the immediately overlying noritic rocks of the Main Mass contain only traces of sulphide, and these rocks are strongly depleted in Ni (Lightfoot and Zotov, 2007). In the presence of volumetrically significant amounts of associated silicate rock, the adjacent rocks with disseminated sulphides are likely to be chargeability targets that can be evaluated with electromagnetic technologies that are sensitive to massive sulphide mineralization.

A special challenge to electromagnetic methods at Noril'sk is the fact that much of the Siberian Trap (Figure 30) is underlain by coal seams that are likely strongly conductive; presumably this limits the value of regional airborne electromagnetic survey methods. This is quite different from

Sudbury where very few of the country rocks are conductive, and the application of electromagnetic methods is very effective in geologically constrained environments (e.g., Polzer, 2000).

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