

Formation of Ni–Cu–Platinum Group Element sulfide mineralization in the Sudbury Impact Melt Sheet

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Summary

The Ni–Cu–Platinum Group Element (PGE) sulfide deposits of the Sudbury Structure have provided a major portion of the world's total nickel production and their host rocks have been the subject of numerous research studies, yet a number of perplexing problems remain to be solved. On the one hand, studies seeking to explain the formation of the Sudbury Structure have now converged on a genetic model which proposes that the Main Mass and Offset Dykes of the Sudbury Igneous Complex (SIC) were produced by crystallization of an impact-generated melt sheet. On the other hand, these models have yet to be fully reconciled with the production of the very large volume of magmatic Ni, Cu, Co, and PGE-rich sulfide mineralization and the associated mafic rock types. This paper explores this problem using new precious metal data from the Main Mass and Offset Dykes. These data are used to understand the relationships between these rocks, and to provide constraints on how the Ni–Cu–PGE sulfide ore deposits fit into the geological evolution of the Sudbury Structure.

In the two drill cores selected for study in this project, the Mafic Norite has 1–5 modal percent pyrrhotite plus chalcopyrite, and elevated Ni (40–1000 ppm), Cu (40–1140 ppm), and PGE (1.9–7.8 ppb Pd, 1.8–7.3 ppb Pt); this is overlain by Felsic Norite that contains pyrrhotite, and has a wide range in concentration of Ni (13–257 ppm), Cu (7–328 ppm), and PGE (<0.01–6.4 ppb Pd, <0.01–5 ppb Pt). For a similar range of MgO, the upper portion of the Felsic Norite unit has 5–10 times lower Ni and Cu abundances than within-plate basalts and local crustal rocks, and PGE abundance levels are mostly below analytical determination limits. Stratigraphic studies of other compositional profiles around the SIC demonstrate that this depletion signature of Ni, Cu, and PGE is widespread and developed not only above mineralized

embayments and offsets, but also above barren sections of the lower contact of the SIC.

The depletion of the upper part of the Felsic Norite in Ni, Cu and PGE is presumably due to equilibration of the magma with magmatic sulfide, and accumulation of this dense sulfide liquid. Results of modeling indicate that the parental magma giving rise to the Mafic and Felsic Norites had initial Ni and Cu contents of ~210 and 110 ppm, respectively. In addition, Ni, Cu and PGE tenors calculated in 100% sulfide from the Copper Cliff Offset average ~13% Cu, ~6% Ni, ~18 ppm Pd, and ~19 ppm Pt indicating that these sulfides had formed by fractionation from magmas that contained ~310 ppm Ni, ~310 ppm Cu, 18 ppb Pd and 19 ppb Pt. These values are factors of 3 to 5 higher than the Ni, Cu, Pd, and Pt contents of the Onaping Formation with average values of 55 ppm Ni, 48 ppm Cu, and 4.9 ppb Pd as well as the marginal sulfide-poor phase of the Worthington Offset quartz diorite, which has average values of 61 ppm Ni, 59 ppm Cu, 2.8 ppb Pd and 4.0 ppb Pt. Both the Onaping Formation and the marginal quartz diorite are believed to represent the initial composition of a large component of the melt sheet. There is therefore a fundamental problem in reconciling the initial metal contents of the SIC magma as indicated by the marginal phases of the Offset dykes and that of the Onaping Formation with the composition of the SIC magma at the times of formation of the sulfides as indicated by their Ni, Cu and PGE tenors.

It is proposed that because the SIC melt sheet was initially superheated with a temperature of 1700 °C, it was able to dissolve ~5 times as much S as it could at its liquidus temperature of ~1200 °C. It was also initially composed of an emulsion of mafic and felsic melts (Marsh and Zieg, 1999), which may have formed discrete magma cells. As the temperature of the melt sheet decreased, some of these magma cells became S-saturated and the resultant Ni-Cu-PGE sulfides settled downwards and on reaching magma cells lower in the melt sheet were re-dissolved thereby raising the Ni, Cu and PGE contents of the lower magma cells. It was from these "enriched" magma cells that precipitation of the ore-forming Ni-Cu-PGE sulfide melts eventually took place.

The mineral potential of Offset and embayment structures appears to be empirically linked to the thickness of the overlying noritic rocks; for example, the most heavily mineralized embayments and Offset Dykes are located in areas where the Felsic Norite is thickest. It appears unlikely that the entire 1-3 km-thick melt sheet was convectively mixing throughout its lateral extent, and so the heterogeneity in sulfide distribution was retained after crystallization and cooling.

Introduction

The Sudbury Igneous Complex (SIC) hosts the largest known resource of Ni, Cu and Platinum Group Element (PGE) sulfides. The historic resource exceeds 1548 million tonnes with an average grade of ~1.2 wt.% Ni, ~1.1 wt.% Cu, ~0.4 g/t Pt and ~0.4 g/t Pd (Lightfoot, 1996). The mineralization occurs within four distinct environments, viz. (1) at the base of the SIC in an inclusion-rich unit known as the "Contact" Sublayer, (2) within footwall breccias immediately beneath the Sublayer, (3) within veins up to 1000 m away from the SIC in the underlying footwall rocks, and (4) deposits associated with quartz diorite dykes known as Offsets which either extend radially away from, or occur as concentric dykes around the SIC; some of these deposits are associated with zones of

breccia that host the quartz diorite (Lightfoot et al., 2001; Farrow and Lightfoot, 2002).

The origins of the SIC and its ore deposits have long been the subject of debate. There is now compelling evidence that the Sudbury Structure (which comprises the SIC together with its footwall rocks) is the product of meteorite impact (Grieve, 1994; Dressler, 1984a, b). The meteorite impact model explains many of the unusual features of Sudbury geology. For example, the impact is believed to have been responsible for not only the strong crustal geochemical signature of all SIC rocks (Bain, 1925; Naldrett, 1989; Lightfoot et al., 1997a, b) but also the production of a melt sheet from which the Main Mass and Offsets of the SIC were produced (Grieve et al., 1991; Grieve, 1994; Golightly, 1994). Notwithstanding this, there remains considerable debate regarding whether any contribution of mantle-derived magma is required to generate the more melanocratic rocks of the SIC and the associated Ni-Cu-Co-PGE-enriched magmatic sulfide ores (Naldrett, 1989; Lightfoot et al., 1997a). Moreover, the role of mafic target rocks (e.g. Early Proterozoic mafic volcanics and intrusions) and possible proto-ores in these rocks needs to be considered in the formation of the SIC (cf. Keays et al., 1994). The coincident location of the Sudbury Structure on the trend of a regional gravity high in the Southern province is an interesting observation (Gupta et al., 1984), and may indicate the presence of some anomalously dense mafic crust as represented by Paleoproterozoic mafic intrusions.

Our goals in this contribution are four-fold, viz: 1) to trace the sequence of crystallization of the melt sheet and Offset dykes; 2) to determine the timing of sulfide-saturation of the silicate melts; 3) to characterize the initial Ni, Cu and PGE contents of the parental melt; and 4) to address whether or not there is a requirement for a mantle or crustal contribution of metals to the melt sheet. We raise a number of important aspects of the data that are not explained by traditional models, and where possible we will attempt to accommodate these observations in our model.

A resolution to these issues has many important implications for the exploration geologist as they provide a more satisfying holistic model that explains the broad distribution of Ni-Cu-PGE sulfide mineralization within the SIC, provide predictions about the quantity, grade, and sulfide metal tenors of the different ore environments, and indicate which parts of the SIC are more likely to carry elevated PGE concentrations.

Regional geology

The Sudbury Igneous Complex (SIC) straddles the contact between Archean gneisses (mainly the Levack Complex) of the Superior Province of the Canadian Shield to the north and Paleoproterozoic Huronian Supergroup sedimentary, volcanic, and mafic intrusive rocks of the Southern Province of the Canadian Shield to the south (Dressler, 1984a, b).

Forward and inversion modelling of seismic, gravity and magnetic studies (Milkereit and Green, 1992; McGrath and Broome, 1994; Hearst et al., 1994) indicate that the contact between the Levack Gneiss Complex and the SIC on the North Range can be traced beneath the Sudbury Structure. The seismic data

indicate that whereas the North Range dips to the south at an angle of 40° , the dip of the South Range ranges from 60° north to over-turned. In the *Milkereit et al. (1994)* model, the contact between the Main Mass and Levack Gneiss Complex dips as far south as the southern limit of exposure of the South Range Norites. *Card and Jackson (1985)* provide an alternative interpretation of the structure as a less deformed basin; this is more easily reconciled with the outcrop shape of the Sudbury Structure.

Detailed accounts of the regional geology of the SIC are available in volumes edited by *Pye et al. (1984)* and *Lightfoot and Naldrett (1994)*. There is an overwhelming amount of geological evidence that supports the model first proposed by *Dietz (1964)* that the Sudbury Structure was produced by the impact of a meteorite that may have been 10 km in diameter and produced a structure that was 200 km in diameter (*Grieve, 1994*). This evidence includes the Onaping Formation, which has been interpreted as a suevite or fall-back breccia (*Grieve, 1994*), the basal shape of the structure and the upturned Huronian rocks around the margins of the SIC (*Dressler, 1984a, b*), shock metamorphic features in the country rocks as well as in

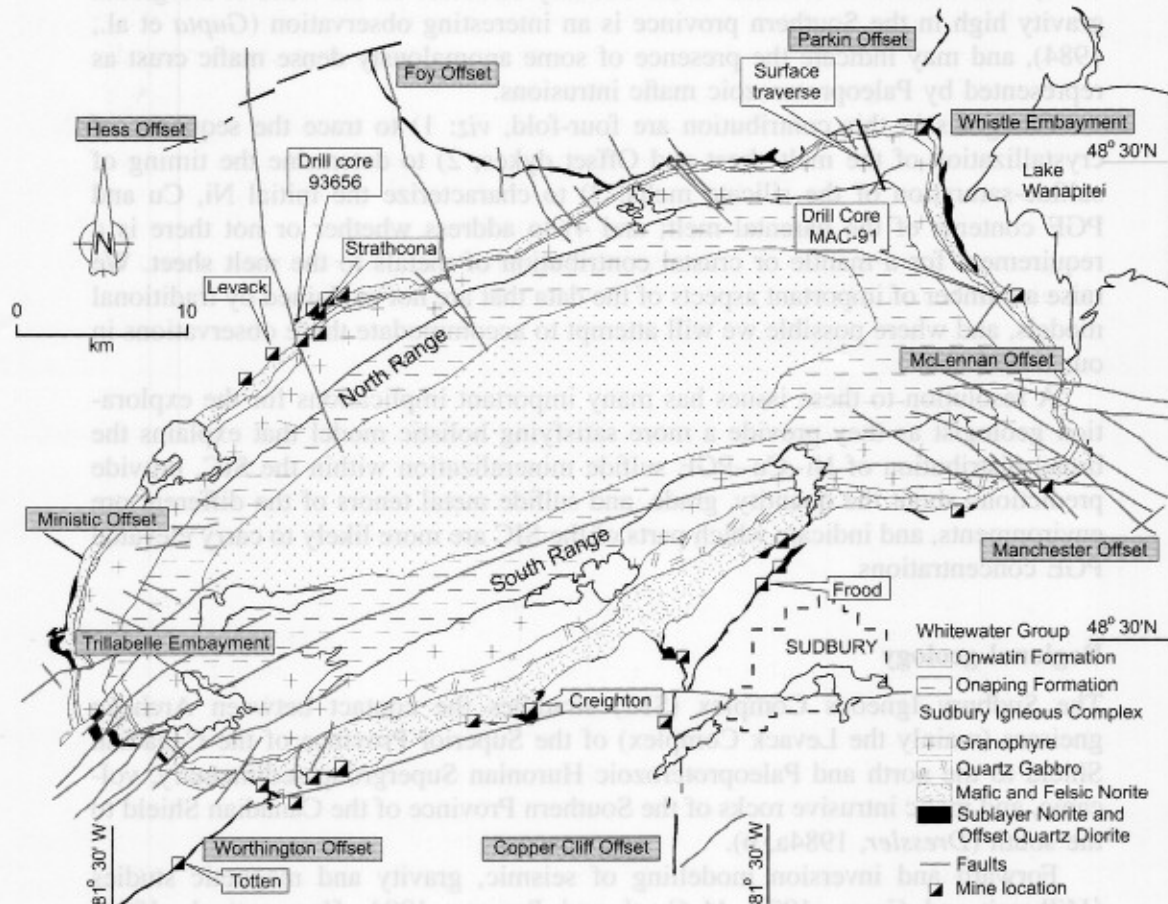


Fig. 1. Geological map showing the location of the drill cores from which samples were analyzed in this study and the locations mentioned in the text

fragments of country rocks in the Onaping formation such as shatter cones (that are only reported from impact structures and sites of nuclear detonations) and shock lamellae in quartz and feldspar (Dressler, 1984a, b), the abundant footwall breccias (Pattison, 1980; Dressler, 1984a, b), and the enigmatic Sudbury Breccia which is interpreted to be a pseudotachylyte (French, 1967; Spray, 1995).

The SIC is comprised of the Main Mass, the "Contact" Sublayer (Souch et al., 1969; Pattison, 1979), which is a discontinuous and highly variable unit that occurs immediately below the Main Mass, and by quartz diorite dykes (termed "Offset" dykes) which occur as concentric and radial bodies within the surrounding country rocks (Lightfoot et al., 1997a; Fig. 1). On the North Range, the upper most member of the Main Mass is the plagioclase-rich Granophyre which is underlain first by the Granophyre, then by the Quartz Gabbro and finally by the Felsic and Mafic Norites. On the South Range, which comprises a deeper level of erosion than the rocks of the North Range, the rocks are typically more metamorphosed and altered. The Granophyre is underlain by the amphibolitised Quartz Gabbro, amphibolitised Felsic Norite, and finally by amphibolitised quartz-rich norite (Naldrett, 1989); the quartz-rich norite is believed to be stratigraphically equivalent to the North Range Felsic Norite. Traditionally, the quartz diorite Offset dykes have been grouped together with the contact Sublayer (Souch et al., 1969; Pattison, 1979); however, Lightfoot et al. (1997a) have shown that the Offset dykes have markedly different mineralogical and chemical composition when compared to the contact Sublayer norite. Detailed case studies of the Sublayer are rare (Lightfoot et al., 1997b), but there is a wealth of general descriptive information (Souch et al., 1969; Pattison, 1979; Morrison, 1984, 1994) which indicate that the igneous-textured noritic Sublayer occupies radial depressions at the base of the Main Mass, termed troughs or embayments, which in-turn have secondary terrace structures within the troughs (Morrison, 1984).

Geology of the Onaping Formation, the Main Mass, Sublayer and Offsets

The Onaping Formation is a 1400 m thick sequence of glass-rich breccias and igneous-textured rocks that overlies the SIC. From the base upward, the Onaping comprises three major units, the Basal Member, the Gray Member and the Black Member. The Basal Member contains sub-angular to sub-rounded xenoliths of Archean country rocks (granitoids), and Huronian country rocks (quartz-arenites and arkoses), ranging in size from less than 1 mm to several tens of metres. The fine-grained matrix is composed of recrystallized country rock and/or igneous-textured minerals. The Gray and Black Members consist of angular to rounded fragments of country rock (Archean and Proterozoic granitoid, gneisses, metavolcanics and metasediments), crystal fragments, recrystallized glass, fluidal-textured material and sulfides. "Melt Bodies" form irregular pipe-like masses (50 m–1 km long) that sporadically intrude both the Gray and the Black Members and consist of a crystalline central part and a chilled margin. The Black and Gray Onaping Members have been interpreted to be fall-back breccias (Grieve, 1994) whereas the melt bodies are believed to be related to the Granophyre (Muir and Peredery, 1984).

The Main Mass of the North Range of the SIC near surface is comprised of ~60% Granophyre, ~25% Felsic Norite, ~10% Quartz Gabbro, and ~5% Mafic Norite (Naldrett and Hewins, 1984). The Main Mass varies considerably in thickness; at some of the larger mineralized embayment structures such as Levack, the Main Mass is at least 2500 m thick (adjacent to the embayment), whereas other large embayment structures such as the weakly mineralized Trillabelle embayment (Fig. 1) are located where the Main Mass is considerably thinner (<600 m on either side of the embayment). In areas between embayment structures, the Main Mass varies considerably in thickness from ~5000 m down to about 300 m. Despite the wide range in thickness of the Main Mass, the ratio of noritic to granophyric rocks remains almost 40:60, although the thickness of the Quartz Gabbro varies from 300 m down to a few meters. In the South Range, the extensive faulting of the Main Mass makes it more difficult to measure the true stratigraphic thickness, but it appears likely that the heavily mineralized Creighton embayment was overlain by up to 5000 m of Main Mass outside of the immediate embayment. The thickness of the Main Mass varies along the southern margin, and tends to thin towards the west down to <1500 m.

The contact Sublayer, which contains almost 50% of the mineral resource at Sudbury, comprises an inclusion- and sulfide-rich noritic rock with an igneous texture underlain by local footwall breccia with a metamorphic-textured matrix (Pattison, 1979). The Sublayer matrix contains a range of inclusion types including local country rocks, cognate xenoliths derived from more mafic domains of the Sublayer (e.g. Whistle embayment; Lightfoot et al., 1997b; Farrell, 1997), and exotic clasts of ultramafic rock (Rae, 1975; Scribbins, 1978). The mafic inclusions from Whistle mine are a suite of brecciated plagioclase glomeroporphyritic diabase hornfels-textured rocks, and a suite of norites, melanorites and olivine melanorites that show variable degrees of alteration. At Whistle, both suites of inclusions are hosted in both Sublayer norite which contains weak (0.5–10%) disseminated sulfide as well as within zones of massive pyrrhotite-rich sulfide mineralization (Farrell, 1997). These inclusions have zircon and baddeleyite ages that are indistinguishable based on U–Pb dating from the 1.85 Ga Sudbury event (Corfu and Lightfoot, 1996; Krogh et al., 1984). Geochemically, the melanorites and olivine melanorites are more primitive cumulate rocks than the Sublayer matrix. The trace element signatures of these rocks are unusual; they have similar abundance levels of high field strength elements and heavy REE to the Sublayer norite matrix, yet a wide range in MgO contents (7–27 wt.%, Lightfoot et al., 1997b). The compositions of these mafic-ultramafic rocks are heavily influenced by the unusually large amounts of apatite and biotite and they also contain chromian spinels (Lightfoot et al., 1997b; Farrell, 1997; Zhou et al., 1997). Some of the freshest melanorite and olivine melanorite inclusions contain disseminated sulfide as well as diabase inclusions, and so they appear to be formed after the Sudbury magma was sulfide-saturated, but under conditions where orthopyroxene ± olivine ± chrome spinel were separating from the melt. Lightfoot et al. (1997b) argue that the diabase-textured inclusions, which are the most abundant inclusion type in the Sublayer in the Whistle embayment, were probably derived from Paleoproterozoic rocks such as the Huronian volcanics and that they have made a very

large chemical contribution to the magma which crystallized to form the noritic Sublayer matrix.

The immediate surrounding country rocks at the margins of embayments tend to be heavily brecciated and are termed granite (or leucocratic) breccias; in some places, large fragments of country rock are found within these breccias, and these units are termed megabreccias (Morrison, 1984). The metamorphic-textured granite breccia Sublayer occurs beneath the igneous textured Sublayer, and/or within the igneous-textured Sublayer (e.g. Coleman and Victor mines), and in both cases the granite breccia can contain disseminated, stringer, and massive sulfide mineralization, especially in places where the matrix of the breccias contains abundant biotite and is recrystallized.

Contact Sublayer deposits on the South Range such as Creighton (Fig. 1) are typically broadly zoned from massive ore at the footwall to disseminated sulfide ore at the hangingwall of the deposits. In the North Range deposits, mineralization occurs mainly within brecciated country rocks below the Sublayer as well as in fractures in the country rocks located below the footwall breccias such as Strathcona. As shown by Keays and Crocket (1970) and Li et al. (1992), the contact ores are rich in Ir, Os, Ru and Ni, while the footwall ores are enriched in Pd, Pt, Au and Cu. Most authors agree that the various ore zones in a deposit such as the Strathcona deposit were ultimately generated from a single pool of sulfide liquid. However, whereas Keays and Crocket (1970) and Li et al. (1992) argued that the deep Cu-rich ores represented the fractionated residual melt generated from the crystallization of the higher level Fe-Ni-rich, Cu-poor sulfides, Farrow and Watkinson (1997) argued that some of the footwall Cu ores were generated in part by hydrothermal fluids which had remobilized magmatic Cu-Ni-PGE sulfides.

The radial and concentric offset quartz diorite dykes (Grant and Bite, 1984; Lightfoot et al., 1997b, c; Fig. 1) have a combined volume in excess of $\sim 100 \text{ km}^3$ of quartz diorite if projected to depth beneath the SIC. Geological features of the Sudbury Offsets are described in Cochrane (1984), Grant and Bite (1984), and Lightfoot et al. (1997a, c). Offset dykes group into two main types; viz: 1) radial offset dykes which extend away from the SIC, and tend to follow domains of Sudbury Breccia, and 2) concentric offset dykes which form ring-like structures centered on the SIC. The radial Offsets are frequently discontinuous (e.g., Copper Cliff; Cochrane, 1984; Mourre, 2000). They often pinch and swell (e.g., Worthington Offset; Lightfoot et al., 1997c), and they are sometimes broken, rather than faulted, for short distances at a high angle to the trend of the offset (e.g., Parkin Offset at Milnet mine; Lightfoot et al., 1997c). South Range radial offsets tend to pinch and swell as in the Worthington Offset (Lightfoot et al., 1997c; Fig. 1) or be discontinuous along strike as in the case of the Copper Cliff Offset (Cochrane, 1984; Grant and Bite, 1984; Fig. 1). The swell zones and discontinuities appear to control mineralization in both the Worthington and Copper Cliff Offsets. The concentric Offsets includes the $\sim 1 \text{ km}$ wide breccia belts containing discontinuous lenses of quartz diorite, some of which are associated with the mineralization (e.g., the Froid-Stobie Breccia Belt; Souch et al., 1969; Scott and Spray, 1998, 1999), and the more continuous dykes of quartz diorite (e.g., the Manchester and Hess Offsets; Grant and Bite, 1984; Lightfoot et al., 1997b; Wood and Spray, 1998). The mineralization in the Froid-Stobie Breccia Belt (e.g. Scott and Spray, 1999) contains $\sim 20\%$ of the

known metal resource at Sudbury. The radial Copper Cliff Offset accounts for a further ~25%, and the remaining Offsets contain ~5% of the resource.

The Worthington Offset (Fig. 1) extends for ~15 km from the Main Mass of the SIC towards the SW, with a thickness of 30–100 m, and a dip of ~80°SE. A number of relatively small deposits are located along the dyke in a series of swells along the strike of the Offset, with the most significant at Worthington and Totten. The unmineralized quartz diorite tends to be in sharp contact with the Huronian metasedimentary rocks and the Paleoproterozoic Sudbury Gabbro (Lightfoot and Farrow, 2002); the quartz diorite at the margin of the offset contains fragments of locally entrained metasedimentary rock. The margin of the offset consists of spherulitic-textured* quartz diorite, which grades inwards over 1–5 m into medium-grained to coarse-grained amphibole–biotite quartz diorite. The spherulitic texture* is interpreted to be a feature produced by rapid cooling of the melt against both the local country rocks as well as against Sudbury Breccia. The sulfide- and inclusion-poor rock types are in sharp as well as gradual (over ~1 m) contact with the inclusion- and sulfide-rich quartz diorite.

Petrology of the Main Mass, Sublayer and Offsets

Naldrett et al. (1970) show that the Main Mass exhibits significant cryptic variations in the modal content of its constituent minerals. The granophyre (micropegmatite) is comprised of micrographic intergrowths and plagioclase in the proportions three to one (Naldrett et al., 1970). Plagioclase grains from the lowest part of the Granophyre and the upper part of the Quartz Gabbro contain up to 25% epidote. Mafic minerals in the granophyre include green hornblende, stilpnomelane, chlorite and rare augite (Naldrett et al., 1970).

The Quartz Gabbro is located below the granophyre and contains up to 8 wt.% oxides, mainly ulvospinel (Naldrett et al., 1970). In addition, an apatite-rich zone occurs in the upper part of the Quartz Gabbro. Plagioclase, augite, ulvospinel, and apatite occur as cumulate minerals whereas micrographic intergrowths and trace pyrite constitute the intercumulus minerals. The plagioclase exhibits strong oscillatory zoning when fresh but most of it has a cloudy appearance due to sericitic alteration.

The Felsic Norite is a coarse-grained hypidiomorphic granular-textured rock that is comprised of hypersthene and augite in the ratio of approximately 2 to 1, plagioclase, biotite, interstitial micrographic intergrowth and minor amounts of pyrite, apatite, ilmenite and ulvospinel (Naldrett et al., 1970). In the lower two thirds of the unit, plagioclase and hypersthene occur as subhedral tabular grains and are cumulus minerals. Augite is molded around the plagioclase and much of it probably grew from the intercumulus liquid, although some of it may be cumulus (Naldrett et al., 1970). The plagioclase grains consist of strongly zoned borders and unzoned cores; the unzoned cores comprise less than half of the volume of the total grains. The dominant iron sulfide in the lower portion of the Felsic Norite is

* The terms “spherulitic-textured” and “spherulitic texture” are used historically at Sudbury to refer to radiating textures of plagioclase and amphiboles in the chilled marginal quartz diorite

pyrrhotite that gives way to pyrite in the upper portion of the Felsic Norite; the pyrite is probably an alteration product of primary pyrrhotite.

The lowermost norites of the Main Mass are Mafic Norites that are in transitional contact with the underlying Sublayer norites in areas of embayments. The Mafic Norite unit decreases in thickness away from the embayment. The contact between the Felsic Norite and the Mafic Norite is irregular and gradational over a meter and is simply delineated by an increase in orthopyroxene content to greater than 50 modal percent of the rock; the transition is marked by a change from hypidiomorphic granular textures in the Felsic Norite to poikilitic textures in the Mafic Norite. The Mafic Norite contains trace to 5% sulfides comprised of pyrrhotite, pentlandite and chalcopyrite.

The contact between the Mafic Norite and the underlying Sublayer norite is transitional over ~5 metres. In some embayments, the Sublayer is partially comprised of Mafic Norite. The boundary between the Mafic Norite and the Sublayer is generally marked by an increase in sulfide content and the presence of inclusions and pods of coarser grained norite and melanorite in the Sublayer (Lightfoot et al., 1997b). The inclusion-rich and sulfide-rich Sublayer is comprised of two members. The upper member has a fine to medium-grained poikilitic to nonpoikilitic igneous textured matrix which has low modal quartz and abundant (10–40%) orthopyroxene (Lightfoot et al., 1997a, b); the matrix is referred to herein as the Sublayer matrix and is classified as either as a gabbro-norite or a norite. Rock fragments, which comprise up to 25 wt.% of the rock, are diabase, gabbro, norite, melanorite, olivine melanorite, and more rarely dunite, harzburgite, and peridotite. Of particular interest are inclusions variably referred to as diabase inclusions or plagioclase-phyric inclusions that comprise the largest proportion of the fragment population in some embayments such as the Whistle embayment (Lightfoot et al., 1997b). The matrix of the lower member of the Sublayer has a metamorphic texture and the majority of the rock fragments in it are comprised of the local country rock; however, all of the xenolith types in the igneous-textured Sublayer can also be present in the metamorphic-textured Sublayer.

The Offset quartz diorite is a gray massive, fine- to medium-grained rock that exhibits equigranular to inequigranular textures and is comprised of 45 to 55% mafic minerals, 30 to 45% feldspar, 5 to 15% quartz and trace amounts of granophyric intergrowths of quartz and K-feldspar and opaque minerals. The proportions of biotite and amphibole as well as the grain size vary considerably, and the main break out in rock types are as follows: 1) A fine-grained quartz diorite with radiating needles of plagioclase and amphibole, and interstitial granophyre which develops at the margin of the Offset; this has traditionally been termed spherulitic* quartz diorite (Grant and Bite, 1984); 2) A medium- to coarse-grained biotite-poor quartz diorite which can contain some inclusions of local country rock, but is more typically free of larger exotic inclusions and has no more than trace primary sulfide. In some cases, there are fine veinlets of chalcopyrite-rich sulfide that cross cut this unit near to the heavily mineralized parts of the Offset; and 3) A fine- to medium-grained quartz diorite contains sulfide, biotite, and inclusions ranging from a few mm to several meters in size (Lightfoot and Farrow, 2002). This unit is referred to as the Inclusion Quartz Diorite, and contains trace to semi-massive

sulfide mineralization. The sulfides are typically pyrrhotite, chalcopyrite, and pentlandite. The sulfides are commonly interstitial through blebby to merging blebs. There is local development of 1–10 mm wide veinlets of chalcopyrite, but there are also many cases where a penetrative fabric is developed in this rock type and there are stringers and veinlets of chalcopyrite that appear to have been injected from domains of more massive sulfide mineralization.

Sampling and analysis

Samples of the Main Mass of the SIC were collected from two drill cores that are located 50 km apart and a surface section (Fig. 1). Drill core 93656 in the Levack area was provided by Inco Technical Services Limited and analyzed for this study; we also use data from *Lightfoot et al.* (2001) for drill core MAC-91 provided by Falconbridge Limited, which was collared on the Nickel Rim Mine property; this is the discovery hole of the Nickel Rim Deposit (*Barnett, 1998; Fig. 1*); data for samples from a surface traverse of the Granophyre near Capreol are also used. The Levack drill hole was collared in the lower part of the Granophyre and contains a thick sequence of Quartz Gabbro, Felsic Norite, Mafic Norite and Sublayer. Samples of ~1.5 kg were selected at regular intervals through the core for analysis. In order to relate surface samples to drill core samples, a relative stratigraphic position for each sample was calculated by assuming a ratio of gabbroic and granophyric rocks to noritic rocks of 3:2, which is more typical of the North Range of the SIC – a thickness of 2500 m is estimated for the Main Mass at Levack. The relative stratigraphic positions of the drill core samples are very tightly constrained, and actual relative position depends on the estimates for the thickness of the sheet and the dip of the basal contact. Samples from the Offsets were collected from both inclusion and sulfide-bearing Quartz Diorite, and inclusion and sulfide-poor marginal phases; whole rock major and minor element data for these samples are reported in *Lightfoot et al.* (1997c). The Onaping Formation samples were collected in the Onaping Falls area on the North Range of the SIC.

Samples were crushed in a jaw crusher equipped with carbon steel jaws and pulverized in 99.85% pure alumina planetary mills following *Lightfoot et al.* (1997a, b). Major element and trace element abundances were determined as described in *Lightfoot et al.* (2001).

Palladium, Ir and Au analyses of the Onaping Formation samples were acquired on rock powders by Radiochemical Neutron Activation Analyses at the University of Melbourne using methods described by *Hoatson and Keays* (1989). The detection limits for Pd, Ir and Au were 0.01 ppb and the accuracy of the analyses at 0.1 ppb was ~10%. The remainder of the PGE analyses were carried out at the low-level PGE facility of the Geoscience Laboratories in Sudbury, following procedures described in *Jackson et al.* (1990). Ten grams of powdered rock was mixed with sodium carbonate, S, SiO₂ flour and Ni powder. This mixture was baked at 1050 °C for 1.5 hours in a fire-clay crucible. After dissolution of the Ni-sulfide button, the PGEs were collected by Te co-precipitation, re-dissolved in acid, and then the concentrations were determined by inductively-coupled plasma mass spectroscopy (ICP-MS).

Table 1. Representative data for samples from drill cores MAC-91 and 93656

Sample ID	Core	Relative depth (m)	Rock type	MgO wt%	Ni ppm	Co ppm	Cu ppm	S ppm	Se ppb	Pt ppb	Pd ppb	Au ppb	S/Se
94PCL-2045	MAC-91	-70.00	Quartz Gabbro	1.05	5	13	4	302	45	ND	ND	ND	6710
94PCL-2048	MAC-91	-160.00	Quartz Gabbro	2.02	6	27	4	144	NA	ND	ND	ND	12000
94PCL-2049	MAC-91	-320.00	Quartz Gabbro	3.69	9	53	27	1180	86	ND	ND	ND	9850
94PCL-2052	MAC-91	-440.00	Quartz Gabbro	3.77	14	26	16	184	23	ND	ND	ND	8000
94PCL-2055	MAC-91	-510.00	Quartz Gabbro	3.86	15	40	24	980	76	ND	ND	ND	12900
94PCL-2060	MAC-91	-560.00	Quartz Gabbro	3.91	16	35	21	909	NA	ND	1.32	3.70	1320
94PCL-2079	MAC-91	-562.20	Quartz Gabbro	3.80	16	28	16	133	NA	ND	ND	ND	11800
94PCL-2061	MAC-91	-566.00	Quartz Gabbro	4.09	20	44	33	1030	91	ND	0.25	ND	11319
94PCL-2064	MAC-91	-685.00	Quartz Gabbro	3.39	12	30	72	266	70	0.25	ND	ND	3800
94PCL-2065	MAC-91	-708.50	Quartz Gabbro	4.28	13	53	18	966	NA	ND	ND	ND	4380
94PCL-2066	MAC-91	-769.00	Felsic Norite	4.37	17	32	14	361	37	ND	ND	ND	9760
94PCL-2068	MAC-91	-885.00	Felsic Norite	4.50	17	32	16	591	NA	ND	ND	9.10	2400
94PCL-2070	MAC-91	-976.00	Felsic Norite	4.91	18	28	15	463	49	ND	ND	ND	9450
94PCL-2072	MAC-91	-1,170.00	Felsic Norite	4.75	18	32	18	487	45	0.27	ND	ND	10800
94PCL-2077	MAC-91	-1,260.00	Felsic Norite	4.52	20	25	16	475	35	ND	ND	ND	13600
94PCL-2073	MAC-91	-1,290.00	Felsic Norite	4.66	21	26	9	504	NA	ND	ND	ND	9830
94PCL-2076	MAC-91	-1,445.00	Felsic Norite	4.75	24	29	12	642	NA	ND	ND	ND	9230
94PCL-2040	MAC-91	-1,545.00	Felsic Norite	5.34	26	32	13	643	40	ND	ND	ND	16100
94PCL-2039	MAC-91	-1,630.00	Felsic Norite	5.40	28	30	15	617	NA	ND	ND	ND	2320
94PCL-2035	MAC-91	-1,727.00	Felsic Norite	5.36	29	30	16	618	43	ND	0.22	7.70	14400
94PCL-2033	MAC-91	-1,845.00	Felsic Norite	5.20	34	28	26	544	NA	0.25	0.25	0.73	
94PCL-2031	MAC-91	-1,883.50	Felsic Norite	5.31	44	29	37	742	NA	ND	0.22	0.53	2310
94PCL-2028	MAC-91	-2,000.00	Felsic Norite	5.57	64	33	53	1150	141	0.56	0.93	4.84	8160
94PCL-2027	MAC-91	-2,048.00	Felsic Norite	5.87	69	30	42	2250	NA	0.46	0.66	0.49	
94PCL-2026	MAC-91	-2,102.00	Felsic Norite	6.15	113	35	100	1600	NA	4.87	6.42	1.68	
94PCL-2014	MAC-91	-2,166.00	Felsic Norite	6.43	108	31	97	1050	NA	0.28	0.72	0.86	2126

Formation of Ni-Cu-PGE sulfide mineralization

(continued)

Table 1 (continued)

Sample ID	Core	Relative depth (m)	Rock type	MgO wt%	Ni ppm	Co ppm	Cu ppm	S ppm	Se ppb	Pt ppb	Pd ppb	Au ppb	S/Se
94PCL-2012	MAC-91	-2,168.00	Felsic Norite	9.30	257	50	265	2730	503	1.33	1.08	1.69	5430
94PCL-2011	MAC-91	-2,170.50	Mafic Norite	11.35	313	60	320	3280	629	1.68	2.91	2.26	5210
94PCL-2010	MAC-91	-2,171.50	Mafic Norite	12.44	328	64	336	3510	NA	1.77	1.95	3.64	
94PCL-2009	MAC-91	-2,179.50	Mafic Norite	13.97	362	67	358	3710	NA	2.23	2.92	2.58	
94PCL-2003	MAC-91	-2,205.65	Mafic Norite	14.61	631	77	629	4920	856	6.37	8.25	4.70	5750
94PCL-2001	MAC-91	-2,214.00	Mafic Norite	12.89	1037	95	1138	9870	1667	7.30	7.71	6.30	5920
94PCL-2016	MAC-91	-2,238.00	Mafic Norite	12.15	485	72	397	4330	630	3.05	3.06	2.56	6870
94PCL-2017	MAC-91	-2,250.30	Sublayer	14.55	5425	308	932	45400	NA	48.12	35.65	19.30	
94PCL-2018	MAC-91	-2,250.30	Sublayer	15.22	2177	149	1751	15800	2572	58.22	44.95	21.50	6140
94PCL-2019	MAC-91	-2,262.20	Sublayer	8.52	369	58	241	1860	454	3.07	2.30	2.82	4100
94PCL-2020	MAC-91	-2,304.20	Sublayer	14.39	913	93	690	7340	1039	15.32	15.05	6.90	7060
94PCL-2021	MAC-91	-2,356.50	Sublayer	14.38	1971	138	1766	14300	2647	40.62	24.95	18.40	5400
94PCL-2022	MAC-91	-2,391.30	Sublayer	8.35	126	53	137	572	243	19.22	22.25	4.09	2350
94PCL-2023	MAC-91	-2,548.00	Sublayer	8.66	484	62	375	2970	701	45.42	29.65	7.90	4240
94PCL-2024	MAC-91	-2,596.20	Sublayer	7.06	252	60	302	2020	658	23.82	27.85	6.60	3070
212	93656	64.6	Granophyre	1.16	8	11	8	130	12	ND	ND	0.55	10800
402	93656	122.5	Granophyre	NA	7	6	7	200	17	ND	0.08	0.46	11800
615	93656	187.5	Granophyre	NA	6	7	27	200	46	ND	0.76	0.61	4350
725	93656	221.0	Granophyre	0.66	8	9	8	100	5	ND	ND	0.46	20000
1020	93656	310.9	Granophyre	NA	7	7	6	100	33	ND	ND	0.44	3030
1620	93656	493.8	Granophyre	NA	7	7	10	300	44	ND	ND	0.57	6820
1935	93656	589.8	Granophyre	0.65	7	8	7	30	2	ND	ND	0.46	15000
2536	93656	773.0	Granophyre	0.49	6	6	6	40	2	ND	ND	0.40	20000
3126	93656	952.8	Quartz gabbro	NA	9	17	6	200	14	ND	ND	0.39	14300
3341	93656	1018.3	Quartz gabbro	3.51	12	44	30	650	50	ND	0.89	0.29	13000
3495	93656	1065.3	Quartz gabbro	NA	15	49	37	1300	80	ND	ND	0.73	16300
3598	93656	1096.7	Quartz gabbro	NA	15	48	35	1100	71	ND	ND	0.45	15500

(continued)

Table 1 (continued)

Sample ID	Core	Relative depth (m)	Rock type	MgO wt%	Ni ppm	Co ppm	Cu ppm	S ppm	Se ppb	Pt ppb	Pd ppb	Au ppb	S/Se
7550	93656	2301.2	Felsic Norite	7.89	160	42	160	2000	NA	6.20	6.43	1.55	
7575	93656	2308.9	Felsic Norite	10.1	393	66	328	2900	430	2.57	3.06	3.13	6740
7603	93656	2317.4	Mafic Norite	4.37	410	61	315	2200	380	1.75	2.40	2.05	5790
7618	93656	2322.0	Mafic Norite	11.56	498	66	451	3400	670	3.38	3.99	2.26	5080
7665	93656	2336.3	Mafic Norite	6.71	390	57	323	2400	340	2.06	2.67	2.01	7060
7685	93656	2342.4	Mafic Norite	NA	658	63	563	3800	680	10.83	15.79	3.75	5590
7692	93656	2344.5	Mafic Norite	10.1	441	61	356	2500	370	2.24	3.19	2.12	6760
7703	93656	2347.9	Sublayer	13.14	2101	NA	1448	19000	2200	21.85	18.19	8.45	8640
7715	93656	2351.5	Sublayer	11.48	1500	110	710	14200	NA	7.31	8.11	5.22	
7750	93656	2362.2	Sublayer	10.84	350	54	250	1900	NA	4.61	6.10	4.40	
7770	93656	2368.3	Sublayer	3.32	333	52	272	2400	260	4.40	5.10	3.18	9230
7800	93656	2377.4	Sublayer	8.78	970	76	830	7200	NA	10.81	9.48	7.61	
7824	93656	2384.8	Sublayer	4.41	685	46	590	4300	660	6.59	5.61	6.55	6520
7844	93656	2390.9	Sublayer	16.88	1200	90	400	6700	NA	11.09	12.34	10.49	
7860	93656	2395.7	Sublayer	10.51	430	47	269	3200	530	5.04	3.97	4.97	6040
7880	93656	2401.8	Sublayer	8.02	2800	130	600	21500	NA	22.92	20.12	9.31	
7930	93656	2417.1	Sublayer	6.55	497	61	363	2600	510	38.97	37.87	16.21	5100
7947	93656	2422.2	Sublayer	10.1	360	52	180	1900	NA	4.28	3.59	2.19	
7975	93656	2430.8	Sublayer	NA	NA	NA	NA	NA	NA	41.41	18.46	7.53	
8002	93656	2439.0	Sublayer	13.14	699	32	876	4500	1400	138.49	151.16	45.90	3210
8021	93656	2444.8	Sublayer	3.36	3200	69	5000	22800	NA	140.71	177.81	43.46	
8035	93656	2449.1	Sublayer	12.57	105	54	169	900	250	18.82	17.64	5.10	3600
8098	93656	2468.3	Sublayer	12.06	104	52	185	900	250	18.62	16.74	4.68	3600
8113	93656	2472.8	Sublayer	NA	NA	NA	NA	NA	NA	17.33	16.45	4.62	
8142	93656	2481.7	Sublayer	10.31	101	53	149	900	250	19.01	18.73	4.83	3600
Procedural Blank: MAC-91										0.20	0.20	0.61	
Procedural Blank: Levack 93656										0.06	0.03	0.26	

ND not detected, NA not analyzed

Table 1 (continued)

3703	93656	1128.7	Quartz gabbro	3.78	27	32	26	640	69	ND	ND	0.55	9280
3804	93656	1159.5	Quartz gabbro	NA	8	8	NA	100	10	ND	ND	0.45	10000
4360	93656	1328.9	Quartz gabbro	4.9	17	23	8	170	19	ND	ND	0.38	8950
4655	93656	1418.8	Felsic Norite	4.7	16	25	11	110	17	0.07	ND	3.38	6470
4755	93656	1449.3	Felsic Norite	NA	20	25	19	600	36	NA	NA	NA	16700
4850	93656	1478.3	Felsic Norite	5.11	19	27	18	360	39	ND	ND	1.30	9230
5050	93656	1539.2	Felsic Norite	5.17	21	28	17	440	44	NA	NA	NA	10000
5360	93656	1633.7	Felsic Norite	5.27	24	27	16	530	48	0.11	0.08	0.68	11000
5680	93656	1731.3	Felsic Norite	5.51	31	28	16	420	41	NA	NA	NA	10200
5860	93656	1786.1	Felsic Norite	5.47	35	28	18	450	53	0.13	0.25	0.54	8490
6050	93656	1844.0	Felsic Norite	5.91	31	28	15	480	52	0.06	0.11	0.44	9230
6155	93656	1876.0	Felsic Norite	NA	32	30	15	700	47	NA	NA	NA	14900
6460	93656	1969.0	Felsic Norite	NA	37	29	20	700	53	NA	NA	NA	13200
6585	93656	2007.1	Felsic Norite	NA	NA	NA	NA	600	48	0.06	0.17	0.40	12500
6795	93656	2071.1	Felsic Norite	NA	39	28	28	600	61	0.14	0.17	0.52	9840
7005	93656	2135.1	Felsic Norite	NA	41	27	30	600	65	0.17	0.22	0.44	9230
7158	93656	2181.8	Felsic Norite	5.86	75	30	41	700	86	0.43	0.48	0.84	8140
7190	93656	2191.5	Felsic Norite	5.83	55	28	42	700	NA	0.76	0.60	5.38	
7218	93656	2200.0	Felsic Norite	NA	84	32	56	800	100	0.24	0.64	1.82	8000
7243	93656	2207.7	Felsic Norite	5.89	57	27	43	700	NA	0.24	0.44	1.84	
7270	93656	2215.9	Felsic Norite	NA	175	38	156	2000	300	2.64	2.05	3.94	6670
7300	93656	2225.0	Felsic Norite	5.78	63	29	42	600	NA	0.47	0.82	0.46	
7332	93656	2234.8	Felsic Norite	5.76	77	32	53	700	91	0.28	0.84	0.65	7690
7357	93656	2242.4	Felsic Norite	5.93	71	29	56	800	NA	0.56	0.42	3.93	
7390	93656	2252.5	Felsic Norite	NA	87	33	53	600	87	0.29	1.01	0.96	6900
7420	93656	2261.6	Felsic Norite	6.42	74	31	60	800	NA	0.35	0.54	2.37	
7450	93656	2270.8	Felsic Norite	5.62	97	33	49	500	82	0.49	0.53	0.81	6100
7480	93656	2279.9	Felsic Norite	6.07	74	29	51	700	NA	0.27	0.39	2.69	
7512	93656	2289.7	Felsic Norite	NA	100	32	30	300	63	0.33	1.13	0.68	4760

(continued)

Formation of Ni-Cu-PGE sulfide mineralization

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During the course of this project, there was a significant decrease in detection limits for the PGE. For the MAC-91 PGE data, the procedural blanks for Pt, and Pd were 0.20 ppb. For the Levack 93656 data, the procedural blanks for Pt and Pd

Table 2. Composition of the Onaping Formation and Marginal Quartz Diorite Phase of the Quartz Diorite Offset Dykes

Rock type	MgO (wt%)	Ni (ppm)	Cu (ppm)	Pd (ppb)	Pt (ppb)	Ir (ppb)	Se (ppb)	S (ppm)	S/Se
Onaping Formation									
Grey Onaping	4.41	49	53	7.4		0.04	391	5500	14100
Grey Onaping	1.73	40	63	3.5		0.11	112	1700	15200
Grey Onaping	3.57	51	68	4.0		0.13	378	3100	8200
Black Onaping	4.67	68	47			0.13	309	3600	11700
Black Onaping	4.58	64	41	6.9		0.48	489	5900	12100
Melt Rock	3.46	92	47	7.7		0.38	396	3300	8330
Melt Rock	1.55	46	53	3.7		0.08	142	800	5630
Melt Rock	3.72	29	11	2.9		0.22	13	100	8330
Average Onaping	3.46	55	48	4.9		0.19	279	3000	10400
Onaping Vitric Bombs & Block*	4.3	60	69						
Worthington Offset, Totten Mine area									
Cg Marginal QD	4.26	79	88	2.35	4.04	0.13		260	
Cg Marginal QD	4.13	62	85	2.24	4.11	1.12		185	
Marginal QD	4.38	79	72	4.38	3.56	0.12		256	
C-mg Marginal QD	2.65	66	70	3.21	3.52	0.10		243	
Mg Marginal QD	4.12	63	56	3.19	4.21	0.08		299	
Cg Marginal QD	3.96	74	54	3.86	4.99	0.16		288	
C-mg Marginal QD	4.38	70	50	1.56	3.96	0.10		209	
M-cg Marginal QD	4.13	63	43					344	
Fg Marginal QD	3.82	68	41	2.41	4.21	0.10		440	
Cg Marginal QD	3.91	68	27	1.97	3.49	0.08		151	
Average low-S QD	3.97	69	59	2.80	4.01	0.22		268	
Parental SIC magma**	3.88	61	59	3.85	4.01	0.21	279	1634	
Bulk Composition of Main Mass***									
Levack 93656	2.69	48	42	<0.13	<0.16		63	484	10800
MAC 91	3.07	45	46	<0.19	<0.19				
Average	3.2	46	44	<0.16	<0.18				
MORB****			72	<0.83		<0.02	196	800	4080

* Average of 6 analyses from Ames et al. (2002). ** Average of Onaping and Marginal phase of quartz diorite offset dykes. *** Calculated assuming Main Mass is 60% Granophyre, 10% Quartz Gabbro, 25% Felsic Norite and 5% Mafic Norite. **** Hamlyn et al. (1985)

were 0.06 and 0.03 ppb, respectively. The limits of detection (average blank plus three standard deviations) for the MAC-91 Pt and Pd data were 0.73 ppb. For the Levack drill core (93656) data, the detection limits for Pt and Pd were 0.10 and 0.06, respectively. To facilitate the extraction of maximum geochemical information for samples, the procedural blanks have been utilized on the plots. Whereas most of the Pd and Pt data for the Levack 93656 samples lie above the procedural blanks, most of the Pd and Pt data for the MAC-91 samples above the lowermost Felsic Norite lie below the procedural blanks.

Tables 1 and 2 provide analytical data for selected elements and PGE; the complete data set is available from the senior author on request.

On some of the plots, the chalcophile metals have been normalized to 100% sulfides by assuming an average value of 37% S in the sulfide component of the samples. It should be noted that the iron sulfide in the upper third of the Felsic Norite is pyrite and not pyrrhotite as it is in the remainder of the norites, the Sublayer, and the ore deposits. It is assumed that all the iron sulfide was initially present as pyrrhotite, but that the pyrite in the upper portion of the Felsic Norite is an oxidation product of the pyrrhotite. It is also assumed that S was conserved during this oxidation; it is believed that this is a valid assumption because of the strong correlations between S, Se and Cu throughout all of the Felsic and Mafic Norite.

Results

Major element and trace element variations with stratigraphic position

As shown by *Lightfoot et al. (1997c)* and *Lightfoot et al. (2001)*, the samples from the Capreol Traverse and MAC-91 provide a reasonable composite stratigraphy of the Main Mass that has no structural repetition or break. The Levack drill core (63656) also provides an excellent cross section of the Main Mass. The geochemical patterns in drill core 63656 and MAC-91/Capreol are remarkably similar even though the two drill holes are 50 km apart as measured around the perimeter of the SIC.

The MgO contents of the Main Mass vary from 15 wt.% to 0.65 wt.%, with the highest MgO contents being at the base of the Mafic Norite, due to the high orthopyroxene content of this unit (Fig. 2A). With increasing height in the Felsic Norite, MgO contents at first decrease rapidly and then more slowly upwards through the Felsic Norite. They then drop off more rapidly through the Quartz Gabbro until the base of the Granophyre. The upwards increasing MgO contents through the Granophyre led *Lightfoot et al. (2001)* to conclude that the Granophyre had solidified from its top downwards and that the Quartz Gabbro had formed from the residual melts of solidification of the Granophyre and the Felsic Norite. An alternative explanation involves expulsion of trapped liquid from the noritic melt (e.g., *Mungall, 2002*), but the noritic rocks are not strong cumulate-textured rocks, so the efficiency of the process has yet to be fully demonstrated.

The incompatible trace element contents of the Granophyre are approximately twice those of the Felsic Norite, as shown by the distribution of Ce and Yb (*Lightfoot et al., 2001*). Such patterns together with the distribution of the major elements had led *Chai and Eckstrand (1994)* to conclude that the Granophyre and the Felsic Norite had formed from different magmas. However, as pointed out by

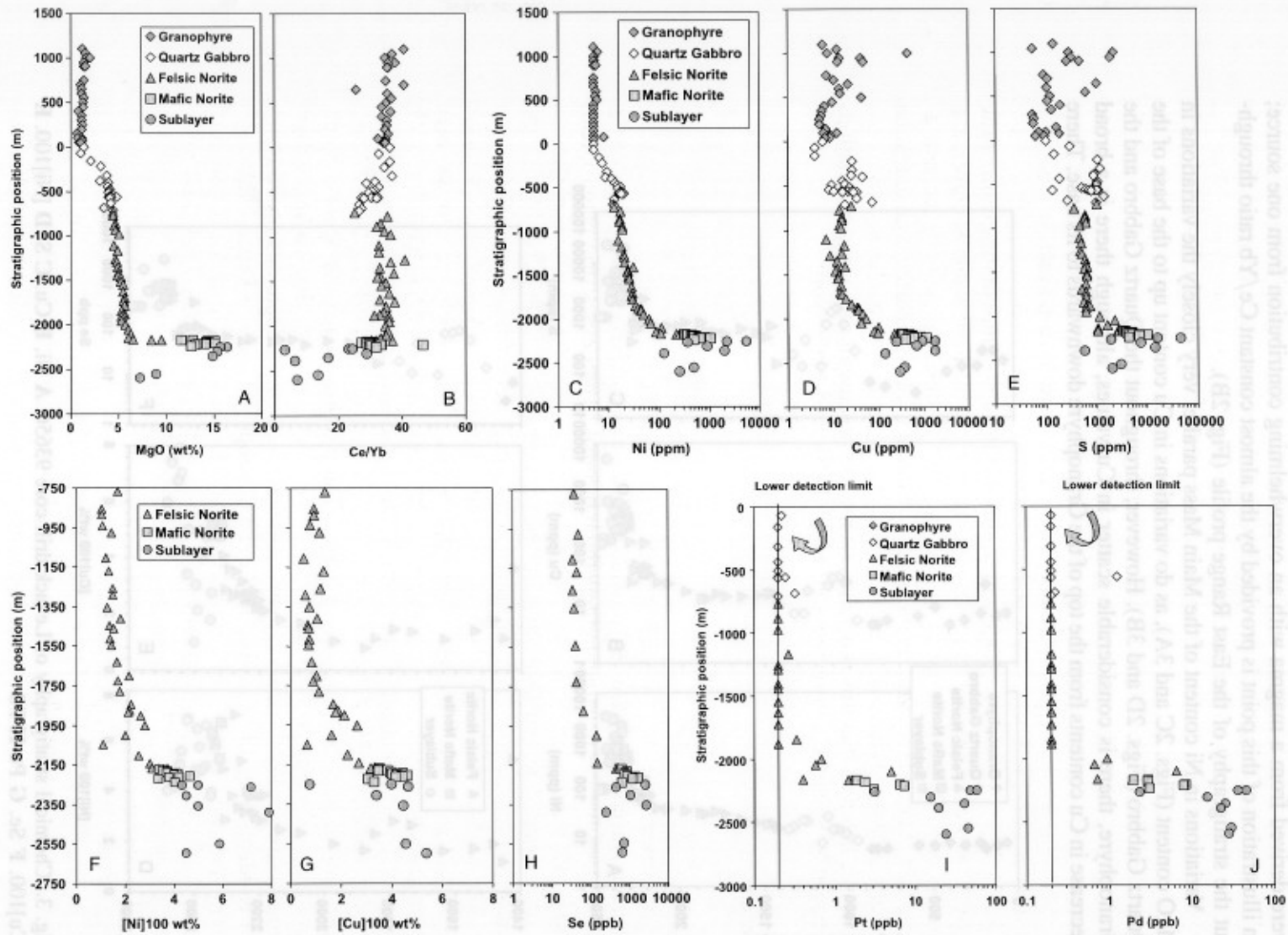


Fig. 2. Chemical stratigraphy of Nickel Rim drill core MAC-91. **A** MgO. **B** Ce/Yb, **C** Ni. **D** Cu. **E** S. **F** [Ni]100. **G** [Cu]100. **H** Se. **I** Pt. **J** Pd. It should be noted that normalized Ni, Cu and Se data are only given for the Norites and Sublayer (Fig. 2F–H) because both S and Cu have been hydrothermally remobilized in the Quartz Gabbro and Granophyre and because no Se data were collected for these rocks. Palladium and Pt data (Fig. 2I–J) are not plotted because they lie below the detection limit of the technique at the time of analysis

Lightfoot et al. (1997c), the fact that the ratios of incompatible elements are virtually identical provides strong evidence that the Granophyre and Felsic Norite were derived from a magma with an overwhelming contribution from one source; an illustration of this point is provided by the almost constant Ce/Yb ratio throughout the stratigraphy of the East Range profile (Fig. 2B).

Variations in Ni content of the Main Mass parallel very closely the variations in MgO content (Figs. 2C and 3A), as do variations in Cu content up to the base of the Quartz Gabbro (Figs. 2D and 3B). However, throughout the Quartz Gabbro and the Granophyre, there is considerable scatter in Cu values, although there is a broad decrease in Cu contents from the top of the Granophyre downwards to its base. There

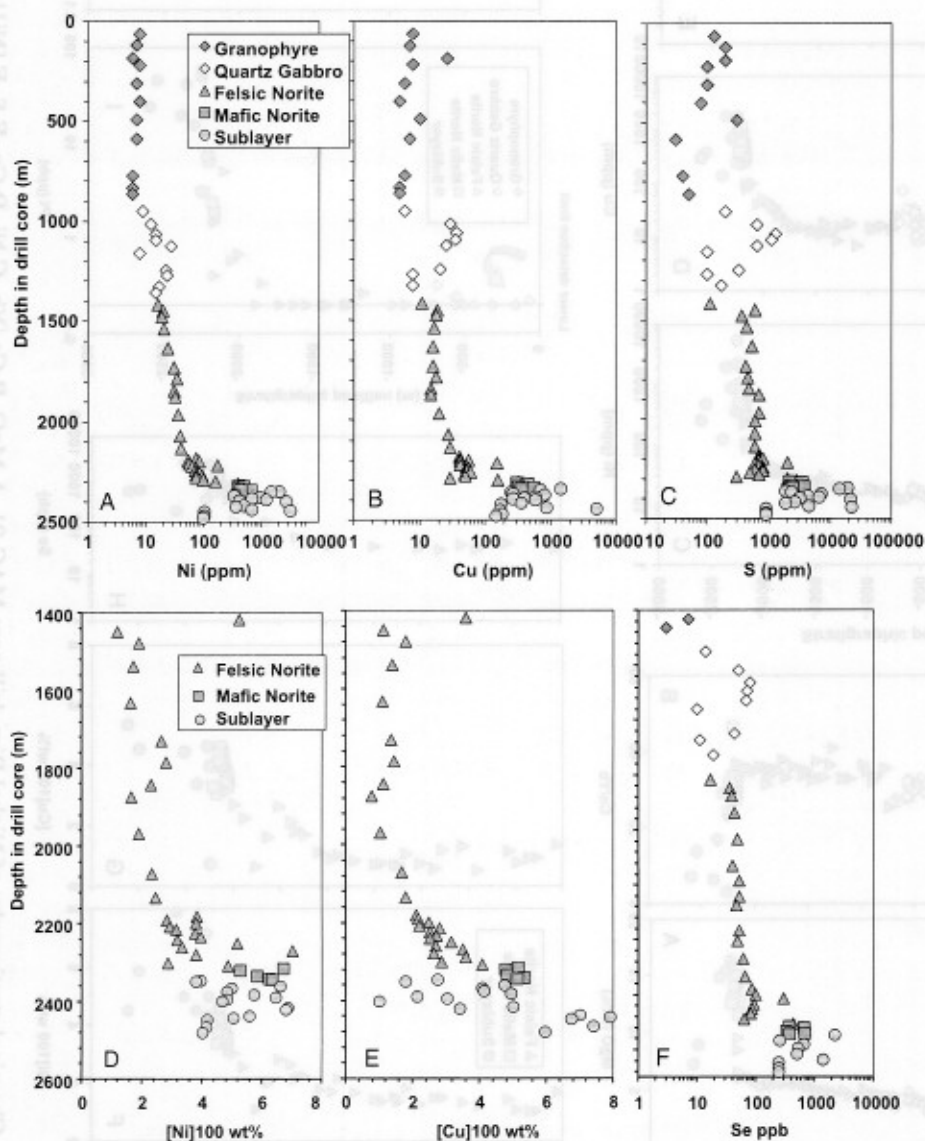


Fig. 3. Chemical stratigraphy of Levack drill core 93656. A Ni, B Cu, C S, D [Ni]100, E [Cu]100, F Se, G Pt, H Pd

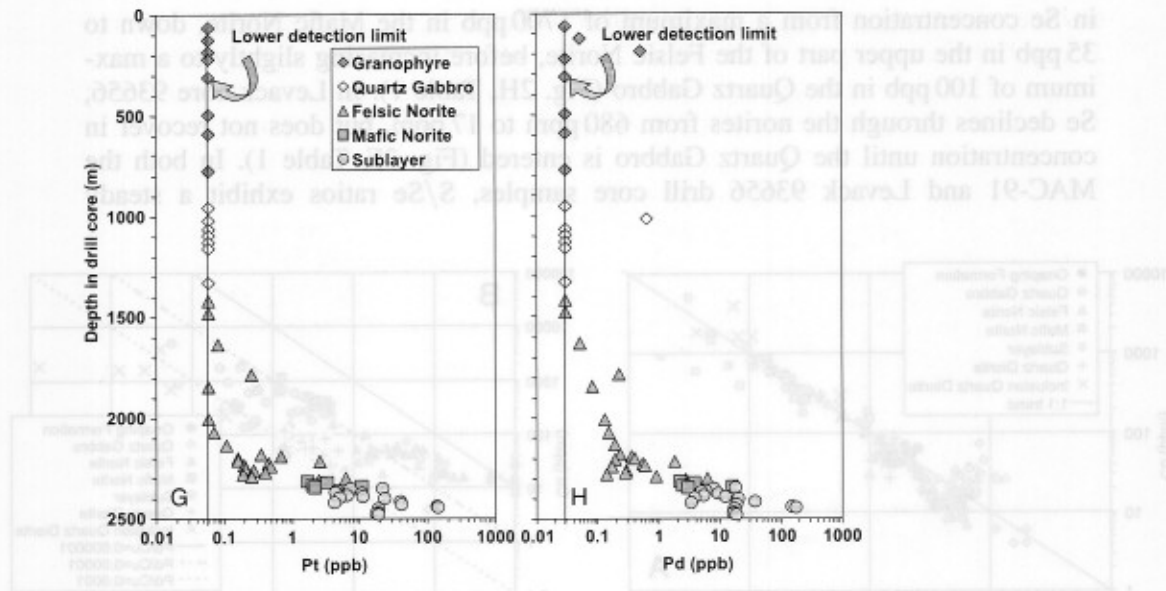


Fig. 3 (continued)

is an erratic variation in both Cu and S content within the Granophyre and the Quartz Gabbro (Figs. 2E and 3C). These variations are believed to be due to the extensive deuteric alteration to which both the Granophyre and the Quartz Gabbro were subjected (cf., *Chai and Eckstrand, 1994*); it is believed that S, Cu and other chalcophile metals were redistributed within the units during this low temperature alteration.

The Ni and Cu contents of samples from the Felsic Norite downwards have been normalized to 100% sulfides by using the S contents and assuming that the average S content of the sulfides is 37%. There is a consistent downwards increase in both Ni and Cu in 100% sulfides (expressed as [Ni]100 and [Cu]100; Figs. 2F-G and 3D-E); in drill cores MAC-91 and 93656, [Ni]100 declines upwards from 4.6% to 1%, and 7% to 1.2 wt.%, respectively. [Cu]100 declines from 4.6% to 0.5 wt.% in the East Range section, and 5.3% to 1.1 wt.% in Levack drill core 93656. There is a slight upwards increase in [Cu]100 at the top of the Levack core, but not the East Range section. The [Ni]100 and [Cu]100 values of unfractionated contact ore deposits varies from ~3.5–6% with a Ni/Cu ratio averaging ~1. The continuum in Ni values in 100% sulfides from the top of the Felsic Norite through the Mafic Norite and into the ore deposits provides very strong evidence that the Ni-Cu-PGE sulfide deposits of the SIC were co-magmatic with the most basal sulfides in the Felsic and Mafic Norites. This implies that the ores in the Sublayer were formed as part of the sulfide saturation event that produced the chemical variations through the noritic rocks.

Selenium was analyzed in the SIC samples because of the possibility that S had been remobilized by low temperature fluids in the SIC rocks. Selenium is a useful proxy for S, not least because it is readily determined down to ~10 ppb, unlike S, and behaves as a highly chalcophile element; in addition, unlike S which is remobilized by low temperature (<250 °C) hydrothermal and weathering processes, Se is generally stable during low temperature processes (*McGoldrick and Keays, 1981*). Samples from drill core MAC-91 illustrate a systematic upwards decrease

in Se concentration from a maximum of 1700 ppb in the Mafic Norite, down to 35 ppb in the upper part of the Felsic Norite, before increasing slightly to a maximum of 100 ppb in the Quartz Gabbro (Fig. 2H, Table 1). In Levack core 93656, Se declines through the norites from 680 ppm to 17 ppm, but does not recover in concentration until the Quartz Gabbro is entered (Fig. 3F, Table 1). In both the MAC-91 and Levack 93656 drill core samples, S/Se ratios exhibit a steady

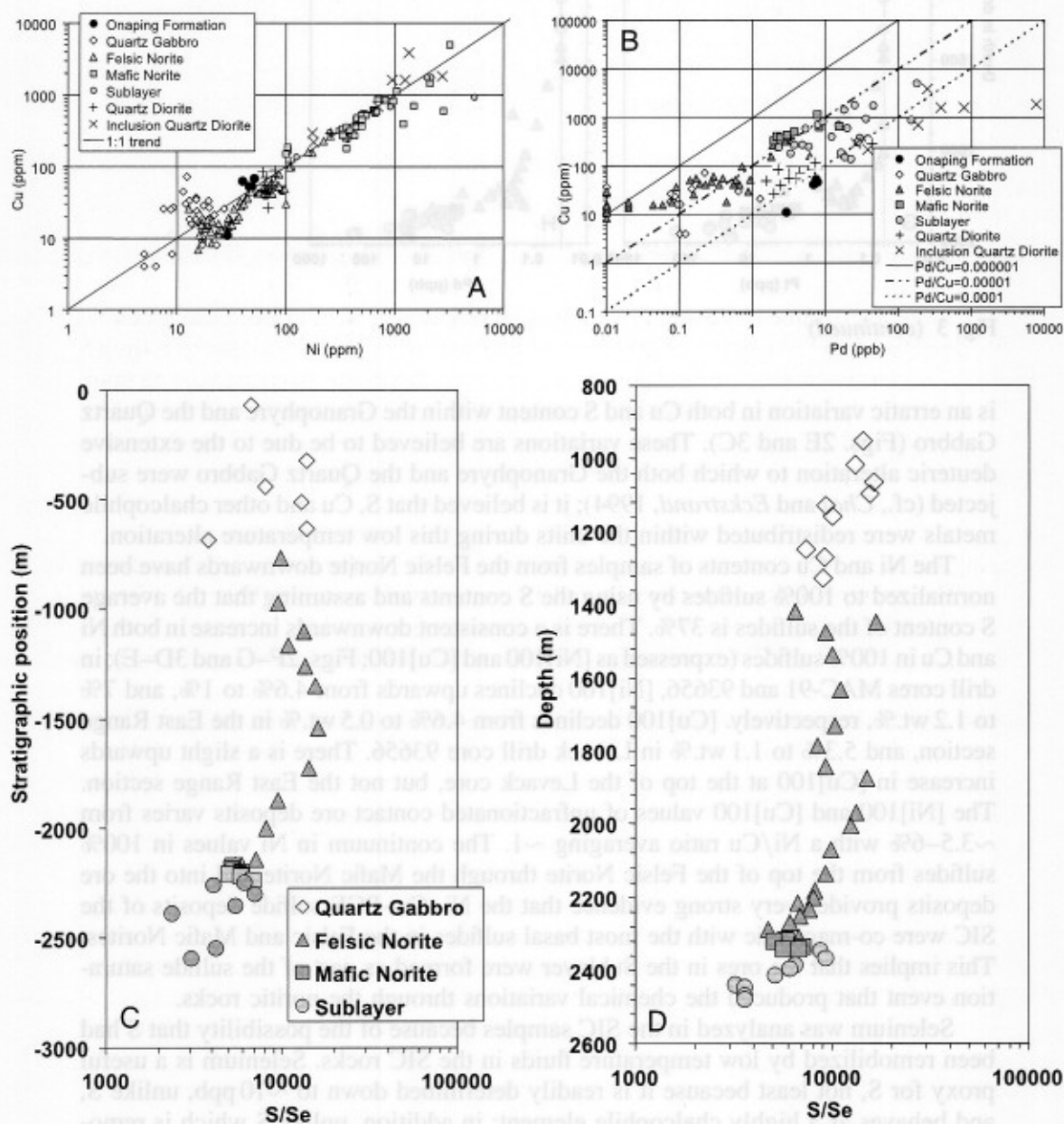


Fig. 4. Plot of Ni versus Cu (A) and Pd versus Cu (B) in 100% sulfide for samples from the Main Mass, Offsets, and Sublayer. Note the tight 1:1 trend, C, D Plots of S/Se versus stratigraphic position and depth, respectively

increase from the base of the Sublayer to the ~1500 m level in MAC-91 and to the 1876 m level in the Levack 93656 samples (Fig. 4C, D). The more extreme decline in Se relative to S from the mid-point of the Felsic Norite downwards is attributed to the fact that Se is more chalcophile than S having a partition coefficient similar to that of Cu (Peach et al., 1990). Indeed, Se is strongly correlated with Cu in both MAC-91 and the Levack 93656 samples (Table 1). In both drill transects, S/Se ratios both decrease and fluctuate above the mid-points of the Felsic Norite.

The average S/Se ratios of the Mafic and Felsic Norites in the MAC-91 and Levack 93656 samples are 9282 and 8704, respectively, values that are ~2.7 times those of the mantle which has a S/Se ratio of 3300 (McDonough, 2003) but considerably lower than the S/Se ratios of the continental crust. The average S/Se ratios of the SIC are consistent with derivation of some or all of the S in the SIC from continental crust.

PGE Variations with stratigraphic position

For Levack drill core 93656, both Pd and Pt exhibit initial rapid declines from the base of the Mafic Norite upwards to a depth of about 2180 m (Fig. 3G–H). Above this level, the decline in Pd and Pt values is more gradual, with Pt decreasing below its detection limit at a depth of 2007 m and Pd decreasing below its detection limits in the uppermost part of the Felsic Norite; however, there is a sharp increase in both Pt and Pd values at a depth of 1785 m (Fig. 3G and H). This increase in Pd and Pt concentration is accompanied by sharp increases in Cu, Se and Ni together with decrease in S/Se (Figs. 3A–B, Table 1, and Fig. 4D).

Although the detection limits for the MAC-91 data are much higher than for the Levack drill core data, the general trends are the same, with both Pd and Pt dropping off very rapidly from the base of the Mafic Norite upwards (Fig. 2I and J).

The average depth-integrated Pt and Pd concentrations of the Felsic Norite in the Levack drill core are <0.23 and <0.24, respectively. (Note: the Felsic Norite sample with the high Pd and Cu contents is not included in this average; this sample occurs towards of the base of the Felsic Norite). These values are significantly less than those reported by Chai and Eckstrand (1993), who obtained averages of 2.8 ppb Pd and 4.4 ppb Pt for the Felsic Norite. In drill core MAC-91, Pt falls from 7.3 ppb to <0.20 ppb, and Pd falls from 7.7 ppb to <0.20 ppb. In Levack drill core 93656 Pt falls from 10.7 ppb to <0.06 ppb and Pd falls from 15.5 ppb to <0.03 ppb. Palladium shows a decline by a factor of >700 in the Main Mass norites of MAC-91 and >1050 in the Main Mass norites of drill core 93656. Likewise Pt falls by factors of >770 and >1550 in drill cores MAC-91 and 93656, respectively. These contrast with Ni and Cu which decline by factors of ~80 and ~170 in Main Mass norites of drill core MAC-91, and ~40 and ~50 in Main Mass norites from drill core 93656. These factors are almost one order of magnitude less than the depletion factors for Pt and Pd. Although the upwards decline in Pt and Pd values is very dramatic, all of the PGE should have been stripped from the bulk of the Felsic Norite magma because of their very high partition coefficients; we will consider why this did not happen below.

In 100% sulfide, the Pt and Pd concentrations also systematically decline upwards. For example, in Levack drill core 93656, both [Pd]100 and Pt[100] decline from ~1100 ppb to <30 ppb through the Main Mass noritic rocks (Fig. 5C). By contrast,

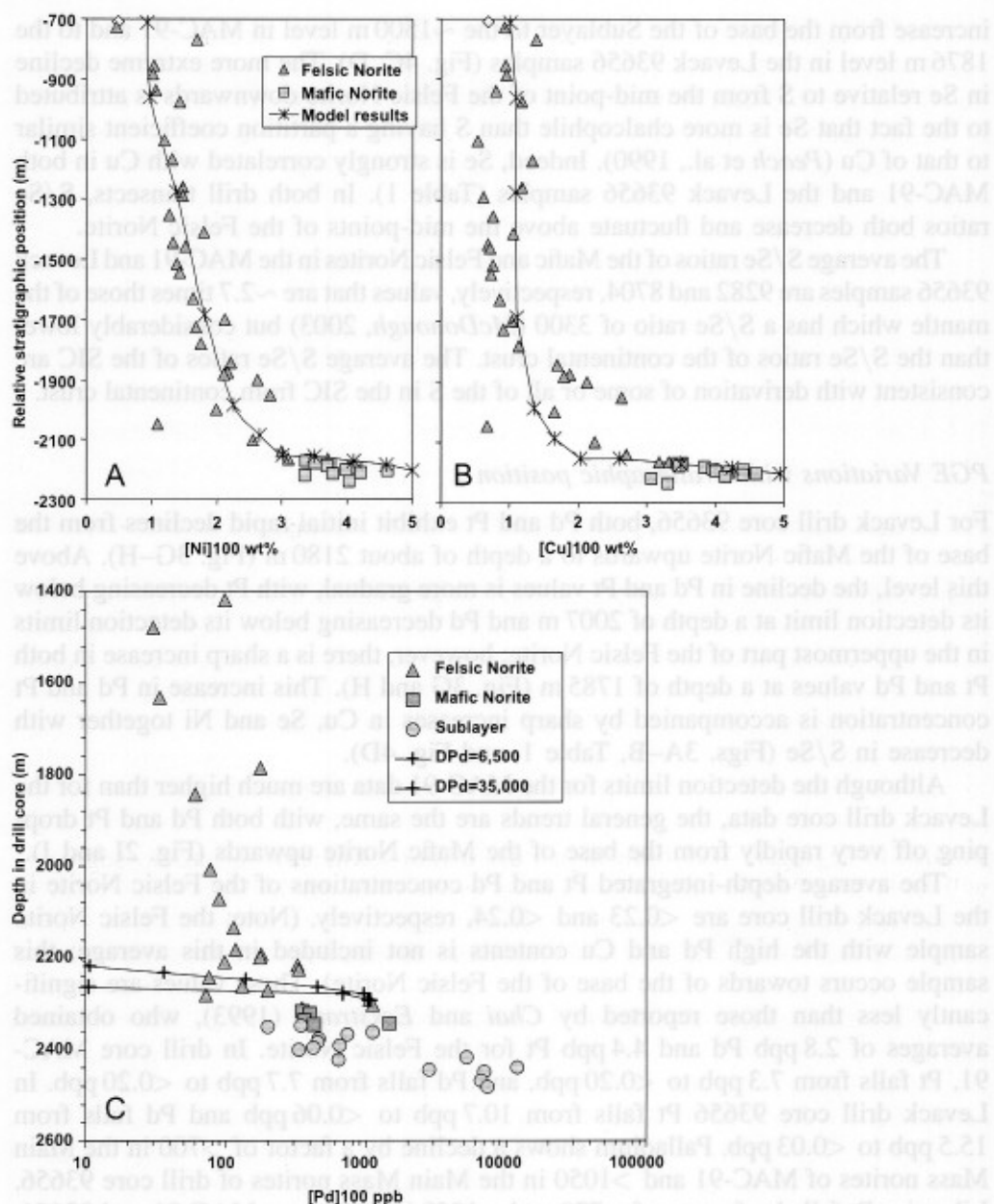


Fig. 5. **A** Modeled Ni in 100% as a function of depth in the Mafic and Felsic Norites of MAC-91; **B** Modeled Cu in 100% as a function of depth in the Mafic and Felsic Norites of MAC-91. **C** Modeled Pd in 100% sulfide as a function of depth in the Mafic and Felsic Norite in Levack drill core 93656. The actual S contents of the rocks have been used for the modelling. Note that all samples have been plotted against their true depth down MAC-91

Cu[100] decreases from 5.34% to 0.77% before it exhibits a sharp increase at a depth of 1450 m, while Ni[100] decreases from 6.7% to 1.2% (Fig. 5A, B). Hence, while the Ni and Cu tenor of the sulfides decrease by factors of 5.6 and 6.9, respectively, the Pd and Pt tenors of the sulfides decrease by more than a factor of 37.

The Sublayer in Levack drill core 93656 exhibits an enormous range in Pd[100] and Pt[100], with Pd[100] ranging from 200–12 000 ppb (Fig. 5C). In MAC-91, Pd[100] in the Sublayer varies from 280–14 000 ppb. In both drill cores 93656 and MAC-91, Pd[100] and Pt[100] steadily increase with depth into the Sublayer (Fig. 5C). This downwards increase parallels the order in which the sulfides would have segregated from the melt sheet; hence, the sulfides with the highest Pd[100] and Pt[100] contents were the first to segregate from the magma and are very strongly enriched in the PGE because of their extremely large partition coefficients.

Variations in Ni versus Cu and Pd versus Cu in the Onaping Formation, the Main Mass, Sublayer and Offsets

Variations in Ni versus Cu for Main Mass norites, gabbros, and granophyres are shown in Fig. 4A along with the compositions of the Onaping Formation, Offset quartz diorite (QD) and inclusion-quartz diorite (IQD) superimposed on the plot. Most of the Main Mass rocks, Onaping and the quartz diorites fall on a single array with Ni/Cu \sim 1, with the concentrations of the metals reflecting the modal sulfide content of the rock. The bulk of the assays of sulfide-bearing (>2% S) inclusion quartz diorite from Worthington tend to be displaced on average to Cu/Ni \sim 1.6, which is higher than the bulk of the Main Mass samples which have a ratio of close to 1. An extension of the Main Mass array would intersect a broad cloud of data for the unfractionated Sublayer ores with Cu/Ni \sim 1.

Figure 4B shows the variation in Cu versus Pd for the same group of samples. Because Pd has a much larger partition coefficient than Cu, Pd/Cu ratios can be used to indicate the order of segregation of sulfides from a magma; the first sulfides to segregate will have high Pd/Cu ratios whereas the last to segregate will have low Pd/Cu ratios. The noritic rocks of the Main Mass show a broad decline in Pd/Cu ratio as Pd and Cu concentrations fall. Most of the Felsic Norite samples have Pd/Cu ratios that are significantly less than the Pd/Cu ratio of MORB, which is the classic example of a PGE-depleted mafic rock produced by a S-saturated magma (Hamlyn et al., 1985). The Pd/Cu ratios of the Sublayer norite samples either overlap with those of the Mafic Norites or are higher than the Mafic Norites. The sulfide-bearing Offset quartz diorite samples have Pd/Cu ratios that overlap with the Sublayer samples having the highest Pd/Cu ratios, or have Pd/Cu ratios that are significantly higher than the Sublayer samples. If all of the rocks (and their sulfides) had formed from the same magma, their Pd/Cu ratios indicate the following order of crystallization: Offsets > Sublayer > Mafic > Mafic Norite > Felsic Norite. The Onaping Formation samples and the marginal quartz diorite Offset samples have Pd/Cu ratios that are significantly higher than the Pd-depleted Felsic Norite samples but somewhat lower than those of the most strongly mineralized Offset quartz diorite samples (Fig. 4B).

Modeling Cu, Ni and PGE Variations in the Main Mass

The variations in the Cu and Ni contents in 100% sulfides of samples of Felsic Norite and the Mafic Norite have been modeled in order to estimate the initial Cu and Ni contents of the magma that produced these rocks and to confirm that the

sulfides in these rocks are co-magmatic with the sulfides in the Sublayer. To do this, it is necessary to use the Rayleigh Law:

$$C_L = C_o * F^{(D-1)}$$

where C_L is the concentration of element in the fractionated silicate melt, C_o is the concentration of the element in the initial silicate melt, F is the fraction of silicate melt remaining after fractionation, and D is the distribution coefficient of the element.

It is also necessary to use the R factor equation:

$$C_s = C_o * D(R + 1)/(R + D)$$

where C_s is the concentration of the element in the sulfide melt, C_o is the concentration of the element in the initial silicate melt, D is the distribution coefficient, and R is the R factor which is the mass ratio of silicate melt to sulfide melt (Campbell and Naldrett, 1979).

Estimates of partition coefficients for Cu, Ni and the PGE based on empirical observations and experiments vary widely, with D_{Cu} ranging from 50–1400, D_{Ni} ranging from 100–840, and D_{Pd} and D_{Pt} ranging from 10^3 – 10^5 (Leshner and Stone, 1996; Barnes and Maier, 1999). Based on natural observations, Vogel and Keays (1996) estimated that D_{Pd} is 3 to 5 times greater than D_{Pt} . Barnes and Maier (1999) noted that the partition coefficients of the chalcophile metals co-vary with changing magma conditions while Peach and Mathez (1993) demonstrated that D_{Ni} is controlled by the FeO content of silicate melts and hence their oxygen fugacity. From a comprehensive investigation of Sudbury ore deposits, Li and Naldrett (1994) showed that the Sudbury ores had formed under R factors that varied from 400 to 4000. For the purposes of the modelling carried out in this study, we have selected an initial R factor of 1000, which decreased in proportion to the remaining volume of silicate melt during solidification of the Main Mass; selection of other R values does not affect the outcome of the modelling radically.

It was assumed that the Mafic and Felsic Norites crystallized as a closed system, except for the loss of some residual silicate melt left over from the crystallization of the Felsic Norite. Bulk distribution coefficients between the silicate magma and the cumulates were calculated for Cu and Ni using the selected sulfide melt/silicate melt partition coefficients for these metals together with the modal percentages of sulfide (calculated from the S contents of each sample) and those silicate phases (olivine and orthopyroxene) which extract Ni from silicate melts as well as the distribution coefficients of these phases.

In order to fit the model curves for Ni and Cu to the real data, it was necessary to use an iterative process to select the most appropriate D_{Ni} and D_{Cu} values and loss of residual silicate melt. The partition coefficients that gave the best fit to the data were $D_{Ni} = 250$, $D_{Cu} = 700$, and a loss of 5% silicate melt from the crystallization of the Felsic Norites. Selecting other D values for Ni and Cu yielded results that failed to reproduce the observed variations. For example, using $D_{Cu} = 250$, the model indicates that the Cu tenor of sulfides at the top of the Felsic Norite should be 29.8 wt.%. Conversely, when a value of $D_{Cu} = 1000$ is used, the calculated Cu tenor of sulfides at the top of the Felsic Norite is 0.11 wt.%.

Implicit in the modeling is the assumption that the Main Mass and Sublayer magma was S-saturated throughout the crystallization of the silicates that produced these rocks and that the bulk of the Ni, and all of the Cu, Pd and Pt were extracted from the magma by sulfide melts. The S-saturation status of the SIC magma can be evaluated by using the FeO content of the parental SIC magma as estimated from its bulk chemical composition and from an estimate of its liquidus temperature. As shown by *Haughton et al. (1974)*, *Mathez (1976)*, *Wentland (1982)* and *Mavrogenes and O'Neill (1999)* the S contents of basaltic melts are strongly dependent on the FeO contents of the melts as well as their temperatures. In a compilation of all experimental data for the solubility of sulfide S in silicate melts, *Poulson and Ohmoto (1990)* showed that the variation of X_S with X_{FeO} is a straight-line correlation which can be described by the equation

$$\text{Log } X_S = -0.92 + 1.92 \text{ Log } X_{FeO} \quad (1)$$

Subsequently, *Li et al. (2001)* also used published data to develop the following equation to estimate the S contents of basaltic magmas:

$$S = 1431 + 221 \times (\text{FeO} - 9) + 5 \times (T - 1200) \quad (2)$$

where FeO is in mole% and T is in degrees celcius.

Of the various rock models that can be selected to provide an estimate of the FeO content of the SIC magma, the highest estimate of 8.13 wt.% (=7.5 mole%) FeO is provided by the marginal quartz diorite phase of the Offsets (cf. *Keays and Lightfoot, 1999*). The thermodynamic model MELTS of *Ghiorso and Sack (1995)* under QFM -1 and 100 bars total pressure predicts that orthopyroxene would be the first liquidus phase (consistent with the dominance of orthopyroxene in both the Sublayer and the Mafic Norite) and that the liquidus temperature of the SIC magma would have been $\sim 1180^\circ\text{C}$. Solution of Eq. 1 yields a S capacity of 405 ppm S whereas solution of Eq. 2 using $T = 1180^\circ\text{C}$ and 7.5 mole% FeO indicates that the S capacity of the SIC magma at its liquidus temperature was 990 ppm.

The SIC magma was clearly S-saturated and sulfides were cotectic phases along with the orthopyroxene (and plagioclase) during the crystallization of the Mafic Norites, which contain 9870 to 3280 ppm S (Fig. 2E). It also remained S-saturated during the crystallization of the Felsic Norites with 1150 ppm S up to a depth of 2000 m (cf. Fig. 2E). Above a depth of 2000 metres, the Felsic Norites contain 640 to 460 ppm S; however, these norites contain $\sim 20\%$ cumulus silicate minerals which do not host S. Had the magma been S-undersaturated, all the S in the rocks contributed by the trapped silicate melt, this melt would have had to have contained 800 to 575 ppm S. The *Poulson and Ohmoto (1990)* equation, which predicts that the SIC magma had a S capacity of 405 ppm S, indicates that the SIC magma remained strongly S-saturated throughout the crystallization of the Norites. However, the *Li et al. (2001)* equation indicates that the SIC magma would have become S-undersaturated during the latter stages of crystallization of the Felsic Norite.

The excellent correlations between Cu and Ni (Fig. 4A) as well as between Pd and Cu (Fig. 4B), and between Cu versus Se and Ni versus Se over three orders of magnitude (cf. Table 1) provide very strong support that the geochemistry of Cu and Ni were controlled by sulfides and that the SIC magma remained S-saturated

throughout its history. For this reason, the *Li et al.* (2001) equation is not believed to be applicable to the SIC magma. In addition to confirming that sulfide melts controlled the chemistry of all of the chalcophile elements, the strong correlations between them in the Main Mass rocks as well as the Sublayer provide very strong evidence that the sulfides in the Sublayer are co-genetic with those of the Main Mass rocks.

The Pd/Cu ratios of the Felsic Norite are very similar to that of average MORB (*Hamlyn et al.*, 1985) that are known to have formed from S-saturated magmas and have lost a considerable proportion of their original chalcophile metal complement. The very low Pd/Cu and Pt/Cu contents of the Felsic Norite indicate that the magma which formed the Felsic Norite was strongly depleted in the PGE, which now reside within the Ni–Cu sulfide ores of the SIC, and was S-saturated throughout its history.

Copper has been exclusively extracted from the magma by the immiscible sulfide droplets, but Ni has been removed by both magmatic sulfide droplets and silicate minerals (predominantly orthopyroxene). Although some olivine may have been on the liquidus at the time of sulfide formation, none is preserved in the rocks today, and in any case olivine would have been a very subordinate phase compared to orthopyroxene (e.g., *Prevec et al.*, 2000; *Prevec*, 2000). Although the amount of orthopyroxene varies from sample to sample, it has been assumed that the modal percentage of orthopyroxene varied from 12 modal percent at the top of the Felsic Norite to 60 modal percent at the base of the Mafic Norite. It should be noted that orthopyroxene gives way to clinopyroxene towards the top of the Felsic Norite; this changeover was not taken into account. Clinopyroxene has a smaller distribution coefficient than orthopyroxene. A distribution coefficient for Ni of 5 was used for the orthopyroxene. It was also assumed that the Felsic Norite and the Mafic Norite were formed from a single magma in a closed system (cf. *Lightfoot et al.*, 1997a).

The results of the modeling are displayed in Fig. 5A–B in which the model curves are superimposed on the actual data sets showing the variation of Ni and Cu in 100% sulfides. Except for the slightly higher Ni in 100% sulfides in the lowermost sample in the model curve, the match between the model curve and the actual distribution of Ni in 100% sulfides as a function of depth is reasonably good. The match between the modeled distribution and the actual distribution of Cu in 100% sulfides is not quite as good, the main problem being that the modeled curve predicts a more rapid decrease in Cu values in 100% sulfides than observed. It should be noted, however, that whereas Ni values decrease systematically from the base of the Mafic Norite upwards (Figs. 2 and 3), variations in Cu in the Felsic Norite above 1876 m (Figs. 2 and 3) are not as regular as those for Ni; indeed there appears to be an increase in Cu contents. This is especially obvious for the Levack drill core data (Fig. 3E) in which the increase in Cu coincides with increases in Ni, Pd and Pt (Fig. 3). The inflection in the Cu trend also coincides with that in S/Se ratios, which increase regularly from the base of the Felsic Norite to reach a maximum of 14 893 at 1876 m before dropping sharply to 9231 (Fig. 4C–D). We suggest that these inflections indicate that the magma chamber was replenished with a fresh supply of metals at the 1876 m level of the Felsic Norite. Most Quartz Gabbro and Granophyre samples contain more

Cu than samples from the upper half of the Felsic Norite. We suspect that much of the Cu in these rocks was introduced by the fluids involved in the alteration of these rocks.

The results of our modeling indicate that the initial silicate magma contained 250 ppm Ni and 120 ppm Cu. These must be regarded as minimum estimates because we have not incorporated the Ni and the Cu present in the sulfide ore deposits nor the non-economic accumulations of sulfides in the Sublayer and Footwall environments.

Selection of appropriate partition coefficients for modelling Pd and Pt in the Levack drill core samples proved difficult. Both *Rehkamper et al. (1999)* and *Brugmann et al. (1993)* found that D_{Pd} values of 10 000 worked well for modelling the distribution of Pd in MORB and the Siberian Trap, respectively. However, *Peck et al. (2001)* found that a D_{Pd} value of 35 000 worked well for modelling PGE distributions in the East Bull Lake Intrusion. We initially chose $D_{Pd} = 35\,000$, this being the partition coefficient documented in MORB by *Peach et al. (1990)*, and $D_{Pt} = 10\,000$ but were unable to model the distribution of Pd and Pt in the Levack drill core (Fig. 5C). Although the Felsic Norite is very strongly depleted in the PGE, the use of these partition coefficients indicates that it should become depleted far more rapidly than it does had the norites formed as a closed system. Using a partition coefficient of $D_{Pd} = 2500$, it is possible to model the observed distributions half way up the Felsic Norite, but after that height the model again predicts that Pd should decrease much more rapidly than it does (Fig. 5C). However, this partition coefficient is considered to be far too small; although the partition coefficients of the PGE do vary considerably as a function of oxygen activity, the variations trend in the same direction as that of Ni and Cu. Although we are not able to model the distribution of Pt and Pd in the drill core, the model does permit us to determine the Pd and Pt contents of the SIC magma at the start of crystallization of the Felsic Norite, these being 1.1 ppb Pd and 1.2 ppb Pt. Again, it must be noted that a considerable amount of the PGE in the initial SIC magma would have been removed in the sulfide melts that segregated from the magma to produce the Ni–Cu–PGE sulfide orebodies as well as the significant amount of non-economic Ni–Cu–PGE sulfides in the Sublayer.

Using an R factor of 1000, we have used the average composition of various Sudbury Ni–Cu–PGE sulfide orebodies as well as sulfides in the Mafic Norite to calculate the Ni, Cu and PGE contents of the silicate magmas from which the sulfides in the ore deposits segregated (Table 3). The Totten ores, which are representative of the Offset deposits, required a silicate magma with 310 ppm Ni, 310 ppm Cu, 18 ppb Pd and 21 ppb Pt (Table 3). (Using a lower R factor of 100, we calculate that the silicate melts from which the Totten ores segregated would have contained 860 ppm Ni, 1450 ppm Cu, 178 ppb Pd and 188 ppb Pt, metal values that we believe to be geologically unreasonable). The Creighton ores, which are representative of the contact Sublayer orebodies, required a silicate melt with 265 ppm Ni and 170 ppm Cu, 2.3 ppb Pd and 2.2 ppb Pt. The compositions of sulfides in the Mafic Norite confirm that at the commencement of crystallization of the Main Mass norites, the SIC magma contained 210 ppm Ni, 110 ppm Cu, 1.1 ppb Pd and 1.2 ppb Pt. These calculations also indicate that the marginal quartz diorite of the Worthington Offset, which contains 69 ppm Ni and 59 ppm Cu, could

Table 3. Calculations showing the compositions of the liquids in equilibrium with Offset, Sublayer, and Main Mass sulfides at Sudbury. In the case of the Offset ores, it is shown in the text that they are not the product of sulfide differentiation in the Sublayer

	Observed averages					Calculated parental magma				
	[Ni] ₁₀₀	[Cu] ₁₀₀	[Pd] ₁₀₀	[Pt] ₁₀₀	[Ir] ₁₀₀	10000*Pd/Ni	C _o (Ni)	C _o (Cu)	C _o (Pd)	C _o (Pt)
Units	wt%	wt%	g/t	g/t	g/t		ppm	ppm	ppb	ppb
Offset Deposits	6.2	12.8	18	19	0.28	2.90	310	310	18	21
Contact Deposits	5.3	7.1	2.2	2	0.01	0.42	265	170	2.3	2.2
Mafic/Felsic Norite	4.2	4.5	0.6	0.45	0.02	0.14	210	110	1.1	1.2
Initial SIC Magma							61*	59*	3.9*	4*

* Observed average quartz diorite and Onaping; see Table 2

not have been in equilibrium with the Totten ores (Table 2). This means that either the marginal quartz diorite phase is a separate intrusive phase (which we suspect) or the sulfides and carrier magma were introduced so rapidly that there was no opportunity for equilibration between the sulfide and silicate melts. That is, the sulfides were transported under conditions of a very small R factor.

Lightfoot et al. (1997, 2001) have demonstrated that the inclusion-free and sulfide-free quartz diorites which comprise the marginal phase of the Offset dykes provide an indication of the bulk initial composition of the Main Mass of the SIC. Although the compositions of the marginal quartz diorite phase of the Offsets do vary, they contain averages of 69 ppm Ni, 59 ppm Cu, 2.8 ppb Pd and 4.0 ppb Pt (Table 2). An independent estimate of the bulk composition of the SIC is provided by the suevites/fall back breccias of Onaping Formation whose composition should represent the average composition of the country rocks impacted by the meteorite. The match will not be perfect because the source rocks for the Onaping Formation would have been at somewhat higher crustal level than the crustal rocks which formed the melt sheet. The whole rock Onaping rocks analyzed have averages of 55 ppm Ni, 48 ppm Cu, and 4.9 ppb Pd (Table 2). These values are well within the range of values obtained for the marginal phase of the Offset dykes. *Ames et al.* (2002) state that the best estimate of the parental composition of SIC magma is provided by the least altered vitric material in the Onaping Formation; for these they obtained average values of 60 ppm Ni and 69 ppm Cu (Table 2). The parental composition of the SIC melt sheet as estimated from the whole rock samples and the least altered vitric material in the Onaping Formation and the marginal phase of the Worthington Offset was 61 ppm Ni, 59 ppm Cu, 3.9 ppb Pd and 4.0 ppb Pt (Table 2).

Because of their very high partition coefficients, it is expected that the PGE would have been removed from the SIC magma once it became S saturated at a much faster rate than the base metals, which have high but nevertheless much smaller partition coefficients. The relative timing of sulfide segregation from the SIC magma should be provided by ratios such as Pd/Ni, with the earliest formed sulfides having the highest Pd/Ni ratios and the latest-formed sulfides having the lowest Pd/Ni ratios. As indicated by their Pd/Ni ratios (Table 3), the sulfides in the SIC system appeared to have formed in the following sequence: Offset Ores > Contact Ores > Sublayer > Mafic Norite > Felsic Norite (base) > Felsic Norite (top). Although Pd/Ni ratios drop off rapidly through this sequence, they do not drop off nearly as quickly as predicted from the partition coefficients of Pd (~35 000) and Ni (~250). In particular, the segregation of the Offset and Contact ore-bodies sulfides from the SIC magma should have reduced its Pd/Ni ratio of practically zero as well as removed the bulk of the Cu and Ni, and all of the PGE, from the SIC magma. Indeed, the segregation of the disseminated Ni–Cu–PGE-rich sulfides in the Sublayer should have completely exhausted the PGE in the SIC magma. The Sublayer is recognized in the field by its high, but extremely variable sulfide contents; the sulfide contents of the Sublayer in MAC-91 and drill core 93656 are 2.9% and 2.1%, respectively. As the Sublayer can be up to 500 m thick, it contains a very significant amount of Ni–Cu–PGE-rich sulfides. The fact that at the time the SIC magma commenced crystallization of the Mafic Norite still contained 1.2 ppb Pt and 1.1 ppb Pd means either that the PGE were not

scavenged efficiently from the magma (that is, the partition coefficients are not applicable) or that additional supplies of Pd and Pt were added to the magma.

These observations create a serious dilemma. Whereas mass balance calculations and estimation of the composition of the melt sheet as determined from analyses of the Onaping Formation and the marginal low-sulfide quartz diorite phase of the Offsets indicate that the melt sheet contained more than enough metals to form the known ores, the observed sulfide orebodies as well as modeling of the initial chalcophile metal content of the Main mass magma require parental magmas with higher Ni, Cu and PGE concentrations, as well as differing Cu/Ni ratios. This dilemma remains incompletely understood, but several factors need to be considered:

1. The high S contents of the Sublayer and the Felsic Norite, and the extreme chalcophile metal depletion indicates that the magma from which these rocks formed was S-saturated. However, the continuum in metal values between these rocks and the sulfide ores provide very strong evidence that the ores segregated from the overlying Main Mass magmas. The high PGE contents of the ores means that the SIC magma was initially S-undersaturated (cf. Keays, 1995). The SIC magma therefore contained a much higher S content than normal for a silicate melt with the composition of the SIC. The SIC melt sheet, however, was superheated, having a temperature of $\sim 1700^{\circ}\text{C}$ (Ivanov and Deutsch, 1997). Naldrett (1989) estimates that the S capacity of a silicate melt increases by a factor of 2.5 over the temperature range $1200\text{--}1450^{\circ}\text{C}$. Extrapolating Naldrett's estimate of the temperature effect on the S capacity of the SIC melt, it is probable its S capacity at 1700°C was a factor of 5 times greater than at $\sim 1180^{\circ}\text{C}$, the liquidus temperature of the SIC melt. (Solution of the Li et al. (2001) equation indicates the S capacity of the SIC magma at 1700°C was a factor of 3.6 times greater than at $\sim 1180^{\circ}\text{C}$).
2. It is probable that the SIC melt would have been grossly S-oversaturated at its liquidus temperature and that therefore the sulfide melts formed well in advance of the crystallization of silicate and oxide phases. As noted above, the S capacity of the melt that formed the Main Mass norites would have been ~ 400 ppm S at the liquidus temperature of the melt. However, the integrated S content of the Felsic and Mafic norite in MAC-91 is 1070 ppm, assigning Felsic and Mafic Norite in the proportions 95:5. If the norites crystallized as a closed system (as indicated by the modeling), then their parental magma contained 2.7 times more S than it should have at 1200°C , the liquidus temperature of the melt. However, all of the S present in the norites would have been dissolved in the superheated melt sheet. This became S-saturated at $\sim 1450^{\circ}\text{C}$. Hence, sulfides commenced segregation from the magma 250°C above the temperature at which silicates appeared on the liquidus. These sulfides would have segregated to form the orebodies as well as significantly raise the sulfide content of the Sublayer. In terms of the timing of segregation of its sulfides from the magmas, the SIC magma was therefore quite unique when compared to any other known terrestrial magma.
3. The composition of the melt sheet may have been continually changing as more mafic inclusions were assimilated into the melt. The melt sheet was probably formed by decompression melting of the target crustal rocks following meteorite impact (Grieve, 1994). Because of their much higher melting temperatures,

- mafic rocks would have melted much more slowly than the felsic rocks in the target area. In addition, because of their high density, they would have accumulated along the base of the superheated melt sheet as it thermally eroded its way downwards into the unmelted, but very hot rocks below. It is envisaged that at least some of the mafic rocks remained as unmelted refractory blocks (e.g., the diabase hornfels inclusions in the Sublayer) whereas others melted to form a significant proportion of the magma the Sublayer matrix (cf. *Lightfoot et al.*, 1997). The average Nipissing Diabase has a Ni/Cu ratio of ~ 2 (*Lightfoot et al.*, 1996) and the average Ni/Cu ratio of the Huronian volcanics at Thessalon is ~ 3 (*Tomlinson*, 1996). Late stage melting of these rocks and incorporation into the lower portion of the melt sheet would have elevated its Ni/Cu ratio.
- Mantle-derived magmas may have been added to the lower part of the melt sheet prior to formation of the first sulfides. As pointed out by *Lightfoot et al.* (1997b) the addition of up to 20% of a mantle-derived magma of picritic composition to the melt sheet would not be detectable in the chemistry of the SIC as the contribution of the mafic magma would be swamped by the strong crustal signature of the melt sheet. A high-MgO tholeiitic magma or a picrite would be denser than the melt sheet and so would be emplaced into its lower portion. The addition of such a magma would not only increase the Ni/Cu ratio of the resulting hybrid magma but could explain the presence of the mafic to ultramafic inclusions and the high proportion of orthopyroxene in the Sublayer and Norites. There is, however, no direct evidence for a mantle contribution to the SIC.
 - Both the Nipissing Gabbro and the East Bull Lake type intrusions of the Southern Province of the Canadian Precambrian Shield contain appreciable Cu–Pd–Pt–Ni sulfide mineralization (*Peck et al.*, 2001; *Lightfoot et al.*, 1996; *Jobin-Bevans et al.*, 1998). It is possible that there were significant amounts of this type of mineralization in the SIC target rocks and that this provided proto-ores for the SIC impact melt sheet (*Keays et al.*, 1995). However, Cu–PGE–Ni sulfide mineralization in East Bull Lake has Cu/Ni ratios of ~ 3 (*Peck et al.*, 2001) while Cu–PGE–Ni sulfide mineralization in the Nipissing Gabbro has Cu/Ni ratios of ~ 2.5 (*Jobin-Bevans et al.*, 1998). Hence, the Cu/Ni ratios of possible proto-ores are too high to be major contributors of Cu and Ni to the SIC melt sheet *unless* their contribution was counterbalanced by contributions from either dissolution of mafic rocks in the target area or high-Mg magmas. In addition, any contribution these proto-ores made to the melt sheet, must have been made *before* it became S-saturated and therefore still capable of dissolving sulfides. These proto-ores would have had to be dissolved before the SIC magma became S-saturated and would have shifted the composition of the melt sheet in the wrong direction as far as Cu/Ni ratios are concerned.
 - It is possible that metals were not extracted simultaneously from the melt sheet, but that parts of it remain S-undersaturated and therefore undepleted in the chalcophile metals while other parts of it became S-saturated and therefore chalcophile metal depleted. The melt sheet had the form of a thin sill that was ~ 3 km thick with a volume of $\sim 35\,000$ km³ (*Grieve et al.*, 1991) and

therefore a diameter of 110 km. Unlike normal sills, the temperature of its footwall contact remained at approximately the same temperature as that of its solidus for much of its solidification history (Marsh and Zieg, 1999). In addition, the SIC melt sheet may have initially been an emulsion in which immiscible mafic and felsic melts were interspersed; in time, the emulsion components separated according to their relative densities to form the bimodal norite-granophyre assemblage (Marsh and Zieg, 1999). It is envisioned that sulfides may have formed in some of these "magma cells" and settled through the emulsion to be re-dissolved in magma cells at the base of the melt sheet thereby increasing its Ni, Cu and PGE contents. The emulsion model may have been the mechanism responsible for preventing complete scavenging of the base and precious metals from the residual magma by the first sulfides formed.

Implications for the sulfide saturation history of the Sudbury melt sheet

The origin of the Ni–Cu–PGE sulfides at the lower contact of the Sudbury melt sheet is now explained by sulfide saturation, and segregation of magmatic sulfides from a melt sheet generated by meteorite impact of crustal rocks. The degree of depletion encountered in the noritic unit is more than enough to explain the known ores and those associated with the extrapolation of the Sublayer and Offsets to depth beneath the sheet (Lightfoot et al., 2001). The new PGE data and Se data presented in this paper refines this model, by indicating several important observations:

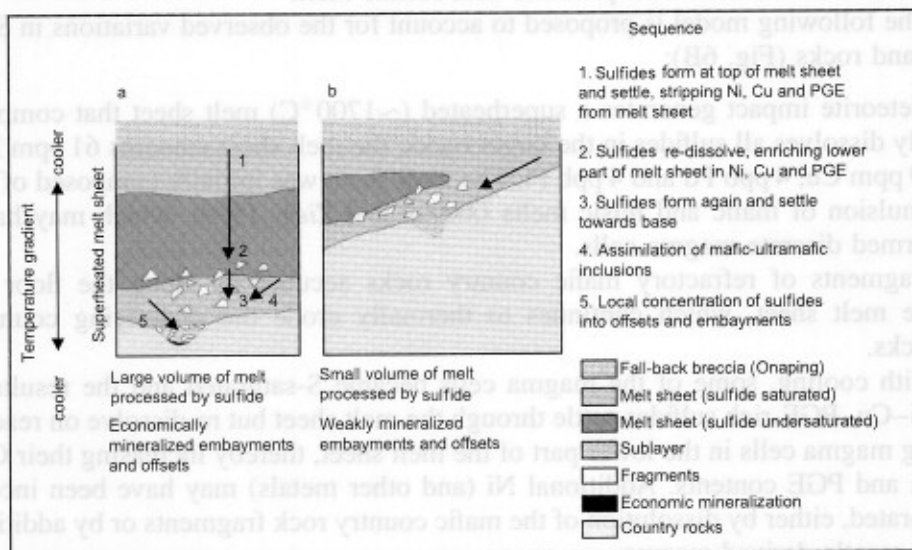
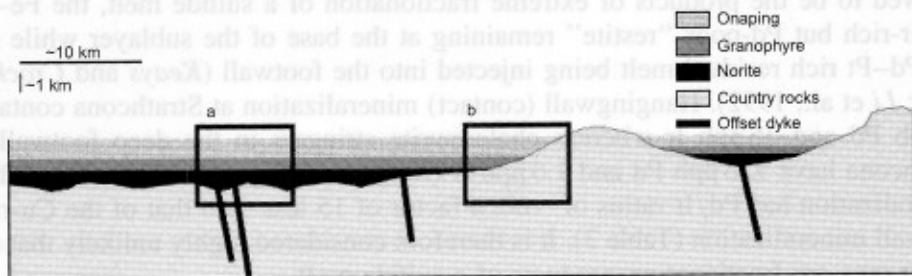
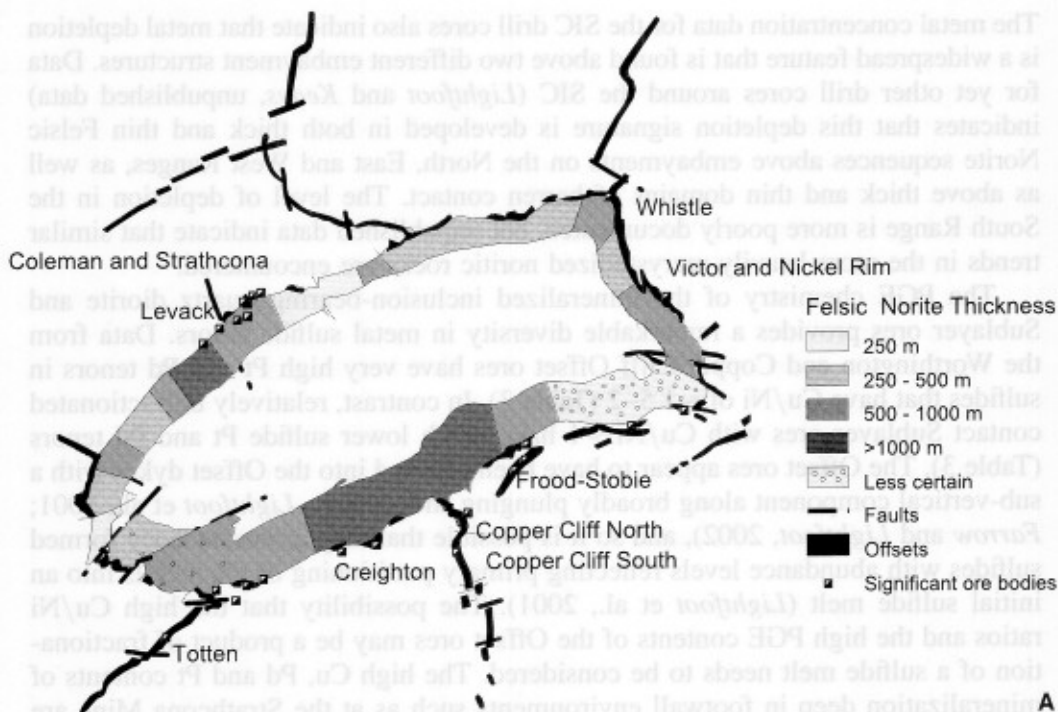
1. The degree of depletion of the PGE through the norites is much more rapid and extreme than the depletion in Ni and Cu. This is presumably because the partition coefficients for Pd and Pt into sulfide liquid are ~ 1.5 orders of magnitude higher than those of Ni and Cu.
2. The evidence that the PGE were not entirely stripped from the Main Mass magma when it first became S-saturated and formed the Offset ores indicates that the process of segregation and accumulation was not efficient; otherwise, the initial saturation and segregation of the sulfides that formed the Offset and Sublayer ores would have entirely depleted the overlying melt sheet. The fact that this did not happen implies either that metals were continually introduced into the melt sheet, perhaps by ongoing assimilation of mafic fragments, introduction of mantle-derived high MgO magmas, or by tapping of metals from previously S-undersaturated portions of the melt sheet.
3. The high PGE contents and high Pd/Cu ratios of the SIC ores indicate that the SIC magma was initially S-undersaturated and PGE-undepleted.
4. The high Pd/Cu ratios of the marginal quartz diorite phase of the Offsets indicate that the silicate melts which formed these rocks were S-undersaturated.
5. The sharp increase in Pd, Pt, Ni and Cu values (Fig. 3) and decrease in S/Se ratios (Fig. 4E) at the 1876 m level in the Felsic Norites of the Levack drill core indicates that a new supply of metals was added to the Felsic Norite magma at this level in the chamber.

The metal concentration data for the SIC drill cores also indicate that metal depletion is a widespread feature that is found above two different embayment structures. Data for yet other drill cores around the SIC (*Lightfoot* and *Keays*, unpublished data) indicates that this depletion signature is developed in both thick and thin Felsic Norite sequences above embayments on the North, East and West Ranges, as well as above thick and thin domains of barren contact. The level of depletion in the South Range is more poorly documented, but unpublished data indicate that similar trends in the more heavily recrystallized noritic rocks are encountered.

The PGE chemistry of the mineralized inclusion-bearing quartz diorite and Sublayer ores provides a remarkable diversity in metal sulfide tenors. Data from the Worthington and Copper Cliff Offset ores have very high Pt and Pd tenors in sulfides that have Cu/Ni of ~ 1.5 – 2 (Table 3). In contrast, relatively unfractionated contact Sublayer ores with Cu/Ni ~ 1 have much lower sulfide Pt and Pd tenors (Table 3). The Offset ores appear to have been injected into the Offset dykes with a sub-vertical component along broadly plunging shoots (e.g., *Lightfoot* et al., 2001; *Farrow* and *Lightfoot*, 2002), and so it is possible that they represent early formed sulfides with abundance levels reflecting primary partitioning of the metals into an initial sulfide melt (*Lightfoot* et al., 2001). The possibility that the high Cu/Ni ratios and the high PGE contents of the Offset ores may be a product of fractionation of a sulfide melt needs to be considered. The high Cu, Pd and Pt contents of mineralization deep in footwall environments such as at the Strathcona Mine are believed to be the products of extreme fractionation of a sulfide melt, the Fe–Ni and Ir-rich but Pd-poor “restite” remaining at the base of the sublayer while the Cu–Pd–Pt rich residual melt being injected into the footwall (*Keays* and *Crocket*, 1970; *Li* et al., 1992). Hangingwall (contact) mineralization at Strathcona contains 71 ppb Pd and 46 ppb Ir whereas chalcopyrite stringers in the deep footwall at Strathcona have 926 ppb Pd and 1.0 ppb Ir (*Keays* and *Crocket*, 1970). The Offset mineralization has Pd/Ir ratios of ~ 60 , a factor of 15 less than that of the Cu-rich footwall mineralization (Table 3). It is therefore considered highly unlikely that the Offset ores are fractionation products of a sulfide melt.

The following model is proposed to account for the observed variations in SIC ores and rocks (Fig. 6B):

1. Meteorite impact generates a superheated ($\sim 1700^\circ\text{C}$) melt sheet that completely dissolves all sulfides in the target rocks; the melt sheet contains 61 ppm Ni, 59 ppm Cu, 4 ppb Pd and 4 ppb Pt. The melt sheet was initially composed of an emulsion of mafic and felsic melts (*Marsh* and *Zieg*, 1999), which may have formed discrete magma cells.
2. Fragments of refractory mafic country rocks accumulate along the floor of the melt sheet, which continues to thermally erode the underlying country rocks.
3. With cooling, some of the magma cells became S-saturated and the resultant Ni–Cu–PGE-rich sulfides settle through the melt sheet but re-dissolve on reaching magma cells in the lower part of the melt sheet, thereby increasing their Cu, Ni and PGE contents. Additional Ni (and other metals) may have been incorporated, either by dissolution of the mafic country rock fragments or by addition of mantle-derived magma.



A

B

4. The lower portion of the melt sheet becomes S-saturated and Cu–PGE-rich Ni–Fe sulfides accumulate along with the refractory mafic country rock fragments along the floor of the melt sheet.
5. The floor of the chamber is breached and the sulfide melts, and country rock fragments are swept into the Offsets by the still unfractionated SIC magma.
6. Additional Cu, Ni and PGE are added to the lower portion of the melt sheet from undepleted sections of the melt sheet, from mantle-derived magmas, or some other source.
7. Additional sulfide melts segregate from the melt sheet, accumulating in depressions in the chamber floor, along with additional mafic rock fragments, to form the contact orebodies; these sulfides have lower Cu, and PGE contents than the first sulfides to segregate from the melt sheet.
8. Silicates finally become a liquidus phase and sulfides and silicates crystallize together.
9. During this process, additional amounts of the Cu, Se and PGE are contributed to that section of the melt sheet in which silicates and sulfides are undergoing cotectic crystallization.

The striking empirical correlation between the distribution of the main ore deposits and the thickness of the Main Mass Felsic Norite is depicted in Fig. 6A. This diagram is compiled from geological sections that project the Felsic Norite–Mafic Norite and Felsic Norite–Quartz Gabbro contacts to depth beneath the SIC. The information for the North, West and East Ranges is more robust than that for the South Range where there is considerable structural complexity. At a simple level, this plot shows that the main economically mineralized environment at Levack–Coleman is correlated with a thick unit of metal-depleted norite, whereas the weakly mineralized large embayment at Trillabelle is overlain by a thin unit of Felsic Norite. This appears to confirm that the quantity of Sublayer in an embayment may be less important in controlling the mineral potential. More important, the thickness of the overlying Felsic Norite, and implied availability of metals from the melt sheet appears to be a primary control on ore deposition at Sudbury.

Figure 6B summarises these features in a diagrammatic section through the primary melt sheet. Several points are worth emphasis:

1. The original melt sheet is laterally extensive for perhaps >100 km diameter, yet only <5 km thick. It is exceptionally unlikely that the entire sheet was able to convectively mix on this scale. Undulations in the basal contact at embayments and offsets are presumably features that radiate away from the central part of the

←
 Fig. 6. A geological model relating the mineral potential of the Sublayer, Offsets and Footwall to the thickness of the melt sheet. **A** Map of the SIC showing the thickness variations in the Felsic Norite in relation to the mineral deposits. Thickness is estimated based on sections compiled from drilling and surface geology. **B** Section showing the original configuration of the melt sheet and the relative locations of prospective and less prospective environments (based on Ames et al., 2002).

- structure. These features likely acted as physical traps along which sulfides were trapped and physically isolated from the main melt sheet.
2. The mineral potential of different embayments likely reflects the available thickness of the overlying melt sheet. Those embayments that now outcrop in locations that are distal from the center of the SIC may have very thick Sublayer accumulations, but very few ores. Those locations which formed closer to the original thick part of the melt sheet tend to have large economic deposits, reflecting the availability of metals from the overlying melt. In detail, there is evidence to suggest that branching systems of embayments may locally act as funnels along which sulfide ores moved, but the mobility of the sulfides was likely restricted to acting as collectors from the immediately adjacent topographic highs at the base of the melt sheet between embayment structures.
 3. The same observation applies to Offset mineralization. Offsets developed distally from the SIC like Manchester and Foy have a commensurately little known mineralization, and so they have been grouped as less encouraging exploration targets. The most distal segments of the melt sheet may have developed in a ring structure around the basin, much like the systems on Earth's Moon and Venus (Ames et al., 2002), but erosion has left no obvious record of these rocks other than very distal Offset dykes like Foy and Hess which may have developed close to the outer rim of the main sheet, or in the ring structure.

Implications for exploration

Like most giant ore deposits, the Sudbury ores are unique and the product of a combination of unusual processes. The Sudbury ores are the only known ore deposits to have been produced as a result of the impact of a very large meteorite. They are probably also the only example of Ni–Cu–PGE sulfide melts that began segregating from a magma at much higher temperatures than silicate and oxide phases. However, many of the processes that led to the generation of these ore deposits were also operative in the generation of other ore deposits and some of the characteristics of the Sudbury ore environs are common to other ore deposits. For example, the Sudbury ores are associated with extensive development of breccias, an empirical feature that it shares with other ore deposits such as Voisey's Bay (cf. Naldrett et al., 1995; Lightfoot and Naldrett, 1999) as well as significant evidence for crustal involvement, a feature that is shared with the Noril'sk ores (e.g., Naldrett et al., 1995).

Many of the features of the SIC are probably unique. However, some of the features may constitute useful exploration criteria as they are also features found in other Ni–Cu–PGE sulfide systems:

1. **Systematic metal depletion signatures:** The recognition of chalcophile metal-depleted rocks at higher stratigraphic levels in the SIC constitutes an important observation. It has parallels with the Noril'sk situation, where the mineralized intrusive systems are juxtaposed beneath a thick sequence of Ni–Cu–PGE-depleted tholeiitic basalts (Brugmann et al., 1993). The scale of the depletion at Noril'sk and Sudbury in terms of quantity of missing metal are at the same

level of magnitude ($\sim 5\text{--}10$ thousand km^3 of magma). Where the metal-depleted noritic unit is thickest in the SIC, the Sublayer and Offsets contain the most significant ore deposits. Where the melt sheet was much thinner, there are often large offsets (e.g., Foy), and embayments (e.g., Trill), but these environments have not yet been shown to contain large mineral resources at the present level of erosion and exploration.

2. **Transport of sulfide melts:** At Noril'sk, there is an increasing body of evidence suggesting that the ore-forming process took place at depth beneath the volcanic center, and sulfide or sulfide-laden melts were injected into their final resting place within the mineralized intrusions. Processes at Sudbury are also believed to have involved segregation and gravitational accumulation of sulfide melts, some of which were injected over considerable distances into both Offset and Footwall environments.
3. **Crustal involvement:** At both Sudbury and Noril'sk, there is overwhelming evidence that the mineralizing event involved the incorporation of large amounts of crustal material. At Sudbury, the system was probably 90–100% crustal in derivation, whereas at Noril'sk, the signature is perhaps no more than 20% upper crust.
4. **Chaotic systems:** Both the Sudbury and Noril'sk systems share a tendency for very chaotic assemblages of rocks and ores. At Sudbury, the inclusion-rich Sublayer and Offset ores are characteristics of the larger deposits, and the mineralization is very much localized in parts of the system where these chaotic rocks assemblages reach their apogee. At Noril'sk, the ores are associated with intrusions that contain taxitic textures, and this association is present to differing extents in all of the mineralized intrusions, but none of the barren intrusions.
5. **Geometric controls on the distribution of mineralization:** The localization of ores in inflections in the footwall, embayment structures, discontinuities in Offset dykes, and breccia belts in the immediate footwall are all key factors that have directed exploration at Sudbury. At Noril'sk, the mineralization is associated with narrow high-level open system intrusions, but the geometric controls on the distribution within the intrusions are less clear.

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