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Sublayer and Offset Dikes of the Sudbury Igneous Complex—an Introduction and Field Guide

1997

LARGE METEORITE IMPACTS AND
PLANETARY EVOLUTION

Ontario

ONTARIO GEOLOGICAL SURVEY

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Sublayer and Offset Dikes of the Sudbury Igneous Complex—an Introduction and Field Guide

by

P.C. Lightfoot, Anthony J. Naldrett and Gordon Morrison

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Sublayer And Offset Dikes Of The Sudbury Igneous Complex—An Introduction And Field Guide

Field Trip Leaders: Peter C. Lightfoot and Gordon G. Morrison

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PREFACE AND ACKNOWLEDGMENTS

This guide is split into two parts. The first part provides an overview of the geology of the Sudbury Igneous Complex (SIC), and attempts to synthesise some of the key pieces of data which bear on the origin of the Sublayer, Offsets, and the associated mineral deposits. The second part of the field guide documents the geology type examples of a North Range embayment structure (located at Whistle Mine), and a South Range radial Offset Dyke (the Worthington Offset).

The authors acknowledge the support of the Ontario Geological Survey in sponsoring a three year study of the Sublayer and Offset environments. Inco Exploration and Falconbridge Exploration provided access to properties, mine working and drill core; they also provided access to unpublished exploration data.

This guide was prepared for the 1997 Lunar Planetary Conference meeting in Sudbury, and the 1998 International Mineralogical Association meeting in Toronto. B.O. Dressler and G. Johns are thanked for assistance with the organisation of the LPI field trip and this guide. S. Cruden coordinated the IMA field trips.

PART A: INTRODUCTION TO SUDBURY GEOLOGY

Peter C. Lightfoot, Anthony J. Naldrett, and G.G. Morrison

The Ni-Cu ores of the Sudbury district were discovered in 1883, during the construction of the Canadian Pacific transcontinental railway. They are associated with the Sudbury Igneous Complex (SIC), a layered igneous body ranging from quartz norite at the base, through gabbro to a granophyric cap. The purpose of this contribution is to describe the geological setting at Sudbury and the relationship of the ore deposits within this setting, discuss recent developments in our understanding of the geology resulting from recent trace element and isotopic studies and the Lithoprobe reflection seismic transect, and discuss possible models accounting for the geology of the Complex and the genesis of the ores.

Geological Setting

The SIC is located at the contact between tonalitic gneisses and intrusive quartz monzonites, all of Archean (>2.5Ga) age to the north, and rocks of the Proterozoic Southern Province, which overlie the Archean basement unconformably and thicken to the south (Figure 1A and B). The gneisses exhibit granulitic metamorphism around much of the northern and western margins of the Complex (James and Dressler 1992). The Proterozoic rocks belong to the Huronian Supergroup; in the Sudbury area they consist of local accumulations of mafic and felsic volcanic rocks, overlain by greywackes and siltstones, which are

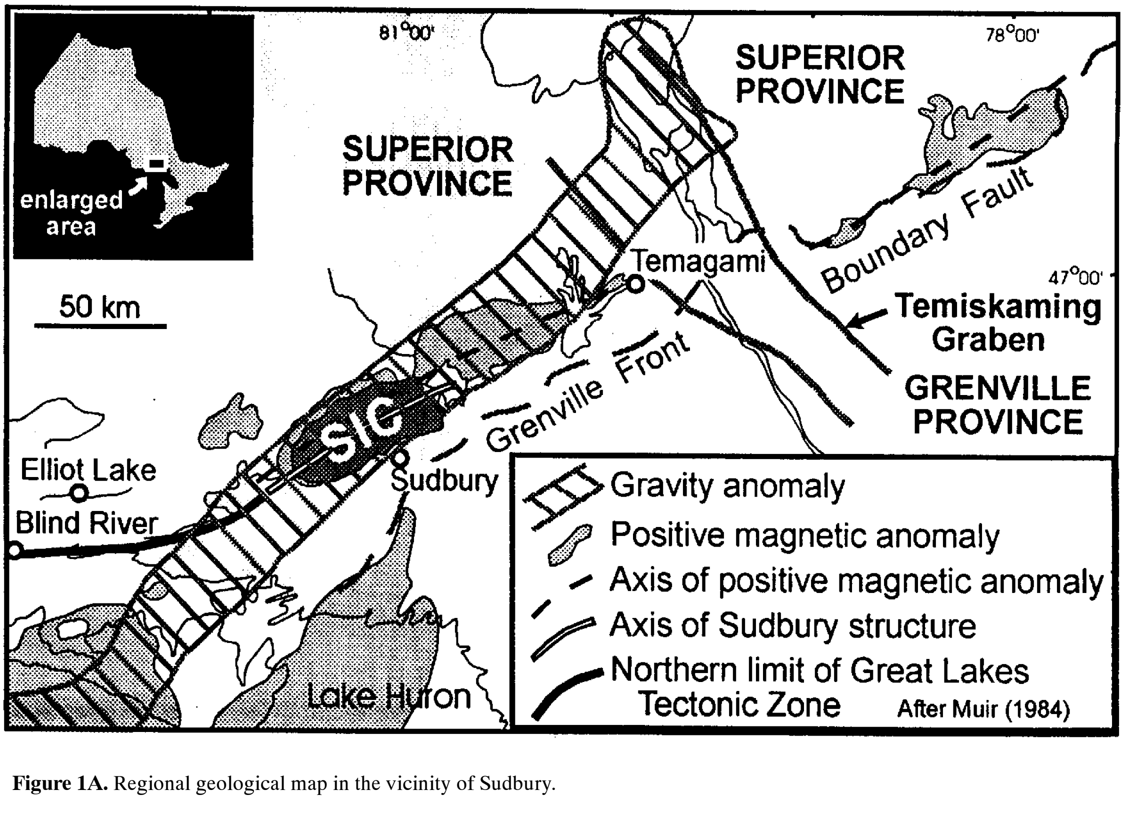

Figure 1A. Regional geological map in the vicinity of Sudbury.

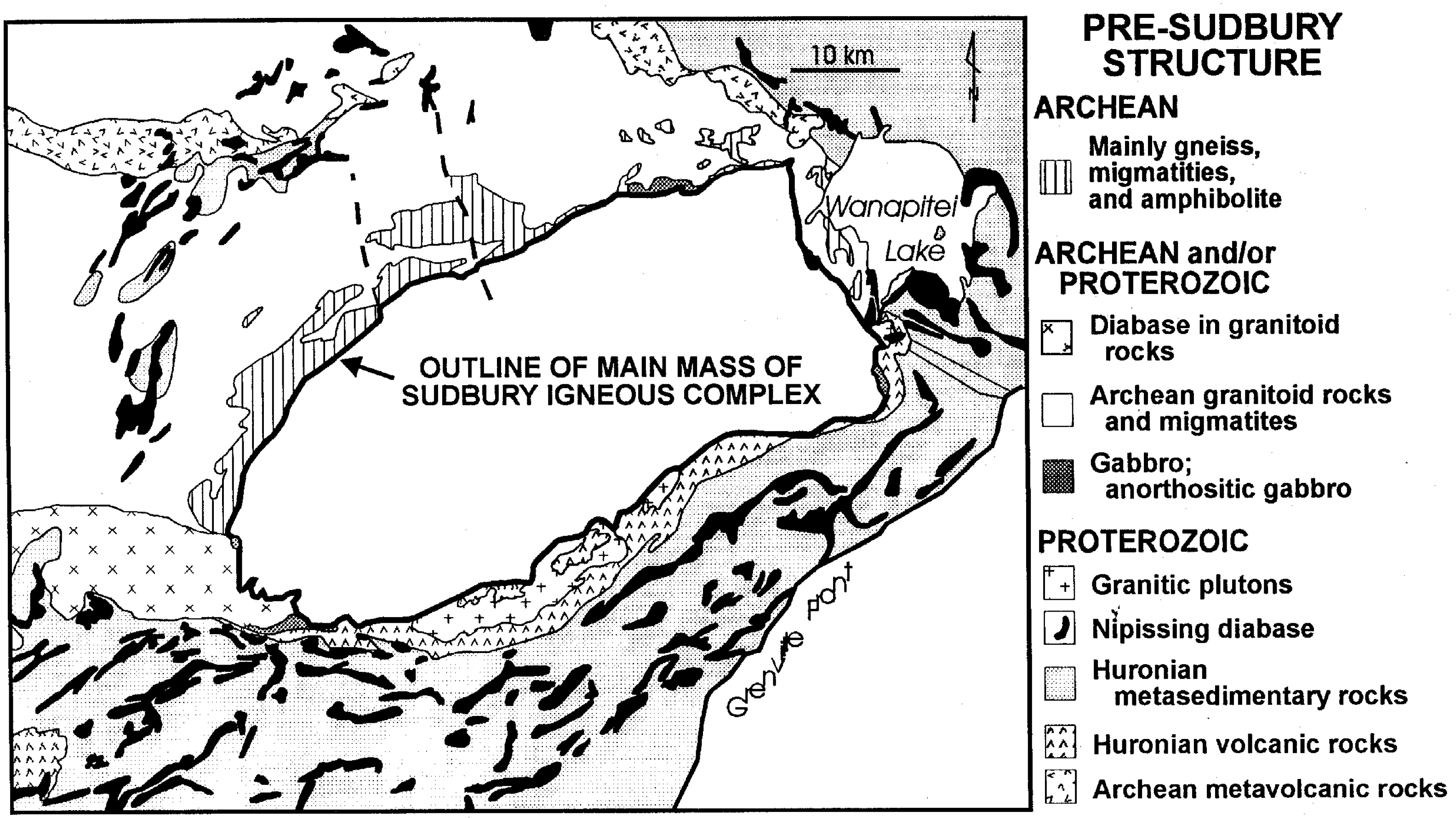

Figure 1. B) Country rocks surrounding the SIC (after Muir, 1984).

overlain in turn by arenites. Where clastic units occur at the base of the Huronian, they may contain high concentrations of detrital U- and Th-rich minerals. The U-mineralisation reaches its maximum development 100 km to the west of Sudbury in the Elliot Lake mining camp.

Geological rock units related to Sudbury event include:

(1) Sudbury Breccia; this is a breccia composed of fragments of country rock ranging from microscopic to more than 10 m in diameter, occurring as dikes and irregular masses in all pre-SIC rock-types outside the Sudbury structure. In places it shows signs of incipient melting. It has never been observed to cut rocks of the SIC or younger rocks.

(2) Footwall Breccia; this is a breccia composed of shattered and crushed country rocks that forms a layer, 10 to 50 m thick between the SIC and the footwall gneisses and monzonites along much of the North Range of the Sudbury structure. It extends up to a further 10 m into these rocks as thin apophyses. It is also present along the South Range but is much less common (Grant and Bite 1984)

(3) Onaping Formation; this is a breccia composed of fragments of country rocks and recrystallized glassy material set in a matrix of glassy shards (Muir and Peredery 1984). It has been variably interpreted as a pyroclastic flow deposit or the "fall-back" breccia from the impact of a meteorite. It is underlain by a breccia consisting of many fragments of quartzite and gneiss in a felsic, igneous-textured matrix ("Melt Rock", Muir and Peredery 1984).

(4) The Sudbury Igneous Complex is located between the Footwall Breccia and the Onaping Formation and its associated "melt rock". The internal structure of the SIC is discussed below.

The Onaping Formation grades upwards into a slate (Onawatin slate) which, in turn, passes upwards into a unit composed of proximal turbidite flows (Chelmsford Formation). The SIC and strata overlying it are exposed as a series of concentric, crudely elliptical rings which dip towards the centre of the Complex and suggest the structure as a basin (Figure 2).

Card et al (1984) have drawn attention to a dominant linear gravity anomaly extending 350 km from Eliot Lake eastward to Engelhardt. The SIC straddles this feature and coincides with one of the three high-spots along it. Gupta et al (1984) analysed the combined residual gravity and magnetic anomaly that marks the Sudbury region itself. They concluded that the broad +20 to +30 mGal anomaly could not be explained by the rocks of the SIC themselves and that a large mass of rock with a density similar to gabbro or gabbroic anorthosite (3.02 ± 0.03 g/cc) underlay the complex at a depth of at least 5 km, extending well to the south of the southern limit of the complex.

Seismic reflection data (Milkereit et al. 1992) show the deep geometry of the Sudbury structure to be markedly asymmetric. The seismic transect across the North Range shows that the sediments and Onaping formation above the SIC, the units of the SIC itself and a dense unit immediately beneath the SIC (which projects up dip to coincide with the granulitic facies of the Levack gneiss complex) dip south at an average of 25° (Milkereit et al. 1992). Reflections from the upper strata (sediments and Onaping formation) are interrupted by faults near the long axis of the Sudbury structure; the lower strata (norite and gneiss) can be traced with a continuous south dip to about the southern margin of the Sudbury structure where they appear to be tightly folded or truncated against the Creighton fault. The base of the SIC is interpreted to be at a depth of 11 to 12 km at this point. In contrast, the seismic image of the South Range is dominated by a distinctive series of reflections with moderate south dip; these are interpreted as thrust faults or shear zones on which severe telescoping and imbrication of lithologic units, and considerable northwest–southeast shortening of the Sudbury structure have occurred. The seismic data revealed no evidence of a large mafic–ultramafic body at a depth of 5 to 8 km as had been proposed previously.

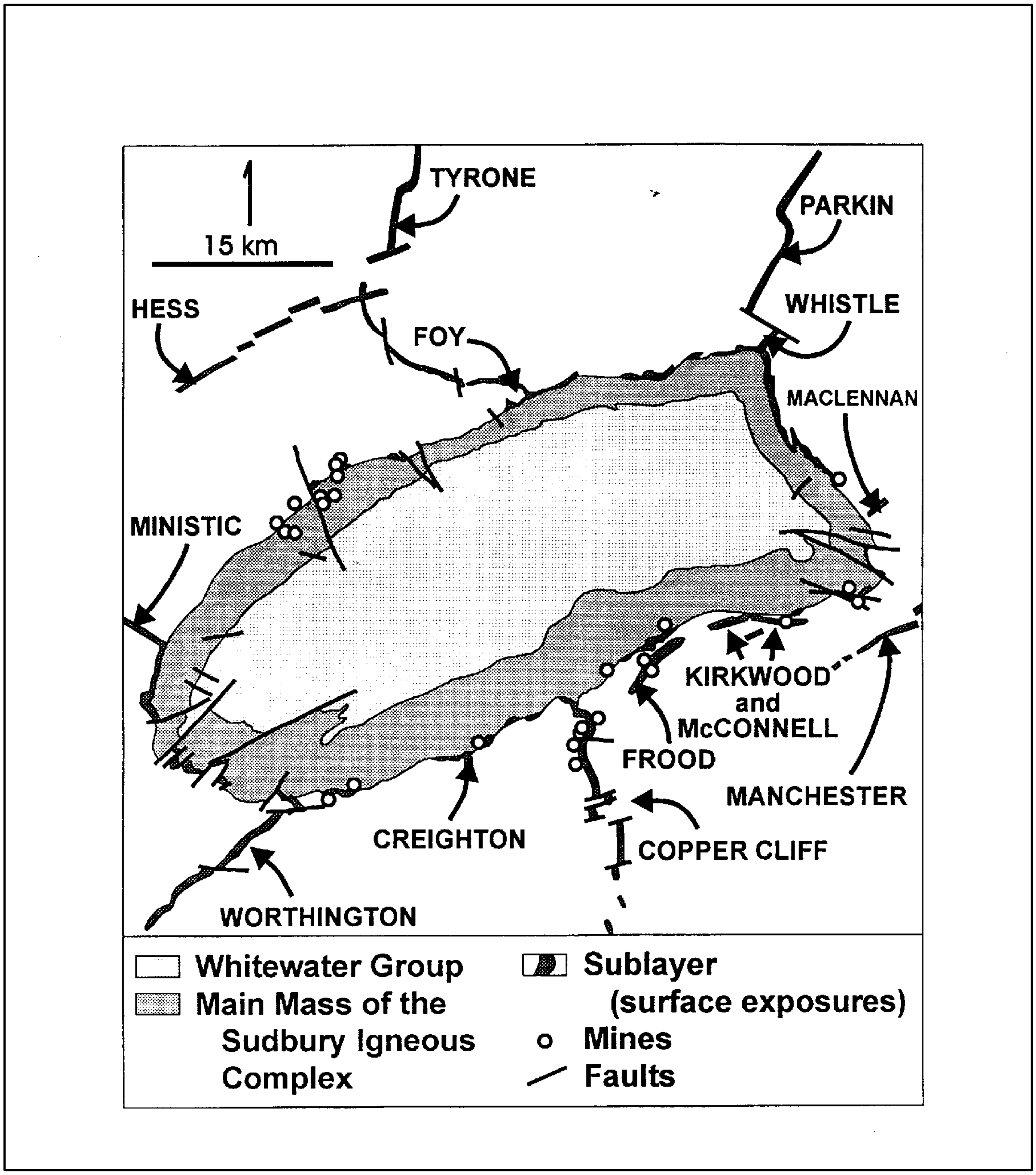

Figure 2. Location of the Sublayer and Offstes of the SIC, and location of mines.

Supplementing existing data with new measurements made along most of the Lithoprobe transect lines, McGrath and Broome (1994) have re-interpreted the gravity map of the Sudbury structure. They conclude that the sub-surface disposition of rock-types that are exposed at surface, as revealed in the seismic survey, can explain the positive anomaly over the Sudbury structure; the hidden layered sill that was proposed by Gupta et al (1984), while not excluded, is not necessary to account for the data. R.B. Hearst (personal communication 1992), commenting on the results of potential field modelling of magnetic data, reported that this was also consistent with the results of the seismic observations.

Many aspects of the local setting suggest that an explosion of unusually large intensity gave rise to a crater at Sudbury (see Pye et al. 1984). The evidence includes:

(1) The basinal shape of the structure as interpreted from surface and underground mapping and drilling.

(2) An upturned collar around the basin, as seen particularly in the Huronian rocks along the southern margin (Dressler 1984).

(3) Shock metamorphic features in the country rocks around the structure (Dressler, 1984).

(4) The Sudbury Breccia (compared with the pseudotachylite of the Vredefort and Ries structures, Dressler 1984) in the country rocks around the structure and the Footwall breccia beneath the Complex.

(5) Evidence of shock metamorphism in country rock inclusions in the Onaping Formation (Muir and Peredery 1984).

(6) The 1800 m of Onaping Formation itself, the lower part of which is variably interpreted as a meteorite fall-back breccia or an ignimbrite (Peredery and Morrison 1984; Muir 1984).

Opinions are divided between an extra-terrestrial and endogenic origin for the structure. These authors believe that meteorite impact is the more likely origin, primarily because so many of the features observed at Sudbury are also found at known impact sites. There are, however, many difficulties with such an origin and these are summarized by Muir (1984).

Petrology of the Sudbury Igneous Complex

The main units of the Complex include (Figure 3A) (i) the Sublayer, (ii) the marginal Quartz-rich Norite of the South Range and Mafic Norite of the North Range, (iii) the South Range Norite and Felsic Norite, (iv) the Quartz Gabbro, and (v) the Granophyre and Plagioclase-rich Granophyre. All units except the Sublayer are included within the Main Mass of the Complex.

MAIN MASS

The Felsic (found on the North Range) and South Range Norites are plagioclase-orthopyroxene–clinopyroxene cumulates; they show cryptic variation in the Mg/(Mg+Fe) ratio of the pyroxenes and An content of plagioclase, with these variables changing upwards in a manner consistent with fractional crystallization (Naldrett et al. 1970). Orthopyroxene disappears and titaniferous magnetite and apatite appear as cumulus phases in the overlying Quartz Gabbro. The cryptic variation characteristic of the underlying norites has been traced into the lower part of the Quartz Gabbro, but cannot be traced across it because of the intense hydrous alteration that has affected the upper part. The upper part is characterized by a rapid increase in a granophyric intergrowth of plagioclase and quartz at the expense of cumulus phases as the gabbro grades into the overlying Granophyre. Most of the Granophyre is a uniform rock consisting of 75 modal percent granophyric intergrowth and 25 modal percent idiomorphic plagioclase plus clinopyroxene, although zones containing up to 50 modal percent idiomorphic plagioclase are present. Peredery and Naldrett (1975) point to the continuity of modal and compositional trends between the Quartz Gabbro and Plagioclase-rich Granophyre, suggesting that the bulk of the Granophyre has been intruded subsequently, laterally from the centre of the Complex into its present position. The marginal unit of the Main Mass on the South Range is the Quartz-rich Norite. In this case, the quartz content increases progressively towards the contact over the outer 300 m (Naldrett et al. 1970). This increase in silica is unlike-

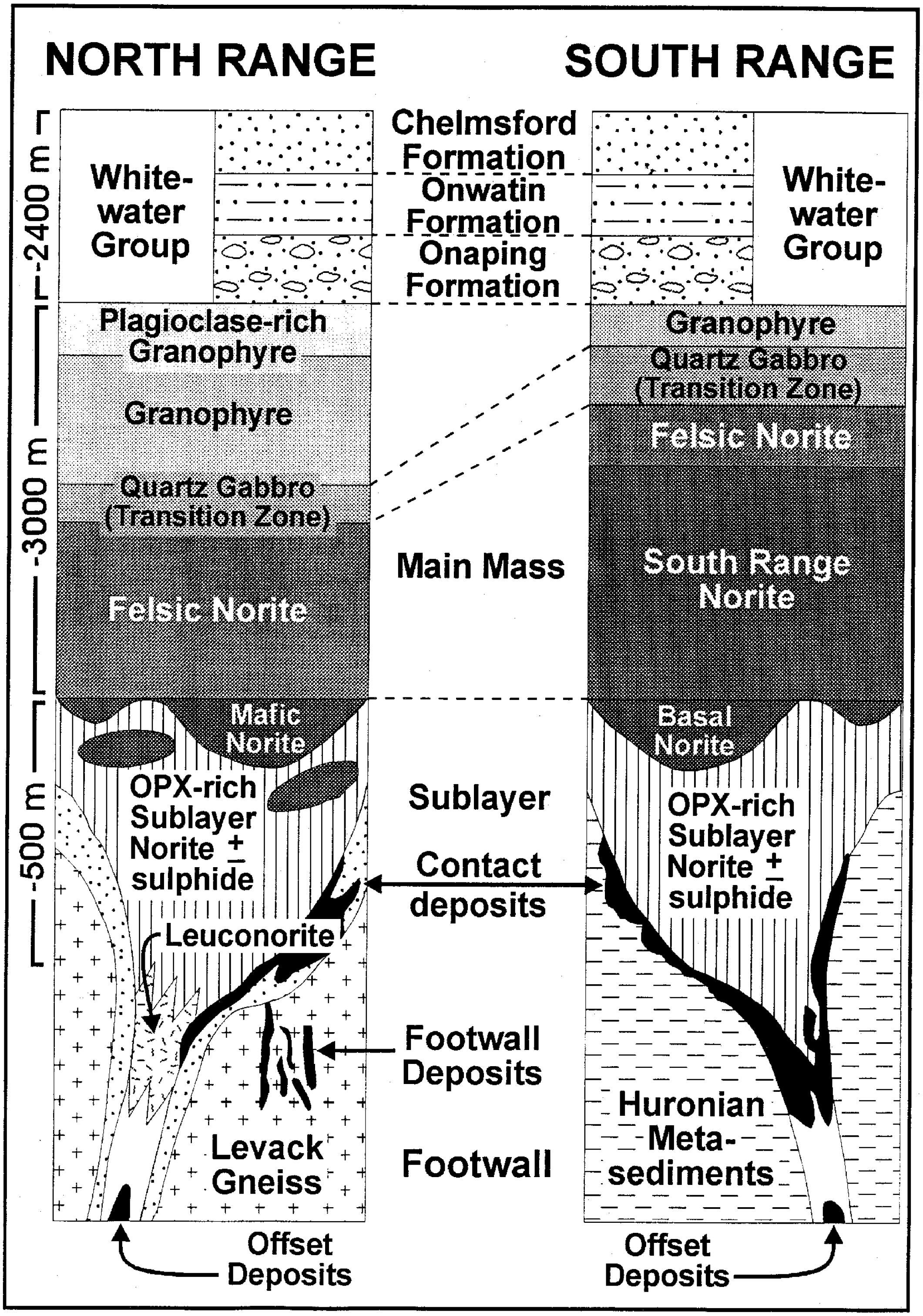

Figure 3. A) Main rock types of the SIC and the modal mineralogical variations through them. B) plan of relationships in an embayment (after Lightfoot et al. 1997); C) Section through one embayment structure (after Lightfoot et al. 1997).

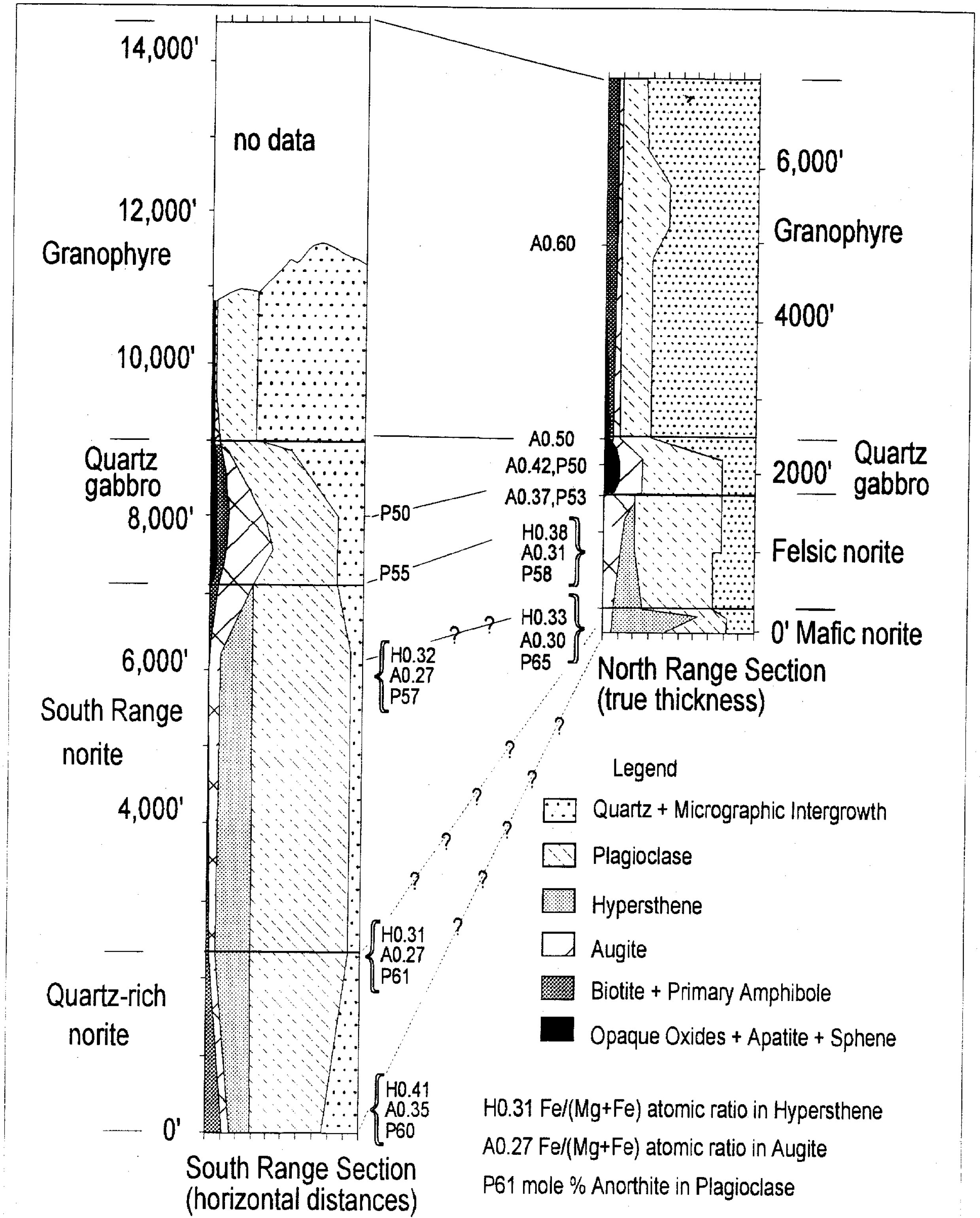

Figure 3. B) Continued

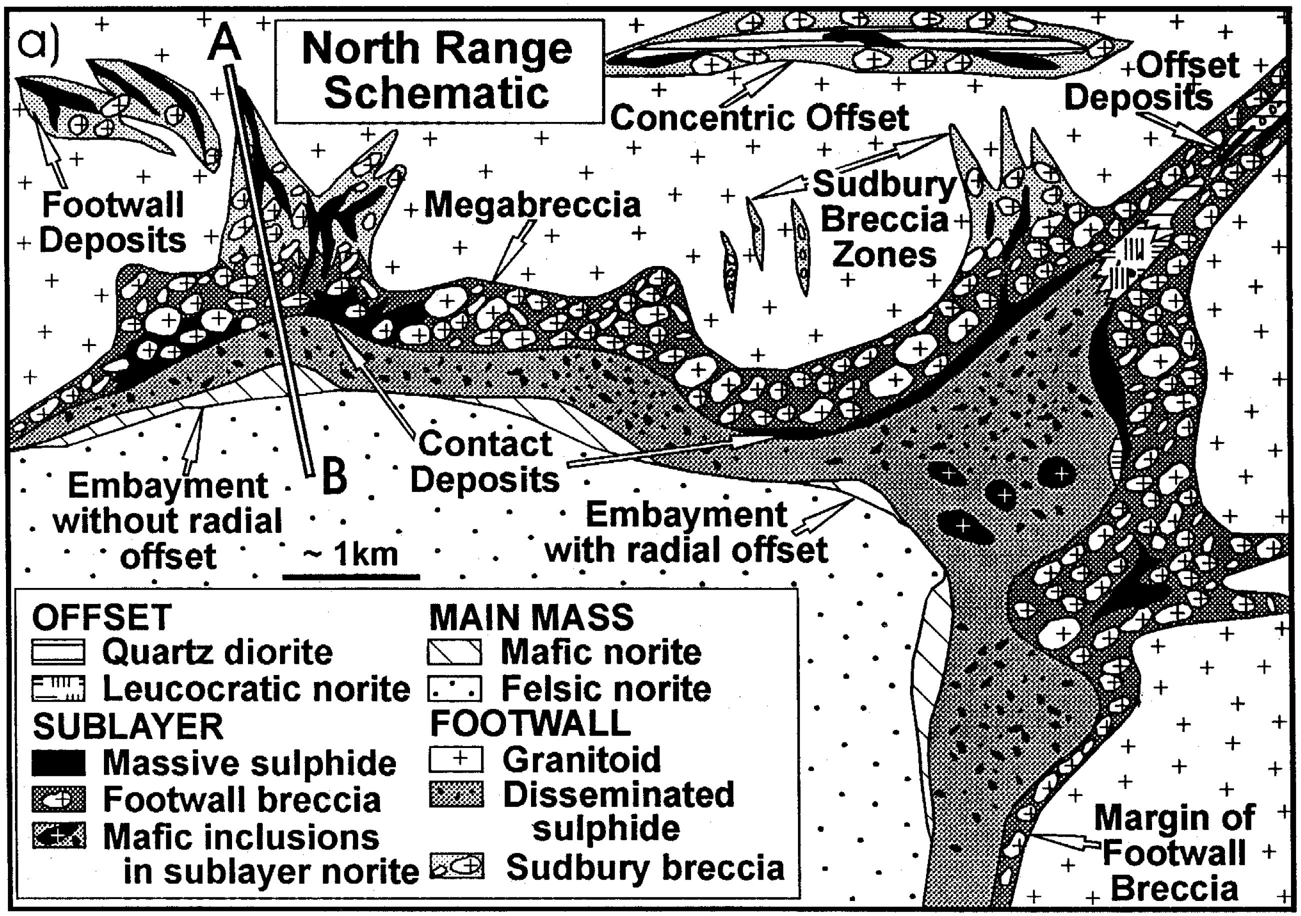

Figure 3 C) . Continued

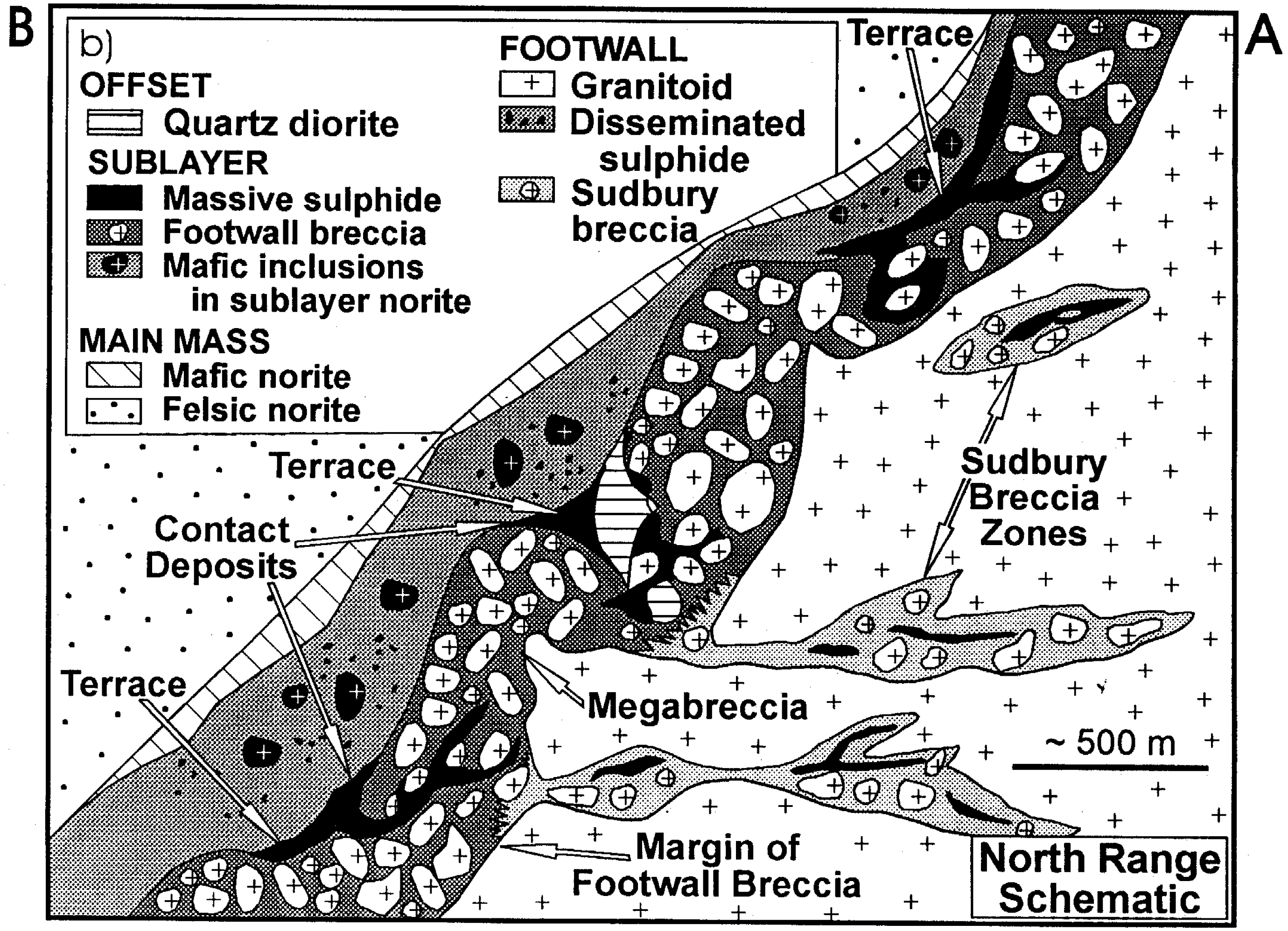

Figure 3 c). Continued

ly to be due to contamination because the increase in quartz occurs as much where the footwall is composed of SiO_2-deficient greenstone as where it is composed of granite. This observation indicates that if contamination is involved, it is not in situ contamination. The increase in quartz is accompanied by an equally progressive decrease in the average Mg/(Mg + Fe) ratio of the pyroxenes (Naldrett et al. 1970). This decrease is due to progressively more strongly zoned pyroxenes, with Mg/(Mg + Fe) decreasing towards the edges of grains while the cores retain a constant composition. These observations, coupled with a decrease in grain size towards the margins (Naldrett et al. 1970), indicate that the outer part of the Quartz-rich Norite is a non-cumulus rock that crystallized essentially in situ.

As discussed below, Grieve (1994) has interpreted the whole of the SIC as an impact melt. Chai and Eckstrand (1994, 1996) studied trace element profiles across the SIC and interpreted these to imply that the norite and granophyre have been derived from two different sources, the former a mantle source that became heavily contaminated in the lower crust, and the latter an impact melt. Lightfoot et al. (1997) have criticised this interpretation, showing that the chemical data are better explained if the granophyre is the result of the fractional crystallisation of a norite magma.

SUBLAYER

The Sublayer occurs discontinuously around the Complex. Traditionally, it has been subdivided into those variants which occur close to the outer contact and those which occur as dikes that radiate outwards from the Complex and are known locally as “offsets”. Lightfoot et al. (1997) have shown (see below under “Trace elements”) that the offsets comprise quartz diorite which is close to the Main Mass in its trace element content, and distinctly different to contact sublayer.

The Sublayer is absent in some areas, but over 700 m thick in other areas; its volumetric distribution being controlled by the morphology of the basal contact of the SIC rather than the base of the Main Mass. Sublayer thicknesses are greatest within kilometre-sized radial depressions called “troughs” which are developed along the basal contact of the SIC (Morrison 1984). Within these troughs are smaller, secondary, lateral embayments in the footwall called terraces (Morrison 1984; Figure 3B and 3C).

The Contact Sublayer consists of a suite of fine to medium-grained norites and gabbros that are distinguished from the Main Mass Felsic Norite and Quartz Gabbro by their lower quartz content in relation to pyroxene (Naldrett et al. 1972). Lightfoot et al. (1996) noted that the texture and composition of the sublayer norites is quite variable, ranging from poikilitic to non-poikilitic norite and melanorite; contacts between different textural and compositional types are gradational. They conclude that many of the melanorites are best described as pods of poikilitic-textured norite; one melanorite pod that they studied at the Whistle mine (northeast corner of the Sudbury structure) grades from poikilitic texture on one side to hypidiomorphic granular on the other over a distance of 5 m. They subdivide the matrix of the sublayer (i.e., excluding the melanorite pods) into (progressing from more evolved to less evolved) non-poikilitic leucocratic norites, orthopyroxene-rich non-poikilitic textured norite and two pyroxene non-poikilitic textured norite.

Sublayer rocks within the offsets generally have the composition of quartz diorite and are referred to as such. Grant and Bite (1984) recognize a number of variants of Quartz Diorite which form a continuum grading from Hypersthene to Biotite Quartz Diorite, a change that is attributed to varying degrees of contamination. Lightfoot et al. (1997) describe the quartz diorite of the Parkin offset (this extends north from the northeast corner of the Sudbury structure) as a fine to medium grained, equigranular to inequigranular rock comprising 45 to 55% mafic minerals, 30 to 45% feldspar, 5 to 15% quartz and trace amounts of granophyre and opaques.

Geological relationships between the Sublayer and the Main Mass give conflicting evidence on the relative ages of the two units. Inclusions of marginal Quartz-rich Norite have been observed in Sublayer and inclusions of Sublayer have been observed in norite of the Main Mass of the Complex. Intrusive contacts are never marked by fine-grained chill zones, suggesting that whichever unit was the older at any particular location, it was still warm at the time of intrusion of the younger unit. On the North Range, the distinction between Main Mass and Sublayer is consistently clear, with the Sublayer having the finer grain-size and lower quartz content. This distinction is not necessarily the case on the South Range, where a number of researchers have commented on gradations between the two units (Slaught 1951; Cochrane 1984). It would seem, therefore, that the introduction of the Sublayer and Main Mass was a complicated process with each preceding the other in different localities.

Inclusions in the Sublayer

In some areas the Sublayer is characterized by inclusions. These can be divided into two groups, those of obviously local derivation, and those composed of mafic and ultramafic rocks, many of which do not outcrop in the Sudbury area. The mafic-ultramafic group are of particular interest here. Scribbins et al. (1984) described them as ranging from peridotite, through clino- and orthopyroxenites, to olivine gabbro and norite. Most of the inclusions either display cataclastic or cumulus textures. Olivines range in composition from Fo_{86} to Fo_{72}, with the Fo content decreasing as the plagioclase content decreases. Scribbins et al. (1984) conclude that the inclusions are derived from layered intrusions that have fractionated at moderate depths in the crust.

Geochemistry of the SIC

MAJOR ELEMENTS

A selection of average and individual major element analyses of representative material from the Sudbury Igneous Complex are listed in Lightfoot et al. (1997A).

Main Mass

Judging from field and petrographic criteria, the Quartz-rich Norite was close in composition to the SIC magma when it was emplaced along the South Range. The Mg/(Mg + Fe) atomic ratio (henceforth referred to as MgNo) of 0.61 indicates that this is a reasonably primitive rock.

The SIC was intruded into a near-surface environment in a continental setting, thus Naldrett (1984) argues that it is logical to compare its magma composition with that of continental flood basalts. He pointed to the high SiO2 and K_2O, low CaO and low Na_2O/K_2O ratio of the Quartz-rich Norite when it is compared with Keewanawan and Columbia River flood basalts on the basis of MgNo, and showed that contamination of a relatively unfractionated Columbia River basalt with 50% of a 1:2 mixture respectively of Archean quartz monzonite and tonalitic gneiss gives rise to a major element composition similar to that of the Quartz-rich Norite. On the other hand, Grieve has shown, using least-squares mixing models, that the average composition of the SIC corresponds to a mix of Archean granite-greenstone terrane, with possibly a small component of Huronian cover rocks.

Sublayer

The texture and field relations of the constituent units of the Sublayer indicate that these units are also not cumulates but are rocks that have solidified essentially in situ, and thus represent magma compositions. MgNos of North Range samples of Contact (as opposed to Offset) Sublayer given by Rao et al. (1983) range from 0.37 to 0.58 and average 0.48 for the North Range and 0.51 for the South Range. Thus the magmas are relatively fractionated, considerably more so than the Main Mass as represented by the Quartz-rich Norite. At the same time, the MgNos indicate a variable degree of fractionation for the Sublayer.

Comparison of the major element compositions of Sublayer with those of flood basalts indicates that the Sublayer is also enriched in SiO_2 and K_2O, and low in CaO and Na_20/K_20 ratio for a given degree of fractionation as indicated by the MgNo. These data therefore are also consistent with contamination by country rocks.

TRACE ELEMENTS

Main Mass

Recent trace element studies of the SIC include those of Naldrett et al. (1986), Chai and Eckstrand (1994, 1996) and Lightfoot et al. (1997). Naldrett et al. (1986) pointed out that, as with the major element data, the trace element data were explicable as the result of the contamination of flood basalt magma by a mix of country rocks exposed at the present erosion level of the SIC. Chai and Eckstrand (1994, 1996) documented a marked compositional break between the quartz gabbro and the overlying granophyre, and argued that this implied derivation from two different magmas originating from different sources. They postulated that the norite and quartz gabbro were the product of a primary mantle melt that had become contaminated in Archean granulites of the lower crust, whereas the granophyre was an upper crustal, impact melt.

Lightfoot et al.'s (1997) trace element data are shown in the mantle-normalised spidergrams in Figure 4, and normalised against their average felsic norite in Figure 5. Lightfoot et al. (1997) point out that, with the exception of Sr, P, Eu and Ti (which are very dependent on addition or removal of plagioclase, apatite or Fe-Ti oxides) the felsic norite, quartz gabbro and granophyre have extremely similar trace element patterns (see Figure 5a). In particular, they draw attention to the similarity in Th/Zr ratios (0.04 to 0.05) between the SIC and granophyre which would be an extraordinary coincidence if they had been contaminated by, or derived from different crustal reservoirs. They point out that 65% fractionation of plagioclase and orthopyroxene from a magma with the composition of the felsic norite would give rise to the granophyre.

The mafic norite, which is a somewhat more mafic variant of the Main Mass of the SIC, also has similar relative proportions of trace elements to the felsic norite (*see* Figure 5b), although they are all more depleted, which is to be expected of a rock that is clearly richer in cumulus minerals than the felsic norite. The cogenetic origin of this with other Main Mass rock types is therefore confirmed by the trace element data.

Offset Quartz Diorite

As mentioned above, although the offset quartz diorite has traditionally been regarded as sublayer, it can be seen from Figure 5c that the trace element concentrations are much closer to those of the felsic norite than the sublayer. Lightfoot et al. (1997) argued that this implies a close genetic relationship, closer than is the case for the sublayer. They note that the Sr, Eu, P and Ti negative anomalies that characterise the Main Mass are either not present or are less pronounced in the offset quartz diorite, which implies that there was less fractionation of plagioclase, apatite and Fe–Ti oxides from the quartz diorite magma, although their data suggest that the quartz diorite has undergone some localised contamination as it has injected along the fractures that now host the offsets.

Sublayer

The match between the relative proportions of trace elements in the felsic norite and sublayer is much less close than between felsic norite and the other rock types discussed above (*see* Figure 5d). The sublayer rocks are poorer in LREE and LILE but have similar HREE and HFSE to the felsic norite. Lightfoot et al. (1997) argue that these differences cannot be explained by closed system fractional crystallisation

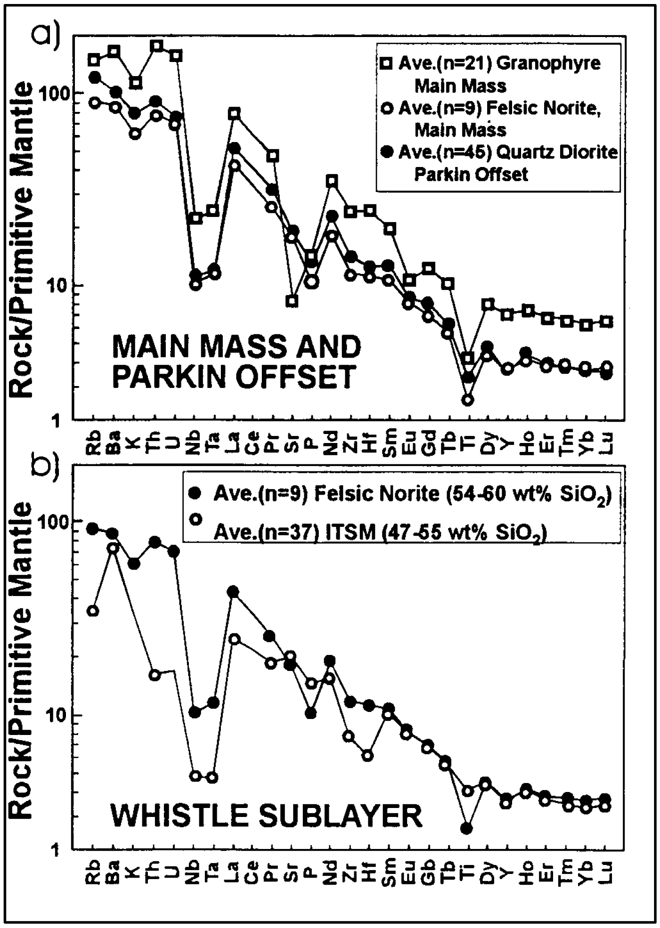

Figure 4. Primitive mantle-normalised trace element data for the Main Mass quartz gabbro, granophyre and the offset quartz diorite.

or partial melting. They found that the sublayer from different embayments, specifically the Levack McCreedy West, Fraser mine, Whistle, Little Stobie and Crean Hill embayments had similar compositions within themselves, but different compositions from embayment to embayment, although they did not put forward reasons to account for this. It is likely that the differences reflect interaction of sublayer magma with country rocks on a very local scale.

Inclusions

The diabase inclusions that characterise the sublayer (Figure 5e) are low in LILE and LREE elements relative to felsic norite, but have similar HFSE and HREE. Their 1.85Ga age (Corfu and Lightfoot 1997) indicates that they are part of the Sudbury event, but precisely how they fit into the sequence of events is unclear at present.

Trace element studies of the melanorite and pyroxenite inclusions in the sublayer indicates (compare Figure 5f with Figure 5d) a general similarity with the sublayer magma itself, suggesting that they represent accumulations that developed during an earlier stage of evolution of the sublayer magmas.

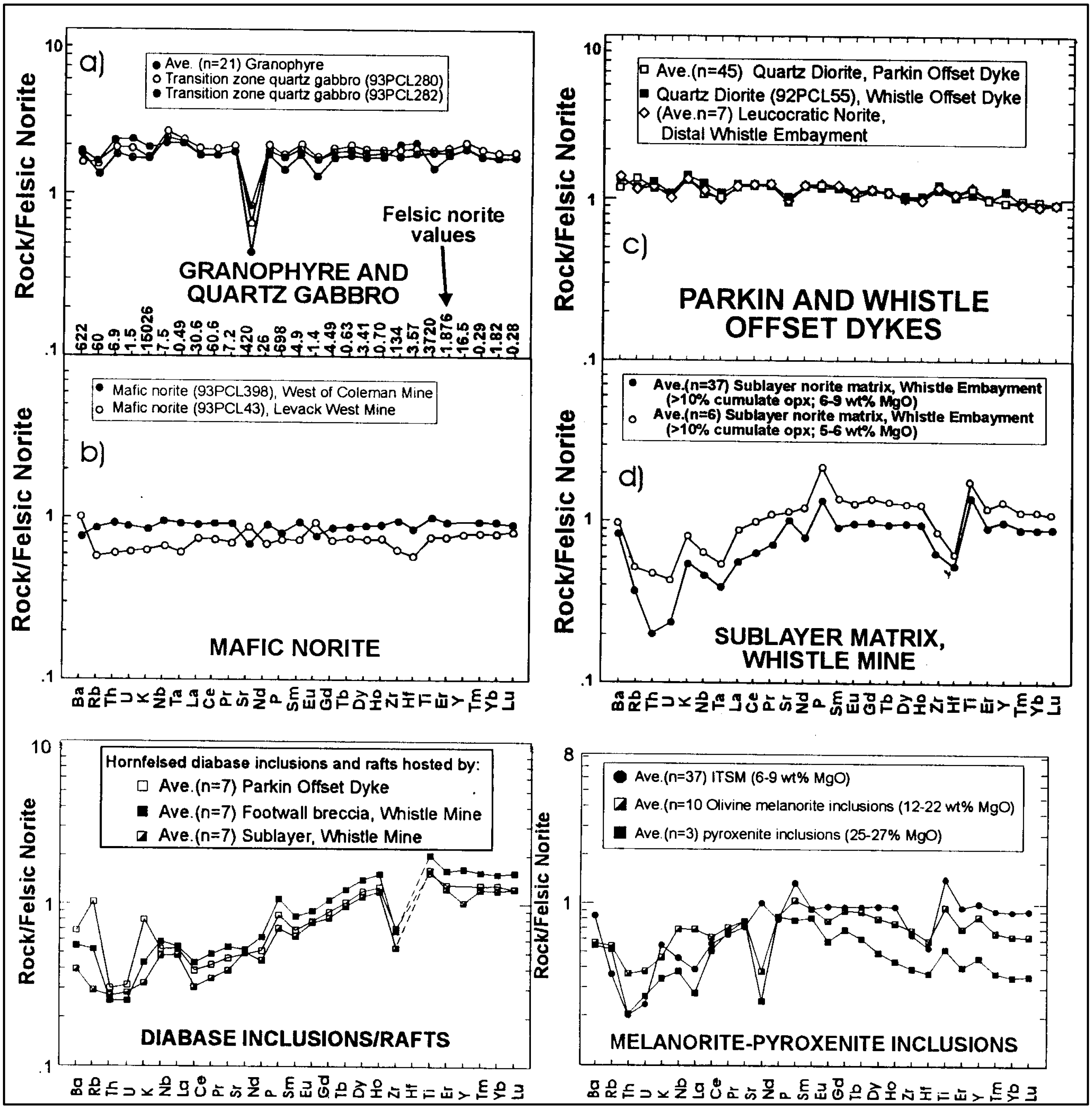

Figure 5. Abundance patterns for selected incompatible elements in rocks normalised to the average composition of the felsic norite from the northeastern part of the SIC. A) The average compositions of the Main Mass granophyre and two samples of quartz gabbro from the northeastern corner of the SIC. B) Mafic norite. C) Average quartz diorite from the Parkin offset, and average leucocratic norite from the distal part of the Whistle embayment. D) Average non-poikilitic sublayer orthopyroxene norite matrix from the Whistle embayment, average composition of the two pyroxene sublayer norite matrix from the Whistle embayment, and the average composition of 5 samples selected to show the amount of local heterogeneity of the sublayer on a 50 cm scale. E) Average compositions of diabase-gabbro inclusions from the Whistle embayment, rafts of diabase in the footwall breccia of the Whistle embayment, and diabase-gabbro inclusions from within the quartz diorite, quartz diorite breccia, and massive Sulpide zones of the Parkin offset. F) Compositions of average sublayer orthopyroxene norite from the Whistle embayment, poikilitic melanorite inclusions (7 to 12 wt.% MgO), average poikilitic-textured olivine melanorite inclusions (12 to 22 wt% MgO), and average altered pyroxenites (22 to 27 wt.% MgO) from the main Sulpide zone, Whistle embayment. (After Lightfoot et al. 1997A,B,C).

ISOTOPES

Krogh et al. (1984) show from Pb-U radiometric dating of zircons and baddeleyite that the SIC has an age of 1.85 Ga. Using this as a model age, both Faggert et al. (1985) and Naldrett et al (1986) showed from studies of Nd–Sm and Sr–Rb isotopes that the both the Main Mass of the SIC and the Sublayer contain less radiogenic Nd and more radiogenic Sr than bulk earth.

Walker et al. (1991) have shown that Re-Os isochrons for Sulpide sublayer ores from three mines, Levack West, Falconbridge and Strathcona, indicate that the Re-Os system remained closed since the time the ores crystallized at 1850 Ma, or shortly thereafter. The isotopic compositions of Os contained within these ores at the time of crystallization was highly variable, with initial 187Os/186Os ratios ranging from 4.70±0.25 at Levack West, to 8.73ñ0.38 at Strathcona.

Corfu and Lightfoot (1997) have dated zircons and baddelyite from inclusions of diabase, melanorite and pyroxenite from the Whistle mine. All dates correspond to the Sudbury age of 1.85Ga, which links the origin of these rocks very closely with that of the SIC.

DISCUSSION OF CHEMICAL DATA

It has been pointed out above that the major element data have variable been interpreted as the consequence of contamination of primary flood basalt magma with about 50% of crustal rocks. Naldrett (1984) discussed the possibility that the LREE enrichment of the Sudbury rocks is attributable to contamination by LREE-enriched country-rocks. He concluded that, as with the major elements, combination of equal parts of a primitive flood basalt and a 1:2 mixture respectively of quartz monzonite and typical tonalitic gneiss can account for the REE data. This conclusion is consistent with the close match that this mixture also produces for the major elements.

Naldrett et al (1986) showed that the Nd-Sm and Sr-Rb isotope data are consistent with contamination of magma giving rise to the SIC by 40 to 70% of rocks that had resided in the crust (with its low Sm/Nd and high Rb/Sr) for a considerable period before contamination occurred, which is consistent with conclusions drawn from the trace element data.

The Levack gneisses, which have the mineralogy and texture of granulites, plot in the southwest quadrant, which is also typically where lower crustal granulites plot. It is interesting to note that while the Sublayer samples from the South Range plot close to a mixing line between primitive mantle values and the average Huronian crust, the North Range samples plot well to the left of this line. Levack gneiss is not present on the South Range. Naldrett et al (1986) concluded from this correspondence between local geology and isotopic composition of the Sublayer magmas that these magmas have been modified in composition as a result of interaction with local rocks.

However, on the basis of essentially the same REE and Nd isotope data, Faggert et al. (1985), and subsequently Deutsch et al. (1989, 1990, 1992) proposed that the SIC was an impact melt with no component derived directly from the mantle. The problem is that when conclusions of this type are based on isotopic and trace element data, the conclusions are very dependent on the assumptions made with regard to the trace element abundances in the crust, and their isotopic abundances, and one has to conclude that the isotopic and trace element data are consistent with either interpretation.

Using estimated Os compositions and isotopic compositions of a hypothetical basaltic melt and measurements of the Os abundance and isotopic composition in samples from the Levack gneiss complex, Walker et al (1991) calculated that the ancient crust had contributed 60 to 75% of the Os contained in the Levack West and Falconbridge ores, and probably nearly 100% of that contained in the Strathcona ores. As Dickin et al. (1992) have pointed out, given the assumptions about the Os content and isotopic composition of continental crust, the Os isotopic data are consistent with 100% of the Os at all three deposits being derived from sources that had been resident in the crust for several hundred million years.

Ore Deposits

The nickel-copper ore deposits of the Sudbury camp can be divided into four categories: Marginal South Range deposits, marginal North Range deposits, Offset deposits, and a miscellaneous group. Some authors recognise copper–rich zones in the footwall as a separate type of deposit, although these can usually be linked to one or more contact deposits. Detailed descriptions of many of the deposits have been given by Souch et al. (1969), Naldrett and Kullerud (1967), Cowan (1968), and Pattison (1979) and by a number of authors in Pye et al. (1984).

The marginal deposits of the South Range, of which the Murray mine is a typical example, are generally zoned from massive ore at the footwall to disseminated Sulphide ore toward the hangingwall. The massive ores rest directly on the footwall rocks and contain inclusions of footwall material as well as fragments of gabbro and peridotite. The host rock of the disseminated ores is sublayer norite which is in sharp contact with the overlying Quartz–rich Norite of the Main Mass.

The Strathcona deposit is typical of the North Range marginal deposits. In these deposits, the mineralization occurs primarily within brecciated country rocks at the basal contact of the SIC and in fractures in country rock underlying the breccias. The footwall breccias consist of fragments of country rock, ultramafic inclusions, and rare norite in a quartzo-feldspathic matrix. It has been postulated that the breccia resulted from and lined the base of the impact crater, although post-ore brecciation can be demonstrated in some places. The Sulphides occur (1) as fine and blebby disseminations and as massive stringers within the footwall breccias, (2) as stringers in the footwall fractures, and, (3) more rarely, as disseminations within overlying sublayer norite (hangingwall ore). Cu-rich ore, consisting of nearly massive chalcopyrite enclosing a small percentage of pentlandite, is present 500 m into the footwall at the Strathcona mine (Abel et al. 1979; Abel 1981). This copper ore occurs in fractures within the footwall gneiss and particularly within veins of Sudbury breccia.

The Offset deposits occur in the dike-like offsets of sublayer norite and gabbros that extend several kilometres away from the Complex into the footwall. In many cases, the Sulpides form steeply plunging, lens-like pods of massive and interstitial disseminated ore associated with high proportions of inclusions in the offset dikes. The Frood Stobie, the largest offset deposit, is unusual in that it lies parallel to the southern contact of the Irruptive. The offset resembles a dike in plan and a downward–pointing wedge in cross section, and dips steeply to the north. Massive, inclusion-bearing Sulpide ore is concentrated at the margins of the wedge and toward the base of the deposit, whereas the upper part of the orebody consists of disseminated sulpides in inclusion-bearing sublayer norite.

The Falconbridge deposit belongs to the miscellaneous class, and is unusual in that it is localized along a fault that parallels the contact of the Complex. The fault forms the contact between rocks of the Complex and the country-rock greenstones over much of its length, although to the west it enters and dies out within the Complex and to the east it enters the greenstones.

RELATIONSHIP OF ORE DEPOSITS TO THE ROCKS OF THE COMPLEX

Although, as outlined above, there is considerable variation in the characteristics of different ore deposits, there are a number of features common to all of them. These include:–

(1) Embayments or other irregularities at the base of the SIC. An increase in Sulphide content is typically observed at the lower contact throughout the Complex, but it is where irregularities exist that the zone of Sulphide thickens and increases in intensity sufficiently to form ore.

(2) The presence of Sublayer. The spatial relationship of ore to Sublayer rocks is such that the sulphides constituting the ore bodies appear to have settled out of bodies of Sublayer. Sulphides also occur within Quartz-rich and Mafic norites; but, except where they have been moved from their original position by faulting, ore bodies are invariably associated with Sublayer rocks.

(3) Ultramafic inclusions within Sublayer host-rocks. Some Sublayer is mineralized, other varieties seem to be devoid of significant Sulphide. There is little to distinguish mineralized from unmineralized Sublayer in so far as texture, mineralogy and chemical composition of the rocks are concerned, except for the obvious presence or absence of Sulphides. All types of Sublayer contain inclusions, but both in the contact and the offset environments, the mineralization is associated only with Sublayer host-rocks that carry members of a suite of mafic and ultramafic inclusions that Scribbins et al. (1984) conclude are derived from one or more deep-seated layered intrusions.

Relationship between Inclusions, Sublayer, and Main Mass of the SIC

As discussed above, trace element profiles of the Sudbury rocks differ from those of continental flood basalts and suggest that contamination by country rocks has occurred on a large scale. While trace elements in the sublayer show distinct differences to those of the Main Mass and offset quartz diorite, a signature of strong crustal contamination is present in these also. The similarity in trace element signature between inclusions in the sublayer and the enclosing matrix is strong evidence that they have both crystallised from the same or at least similar magma. Corfu and Lightfoot's (1997) dating also ties the inclusions closely to the Sudbury event, and rules out their being derived from an older layered intrusion that was present in the target area of the meteorite.

Using Roeder and Emslie's (1970) relationship between the Mg/Fe ratio of olivine and the basaltic liquid in equilibrium with the olivine, Naldrett (1984) showed that the MgNos of liquids in equilibrium with the olivine of the inclusions span the range of MgNos exhibited by the Sublayer samples. He argued that the range of olivine compositions observed in the inclusions is precisely that which would be expected in cumulus rocks crystallizing from a magma evolving along a compositional trend such as that recorded within the Sublayer.

Thus, three geochemical aspects, trace elements, U-Pb dating and olivine compositions provide a strong body of evidence that inclusions, Sublayer, and Main Mass norite are all genetically related.

Segregation of Sulphides

The SIC differs from other layered complexes in a number of significant ways, including:

(1) evidence that the area into which it was intruded had been involved in a catastrophic explosion, probably the consequence of the impact of a meteorite in the view of many workers.

(2) rocks of the Complex are very siliceous in comparison with other intrusions judged on the basis of the Mg/(Mg + Fe) ratios of their pyroxenes; this observation implies that the source magma was unusually siliceous for its state of fractionation.

(3) other compositional data (major and trace elements and isotopic analyses) indicate that the high SiO2 content is the consequence of country-rock assimilation.

(4) the presence of an unusually large number of occurrences of very concentrated Sulphide mineralization.

Irvine (1975) pointed out that assimilation of SiO_2-rich material by a mafic magma could lower the solubility of sulpur within it, and suggested that this effect had occurred at Sudbury. Naldrett and Macdonald

(1980) used the 1200°C isothermal section of the FeO-FeS-SiO_2 system, to illustrate the principle. Composition A lies in the field of homogenous liquid, but addition of SiO_2 to change its composition to B moves it into a 2-liquid field, and results in the segregation of 2 immiscible liquids, one silicate-rich (Y) and the other Sulpide-rich (X). Li et al. (1993) have shown that the solubility of Sulphur in silicate magma can be successfully modeled by treating the interaction of the Sulpur with FeO in the magma thermodynamically. Their calculations indicated that a mixture of flood basalt magma that contains Sulphur at about two-thirds of its saturation level and a Sulphur-free variant of the tonalite-monzonite mixture proposed by Naldrett et al. (1984) will segregate immiscible Sulphides for mixing proportions of between 20 and 80 wt.% of the tonalite-monzonite.

Possible Models for the Sudbury Igneous Complex

It is suggested that a meteorite impacted in the Sudbury region 1.85 Ga ago, gave rise to a fall-back breccia (the Onaping Formation), produced a large volume of impact melt and caused extensive fracturing of the underlying crust, along much of which Sudbury breccia developed. Grieve (1992, 1994) has summarized evidence that indicates that the transient crater produced by the impact was about 100 to 135 km in diameter and 15 km deep. A crater of this size would have a final diameter, after structural readjustments, of 175 to 240 km and a depth of about 10 km. Grieve (1994) calculated that about 35,000 km^3 of country rock would be melted by an impact of this magnitude, which is ample to account for his estimate of 8000 km^3 for the volume of the SIC.

Two models are current to explain the origin of the SIC and its associated mineralization:

Model 1 is based on the concept that the pressure release associated with sudden removal of 50% of the thickness of the crust was sufficient to cause melting in the underlying mantle and that the fracturing related to this event allowed magma to ascend into the crust. The magma encountered zones of impact melt beneath the crater floor, where the impact melt had infiltrated during structural readjustment in the crater. It therefore became somewhat contaminated before it reached the crater, and some of this crystallized to give rise to ultramafic-mafic sills below the footwall of the crater. Because of the contamination, Sulphides segregated at an early stage within these sills and formed rich concentrations along their floors, overlain by ultramafic and then gabbroic cumulates. It is possible that these hidden, deep-seated intrusions account for the relatively flat-lying reflectors visible at depths of 9.5 to 12 km in the seismic profile of Milkereit et al (1992).

Naldrett (1984), Naldrett et al. (1986) suggested that partially fractionated magma rising from some of the lowermost of these bodies rose through, disrupted, and picked up Sulpides and inclusions of mafic and ultramafic cumulates from overlying bodies. This sulpide-enriched, inclusion-bearing magma continued to rise and came to rest along the base of the SIC as bodies of mineralized sublayer. The data linking the range of compositions exhibited by the sublayer with the magma compositions required to crystallize the olivines found in the inclusions that is referred to above, the similarity in trace element composition between sublayer and inclusions, the unusually contaminated trace element signature (for such mafic/ultramafic rocks) of the inclusions themselves, and the 1.85Ga age of the inclusions are explained by this model, and constitute strong support for it.

The main body of basaltic magma rose to spread beneath and then mix with the impact melt occupying the bottom of the crater itself. This mixture crystallized to produce the mafic layers (South Range norite, Felsic norite, Quartz gabbro) of the SIC.

The SiO_2-rich nature of the SIC lends support to this hypothesis. It is possible that some of the granophyre represents original impact melt that did not mix with the primary basaltic magma intruding into the structure.

Model 2 is based on the premise that the whole of the SIC is an impact melt sheet. While this proposal is aesthetically appealing because it is inherently "simpler" than that proposed above, it does not supply immediately obvious answers to certain questions. These include;

(1) Why is the complex so homogeneous? What caused melting of what must have been large scale heterogeneities in the target area to give rise to a relatively homogeneous impact sheet?

(2) What caused the development of so many rich accumulations of Sulphide? Mixing of a sulphide–bearing primary basaltic magma with felsic impact melt can no longer be called upon as the answer to this, if model 2 is accepted.

(3) What is the origin of the Sublayer? Why is the contact between the Main Mass norite and Sublayer so sharp on the North Range?

(4) What is the origin of the mafic-ultramafic inclusions? It is clear that they formed in the crust since they contain plagioclase. The available trace element data indicate a close similarity between the magma giving rise to the inclusions and that giving rise to the sublayer. The 1.85Ga age essentially precludes the inclusions from being exotic and derived from pre-existing rocks in the meteorite target area. On the other hand, it is very difficult to conceive how the sequence of ultramafic cumulates giving rise to the inclusions could have originated, since the present bulk composition of the SIC is much too rich in SiO_2 to have crystallized olivine. The inclusions must therefore represent a phase of crytallisation that occurred from a batch, or batches, of magma that had not undergone such extreme contamination as that exhibited by the Main Mass of the SIC. It is difficult to see how this could fit with a model explaining the whole of the SIC as an impact melt.

(5) What is the origin of the Sulphides? Keays (1995) has suggested that the Sulphides, along with the inclusions, were derived from a pre-existing layered intrusion. Whereas an accidental correlation of this kind between meteorite impact and one of the largest accumulations of Ni Sulphides in the world, would be rather serendipotous.

The relative merits of these two models is currently being debated, and the debate will undoubtedly continue. However, it is our current opinion that a model more akin to model 1 provides a better explanation for the facts as they are known at present than one along the lines of model 2.

PART B: A FIELD GUIDE TO THE GEOLOGY OF THE WHISTLE MINE EMBAYMENT AND WORTHINGTON OFFSET

Peter C. Lightfoot, and Gordon G. Morrison

GEOLOGY OF THE WHISTLE EMBAYMENT

The Whistle Sublayer Embayment is presently being mined by INCO Limited via an open pit; massive pyrrhotite–rich sulphide ore typically grading 2 to 3 wt.% Ni, with greater than 0.2 wt.% Cu and less than 500 parts per billion Pt+Pd, occurs within the embayment in contact Sublayer. By September, 1991, 3.3 million tons of ore had been removed, using a ramp and terrace blast method, while about 1.5 million tonnes remain to be removed by open pit methods (Morrison and Sweeny 1993). Mining recommenced at Whistle in October of 1994, and efforts are presently under way to document the changing geology of the embayment as mining of the embayment continues by open pit methods (Lightfoot et al. 1995).

The Whistle Embayment, located at the northeastern margin of the SIC (see Part A, Figure 1B), is comprised of a thick zone of Sublayer and an Offset dike which protrudes into the footwall Archean. The only systematic description of the embayment was made by Pattison (1979) before mining commenced at Whistle. Based on drill hole data and surface outcrops, Pattison (1979) suggested that a small accumulation of mafic norite occurs at the base of the Main Mass norite as depressions within the Sublayer norite; on the grounds of this observation and the presence of mineralised Sublayer inclusions, disseminated sulphide in the felsic norite, and the apparent truncation by the Main Mass of internal contacts in the Sublayer, Pattison (1979) suggested that the SIC Main Mass is younger than the Sublayer in the Whistle Embayment.

Pattison (1979) described a well-defined zonation of the Sublayer rock types within a funnel; the zonation being from orthopyroxene-rich, olivine-bearing igneous Sublayer in the core of the embayment succeeded by progressively more siliceous varieties of igneous Sublayer as the footwall contact is approached. Patches of leucocratic breccias have gradational relationships with the igneous-textured phase, with some of the Sublayer showing quench textures (Pattison 1979). Microprobe data for pyroxenes define a Fe-enrichment trend toward the Offset (Pattison 1979).

In detail, we have found that the Whistle Embayment comprises a number of Sublayer types which we show in a simplified anatomical cartoon in Figure B1. The rocks of the embayment show a very broad outward zonation from the base of the Main Mass towards the Offset and Footwall. These features are described in detail below, and are the subject of stops within the mine.

LOCATION A1:
The Main Mass Norites

The Main Mass norites directly above the Sublayer consist of sulphide-bearing biotitic hypidiomorphic granular to poikilitic-textured norites. These norites have low cumulate orthopyroxene content and therefore are less mafic than the most basal Mafic Norites of the Main Mass at Levack; this lends support to the observation that the Mafic Norite unit at the base of the Main Mass is a discontinuous unit around

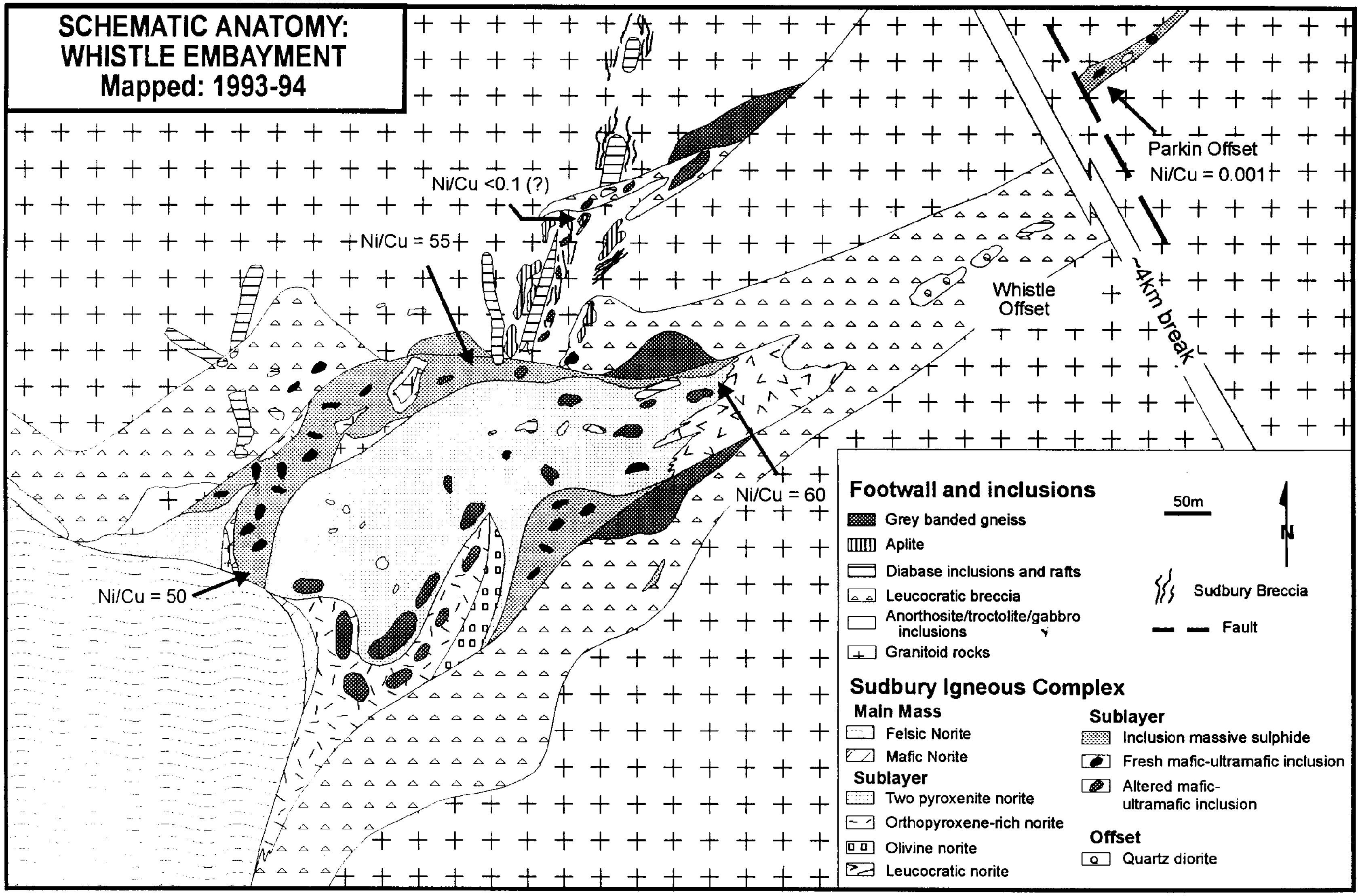

Figure B1. Diagramtic representation of geological relationships at Whistle Mine (after Lightfoot et al. 1997A,B,C).

the margin of the SIC. The basal norites of the Main Mass contain rare inclusions of hornfelsed diabase and more common anorthositic segregations. Above the Whistle embayment, the anorthositic fragments define a pronounced lineation which dips at about 30○ SW which is approximately the same dip as the contact between the Sublayer and footwall to the west of Whistle Mine. The most basal norites contain 1 to 5 modal percent sulphide, and 3 to 5 modal percent biotite, and have a sub-poikilitic to granular texture suggesting that they are intermediate in texture between typical Mafic and Felsic Norite. The contact between the basal norite and the Sublayer is highly irregular. At one location in Whistle Mine, the Sublayer norites contain rounded fragments of sulphide-rich basal norite. In another location at Whistle Mine, the basal norite is in sharp contact with a large pod of poikilitic-textured which is partially enclosed within Sublayer norite, but appears to protrude into the overlying felsic norite as a body 2 to 3 m wide for more than 2 m into the Felsic Norite (Lightfoot et al. 1997). This melanorite is texturally similar to the Mafic Norite of the Main Mass and to some of the melanorite inclusions enclosed in the Sublayer of the Whistle Embayment. An important issue raised by these rocks is whether the melanorite patches in the Sublayer at Whistle Mine are compositionally like those of the Main Mass Mafic Norite.

LOCATION A2:
Sublayer Norites and Gabbros

The igneous-textured Sublayer matrix rocks of the Whistle embayment are norites, gabbronorites, and gabbros which are dominantly porphyritic to non-poikilitic textured, but in places develop poikilitic patches. These rocks are grouped as ITSM (igneous-textured Sublayer matrix).

The contact between the Felsic Norite and the Sublayer is sharp. The ITSM which is developed closest to the Main Mass along the southeastern margin of the embayment are dominantly a more mafic non-poikilitic-textured rocks with variable (10 to 50%) cumulate-textured hypersthene content. A few examples of ITSM with resorbed cumulate-textured olivine have been found along the southeastern margin of the embayment. The ITSM carries disseminated, blebby, and heavily disseminated sulphides, pods of more massive sulphide, and a few examples of stringers and veinlets of sulphide which appear to be remobilised. The sulphide blebs sometimes have a spongy textural relationship with the surrounding silicates in both hand and polished sample. The ITSM frequently develops felsic wispy textures which appear to be defined by the presence of leucosomes which cut the norite, and are associated with more heavily disseminated sulphide.

Towards the centre of the embayment at Whistle, and away from the southeastern margin, the proportion of cumulus orthopyroxene declines to about 20%, and the hypersthene crystals retain rather corroded cumulate textures. These rocks more typically are gabbronorites and gabbros, and at the distal extreme of the embayment, the rocks are highly leucocratic.

LOCATION A3:
Norite and Melanorite Inclusions in the ITSM

The ITSM has a variable inclusion content and inclusion size. Inclusions make up 1% to 90% of the Sublayer and are grouped as: 1) Common (less than 30% of all inclusions) variably anhedral plagioclase porphyritic magnetic oxide–rich diabase inclusions from 2 mm up to 2 m across; 2) Rare (less than 1% of all inclusions) altered anorthositic, troctolitic, and gabbroic inclusions which often have a strained fabric, and 3) The most common type (>60% of all inclusions) which are discrete inclusions and segregations of poikilitic-textured melanorite and olivine melanorite, and rarer (less than 1%) inclusions of pyroxenite.

The inclusion content of the Sublayer changes away from the Main Mass; the proportion of poikilitic–textured melanorite falls and the number of diabase inclusions increases such that the malanorite:diabase inclusion ratio changes from 0.5 to 0.25.

The melanorite and olivine melanorite inclusions vary in size from less than 1 cm to over 5 m in at least two dimensions. The sides of these inclusions tend to be rimmed with sulphide and are locally associated with the development of pronounced slickensides with associated serpentine alteration. At least one of the melanorite pods grades from olivine melanorite on one side into hypidiomorphic granular felsic norite on the other side over a distance of 5 m. No examples of dunite, peridotite, orthopyroxenite, or clinopyroxenite have been found in the Whistle embayment, although they are described in other embayments (Rae 1975; Scribbins 1978; Scribbins et al. 1984; Moore et al. 1995), and are well-developed in the South Range Sublayer (E. Pattison 1994, personal communication). Variably altered melanorites have been described as the dominant inclusion types within sulphide–rich portions of the Parkin, Foy and Ministic Offsets (Farrell et al. 1995).

The melanorite, olivine melanorite, and pyroxenite bodies are generally fresh, and marked by fine-grained (intercumulus plagioclase, augite and biotite with 2 mm grain size) to coarse-grained (intercumulus plagioclase and biotite with 2 cm grain size) poikilitic relationships between euhedral cumulate spinel in embayed anhedral cumulate olivine (olivine melanorites) which are in–turn hosted in euhedral cumulate hypersthene. Euhedral apatite occurs within the intercumulus minerals, and both zircon and baddeleyite have been extracted from these inclusions (Corfu and Lightfoot 1997) The intercumulus minerals are plagioclase feldspar, augite, biotite, and sulphide minerals. Typically, silicate minerals such as olivine are altered to serpentine and biotites are altered to chlorite when in contact with sulphide.

In thin section, the contact between the melanorite inclusions and matrix is not sharp. The transition from poikilitic textured melanorite into porphyritic non-poikilitic norite is marked by a textural change; phenocrysts within feldspar or biotite oikocrysts of the melanorite are not cut at the contact with the matrix, but appear to protrude into it . In some samples, the textural change from melanorite to matrix occurs over a distance of 1 mm to 10 cm, and is marked by the development of poikilitic patches of melanorite within the Sublayer matrix. On textural grounds there is therefore some doubt as to whether the term inclusion is texturally appropriate for the poikilitic–textured melanorites.

LOCATION A4: Diabase Inclusions in ITSM

The diabase inclusions make up less than 30% of the inclusion population in the Sublayer at Whistle, and are essentially very similar to diabase fragments and lenses which crop out at the margin of the embayment adjacent–to and within the underlying breccias.

LOCATION A5:
Inclusion-rich Massive Sulphide

Massive sulphides of the Whistle embayment are dominantly pyrrhotite-rich inclusion-bearing sulphides with frequent 1 mm to 1 cm equant pyrite porphyroblasts (up to 5 modal percent of the sulphide). The sulphide occurs in a zone which roughly follows the margin of the embayment and terrace from beneath the Main Mass norites outwards towards the radial Offset. The sulphide zone is between 1 m and 50 m wide, and comprises an inclusion rich Sublayer facies. The inclusion population within the breccia-free massive sulphide are: rounded fragments of generally altered pyroxenite (5% of inclusions), melanorite (40% of all inclusions) and olivine melanorite (30% of inclusions), diabase (15% of all inclusions), and inclusion of non-poikilitic-textured mineralised Sublayer norite (10% of all inclusions). Towards the eastern margin of the massive sulphide zone, this Sublayer type gives way to Sublayer norite which is particularly rich in melanorite inclusions; here the massive sulphide grades into Sublayer rich in melanorite inclusions; this gradation can be from a melanorite with 60 to 75 modal percent pyrrhotite into pods of melanorite with as little as 2% pyrrhotite. In contrast to the melanorite inclusions, the pyroxenite inclusions tend to have sharp margins and are broken-up and/or cross-cut by veins of pyrrhotite; pyroxenite inclusions are very often rimmed with chalcopyrite.

LOCATION A6: Footwall Breccias of the Sublayer, and Footwall Rocks

The footwall rocks of the Whistle Embayment are dominantly pink porphyritic feldspathic granitoids and gneisses. Locally, small areas of banded grey gneiss are developed within the Footwall Breccias, and these do not appear to be common country rocks. Rare banded and strongly contorted segregations of foliated amphibolite occur within the country rocks. The northern wall of Whistle Mine consists of gneiss with a vertical zone of strong brecciation, along which aplitic veins, large fragments (up to 5 m by 5 m by 10 m) of diabase, inclusions of amphibolite, and Sudbury Breccia (see Dressler 1984 for a description) occur along a zone which reaches 100 m in width. The aplitic veins cross-cut the gneiss, and quartz-rich veins cross cut and brecciate the diabase. The granular amphibolites occur as large rounded fragments (25 cm to 3 m across). The Sudbury Breccia consists of a fine-grained grey pseudotachylite with a large proportion of comminuted granitoid; The Sudbury Breccia cross-cuts the country rock granitoids, aplite and diabase. In rare cases, aplite veins appear to cross-cut Sudbury Breccia. The Sudbury Breccia zone contains large fragments of granitoids and, locally, pods and disseminated blebby chalcopyrite mineralisation. The granitoids contain small irregular blebs of chalcopyrite.

At the contact between the footwall gneisses and the Footwall Breccia, are an increased number of small fragments (1 cm to 1 m sized) and very large (>10 m) rafts of diabase. The diabase contains anhedral clusters of feldspar phenocrysts, and is sometimes cut by late veins of quartz which merge into the footwall breccia. These diabase bodies are remarkably similar in grain size, texture, and magnetic properties to the inclusions of diabase within the Sublayer.

The footwall breccias follow the margins of the embayment, and occur within the footwall. The footwall breccias consist of sub-angular to angular fragments of granitoid rocks, phenocrysts similar to those within the granitoid rocks, fragments of diabase, fragments of amphibolite, fragments of Sublayer norite, and fragments of orthopyroxene-rich melanorite and pyroxenite. The breccias have a wide range in sulphide content (0 to 25%), but tend to be richer in chalcopyrite than pyrrhotite (75:25). The disseminated to blebby and heavily disseminated sulphides are dominated by chalcopyrite, but the sulphide with a fragmental habit is dominated by pyrrhotite. The fragments of norite contain inclusions of diabase and blebby disseminated sulphide; they also contain a larger amount of wispy feldspar, which merges into the breccia groundmass. Texturally, these fragments resemble the ITSM.

The transition from footwall breccia into massive sulphide occurs over 1 to 2 m and is marked by a progression from a metamorphic to igneous texture in the matrix, and a change from more angular fragments to rounded inclusions. The amount of pyrrhotite increases into the sulphide zone, and in some places there is a clear contact relationship between chalcopyrite within the breccia and pyrrhotite of the sulphide zone. The ultramafic rocks in the breccia are less altered than those within the sulphide zone. The breccia zones around the sulphide zones contain large clasts of granitoid rock which may be rafts of footwall material which were incorporated within the breccia. On a local scale, there are some cases where a feldspathic matrix of the breccia, especially between ultramafic fragments grades into to small (3 m by 20 cm) veins of aplitic material which cross-cut the footwall breccias. These appear to be igneous textured and may correspond to an expunged semi-molten matrix of the Sublayer breccia.

Local development of leucocratic gabbronorite which can reach 5 mm in grain size is found where ITSM is in contact with or close to the footwall and footwall breccias. These norites have a hypidiomorphic granular texture which contrasts with the non-poikilitic to sub-poikilitic-textured Sublayer norite.

LOCATION A7:
Distal Embayment, Sudbury Breccia, and Offset Environment at Whistle

The distal portion of the Whistle embayment is covered by an overburden rock pile, and so relationships between the facies must be deduced from drill core data. The Sublayer facies of this distal environment consist of a gabbronoritic ITSM (characterised by poorly developed cumulate orthopyroxene) and leucocratic ITSM gabbronorite as the main matrix components. These rocks contain large (1 to 10 m^3) rafts of melanorite and frequent centimetre-metre sized fragments of diabase.

At the point where the ITSM of the Embayment thins to less than 25 m wide, the embayment joins the Whistle Offset; this is marked by a facies change from ITSM into an inclusion-rich quartz diorite (25% inclusions). It is not known whether there is a transitional relationship or a continuum in compositions between leucocratic norite and quartz diorite, as the contact is neither exposed in the field nor in available drill core. The quartz diorite is discontinuous, and is hosted by brecciated footwall granitoids. The quartz diorite terminates at surface within 1.4 km of the Main Mass in a Footwall and Sudbury Breccia zone which contains many fragments of diabase, granitoids and gneiss. Sudbury Breccia dominates over Footwall Breccia towards the northeast. Two kilometres from the base of the Main Mass, the Offset is fault-bound, and perhaps decoupled from the branching Parkin Offset.

LOCATION A8:
Parkin Offset at Northbridge Grid

The Parkin Offset is a radial dike trending approximately 030°, and located north of the Whistle Embayment (see Figure 2, Part A). It is possible that this north-trending Offset dike was once linked to the Sublayer at Whistle, but is now decoupled from it by a sinistral fault.

The southern end of the Parkin Offset consists of a series of sub-parallel anastomosing sheets composed of pyroxene-rich quartz diorite. These sheets vary in thickness from less than 1 m to over 30 m, and branch and join along the length of the Offset (Figure B2 for a schematic cartoon of these relationships). The quartz diorite is often inclusion-free but invariably has 0.5 to 2% sulphide. Inclusions within the diorite are dominantly a magnetite-rich fine-grained hornfelsed pyroxene diabase and leucocratic clots of feldspathic minerals. The country rocks are: 1) Strongly brecciated Archean quartz porphyries and quartz porphyries cut by Sudbury Breccia; 2) Huronian metasediments; and 3) Gabbros. The breccia zone extends from a few metres to 50 m into the country rocks. The breccias contain metre-sized fragments of diabase, and these fragments are cut by Sudbury Breccia.

A discontinuous sulphide zone occurs associated with the margins of the quartz diorite. Mineralisation is dominated by chalcopyrite and pyrrhotite with 1 cm to 2 m sized inclusions of diabase, fine-grained amphibolite, metamelanorite and metapyroxenite. The massive sulphides can have up to 44 wt.% Cu, 23 ppm Pt, 1 ppm Pd, and 0.1 ppm Au with a Ni content of 620 ppm in a grab sample from a property north of Malbeuf Lake (see Lightfoot et al. 1997 for details). South of Malbeuf Lake, typical grab samples carry 2.75 wt.% Ni, 5.64 wt.% Cu, 7 ppm Pt, 4 ppm Pd, and 2 ppm Au (Sweeney, pers. comm., 1994). The sulphide veins range from 4 m down to a few centimetres in width, and are elongated parallel to the Offset over distances of 50 to 100 m, but they are discontinuous along the length of the Offset, and do not appear to be joined at Surface.

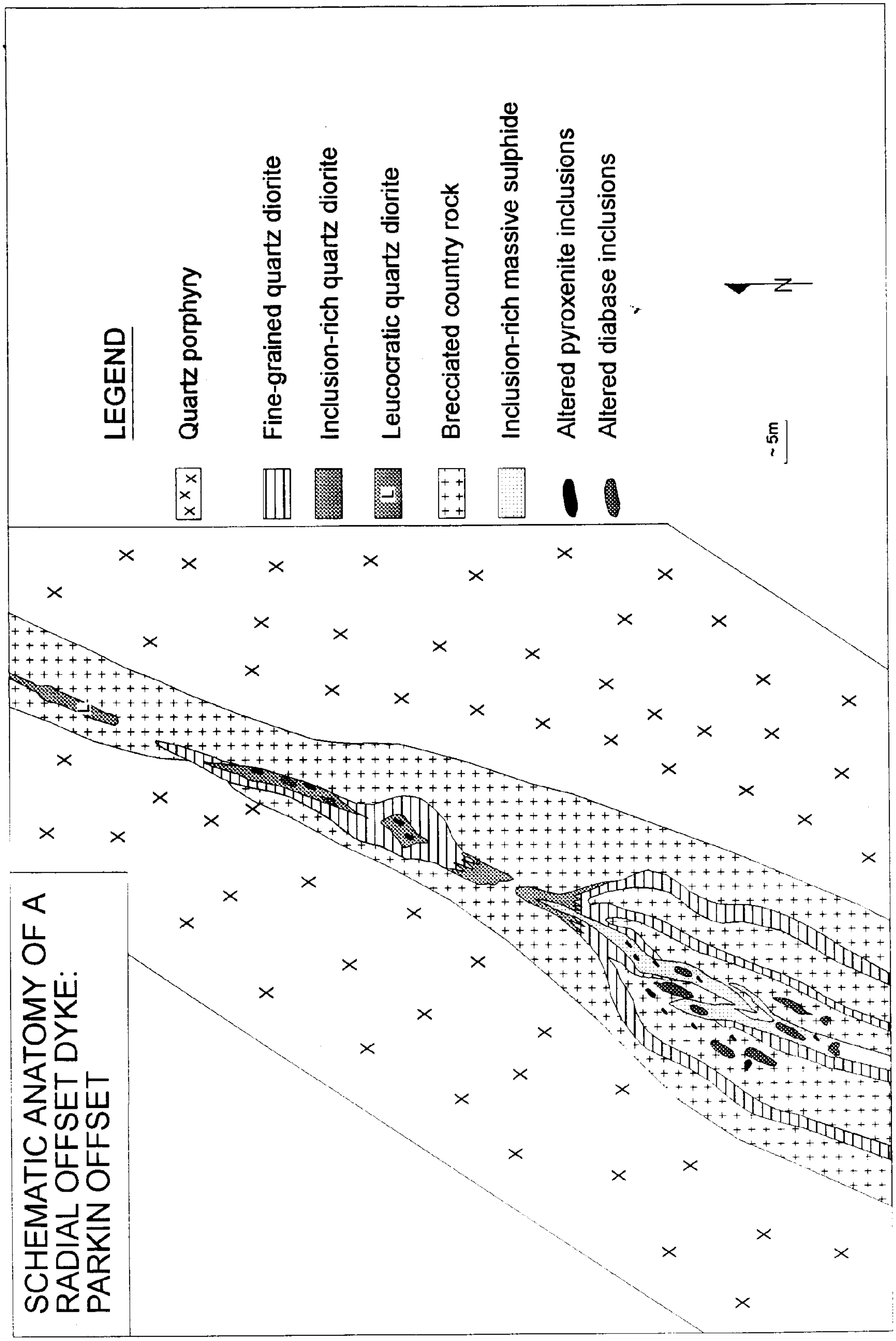

Figure B2. Diagramatic representation of relationships in the Parkin Offset (after Lightfoot et al. 1997A).

South of the Portelance Lumber Road, the quartz diorite sheets converge towards a single branch over a distance of about 1000 m. North of Malbeuf Lake, the branch thins from 15 m down to 1 m over a strike length of 200 m. Where the quartz diorite thins and pinches-out, there is a reduction in the width of the zone of massive sulphide. North of this point, the quartz diorite becomes very leucocratic, and then pinches out before the dike cuts quartzites of the Mississagi Formation. Quartz diorite does not crop out again until Milnet Mine, where the Offset changes direction to strike at 320ø, before returning to a trend of 020^{0}. This change in direction corresponds with the point where the Offset dike cuts Espanola Formation carbonates, and is shown as a fault on OGS map 2180. This sudden change in Offset orientation is the site of the mineralisation at the abandoned Milnet Mine.

The Offset crops out for a further 10 km to the north, and is parallelled by the development of extensive brecciation of the Huronian-aged Gowganda Formation argillites and quartzites. No outcrop of quartz diorite was found further north than the Gowganda Lorrain Formation boundary, although maps from INCO Exploration and Technical Services suggest that the Offset can be mapped for a further 3 km.

The quartz diorite is a massive grey fine- to medium-grained equigranular to inequigranular rock comprising 45 to 55% mafic minerals, 30 to 45% feldspar, 5 to 15% quartz, and trace amounts of granophyre and opaque minerals. Where the Offset narrows and terminates in the breccia, the quartz diorite becomes more felsic and quartz-rich. Feldspars are typically saussuritized and locally recrystallized, and mafic minerals are extensively altered to secondary amphibole ñ chlorite and possibly secondary biotite. The quartz diorite breccia contains fragments of quartz diorite. metavolcanic rocks, granite, gneiss, pyroxenite, diabase, and metagabbro. Locally the metabreccia is highly siliceous.

PART II: THE WORTHINGTON OFFSET AND OFFSET ENVIRONMENTS

Quartz diorite is the dominant rock type of the Offsets of the SIC. Traditionally, this rock type has been included in the group of rock types composing the contact Sublayer (Souch, Podolsky et al. 1969; Pattison 1979; Grant and Bite 1984). The Offsets extend either radially away from the margin of the SIC (e.g., Foy, Copper Cliff and Worthington Offset Dykes), or crop our as concentric ring dikes (Frood Stobie, Manchester, and the Hess section of the Foy Offset) (Figure 2 of Part A). A number of small discontinuous segments of quartz diorite are associated with areas of the footwall (Maclennan Offset), and the larger embayments (Creighton). Quartz diorite is also found cropping out in zones of Sudbury Breccia at McCreedy East Mine as small pods typically 25 cm in diameter. The Offset quartz diorites are usually associated with wide zones of brecciation characterised by the frequent development of Sudbury Breccia. A comprehensive petrological and morphological description of the quartz diorites is given in Grant and Bite (1984). The purpose of this work is to document the detailed distribution of the Offsets, the detail geochemical variations in the context of petrological and geological relationships. The geochemical data are used to describe: 1) variations within (across and along) individual Offsets; 2) variations between individual Offsets and North and South Range Offsets; and 3) the relationship of the Offset quartz diorites to the Sublayer norites and the Main Mass of the SIC.

A CASE STUDY: The Worthington Radial Offset Dyke

The Worthington Offset Dyke is a branching Offset that extends southwest from the margin of the SIC from Denison to Lorne Townships (Figure B3; Card 1965; 1968; Ginn 1965). The proximal part of the Offset occupies what may once have been an embayment structure north of the abandoned Victoria Mine, but now crops out as large faulted segments of quartz diorite in contact with the SIC (Grant and Bite, 1984). The Offset extends from the SIC and broadens before bifurcating into an eastern and western limb. The eastern limb tapers gradually for a distance of 1500 m at the surface and then plunges to the southeast, broadening with depth (Grant and Bite 1984). The western limb extends to the southwest for at least 15 km, with a relatively uniform thickness of 70 m (Grant and Bite 1984; INCO Exploration and Technical Services, Unpublished Data).

The dike contacts dip 60 to 70oSE in the proximal part, are near vertical in the eastern limb, and dip 80oSE in the western limb. The contacts between quartz diorite and country rock are knife sharp, and the grain size is finer towards the margin. Locally, Sudbury breccia is developed at the margins of the dikes, and at Totten #1 shaft, there is a narrow apophysis of quartz diorite which branches from the main quartz diorite and cross-cuts the breccia (Pekeski et al. 1994, 1995).

Grant and Bite (1984) describe the sulphides in the Offset dike as pipe-shaped sub-vertical ore deposits. Much of the sulphide mineralisation is restricted to lenses which terminate within the core of the Offset and widen towards the margin where the inclusion-rich and sulphide-rich quartz diorite is in contact with or cross-cuts and brecciates the country rocks. The inclusion- and sulphide rich quartz diorite is in sharp contact with the marginal inclusion-free and sulphide-poor quartz diorite (Pekeski et al. 1994, 1995), and interestingly the inclusion-rich quartz diorite frequently contains fragments of inclusion-free quartz diorite resembling the marginal phase (Pekeski et al. 1994, 1995). The inclusion population con-

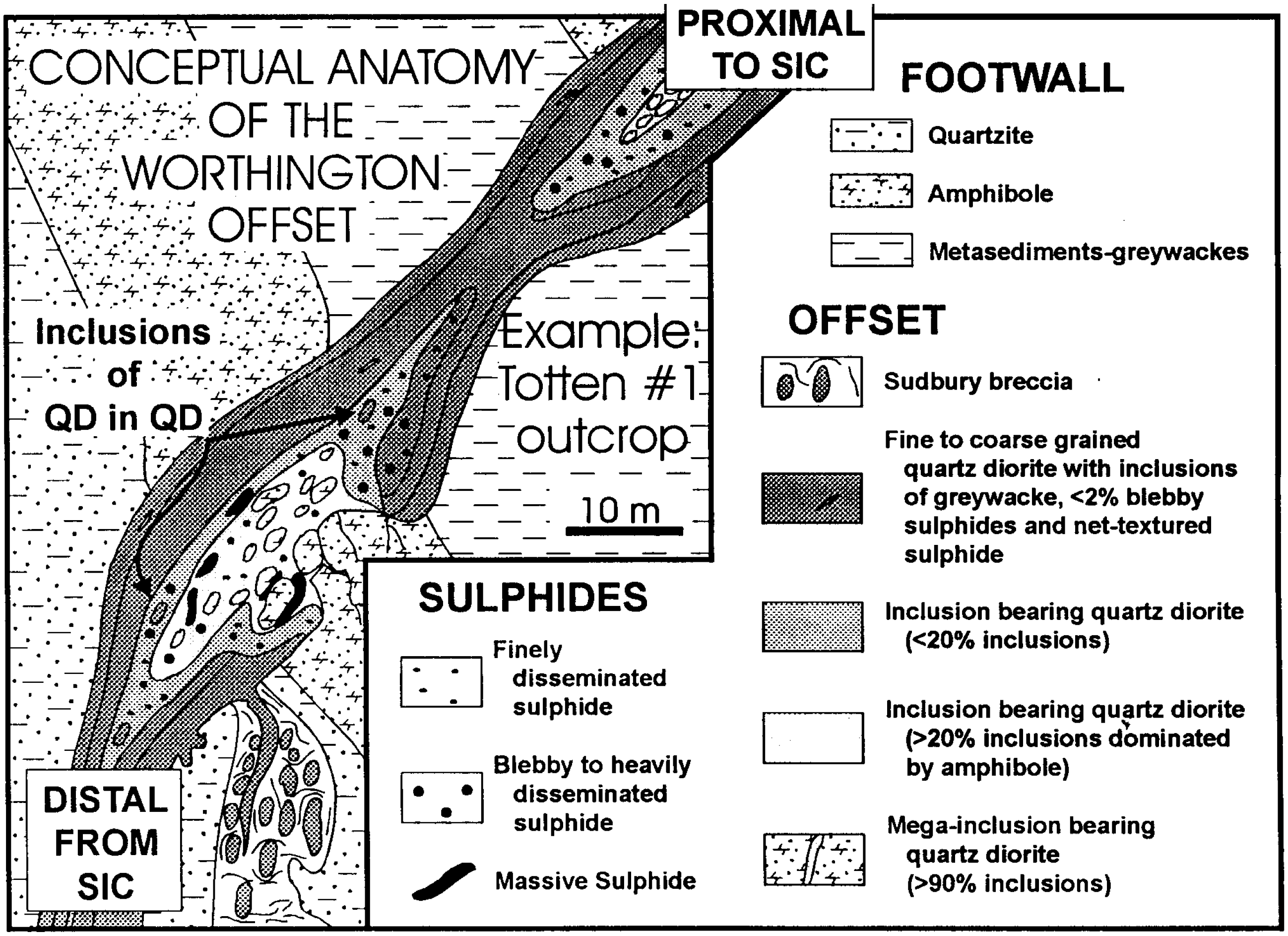

Figure B3. Diagrantic representation of relationships in the Worthington Offset (after Lightfoot et al. 1997A).

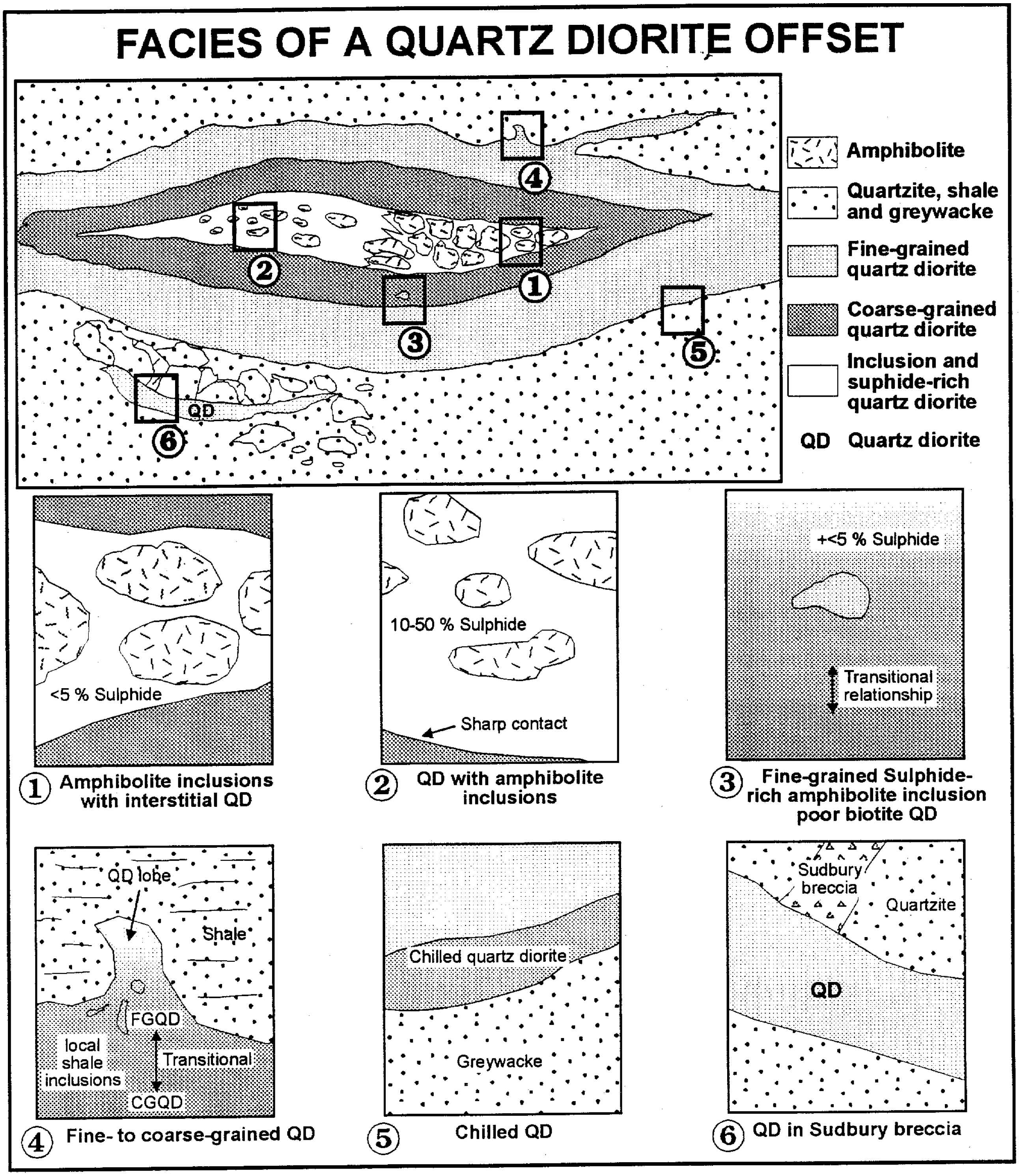
FACIES OF A QUARTZ DIORITE OFFSET
Amphibolite
Quartzite, shale and greywacke
Fine-grained quartz diorite
Coarse-grained quartz diorite
Inclusion and suphide-rich quartz diorite
QD Quartz diorite
QD
①
②
③
④
⑤
⑥
<5 % Sulphide
① Amphibolite inclusions with interstitial QD
10-50 % Sulphide
Sharp contact
② QD with amphibolite inclusions
+<5 % Sulphide
Transitional relationship
③ Fine-grained Sulphide-rich amphibolite inclusion poor biotite QD
QD lobe
Shale
FGQD
local shale inclusions
Transitional
CGQD
④ Fine- to coarse-grained QD
Chilled quartz diorite
Greywacke
⑤ Chilled QD
Sudbury breccia
Quartzite
QD
⑥ QD in Sudbury breccia

Figure B3b.

sists dominantly of amphibolite which is texturally similar to the footwall amphibolites. These amphibolites have variously been termed “Sudbury Gabbro”, but are probably metamorphosed Nipissing gabbros (Card 1968); based on unpublished geochemical data (Lightfoot, unpublished data), these inclusions and the surrounding Sudbury Gabbro are geochemically like average Nipissing gabbro in MgO and incompatible element abundance patterns. Frequently, the amphibolites of the country rock are cross-cut and broken up by veins of quartz diorite laden in sulphide and small inclusions. Exotic inclusions are rare, but include pyroxenite and gabbro.

The Worthington Offset consists of medium-grained inclusion-rich amphibolite-biotite quartz diorite within the sulphide-bearing zones, and a medium- to fine-grained inclusion-free marginal phase of pyroxene-amphibole quartz diorite. Close to where the Offset branches, there is an area of coarse-grained quartz diorite containing abundant large crystals of blue quartz, 1 to 5% sulphide and few inclusions. This appears to be a coarse grained equivalent of the quartz diorite developed at the margin of the Offset. Close to the Main Mass, the quartz diorite developed close to the Main Mass (which might be a Sublayer type) contains inclusions similar mineralogically and texturally to the basal blue quartz-rich norites of the Main Mass. Grant and Bite (1984) report similar inclusions on the eastern limb and as far south as the Totten Mine. These geological relationships suggest that: 1) The quartz diorite was injected as two or more pulses of magma, the first which was devoid of inclusions and poor in sulphide, and the second of which was emplaced after the first pulse had substantially crystallised and contained abundant inclusions and sulphide as well as fragments from the marginal quartz diorite; 2) that the quartz diorite dike was injected after the crystallisation of the basal norites of the Main Mass; 3) the inclusion population consists dominantly of country rock fragments with remarkably few exotic fragments; much of the inclusion-rich and heavily mineralised quartz diorite is localised in regions where the dominant footwall lithology is amphibolite.

LOCATION B1:
South Range Norite Proximal to The Main Mass

The lower part of the South range Norite is a coarse-garined hypidiomorphic granular-textured rock. The main primary minerals of this rock are cumulus plagioclase and hypersthene, with intercumulus augite, quartz, titaniferous magnetite, and ilmenite. The South Range Norite grades upwards into quartz gabbro of the Transition Zone.

LOCATION B2:
Inclusions of Sublayer in Quartz Diorite North of Victoria Mine

The transition between the Main Mass and the quartz diorite of the Offset is marked by the very limited development of Sublayer. At location B2, a glaciated surface shows the development of inclusions of Sublayer norite in quartz diorite. The Sublayer norite fragments are biotitic and mineralised, and occur as less than 2 m fragments with rounded margins.

LOCATION B3:
Victoria Mine Glory Hole

Sulphides in the Offset dike occur as pipe-shaped, subvertical ore deposits at the dike margin. The mineralisation consists of heavy disseminated sulphide blebs up to 2 cm in length. Surface outcrop of gossanous sulphide illustrates that the sulphides are fragment-laden.

LOCATION B4: Coarse-grained Mineralised Quartz Diorite

The coarse-grained quartz diorites south of Victoria Mine and north of Ethel Lake crop out as a complex sheet with patchy coarse-grained quartz diorite as pods/inclusions in finer-grained quartz diorite. Mineralisation is blebby, and has a typical Sudbury average Ni/Cu approximately 1:1.

LOCATION B5:

Sudbury Breccia and Quartz Diorite Pods

This location demonstrates the development of Sudbury Breccia within arkosic quartzite of the Matinenda Formation of the Elliot Lake Group.

LOCATION B6:

Zonation Across a Typical Segment ofthe Worthington Offset in Amphibolitic Country Rocks

At Howland Pit, the Offset quartz diorite cuts through amphibolites of the Southern province. These amphibolites are petrologically and geochemically similar to the Nipissing Gabbro, and may be metamorphosed equivalents of the more pristine gabbros found east and northeast of Sudbury. The Offset shows the development of a marginal fine-grained inclusion- and sulphide-poor phase. Ajacent to the amphibolite, the mineralised inclusion-rich quartz diorite cross-cuts and brecciates the amphibolite. See Figure B3 for a summary of the relationships.

LOCATION B7:

Contact Relationships Between Phases of Quartz Diorite, and Inclusions of Sulphide-poor Quartz Diorite

This location shows the contact relationship of quartz diorite with the greywackes of the Ramsey Lake Formation. A contact between unmineralised marginal quartz diorite, and a core phase of inclusion- and sulphide rich quartz diorite is examined. Inclusions of the marginal quartz diorite in the core quartz diorite are examined (Figure B3).

LOCATION B8:

Relationships between Country Rocks, Quartz Diorite, Amphibolite Inclusions, Quartz Diorite Inclusions, and Sudbury Breccia

These relationships are examined along an approximately 1 km segment of the Offset that has been mapped in detail by Pekeski (in prep.) as part of a MSc thesis study. The following are the relationships examined on this section of the Offset: 1) Contact relationships between greywackes and fine-grained quartz diorite; 2) Transition from fine-grained quartz diorite with local country-rock fragments to coarser-grained inclusion-free quartz diorite; 3) Contact relationship and transition relationship between marginal inclusion-free sulphide-poor quartz diorite, and the central part of the Offset which contains abundant exotic fragments and sulphide in a biotite-amphibole quartz diorite; 4) Amphibolite inclusion population in the centre of the Offset; 5) Fragments of the marginal quartz diorite within the central inclusion-rich quartz diorite; 6) Sudbury breccia developed in quartzite; and 7) A vein of quartz diorite cross-cutting the Sudbury Breccia. See Figure B3 for summary of relationships.

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Metric Conversion Table

Conversion from SI to Imperial			**Conversion from Imperial to SI**		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
			LENGTH		
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
			AREA		
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
			VOLUME		
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
			CAPACITY		
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
			MASS		
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 90**	t
			CONCENTRATION		
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.

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