Economic Geology
Vol. 92, 1997, pp. 289–307

Geochemical Relationships in the Sudbury Igneous Complex: Origin of the Main Mass and Offset Dikes

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Abstract

Petrological models relating the different rock types constituting the 1.85 Ga Sudbury Igneous Complex are constrained with extensive new geochemical data. We show that the main mass felsic norite, transition zone quartz gabbro, and granophyre have similar ratios of the highly incompatible trace elements (e.g., La/Sm = 4.5–7, La/Nb = 2.8–4.2, Th/Zr = 0.04–0.05) and that these variations are consistent with the crystallization and differentiation of magma types largely (>80%) derived from the upper crust, with a smaller contribution from a mantle source. Although there is presently no conclusive proof that magma was generated in situ as a melt sheet produced by meteorite impact, we find no principal reason why this model should be rejected. However, we propose that a small contribution of mantle-derived picritic magma is required to explain the abundant Ni, Cu, and platinum-group elements (PGE) in the Sudbury deposits, as well as the compositions of the ultramafic inclusions (MgO = 12–36 wt %; Fo_{68-87} olivines with 450–3,700 ppm Ni, and abundant chrome-rich spinel), and the magnesian composition of the mafic norite (8–14 wt % MgO) and the sublayer (6–12 wt % MgO). We believe that the main mass of the Sudbury Complex achieved its present composition through incorporatation of up to 20 percent mantle-derived picritic magma emplaced along crustal fractures produced by the impact event. These picritic magmas entered the melt sheet as a dense plume, vigorously mixing with it, and due to the marked compositional shift, the mixed magma formed magmatic sulfides which sank through the magma column, depleting the melt in Ni, Cu, and PGE. Since both the felsic norite and granophyre have indistinguishable ratios of the incompatible trace elements, we see no requirement to derive these units of rock by the crystallization of magmas derived from different sources. Rather, the compositional difference between the felsic norite and granophyre is attributed to the in situ differentiation of the magma.

We show that the main mass has many compositional traits similar to those of most of the offset dike quartz diorites (e.g., the Parkin offset dike: La/Sm = 6.3, La/Nb = 4.5; Th/Zr = 0.05) and of embayment-related leucocratic norites from the Whistle mine (La/Sm = 6.2, La/Nb = 5.0, Th/Zr = 0.02). These rocks have compositions intermediate between the felsic norite and the granophyre, and therefore crystallized from the same magma type; arguably, the unmineralized quartz diorites provide the best possible estimate of the original magma from which the Sudbury Complex crystallized. In detail, there are subtle variations in composition within and between offset dikes, with the largest difference being between the North and South Range offsets; the North Range offset dikes cut Archean granitoids and gneisses and have elevated Sr, La/Yb, La/Sm, and Gd/Yb and low TiO_2 whereas the South Range dikes cut Early Proterozoic sediments, mafic volcanics, and intrusions, and have low Sr, La/Yb, Gd/Yb, La/Sm, and high TiO_2. These differences may be caused by the assimilation of different country rocks during emplacement of the dike. A strongly mineralized offset dike at the Creighton mine has geochemical variations that are different when compared to the main mass, and in the case of Creighton, are more similar to the local mineralized sublayer. These data suggest that mineralized and barren quartz diorites have different geochemical compositions, and that these traits may be of value in mineral exploration.

Introduction

THE Sudbury Igneous Complex hosts the largest known concentration of Ni, Cu, and platinum-group element (PGE)-bearing sulfides, with >1,548 million metric tons (production plus reserves) grading ~1.2 wt percent Ni, with Ni/Cu ~ 1.1, Pt ~ 0.4 g/t, and Pd ~ 0.4 g/t (Lightfoot, 1996). The mineralization occurs within four principle environments: (1) at the base of the main mass within a zone of inclusion-rich norite termed the "sublayer"; (2) as deposits within the breccias beneath the igneous-textured sublayer; (3) as vein and stockwork systems in the underlying country rocks; and (4) within dikes, termed "offsets," consisting of quartz diorite and breccia extending radially away from the complex and as concentric dikes. Understanding the origin of mineralization in these different envionments is linked to the understanding of the petrologic relations among the different components of the complex and their contributing magma sources. Although geologic and petrological data have previously been used to address these questions, only limited geochemical data are available to constrain the geochemical relations among the different components of the complex, and high-quality geochemical data for the offset dikes are lacking. Similarly, despite a consensus on significant contributions of continental crust to the formation of the complex (Naldrett et al., 1986; Grieve, 1994), several models are still proposed for the generation of the entire intrusion: by contamination (e.g., Naldrett et al., 1986), by melting of older crust (e.g., Grieve, 1994), or by a combination of models (e.g., Chai and Eckstrand, 1994).

In this study we present some geologic evidence and new geochemical data pertinent to these issues. We use these data to evaluate models for the origin and evolution of the main mass, the sublayer, and the offset magmas. To achieve these objectives, we describe the geology and present new geochemical data for samples dominantly from the northeastern margin of the complex at (1) the termination of the Whistle embayment which is dominantly composed of the sublayer, (2) along the Whistle-Parkin offset dikes, and (3) from a section through the main mass. We also present reconnaisance data from a study of quartz diorites from seven different offset dikes; some data for the sublayer environment and a model for the formation of the mineralization appear in a companion paper.

Regional Geologic Setting

The Sudbury basin is located at the contact between Archean-aged gneisses of the Levack Complex to the north, and Proterozoic Huronian Supergroup sediments, volcanic rocks, and intrusions to the south (Dressler, 1984a; Figs. 1 and 2). It lies close to the junction of three different terranes in an area of unusually high metallogenic potential (Peck et al., 1993; Lightfoot et al., 1997a). The main units of the Sudbury Complex (Fig. 3) are (1) concentric and radial offset dikes; (2) a discontinuous zone of the sublayer at the lower contact; and then in upward succession through the complex, (3) a marginal quartz-rich norite of the South Range and the orthopyroxene-rich poikilitic-textured melanorite (mafic norite) of the North Range, (4) a transition zone quartz gabbro, and (5) the granophyre and plagioclase-rich granophyre. Traditionally, all of the units except for the offsets and the sublayer have been grouped into the main mass of the complex. The Ni-Cu ores of the Sudbury region are associated with the outer margin of the Sudbury Complex as a unit of inclusion-rich norite termed the "(contact) sublayer" (Souch et al., 1969; Pattison, 1979) and a series of concentric and radial dikes composed dominantly of quartz diorite, termed "offset dikes" (Figs. 1 and 3; e.g., Grant and Bite, 1984). The rocks of the main mass of the Sudbury Complex are exposed as a series of crudely elliptical rings, and model-dependent calculations point to an original sheet with a volume in excess of 8,000 km^3 (Golightly, 1994). Recent geophysical studies using seismic, gravity, and magnetic data (Milkereit et al., 1994;

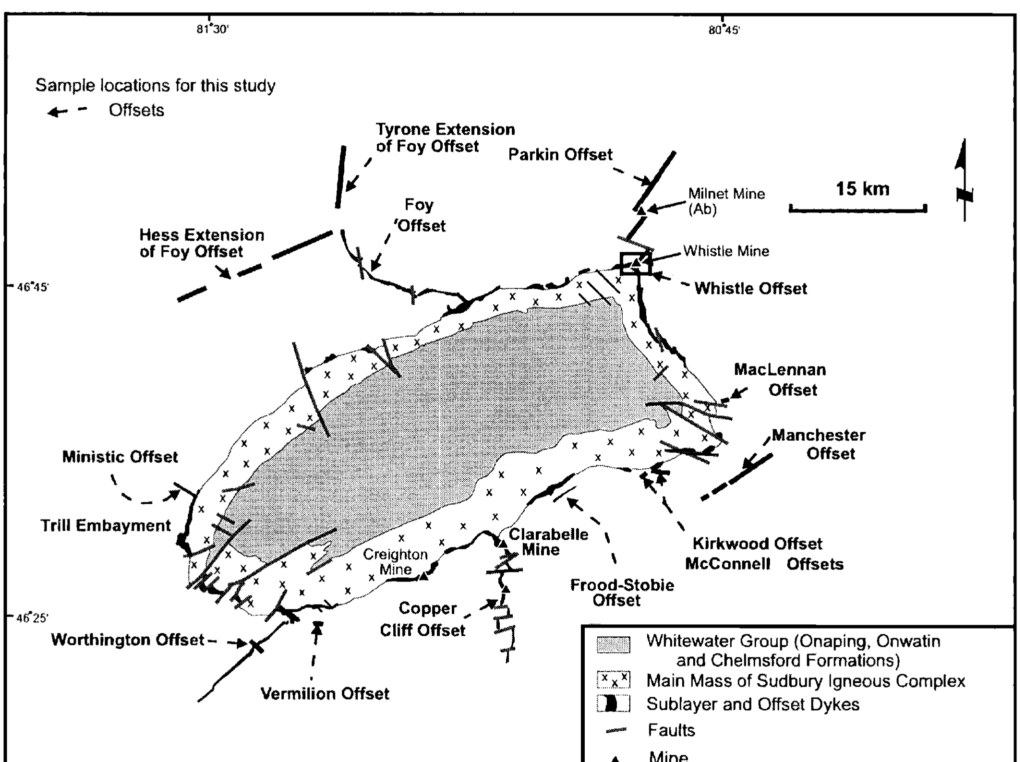

FIG. 1. Geologic map showing the distribution of the main mass, the sublayer, and the offsets of the Sudbury Igneous Complex. The location of the study area is shown at the far northeastern margin of the complex in the vicinty of the Whistle mine and the Parkin offset dike (after Lightfoot et al., 1995a).

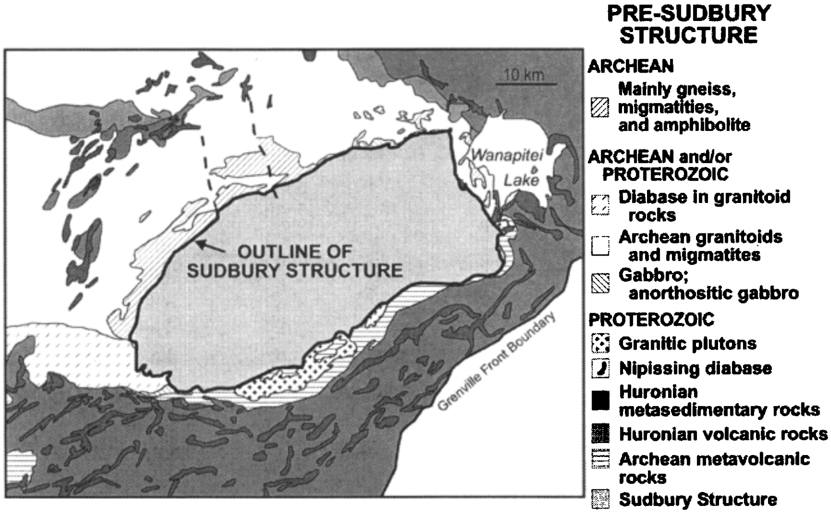

FIG. 2. Geology of the footwall of the Sudbury Complex showing the location of the Levack Gneiss Complex, the Archean granitoid rocks, the ~2.4 Ga Huronian-aged Creighton, Murray, and Skead granite plutons, early Proterozoic mafic intrusions, and the Huronian-Nipissing sedimentary, volcanic, and intrusive sequence (after Muir, 1984).

McGrath and Broome, 1994; Hearst et al., 1994) suggest that the northern contact between the Sudbury Complex and the underlying Levack Gneiss can be traced beneath the axis of the basin as far south as the southern limit of outcrop of the complex in the South Range. Milkereit et al. (1994) show evidence that numerous south-dipping reflectors, apparently corresponding to reverse faults, are developed south of the long axis of the basin. Gupta et al. (1984) suggested that the gravity data for the complex can only be explained by the presence of a deep hidden ultramafic complex, whereas McGrath and Broome (1994) modeled gravity data using constraints from the seismic data (Milkereit et al., 1994), and concluded that the observed gravity field can be explained on the basis of the observed surface distribution of rocks without recourse to a hidden layered intrusion.

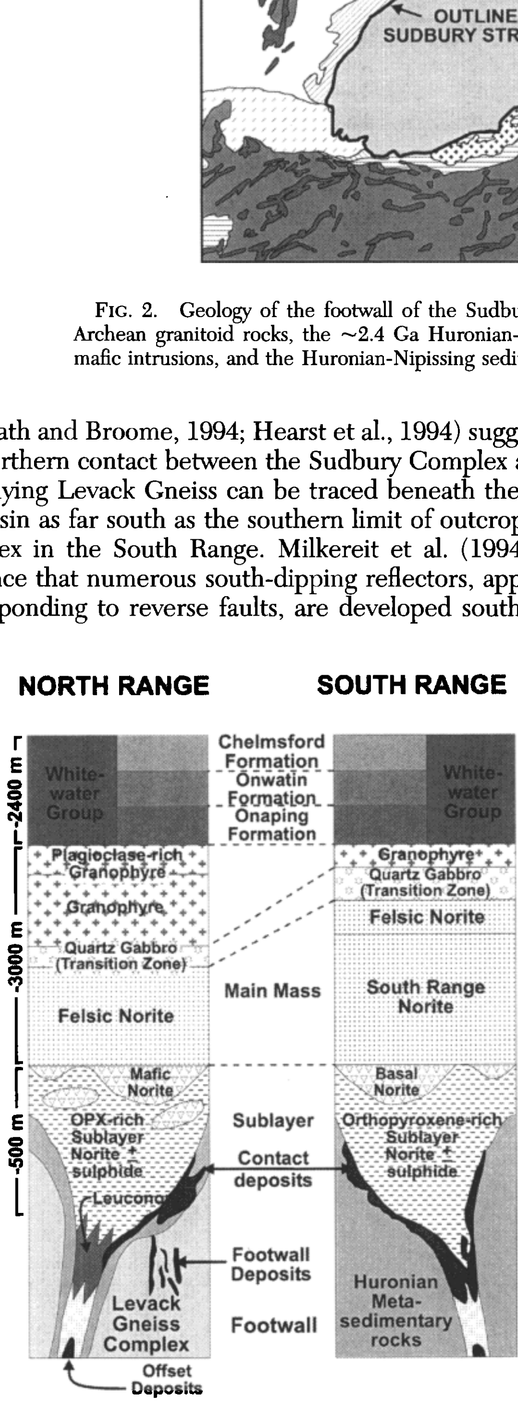

FIG. 3. Principal units of the North and South Ranges of the Sudbury Igneous Complex. Note the change in scale for the sublayer environment and the various types of deposit referred to in the text. Based on Naldrett et al. (1970).

Detailed local geology of the Sudbury Complex is given in volumes edited by Pye et al. (1984) and Lightfoot and Naldrett (1994). Many aspects of the geology, summarized by Naldrett (1989), suggest that an explosion of unusually large intensity gave rise to the Sudbury structure (Dietz, 1964), viz: the basinal shape of the structure (Morrison, 1984), the upturned Huronian rocks around the margin of the complex (Dressler, 1984b), the shock metamorphic features in the inclusions and country rocks such as shatter cones and shock lamellae in quartz and feldspar (e.g., Dressler, 1984b), the abundant footwall breccias (e.g., Dressler, 1984b), and the presence of a thick (1,800 m) breccia on top of the complex which is variously interpreted as a meteorite fallback breccia or an ignimbrite (e.g., Peredery and Morrison, 1984). However, opinions remain divided between an extraterrestrial and endogenetic origin for the structure (e.g., Grieve, 1994; Muir, 1984), and recent data for the igneous component of the system demand a more exacting model for its formation (e.g., Lightfoot et al., 1995a, 1995b, 1995c, 1997a).

Petrology of the North Range of the Sudbury Complex

The most basal norites of the main mass of the North Range are orthopyroxene-rich poikilitic-textured melanorites with 40 to 60 modal percent orthopyroxene (Naldrett et al., 1970; Fig. 3). The overlying felsic norite is a hypidiomorphic granular-textured norite with <15 modal percent hypersthene (Naldrett et al., 1970). The transition zone quartz gabbro is marked by the entry of abundant opaque oxides (Gasparinni and Naldrett, 1972), apatite, and sphene and the disappearance of hypersthene. The uppermost unit of the

Sudbury Complex consists of the granophyre and is marked by the presence of abundant granophyric intergrowths of plagioclase and quartz.

The term "sublayer" is used to describe the igneous-textured inclusion-rich sulfide-bearing subpoikilitic- to nonpoikilitic-textured gabbronoritic to noritic rocks, the inclusion-rich sulfides, and the metamorphic-textured breccias at the base of the complex, but excludes the poikilitic-textured main mass mafic norite; traditionally, the rocks of the offsets have also been grouped with the sublayer (Pattison, 1979). The offsets consist of dominant quartz diorite with patchy to extensive local development of Sudbury breccia along the trend of the offset. The quartz diorite varies from a marginal inclusion-poor type which either grades into, or is in sharp contact with, a more inclusion- and sulfide-rich phase which can have economic concentrations of Ni, Cu, Co, and PGE (e.g., the Copper Cliff offset and the Frood-Stobie offset). The dominant quartz diorite lithology of the offsets is sparsely mineralized, and this has led us to consider the offsets as composite systems comprised of both main mass-like and sublayer-like contributions. For these reasons we do not include the inclusion- and sulfide-poor offset quartz diorite analyzed in the course of this study within the sublayer grouping.

The igneous-textured silicate matrix rocks of the sublayer are fine- to medium-grained poikilitic to nonpoikilitic-textured gabbronorites and norites with low modal quartz content and abundant orthopyroxene (10–40%). Dressler recognized three phases of these rocks (see Naldrett et al., 1984). Geologic relationships between the sublayer and main mass give conflicting relationships, and these have never been investigated with detailed geochemistry. For example, inclusions of what have been termed "main mass quartz-rich norite" have been observed in these silicate matrix rocks (e.g., the Whistle embayment), whereas dikes of what are thought to be silicate matrix rocks (e.g., the Creighton embayment) have been observed cutting the main mass (e.g., Naldrett et al., 1984; Lightfoot et al., 1997a). Grant and Bite (1984) and Pekeski et al. (1995) demonstrate field evidence supporting at least two different phases of quartz diorite within the Worthington offset (Fig. 1), but once again, there are no published geochemical data to develop an understanding of their petrogenic relationships. Naldrett et al. (1984) concluded that the introduction of the sublayer and main mass was a complicated process with each preceding the other at different locations.

The sublayer and offset dikes are characterized by the presence of inclusions. These are divided into two groups: those of locally derived footwall (which are rare in much of the silicate matrix rocks), and exotic inclusions, the majority which do not crop out in abundance in the Sudbury region (cf. Farrell et al., 1995). The mafic-ultramafic inclusions have been broadly described by Rae (1975), Scribbins (1978), and Scribbins et al. (1984) and range from norites, gabbros, and melanorites to peridotites, clinopyroxenites, and orthopyroxenites. Inclusions from the Whistle mine have cumulus textures, Fo_{68-87} olivines, and Cr-rich spinels (Lightfoot et al., 1995b, 1997a). Scribbins et al. (1984), following from the geophysical evidence of Gupta et al. (1984), suggested that a hidden ultramafic complex was the source of the inclusions. It is therefore critical to an understanding of the very complex sublayer environment that the relationships between the main mass and offset rocks be defined.

Geology of the Main Mass and the Offset Rocks

The Whistle embayment, located at the northeastern margin of the Sudbury Complex, is comprized of a 1-km-thick zone of the sublayer and an offset dike which protrudes into the footwall Archean granitoids (Fig. 1; Lightfoot et al., 1997a). 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; on the grounds of this observation and the presence of mineralized sublayer inclusions, disseminated sulfide in the felsic norite, and the apparent truncation by the main mass of internal contacts in the sublayer, Pattison (1979) suggested that the Sudbury Complex 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, rarely olivine-bearing silicate matrix rocks in the core of the embayment succeeded by progressively more siliceous varieties of these rocks as the footwall contact is approached. Patches of marginal leucocratic breccias have gradational relationships with the silicate matrix rocks, and some of the sublayer shows quench textures (Pattison, 1979, his fig. 16). Electron microprobe data for pyroxenes define an Fe-enrichment trend toward the offset (Pattison, 1979).

Main mass norites: At the Whistle mine, the most basal norites of the main mass are mafic norites; these are in transitional contact with the underlying sublayer norite and texturally resemble melanorite pods within the sublayer (Lightfoot et al., 1997a). The contact between the mafic norite and felsic norite is transitional over a meter and is marked by the presence of 1- to 50-cm-diam pods of mafic norite within the felsic norite. The mafic norite is marked by coarse grain size (1–10 mm), poikilitic plates of plagioclase and biotite (up to 10 modal %), and disseminated sulfide (0.5–10 modal %). The overlying felsic norite has a hypidiomorphic granular texture, <2 percent biotite, and is locally altered to albite. The felsic norite contains 1- to 30-cm inclusions or patches of anorthosite (<10 m from the base of the felsic norite and constituting 1% of the rock) which all have a $\sim 30°$ south-southwest-dipping orientation, roughly concordant with the basal contact of the Sudbury Complex. Locally, there are patches of felsic norite which contain 1 to 20 percent blebby to disseminated sulfide within 20 m above the top of the mafic norite. A suite of samples was collected for analysis from the main mass along a north-south traverse located 2 km west of the Whistle mine (Lightfoot et al., 1997a).

Distal embayment and offset rocks: The sublayer facies of this distal environment consists of inclusion-rich silicate matrix rocks (characterized by poorly developed cumulate orthopyroxene) and inclusion-bearing leucocratic norite that has traditionally been considered part of the sublayer. These rocks contain large (1–10 m^3) pods of more feldspathic poikilitic-textured norite and centimeter- to meter-sized fragments of diabase.

On progressing from the embayment into the offset dike (see Fig. 4), the sublayer facies changes 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. The quartz diorite is discontinuous and is hosted by brecciated footwall gneiss and associated with Sudbury breccias. The quartz diorite terminates at surface within 1.4 km of the main mass in a heavy breccia zone which contains many fragments of diabase and granitoids. The footwall breccia continues to trend northeast for 2 km from the base of the main mass and ends at a major fault zone which may represent displacement of the Whistle offset dike from the Parkin offset dike.

The Parkin offset dike: This is a radial dike beginning approximately 3 km north of the Whistle embayment and trending approximately 033° to 030° (Fig. 1). It is possible that this north-trending offset dike was once linked to the sublayer at Whistle, but is now displaced from it by a sinistral fault. The southern end of the Parkin offset dike consists of a series of subparallel anastomosing dikes or sheets composed of orthopyroxene-bearing quartz diorite. These sheets vary in thickness from <1 m to over 30 m, and branch and join along the length of the offset (Fig. 5). The quartz diorite is frequently inclusion free but always has 0.5 to 2 percent sulfide. Inclusions within the diorite are dominantly magnetite-rich plagioclase-glomeroporphyritic fine-grained hornfelsic pyroxene diabase similar in texture to those in the sublayer at the Whistle mine (Lightfoot et al., 1997a). The country rocks are strongly brecciated quartz porphyries; the breccia zone extends from a few meters to 50 m into the country rocks (Lightfoot et al., 1997a).

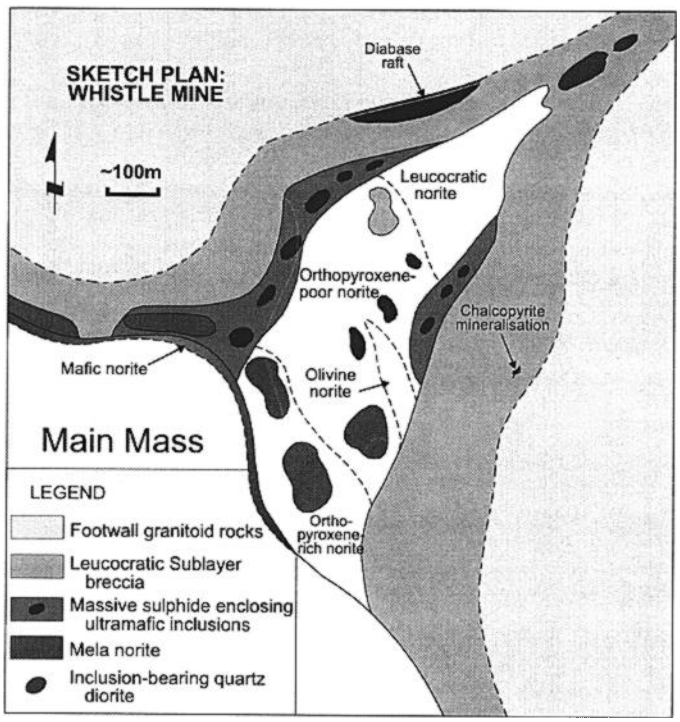

FIG. 4. Scheematic relationships between the main rock types of the Whistle embayment and the leucocratic norites and quartz diorites sampled in this study. Full details of the study of the sublayer in the Whistle embayment are presented in Lightfoot et al. (1997a). A complete geologic map and sample locations will be given in Lightfoot et al. (1997a). After Lightfoot et al. (1995c).

A discontinuous sulfide zone occurs between quartz diorite sheets and is dominated by chalcopyrite and pyrrhotite with 1 cm- to 2-m-sized inclusions of diabase, fine-grained amphibolite, and melanorite.

Northward within 3 km of the southern termination of the offset, the quartz diorite converges into one branch (Fig. 5) which thins from 15 m down to 1 m over a strike length of 150 m. Where the quartz diorite thins and pinches out, there is a reduction in the width of the zone of massive sulfide (Fig 5). North of this point, the quartz diorite pinches out in a quartz porphyry breccia and then reappears as a very leucocratic amphibole-rich quartz diorite 50 m to the north. The quartz diorite is continuous over about 20 m before it pinches out again in a breccia zone that continues along the trend of the offset to within 100 m of the abandoned Milnet mine (Fig. 1) where the pyroxene-rich quartz diorite reappears as a highly altered phase which is associated with large pods of sulfide. The offset changes direction 2.75 km along its length, at the Milnet mine, to 320°, before returning to a trend of 020°; this break in the trend of the offset occurs at the point where the offset crosses from Archean quartz porphyries and diabase into a carbonate-rich portion of the Huronian Supergroup; it is also the location at which mineralization is developed in the old Milnet mine. The offset then crops out for a further 10 km from the Sudbury Complex, to the north, as an altered leucocratic quartz diorite containing blebby sulfides.

The quartz diorite is a massive gray, fine- to medium-grained, equigranular to inequigranular rock comprising 45 to 55 percent mafics, 30 to 45 percent feldspar, 5 to 15 percent quartz, and trace emounts of granophyre and opaques. Where the offset narrows and terminates in the breccia, the quartz diorite becomes more felsic and quartz-rich with acicular hornblende.

Other offset dikes: Samples were selected and analyzed on a reconnaisance basis from the offset dikes of the Sudbury Complex shown in Figure 1. These included both concentric offsets like Manchester, Frood-Stobie, and Hess and radial offsets like Foy, Ministic, Worthington, Creighton (only exposed underground), and Copper Cliff. Detailed geologic setting, sample descriptions, and geochemistry are presented elsewere (Lightfoot et al., 1997a). Features of the geology of these offset dikes are given in Thompson (1935), Grant and Bite (1984), and Cochrane (1984).

Geochemical Variations among Components of the Sudbury Igneous Complex

Sampling, analysis, and data

Samples were selected, prepared, and analyzed according to the criteria presented in Lightfoot et al. (1997a). In-house standard reference materials were analyzed in the course of this study, and method, precision, accuracy, and determination limits are given in Lightfoot et al. (1997a). To illustrate the reproducibility for samples from a single inclusion-bearing outcrop, data for five samples from one outcrop of quartz diorite on the Parkin offset are shown in Figure 6A; the

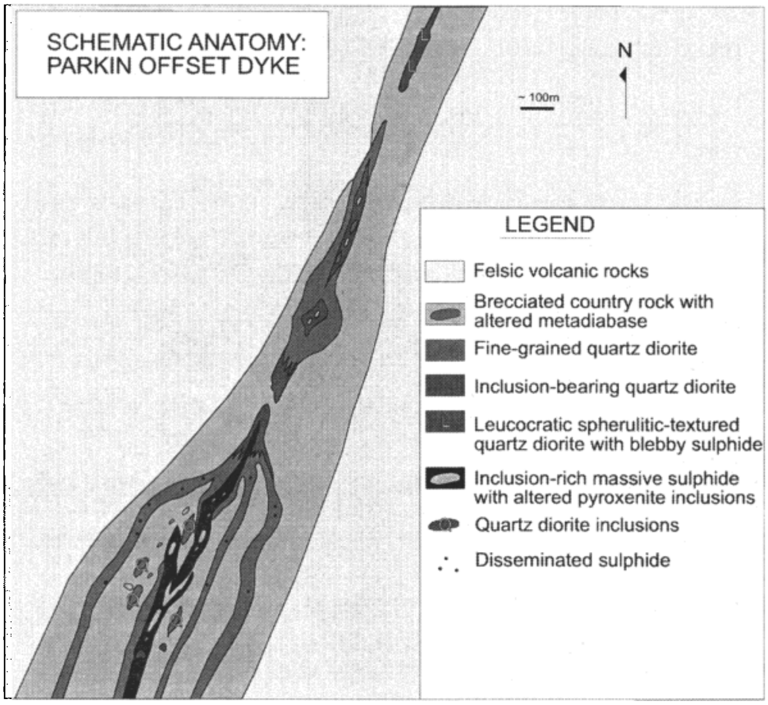

FIG. 5. Schematic cartoon showing the distribution of lithologies in the Parkin offset.

amount of variation between these five samples is comparable in magnitude to the amount of variation recorded by samples collected along the length of the offset (Fig. 6B). These data suggest that the sampling protocols were effective in minimizing the contribution of material from small fragments.

Main mass felsic norite, transition zone quartz gabbro, and granophyre

The average normalized compositions of felsic norite and granophyre of the main mass along the Whistle-Capreol transect (Fig. 1) are summarized in Figure 7 and Table 1A. Figure 7 confirms the established observation that the main mass norites and granophyres are enriched in large ion lithophile elements and light rare earth elements (REE) (e.g., Naldrett et al., 1986; Chai and Eckstrand, 1994), and moreover, demonstrates that these features are accompanied by marked negative Ta + Nb and Ti anomalies. These features and the silica-rich compositions and negative $\epsilon_{Nd_{CHUR}}$ values led Naldrett et al. (1986) and Chai and Eckstrand (1994) to propose that these rocks contain a very significant contribution from the Archean and Proterozoic continental crust. Further, Chai and Eckstrand (1994) concluded that the felsic norites and granophyre were derived from different magma sources; they suggested that the granophyre is a melt of the upper crust generated in situ by meteorite impact, whereas the norite is a mantle-derived magma that has been heavily contaminated by ca. 60 percent by lower crust.

Chai and Eckstrand (1994) calculated the average compositions for the main mass felsic norite and granophyre. They showed that these rock types have different absolute concentrations of incompatible trace elements with a marked compositional gap between them. Most of the transition zone quartz gabbro samples fall close to, or within, the field of the granophyres on many of the plots. Our new data for the northeastern portion of the main mass and unpublished data for a detailed section through the western limb of the Sudbury Complex (Lightfoot et al., 1997a) confirm the gross compositional difference between the granophyres and norites. However, we emphasize the important point, based on our data and that of Chai and Eckstrand (1994), that the ratios of the incompatible trace elements are the same in the granophyre as they are in the norite. It would be a very serendipitous feature if the felsic norite and granophyre had such diverse source regions as suggested by Chai and Eckstrand (1994). To illustrate this point we show the compositional average of the granophyres from the main mass normalized to the compositional average of North Range felsic norite (Table 1A and Fig. 8A). The normalized spidergrams for the average granophyre show overall higher abundances of incompatible elements when compared with the felsic norite. Moreover, negative anomalies are developed for Sr, P, Eu, and Ti. Since the abundance of Sr and Eu is controlled by plagioclase feldspar, the P abundance reflects the amount of apatite, and the Ti content reflects the amount of ilmenite and/or titanomagnetite, these four elements are not incompatible and their variations are not a function of the liquid composition. The abundances of the remaining incompatible elements in the granophyre unit is between 1.7 and 2.2 times the abundance in the average felsic norite (Fig. 8A).

The similarity in the relative abundance of incompatible elements in the granophyre and felsic norite is emphasized by the tight trend of the data for pairs of incompatible elements. For example, Figure 9 shows the variation in La versus Sm in the samples from the main mass of the Sudbury Com-

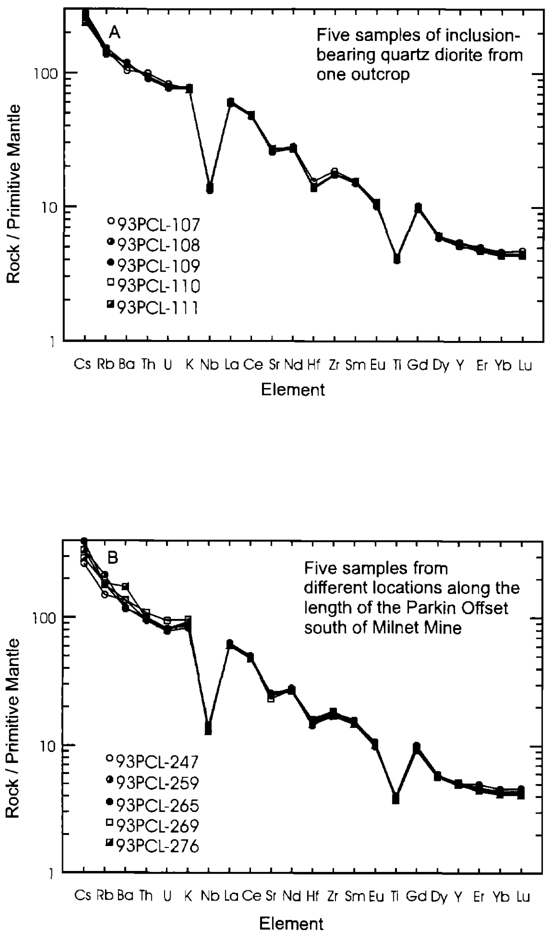

FIG. 6. A. Primitive mantle-normalized (Sun and McDonough, 1989) diagrams showing the similarity in composition of five different samples of quartz diorite taken from one inclusion-bearing (<2% inclusions) outcrop north of Malbeuf Lake on the Parkin offset. B. Primitive mantle-normalized (Sun and McDonough, 1989) diagrams showing the similarity in composition of five different samples of quartz diorite (<2% inclusions) taken from along a 2-km section of the offset south of the Milnet mine on the Parkin offset. These data can be reproduced for inclusion-poor samples from other sections of the Parkin offset. Similar small ranges in compositional variation are also characteristic of the inclusion-poor quartz diorites of other offsets.

plex from our study. The data define a tight linear array which intersects the origin and falls close to a 1:1 trend that might be produced, for example, by the fractionation of a liquid where La/Sm in the cumulate and liquid remained constant when the partition coefficients of La and Sm into crystallizing minerals were very similar. Data for the other incompatible elements are well correlated (Lightfoot et al., 1997a); all of the trends are very tightly correlated with r^2 values of >0.80. Despite the observation that the granophyres and norites fall on a single La versus Sm array, there remains a wide compositional gap between the fields of the two rock types that is also evident in the data of Chai and Eckstrand (1994).

The transition zone quartz gabbro samples from the Capreol-Whistle transect of the main mass are represented by two analyses in Figure 8A. The patterns of these samples resemble those of the average granophyre, with the exception that there is no positive Ti anomaly, and less pronounced negative P and Eu anomalies. On the La versus Sm plot (Fig. 9,) the transition zone quartz gabbros overlap with the compositional array of the granophyres. These variations are consistent with their derivation from a magma type very similar to that of the felsic norite and granophyre.

The most basal main mass lithology of the North Range is the poikilitic-textured mafic norite. This rock type was not found to be well developed at Whistle during this study, but subsequent mining activity in 1996 has revealed that the unit can reach 10 m in thickness; however, we believe that this unit is discontinuous around the northern rim of the Sudbury Complex. Poikilitic-textured mafic norite from an outcrop west of the Coleman mine and from underground at the Levack West mine have a normalized pattern that is flat and depleted in most elements relative to the felsic norite (Fig. 8B). These variations are consistent with the mafic norite having a similar parentage to the other main mass rocks. However, the lower felsic norite-normalized abundance of the incompatible elements, the absence of Sr, Eu, P, and Ti anomalies on the felsic norite-normalized plot, and the petrography is consistent with a genetic link between the mafic norite and the felsic norite. One possible reason for these features is that the mafic norite contains cumulus orthopyroxene which settled from the overlying magma column.

The important point to be emphasized from these data is the close similarity in the incompatible element ratios of the mafic norite, felsic norite, and granophyre units. If these similar ratios are to be features of magmas from mantle and crustal sources, then it should be possible to place constraints on the nature of the sources and their relative contributions as demanded by petrological modeling.

Offset quartz diorite

When normalized against primitive mantle, the average quartz diorite from the Parkin offset is seen to be markedly similar in composition to the average felsic norite of the main mass (Fig. 7). The patterns of average felsic norite and Parkin offset quartz diorite are not identical, and this is seen in Figure 8C in which the average quartz diorite from the Parkin offset and a sample of quartz diorite from the Whistle offset

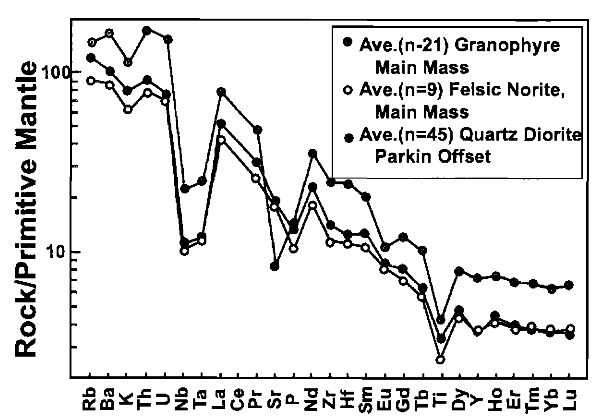

FIG. 7. Primitive mantle-normalized (Sun and McDonough, 1989) average main mass data for the felsic norite, granophyre, and offset dike quartz diorite.

TABLE 1. Average Compositions of Samples from the Main Mass Felsic Norite, Transition Zone Quartz Gabbro, and Granophyre of the Main Mass and of the Offset Dikes (based on Lightfoot et al., 1997a)

n	Avg. 37	Avg. 12	Avg. 28	Avg. 6	Avg. 7	Avg. 86	Avg. 13	Avg. 27	Avg. 22	Avg. 35	Avg. 43	Avg. 7	Avg. 18	Avg. 25	Avg. Calculated	Avg.
Location	WM	WM	CM	CMO	MO	WO	FO	CCO	CMO	MNO	PO	MM	MM	MM	SIC	Upper crust
Rock type	ITSM	LITSM	ITSM	QD	QD	QD	QD	QD	EMB	QD	QD	MN	FN	G		
wt %																
SiO_2	50.01	57.38	51.79	55.07	58.93	55.53	59.31	56.42	56.09	59.57	58.70	55.78	56.47	67.57	62.50	65.9
TiO_2	0.83	0.82	0.75	0.93	0.74	0.93	0.72	0.89	0.71	0.70	0.73	0.56	0.62	0.89	0.78	0.5
Al_2O_3	13.37	14.60	15.08	14.90	14.60	14.41	14.92	15.03	15.32	14.27	14.86	11.71	16.30	12.79	13.83	15.2
Fe_2O_3	13.49	8.66	11.17	10.12	8.20	10.71	7.53	9.69	8.83	7.56	7.97	9.93	7.91	6.47	7.47	5
MgO	7.73	4.45	6.53	4.42	4.00	4.40	3.75	4.22	5.03	3.89	3.71	10.61	4.95	1.23	3.23	2.2
MnO	0.18	0.13	0.15	0.13	0.12	0.13	0.12	0.14	0.13	0.07	0.11	0.16	0.13	0.09	0.11	0.08
CaO	8.49	5.38	7.12	6.84	4.79	5.98	5.18	6.40	6.79	4.08	4.73	4.54	6.38	1.80	3.67	4.2
Na_2O	2.41	3.21	2.63	2.89	3.13	2.64	3.06	2.61	2.79	3.60	2.88	2.03	2.85	3.62	3.21	3.9
K_2O	1.00	2.07	1.38	1.56	2.27	1.79	2.33	1.87	1.61	2.07	2.49	1.41	1.81	3.46	2.73	3.4
P_2O_5	0.19	0.24	0.16	0.16	0.16	0.13	0.18	0.16	0.11	0.14	0.19	0.11	0.16	0.22	0.20	0.16
L.O.I.	1.35	1.92	1.64	0.60	1.90	1.36	1.58	1.18	1.05	2.89	2.31	1.55	1.70	1.71	1.74	n.a.
Total	99.04	98.84	98.39	97.62	98.85	98.02	98.68	98.62	98.47	98.84	98.68	98.38	99.26	99.85	99.47	100.5
CO_2	0.18	0.43	0.17	0.11	0.28	0.33	0.39	0.29	0.11	1.03	0.32	0.20	0.32	0.19	0.24	n.a.
FeO	8.18	5.44	7.50	7.37	5.31	7.19	4.87	6.83	6.23	4.75	4.51	7.39	5.40	3.40	4.44	n.a.
H_2O^+	0.25	0.24	0.24	0.26	0.23	0.28	0.18	0.18	0.20	0.25	0.31	0.27	0.25	0.33	0.30	n.a.
H_2O^-	1.43	1.96	1.98	1.24	1.85	1.83	1.54	1.56	1.41	2.23	2.30	1.94	2.06	1.60	1.80	n.a.
S	0.98	0.28	0.89	0.41	0.19	0.72	0.13	0.22	0.12	0.07	0.23	0.29	0.12	0.04	0.13	0.002
ppb																
Se	1,224	237	n.a.	n.a.	470	77	167	590	n.a.	161	358	419	230	310	338	50
ppm																
Co	85	32	82	43	32	58	28	40	35	25	33	60	33	12	25	10
Cu	623	1,166	1,404	2,974	297	1,324	106	347	222	86	584	358	155	31	161	25
Ni	803	169	1,595	1,381	203	1,168	119	305	217	87	331	341	126	5	120	20
Zn	121	110	107	103	107	95	112	116	97	37	88	103	99	63	79	71
Cr	407	182	471	177	169	187	161	170	251	164	162	1,690	213	6	190	35
Sc	30	18	21	21	17	19	16	22	19	17	16	21	19	13	16	11
V	224	144	168	172	132	173	137	178	149	133	128	157	126	70	101	60
La	18.13	35.22	24.91	40.23	36.64	32.44	36.37	32.56	29.58	32.19	38.16	27.12	30.60	56.28	44.78	30.00
Ce	40.35	74.16	50.81	83.02	73.48	66.52	73.41	65.85	60.27	64.87	76.33	55.08	60.60	111.53	89.05	64.00
Pr	5.37	9.09	6.35	10.53	8.84	8.12	8.85	7.94	7.13	7.74	0.07	6.14	7.29	13.57	10.77	7.10
Nd	21.72	34.06	24.30	40.47	31.92	30.74	31.94	29.36	26.77	27.75	32.55	22.89	26.00	49.51	39.23	26.00
Sm	4.64	6.36	4.64	8.22	5.87	5.96	5.82	5.86	5.00	5.20	5.93	4.13	4.90	9.03	7.22	4.50
Eu	1.35	1.63	1.27	1.67	1.49	1.45	1.50	1.49	1.31	1.34	1.49	1.08	1.40	1.82	1.62	0.88
Gd	4.18	5.25	4.21	7.79	4.95	5.67	4.90	5.53	4.88	4.57	4.95	1.85	4.49	7.60	6.08	3.80
Tb	0.61	0.73	0.62	1.22	0.72	0.86	0.70	0.86	0.73	0.69	0.70	2.11	0.63	1.13	1.00	0.64
Dy	3.40	3.71	3.62	7.45	3.85	4.98	3.69	4.97	4.11	3.75	3.68	2.80	3.41	5.98	4.81	3.50
Ho	0.68	0.73	0.71	1.50	0.79	1.01	0.75	1.06	0.84	0.77	0.75	0.59	0.70	1.24	0.99	0.80
Er	1.83	1.96	2.07	4.40	2.06	2.88	1.97	2.87	2.45	2.05	1.93	1.62	1.88	3.38	2.69	2.30
Tm	0.27	0.28	0.30	0.65	0.31	0.41	0.29	0.45	0.36	0.31	0.29	0.25	0.29	0.50	0.40	0.33
Yb	1.70	1.75	1.99	4.24	1.97	2.75	1.88	2.87	2.48	1.94	1.80	1.61	1.82	3.15	2.53	2.20
Lu	0.26	0.27	0.31	0.64	0.31	0.41	0.30	0.44	0.37	0.29	0.27	0.25	0.28	0.50	0.40	0.32
Ba	484	794	448	523	779	515	719	500	500	452	755	492	622	1,155	915	550
Th	1.95	6.33	4.94	9.67	8.91	8.65	8.64	8.38	7.39	8.21	8.70	6.19	6.90	14.90	11.24	10.70
U	0.38	1.18	1.06	2.14	1.85	2.06	1.68	1.96	1.58	2.09	1.68	1.24	1.50	3.26	2.43	2.80
Rb	25.5	58.0	58.9	72.9	83.8	70.3	79.6	91.8	61.0	74.8	83.3	50.7	60.0	92.8	78.4	112.0
Sr	446	490	371	321	384	316	441	290	360	213	439	305	420	181	284	350
Cs	0.74	0.96	3.54	2.81	1.04	5.69	1.23	6.41	2.78	1.50	1.85	1.39	1.11	0.40	0.79	3.70
Be	0.74	1.21	6.00	n.a.	1.33	1.39	1.28	1.57	3.84	1.44	1.32	1.02	1.16	2.08	1.65	3
Hf	2.00	3.37	1.47	2.38	3.84	4.11	4.40	3.84	2.66	3.33	3.95	2.80	3.57	7.41	5.61	5.80
Zr	88	152	104	195	158	167	166	162	130	152	173	113	134	271	210	190
Y	16.1	17.5	17.4	33.9	19.3	23.2	18.0	25.8	20.3	18.8	18.7	15.2	16.5	32.5	25.4	22.0
Nb	3.65	7.76	7.57	16.82	8.83	10.59	8.62	10.27	9.05	8.49	8.69	6.44	7.50	15.65	11.88	25.00
Ta	0.20	0.43	0.46	0.89	0.53	0.69	0.51	0.71	0.67	0.56	0.52	0.39	0.49	0.99	0.75	2.20

Average upper crust from Taylor and McLennan (1995); average Sudbury Complex based on 4% ITSM, 6% MN, 25% FN, 55% G, and 10% Parkin offset QD

Abbreviations: location: WM = Whistle mine, CM = Creighton mine, CMO = Creighton mine offset, MO = Ministic offset, WO = Worthington offset, FO = Foy offset, CCO = Copper Cliff offset, CMO = Clarabelle mine section, Copper Cliff offset, MNO = Manchester offset, PO = Parkin offset, MM = main mass; rock type: ITSM = igneous-textured silicate matrix, LITSM = leucocratic igneous-textured sublayer matrix, QD = quartz diorite, EMB = samples from embayment and funnel of offset, MN = mafic norite, FN = felsic norite, G = granophyre; *n* = number of analyses, Avg = average, wt % = weight percent (not recalculated free of L.O.I.), n.a. = not analyzed

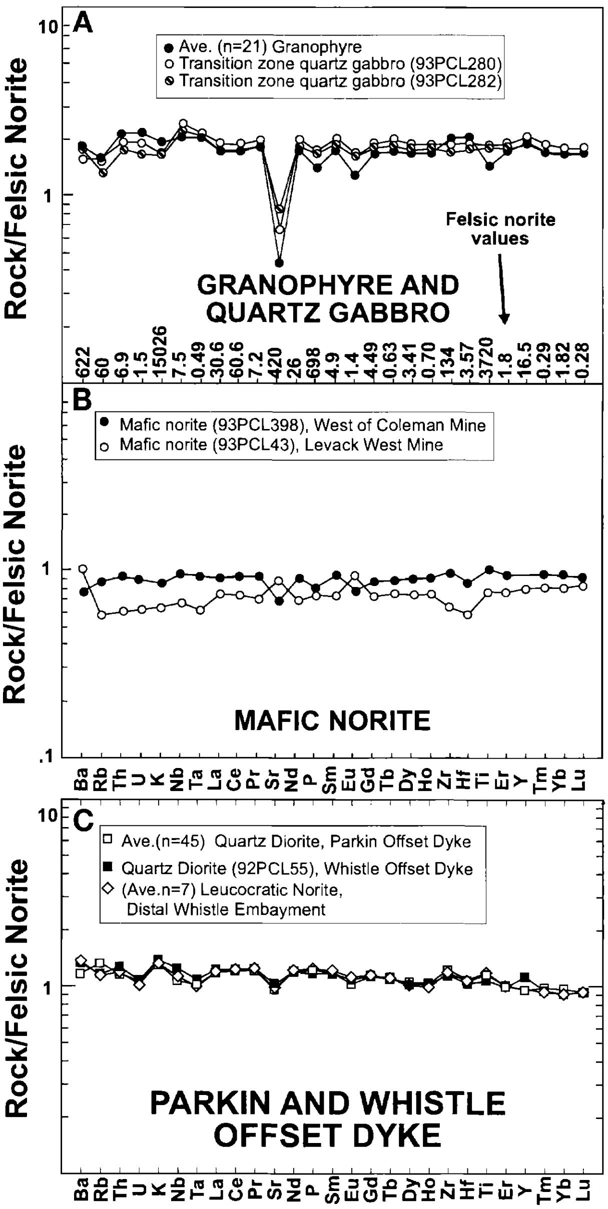

FIG. 8. Normalized abundance patterns for selected incompatible elements in rocks normalized to the average composition of felsic norite from the northeastern part of the Sudbury Complex. A. The average compositions of main mass granophyre and two samples of transition zone quartz gabbro from the northeastern corner of the Sudbury Complex. B. Representative samples of mafic norite. C. Average quartz diorite from the Parkin offset, average leucocratic norite from the distal (from the Sudbury Complex) part of the Whistle embayment, and one sample of quartz diorite from the Whistle offset. The normalization factors used for felsic norite are shown on the abscissa.

are normalized against average felsic norite. Figure 8 shows the field of the leucocratic norites (Fig. 4) from the Whistle embayment; these rocks overlap with the pattern of the quartz diorite of the Parkin offset. The very strong similarities in incompatible trace element contents provide evidence that these rock types were derived from the same magma source. In detail, however, the slightly different slope of the plot on the spidergram (Fig. 8C) requires a small contribution to the quartz diorite from a large ion lithophile element and light REE-enriched reservoir such as the Archean country rocks.

Summarizing, the data (this study and Chai and Eckstrand, 1994) are consistent with derivation of the main mass rocks and the offsets from a single magma type. The small shift to elevated large ion lithophile element and light REE in the Parkin offset quartz diorites may be a function of local contamination by footwall rocks rather than derivation from a different source, and the broad differences between North and South Range offsets documented later in this study are further evidence for a local country-rock effect on composition of the quartz diorite.

Discussion of Geologic and Petrologic Relationships

The geologic and geochemical relationships between the different rock types of the Sudbury Complex demand an explanation in the context of geologic models. Presently, there are three main theories that account for some of the features of the main mass of the Sudbury Complex:(1) substantial contamination of a mantle-derived magma by upper crust (Kuo and Crocket, 1979; Naldrett et al., 1986; Walker et al., 1991, 1994; Dickin et al., 1992); (2) derivation of the main mass of the complex by in situ melting of upper crustal country rocks as a direct response to a high pressure and temperature melting event (frequently considered to be synonymous with meteorite impact conditions (Faggart et al., 1985; Grieve, 1994; Dickin et al., 1996); and (3) a combination of these models (Chai and Eckstrand, 1994). The new data presented in this study provide important additional evidence that constrain not only the origin of the main mass but also the economically important sublayer and offset rocks. We develop a model around these and other published relationships by first reviewing the evidence for the origin of the main mass, then evaluating how the offsets relate to this model. We show that North and South Range offsets have compositional differences; these differences demand explanation in the context of a model for the genesis of the complex. Finally, we show that compositional variations in the strongly mineralized Creighton offset quartz diorites contrast with the less heavily mineralized quartz diorites, and suggest implications for mineral exploration.

Source of the magma

Chai and Eckstrand (1994) argued that the parental felsic norite magma was derived by contamination of a mantle-derived parental magma by up to 60 percent Archean granulite facies lower crust, whereas the granophyre represents a crustal melt produced from upper crust (75% Archean rocks and 25% Huronian granite). Our new data for the main mass show that the granophyre typically has double the abundance of incompatible elements when compared to the felsic norite (Fig. 8A), and that the ratios of incompatible elements are the same in the felsic norite and granophyre (Fig. 9). If the felsic norite is a linear combination of picritic mantle-derived magma (e.g., the picritic asthensopheric-derived lavas from Qeqertarssuaq in West Greenland; Lightfoot et al., 1997a) and lower crust (e.g., Taylor and McLennan, 1995), then the upper crust-normalized pattern of the mixture should fall between the average primitive melts and average lower crust. This mixture would have a spidergram pattern with low abun-

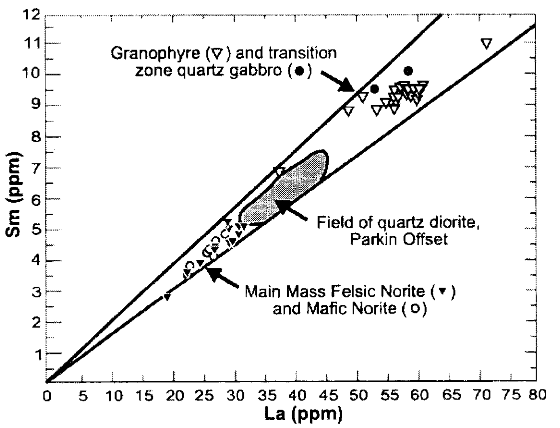

FIG. 9. Variation in Sm versus La in Parkin offset quartz diorites, main mass felsic norite, mafic norite, transition zone quartz gabbro, and granophyres.

dances of the light REE and large ion lithophile elements and elevated abundances of the high field strength elements and heavy REE as bracketed by the composition of the lower crust and primitive magma compositions shown in Figure 10A. The pattern of the felsic norite is subparallel to the average upper crust (Fig. 10B), and so simple mixing models involving mantle-derived magmas and lower crustal melts are not applicable to the formation of the main mass felsic norite.

The similar ratios of the incompatible trace elements in the felsic norite and the granophyre indicate that these magmas crystallized from a very similar parental magma type, albeit the absolute abundances were quite different. At issue is whether we can say anything about the composition of the crust from which these magmas were generated, and place lower and upper limits on the amount of mantle-derived magma that may have contributed to the Sudbury Complex.

A comparison of the felsic norite and granophyre with the average upper crust of Taylor and McLennan (1995) demonstrates that the felsic norite and granophyre are depleted in Rb, Nb, and Ta relative to average crust, whereas the felsic norite has comparable abundance levels of most other incompatible elements, and the granophyre has one and a half to two times the abundance of most incompatible elements in average crust (Fig. 10B). Whereas the average upper crust here has the correct inventory of all the incompatible elements except Nb and Ta to produce the felsic norite, the granophyre is strongly enriched in the incompatible elements relative to the felsic norite. The average composition of the Sudbury Complex, barring the presence of a hidden ultramafic series (Gupta et al., 1984) should lie between the felsic norite and the mafic norite, and this composition would be incompatible element-enriched relative to average upper crust.

No comprehensive systematic study of the geochemistry of the country rocks surrounding the Sudbury Complex has been made, although Chai and Eckstrand (1994) and Lightfoot et al. (1997a) present some data for footwall lithologies. The most incompatible element-enriched footwall rocks belong to the Huronian-aged Murray pluton (Chai and Eckstrand, 1994), but these granitoid rocks have very high REE abundance levels, but much lower Ce/Yb than average upper crust. Models combining average upper crust with Huronian granite fail to generate a crustal end-member with similar or higher La/Nb, Ce/Yb, or La/Sm compared to those of rocks of the Sudbury Complex. Chai and Eckstrand (1994) use an average Archean component incorporating Archean granite, migmatite, and Levack gneiss in the ratio 2:1:1 together with Huronian granite, and achieve a fit for La/Yb and Eu/Eu* for the granophyre with 25 percent Huronian granite. In detail, they do not present data for the other incompatible elements like Nb and Ta or utilize trace element ratios as a test of this model. Our best estimates of average upper crust (Taylor and McLennan, 1995) indicate that it would have a lower La/Nb (1.5) than the Huronian granite (3.5), whereas La/Nb ratios for the main mass (3.5–4.5) are similar to or higher than those of the Huronian granite. Furthermore, Chai and Eckstrand's composite Archean crust has Ce/Yb = ~30 and Huronian granite with Ce/Yb = 19, whereas all of the main mass rocks have Ce/Yb = 30 to 40. This suggests that the crustal end member used by Chai and Eckstrand (1994) may only fit for some elements and element ratios, and that in detail, a crustal end member with a much higher Th/Nb and Ce/Yb than those of their average crust is required; there are no crustal analyses showing these features from the Sudbury region and this compromises serious efforts at modeling.

At a general level, one promising approach is to investigate how much primitive picritic magma can be incorporated into an average crustal melt without producing a significant change in the ratios of incompatible trace elements. The choice of end members is important, and in the absence of a good database for the country rocks of the Sudbury region, reasonable models might start with representative uncontaminated mantle-derived primitive picritic melts and average upper crust. In detail, conclusions different from ours are reached if averages of local outcropping samples are used to derive an estimate of the average crustal composition (Chai and Eckstrand, 1994). We have chosen to base our models on crustal averages rather than attempt to determine the average composition of the footwall rocks around and beneath the complex. Figure 10C shows one such model which strives to show how much change in the slope of the primitive mantle-normalized trace element abundance patterns might be produced at various intervals of mixing between average upper crust and picrite. Since the proportion of crust to mantle exceeds 0.6, the patterns of the average upper crust and the pattern of the mix start to converge closely, and at a ratio of >0.8, the patterns are almost analytically indistinguishable. This is best illustrated by plotting the proportion of mantle/crust in the mixture against a ratio that reflects the behavior of large ion lithophile elements versus heavy field strength elements (e.g., Th/Y in Fig. 10D). The actual error on the determined Th/Y ratio corresponds to approximately the size of the data points, and therefore this ratio is particularly sensitive to whether there is any difference in the proportion of crustal and mantle end members in the granophyre versus the felsic norite. The average felsic norite has a Th/Y of 22 and the granophyre has an overlapping range of Th/Y averaging 24. In our simple model, if these magmas were produced by mixing average crust with a picritic melt, then a ratio of crust/mantle of 0.8 for the average felsic norite and 0.9 for

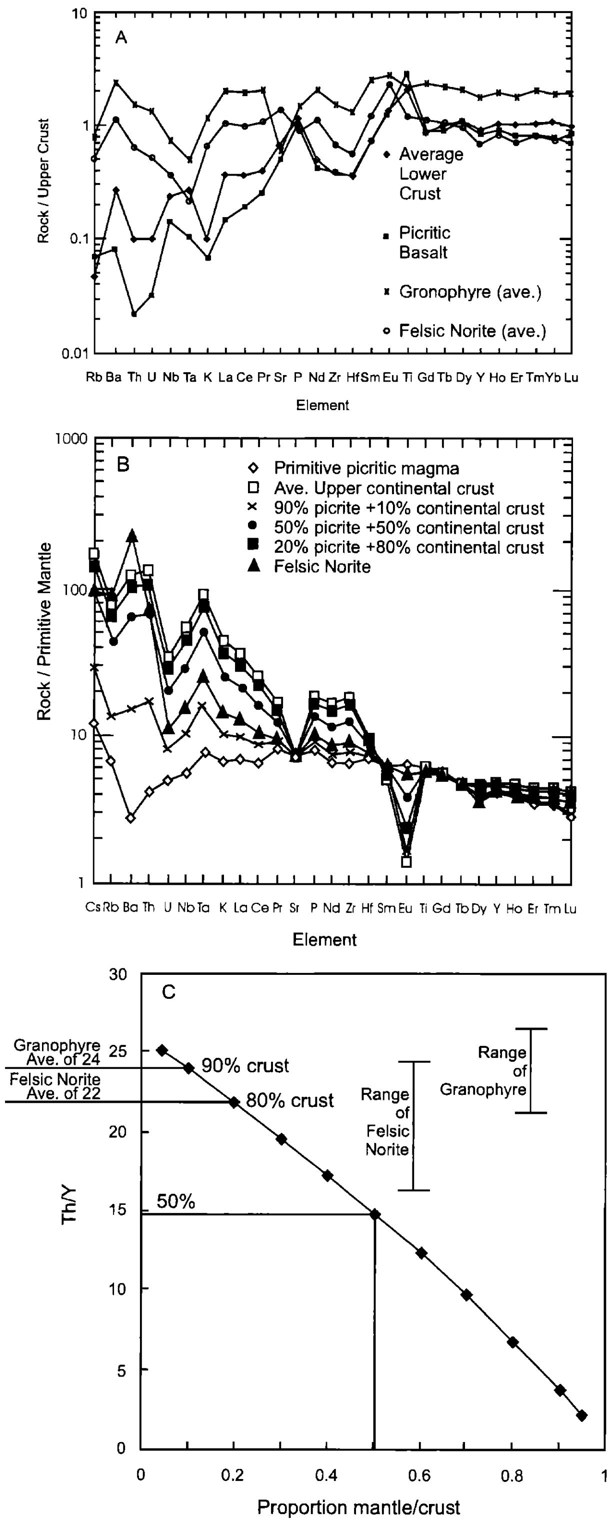

FIG. 10. A. Normalized plots of lower crustal average (Taylor and McLennan, 1995) and a representative primitive mantle-derived asthenospheric magma from Qeqertarssuaq, West Greenland (Lightfoot and Hawkesworth, 1997; Lightfoot et al., 1997b). B. Rock-upper crust showing the patterns of average felsic norite and granophyre. Upper crustal average from Taylor and McLennan (1995). Also shown are the primitive mantle-normalized spidergram of successive mixtures of average upper crust with primitive mantle-derived picritic magma. The composition of felsic norite overlaps with 80:20 to 100:0 mixtures of crust with primitive magma. C. Plot of proportion of mantle/crust versus Th/Y based on the models shown in B. The felsic norite and granophyre have similar Th/Y ratios, and they plot very close to the Th/Y ratio of the crustal end member, indicating that no more than a 10 percent difference in the amount of picritic magma is required by the main mass data. Furthermore, assuming an average crustal end member, these data do not require significantly more than 20 percent picritic melt to produce the compositions of the main mass rocks.

the average granophyre is required. As we do not know the actual composition of the crustal end member, the fact that the mixtures appear to correpond to approximately 80 and 90 percent of the crust, respectively, should be treated with caution. Furthermore, the estimate is sensitive to the degree of incompatibility of the elements; 10 percent may be a minimum estimate. However, this graph does show that the felsic norite and granophyre, for geologically reasonable end-member mixing models, are not produced by the combination of radically different amounts of mantle- and upper crustal-derived material. Moreover, since average lower crustal melts will have low incompatible element concentrations, approaching that of the primitive mantle-derived magmas (Fig. 10A), there is no demand for a chemically different contribution from the lower crust. This in turn suggests that any fundamental absolute compositional difference between the felsic norite and the granophyre is more likely to be found in an examination of in situ differentiation of one magma rather than very large differences in the relative proportions of upper crustal-, lower crustal-, and mantle-derived magma. Furthermore, these data suggest that the compositional gap between the felsic norite and the granophyre is unlikely to result entirely from different proportions of mantle and crustal magma, even though it may be reasonable to acommodate as much as 20 percent picritic magma into a melt with the composition of average upper crust without observing a significant difference in the ratios of highly incompatible trace elements. Clearly, these results are model dependent, and choosing a crustal end member with much higher Th/Y than the main mass would mean that larger contributions of mantle-derived magma are possible, but we have presently no constraints on geologically reasonable crustal end members and very incomplete existing data for the country rocks around the Sudbury structure.

Magma evolution: Assuming that the felsic norite and granophyre come from a similar source and that the relative contributions of mantle to crust in both are no different than 10 percent from one another, then an explanation for the compositional gap between the felsic norite and granophyre is not readily explained by the different proportions of crustal- and mantle-derived magma. This gap could be the result of in situ differentiation, and previous studies have concluded that this model is reasonable (Naldrett et al., 1970; Hewins, 1971); more recently Chai and Eckstrand (1994) question whether this relationship is possible on chemical and physical grounds. Alternatively, the gap could be produced if the Sudbury Complex was not a melt sheet, but was formed by the emplacement of two batches of magma derived from a common source, yet showing very different degrees of differentiation. This model lacks credibility in the context of the physical requirement that a large meteorite impact event would need to generate a significant amount of melt material, and that the actual volume of melt should be commensurate with the size of the impact crater (Golightly, 1994; Grieve, 1994). On these grounds, we prefer to reexamine the evidence pointing to another process: in situ differentiation processes within a melt sheet that may be supplemented with volumetrically small influxes of mantle-derived picritic magma.

The granophyre is enriched in incompatible elements by a factor of one and a half to two times their content in the felsic norite. The granophyre tends to be low in Sr, Eu, Ti, and P relative to the felsic norite and has high SiO_2, low MgO, and low CaO and Al_2O_3 contents (Chai and Eckstrand, 1994). The average granophyre has 67.5 wt percent SiO_2 and 1.8 wt percent CaO; this is similar in silica to the upper crust (66 wt %) but shows a lower CaO content (4.2 wt %; Taylor and McLennan, 1995; and Table 1). The abundance of incompatible elements in the granophyre is roughly twice that of upper crust. Removal of plagioclase from a crustal melt would tend to deplete the residual magma in CaO, Sr, and Eu and produce a slight increase in SiO_2, which are all observed features. Depletion of P may reflect removal of apatite, and since P_2O_5 increases with Ce through the felsic norite and only drops in the transition zone quartz gabbro (Chai and Eckstrand, 1994, and unpub. data), this indicates that apatite entry was late. Removal of titaniferous magnetite or ilmenite may have coincided with apatite fractionation, and it may be no coincidence that portions of the transition zone quartz gabbro (especially the upper part) are P_2O_5 and TiO_2 enriched relative to the granophyre. Finally, the base of the felsic norite is an orthopyroxene cumulate, and there is therefore good evidence for early orthopyroxene fractionation. This was from a parental magma which was sufficiently rich in MgO and SiO_2 to permit orthopyroxene to remain a liquidus phase for a considerable interval in the fractionation history of the magma. The incompatible elements fall on tight arrays of increasing Yb, Th, and Nb with Ce, and these and other trends can be fitted with Rayleigh fractionation arrays assuming removal of 25 percent orthopyroxene, 70 percent plagioclase feldspar, 4.5 percent K feldspar, 0.1 percent titanomagnetite, and 0.1 percent apatite (Lightfoot et al., 1997a). Back projection of the trend of Eu/Eu^* versus Ce indicates that the crystal phase extract at 0 ppm Ce would have Sr = 750ppm and $Eu/Eu^* = 1.4$, which is consistent with a positive Eu anomally and elevated Sr found in a plagioclase cumulate (Lightfoot et al., 1997a). Finally, our new Cu and Ni determinations for the granophyre indicate low abundance levels of these analytes in these rocks; the values are credible since the determinations were made by ICP-OES and the abundance levels are an order of magnitude higher than the determination limits. The main point is that the Cu abundances are 6 to 20 ppm and Ni varies from 5 to 20 ppm. These figures are equivalent or lower than typical Cu and Ni abundances in average upper crust (25 ppm Cu and 20 ppm Ni; Taylor and McLennan, 1995). This implies that if the Ni and Cu in the ores were concentrated from the main mass magmas, then the original melt had a much higher Ni and Cu concentration than a melt of average upper crustal composition.

Our analytical data also indicate that previous estimates of the densities of the different components of the Sudbury Complex may be in error. For example, calculated densities for the rocks of the main mass indicate that early estimates of 2.6 to 2.7 g/cm^3 for the felsic norite and 2.7 to 2.85 for the granophyre (Chai and Eckstrand, 1994) may be high. Our estimates are closer to 2.35 to 2.45 and 2.5 to 2.8 g/cm^3, respectively, which would permit plagioclase to sink toward the base of the felsic norite. Although there is good evidence that differentiation of the Sudbury Complex main mass has occurred, this process cannot easily account for the compositional gap between the felsic norite and the granophyre. Our present investigations aim to resolve this issue with new comprehensive data for samples collected across this interface from drill core.

Relationships between the quartz diorite and the main mass

The quartz diorites of the Whistle and Parkin offsets and the leucocratic norites from the Whistle embayment all plot on the array of the main mass norites and fill a part of the compositional gap between the norites and the granophyres (Fig. 9 and Table 1B). In detail, the patterns of the average leucocratic norite from the Whistle embayment and the quartz diorite from the Parkin offset are very similar and show a very slight overall enrichment of large ion lithophile elements and light REE relative to high field strength elements and heavy REE (Fig. 8C). The gentle slope of the pattern may be the product of adding a very small fraction of large ion lithophile element- and light REE-enriched and high field strength element- and heavy REE-depleted Archean granitoid to a main mass magma. In detail, there is a small negative Sr anomally (Fig. 9C), but no pronounced Eu, P, or Ti anomalies in the quartz diorite, and this suggests that the magma did not lose feldspar, ilmenite, magnetite, or apatite by fractionation, as we suggest for the granophyre. The quartz diorite has slightly higher SiO_2 and lower MgO than the felsic norite (e.g., Parkin offset quartz diorite avg $\pm 2\sigma$: 58.7 wt % SiO_2, 3.7 wt % MgO; felsic norite avg $\pm 2\sigma$: 56.5 ± 1 wt % SiO_2, 4.9 ± 0.5wt % MgO). These data are consistent with a higher modal orthopyroxene content in the felsic norite and more quartz and K feldspar in the quartz diorite, but there is no major element argument against a linkage of these magmas by differentiation. Since we do not see a large amount of compositional variation in the quartz diorite, we suggest that it is not displaced very far from the original composition of the parental magma type responsible for the offsets. The similarity in composition to the main mass suggests that the offset magma was generated by the same processes as the one that generated the main mass magma. It is possible that this magma either was generated as part of the main irruptive and injected outward into the country rocks or was generated in the offset environments by extreme melting of country rocks. Because the offsets have such a similar composition, despite the very different country rocks, we would argue that the offset magma was generated from a well-mixed reservoir, and only locally influenced by country-rock composition. This would suggest that the magma was generated as part of the main irruptive, and because of the well-mixed composition, this site was more likely to have been within the main irruptive rather than in the structures surrounding it.

The quartz diorites are interesting from the perspective that they partially fill the compositional gap between the felsic norite and the granophyre. If the array of the main mass rocks can be considered a product of in situ differentiation, then the presence of the relatively tight field of quartz diorites on this trend may be telling us that the compositionally intermediate quartz diorites are produced by expulsion of magmas intermediate in composition between felsic norite and granophyre. However, this appears unlikely since the quartz diorite offset dikes were formed by the early emplacement of magma before the main mass had undergone significant amounts of differentiation. Evidence for this is the rare occurrence of felsic norite fragments within the quartz diorite. Although a few inclusions of felsic norite are found in quartz diorite along the Worthington offset (Lightfoot et al., 1997a), these are rare, and we believe that the quartz diorite magma was injected largely before any significant crystallization of the main mass, and possibly also before the sublayer was formed (Lightfoot et al., 1997a). If this suggestion is correct, then the offset quartz diorite composition may turn out to be a good estimate of the parental liquid composition; this should greatly simplify differentiation models. If the offsets were emplaced late after the crystallization of the felsic norite, then a particularly complex dynamic model must be constructed to explain these relationships.

Summary of petrogenic relationships between the rocks of the main mass and the offsets

The main mass granophyre, transition zone quartz gabbro, and felsic norite have similar relative abundances of incompatible elements (Fig. 8A) which demands that they crystallized from a compositionally similar parental magma. These similarities in the ratios of incompatible trace elements place constraints on the relative contributions of mantle, lower crustal, and upper crustal material.

Our new data for the main mass and offset samples confirm a close genetic link between the main mass rocks and the offset quartz diorites and suggest that the formation of the quartz diorite parental magmas resulted from the expulsion of a main mass magma type into the offset dikes. The offset quartz diorites may therefore hold the best possible estimate of the parental liquid composition, albeit one that may have locally been affected by assimilation of crust.

Compositional variations between quartz diorites of the offsets

As part of a reconnaisance study, samples were acquired from eight different offset environments (located in Fig. 1A; South Range concentric offsets: Manchester, Vermilion, and Kirkwood; South Range radial offsets: Copper Cliff and Worthington; North Range radial offsets: Foy, Parkin, and Ministic). The compositional differences between the offset samples is less pronounced compared to the sublayer as demonstrated by the representative samples shown in Figure 11A–D. In detail, there are important differences between the offsets which are best illustrated on elemental and element ratio plots. Figure 11A–D shows data fields of the different offsets. The TiO_2 versus SiO_2 variations (Lightfoot et al., 1997a) demonstrate that most South Range offset samples are displaced to high TiO_2 compared to most North Range offsets. The exception to this observation is the Manchester offset which plots with the fields of North Range offsets. All of the South Range offsets overlap with the main mass norites in SiO_2, but have elevated TiO_2, whereas all of the North Range offsets have slightly elevated TiO_2 and higher SiO_2 compared to the main mass felsic norites. Differences between North and South Range offsets are also evident in Sr, La/Yb, Gd/Yb, and La/Sm (Fig. 11A–D); however, the Manchester offset falls with the North Range offsets in terms of SiO_2, TiO_2, Gd/Yb, and La/Sm, but is displaced toward the compositional fields of South Range offsets in terms of La/Yb, and has low Sr, Yb, and Ce abundances which are features of the South Range offsets.

A final observation of some importance is that the offset quartz diorite dike at the Creighton mine is compositionally quite different from dikes of all of the other offsets (Fig. 12A), and its composition more closely resembles that of the local igenous-textured silicate matrix at the Creighton mine (Fig. 12B). The quartz diorite dike at Creighton is relatively unmineralized, but is proximal to large amounts of inclusion-rich sulfide mineralization (Lightfoot et al., 1997a), which contrasts with many of the other offset samples that were studied. Pekeski et al. (1995) recognized two different phases of quartz diorite along the Worthington offset based on contact relationships between marginal inclusion-poor and sulfide-poor quartz diorite and a core of inclusion-rich sulfide-rich quartz diorite, and on 1- to 50-cm-sized inclusions of the marginal inclusion- and sulfide-poor phase within the inclusion- and sulfide-rich core of the offset. We await the outcome of a detailed geochemical study to determine whether there are marked geochemical differences between mineralized and unmineralized quartz diorite, but based on the data from the Creighton offset, we suspect that this approach may yield a new understanding of the mineralization of the offsets.

A Genetic Model for the Sudbury Complex

In proposing a genetic model for the Sudbury Complex, a number of parameters need to be taken into account. The first of these is that the complex is not a normal "layered intrusion." It has long been recognized that there is far too much granophyre, which comprizes almost one-half to two-thirds of the volume of the observed complex. Indeed, if the Onaping Formation breccias overlying the granophyre were derived from the same magma as the granophyre, noritic rocks may have comprized much less than one-third of the total observed volume of the complex. If formed from a single mantle-derived magma, this magma would have had a composition approximating that of an andesitic magma and not a tholeiite, as suggested by Dickin et al. (1996). This point is shown by a simple comparison of the estimated bulk composition of the complex compared to the average andesitic upper crust of Taylor and McLennan (1995). Indeed, our data and other studies of the Sudbury Complex indicate that all of the igneous rocks of the main mass and sublayer have bulk major and trace element compositions that are similar to those of broadly andesitic upper crustal rocks. This evidence is provided by their high SiO_2, K_2O, elevated light REE/heavy REE and large ion lithophile element/heavy field strength element ratios, and their isotopic signatures, particularly their strongly negative $\epsilon_{Nd_{(CHUR)}}$ (−6 to −8; Naldrett et al., 1986), elevated $^{87}Sr/^{86}Sr$ (0.706–0.707; Fairburn et al., 1968; Gibbins and McNutt, 1972; Hurst and Wetherill, 1974; Naldrett et al.,

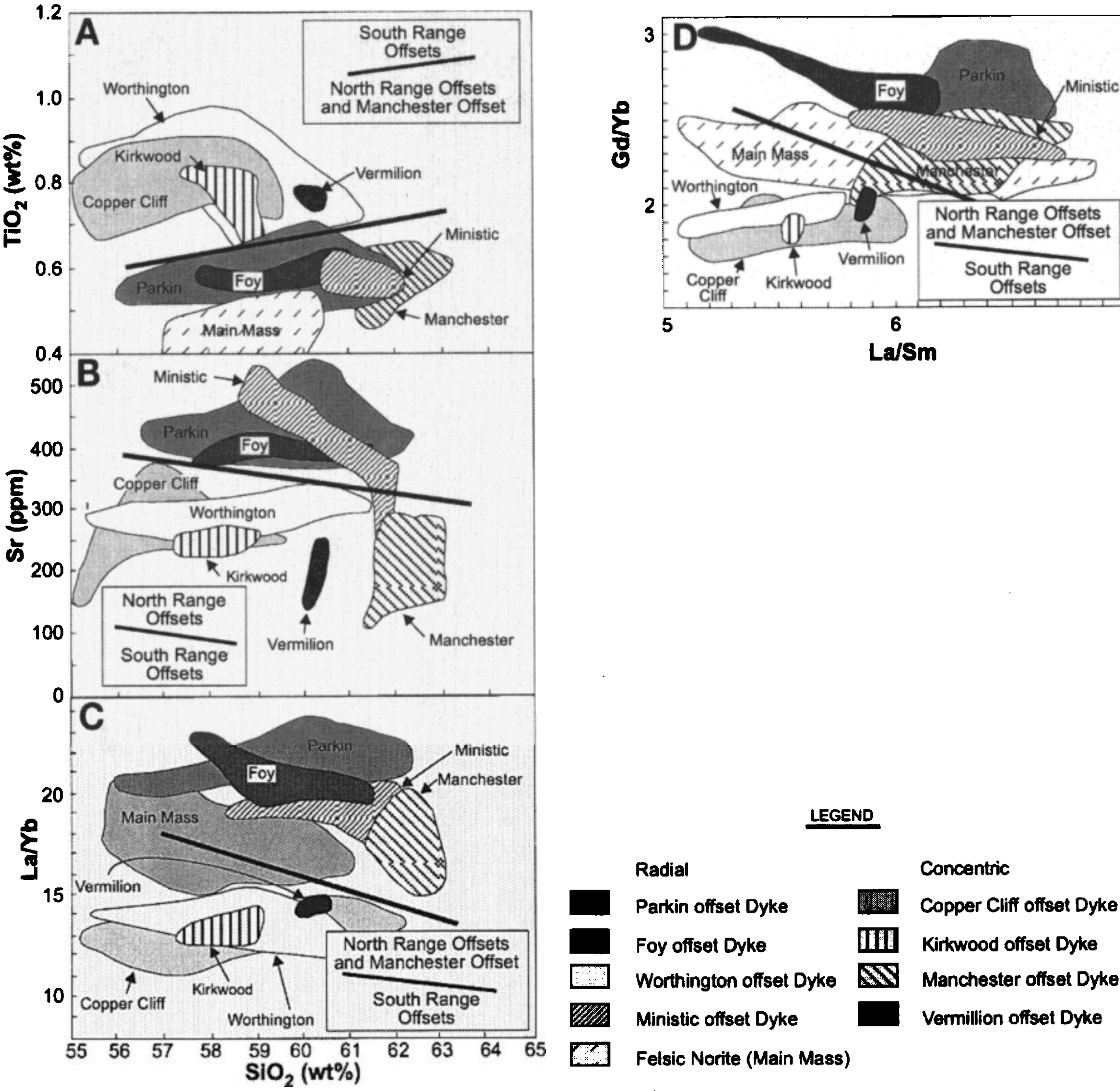

FIG. 11. Comparison of the geochemical variations within different North and South Range offset dikes. A. SiO_2 versus TiO_2. B. SiO_2 versus Sr. C. SiO_2 versus La/Y. D. La/Sm versus Gd/Yb.

1986), very high initial Os isotope ratios (γOs = +500; Walker et al., 1991, 1994; Dickin et al., 1992), and unusual oxygen isotope compositions (Ding and Schwarcz, 1984).

Although there is some debate (Muir, 1984), there is an overwhelming amount of evidence (e.g., widespread development of shock lamellae in quartz and feldspar, shatter cones, the pseudotachylite, and breccias) that the Sudbury structure is the product of a meteorite impact event (Grieve, 1994). Some authors (e.g., Grieve, 1994) have suggested that the impact of this meteorite generated not only all of the components of the Sudbury Complex but also the Ni-Cu-PGE sulfide mineralization. A major problem with this proposal is that there are no known examples of Ni-Cu-PGE sulfide deposits genetically related to rocks of andesitic composition which are broadly similar in composition to average crust. Another problem is that whole-scale melting of the crust does not produce an obvious mechanism for the generation of the immiscible Ni-Cu-PGE-enriched sulfide melts.

Data for the felsic norite and the granophyre indicate very strong crustal involvement, but there are some rather fundamental reasons why we believe that some portions of the Sudbury Complex may not have been derived from crustal rocks. The sublayer contains ultramafic inclusions that have unmetamorphosed and largely unaltered primary igneous cumulate textures and entirely fresh mineralogies. Had these been inherited from the Archean country rocks, one would have expected to see signs of shock metamorphism and perhaps thermal metamorphism. Furthermore, magmatic zircon and baddeleyite from within mafic and ultramafic inclusions have been dated by U-Pb methods (Corfu and Lightfoot, 1997) and yield a 1.85 Ga age, which is similar to that of the main mass (Krogh and Davis, 1974; Krogh et al., 1982, 1984), albeit on four different inclusions and/or pods which come from one embayment at the Whistle mine. Moreover, these same inclusions have incompatible trace element abundance patterns that have many similarities to the silicate matrix rocks

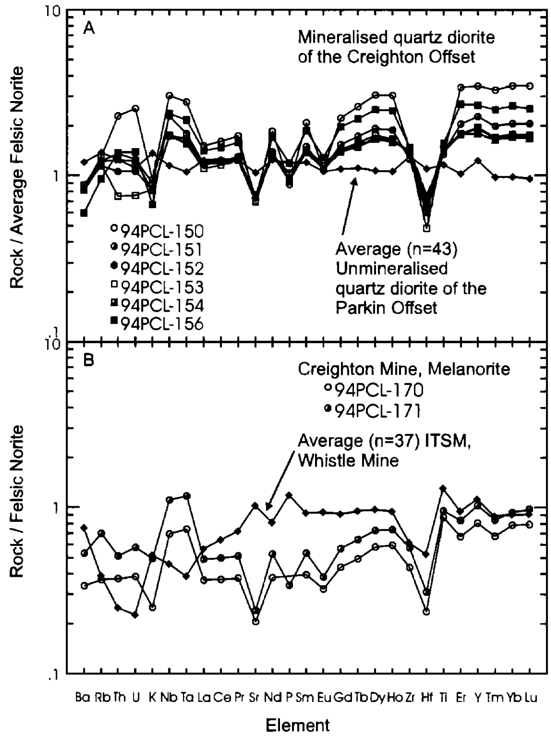

FIG. 12. A. Compositions of Creighton offset quartz diorite normalized to average felsic norite (see Lightfoot et al., 1997a, for detailed sample locations). B. Compositional data for the sublayer at the Creighton mine and the Whistle mine based on average data from Lightfoot et al. (1997a). ITSM = igneous-textured silicate matrix of the sublayer.

at Whistle (Lightfoot et al., 1995a,b,c); an ultramafic body from the footwall breccias at the Levack mine also has some of these features (Moore et al., 1995). Nd isotope data for the ultramafic fragments indicate that epsilon values at 1.85 Ga are similar to those of the sublayer matrix (approx −6; Prevec et al., 1996). Some of the olivine melanorites from the Whistle mine contain fresh olivines which have Fo_{68-87} compositions, and 450 to 3,700 ppm Ni (Lightfoot et al., 1997a). Olivines with an Fo_{87} composition have typically crystallized from a magma which has the Mg/Fe ratio of an Mg-rich theoleiitic parental magma, albeit a magma heavily enriched in silica and incompatible elements. This magma must also have had a relatively normal Ni content of several hundred ppm, since many of the olivines are not abnormally Ni depleted (Lightfoot et al., 1997a), which might be expected if they had crystallized from a magma after the fractional segregation of a magmatic sulfide liquid (e.g., Lightfoot and Naldrett, 1984; Lightfoot and Hawkesworth, 1997; Lightfoot et al., 1997b). A futher observation is the presence of fresh ultramafic inclusions from the sublayer environment close to the Craig mine on the North Range and the Gertrude embayment on the South Range. These fresh ultramafic rocks have 32 to 36 wt percent MgO and approach wherlites in mineralogy; they contain fresh cumulus olivine (see Lightfoot et al., 1997a). These ultramafic rocks must have formed from a particularly primitive parental magma and cannot have formed from a magma of andesitic bulk composition. Another feature of the sublayer ultramafic inclusions and the mafic norite of the main mass is their very high Cr content (1,000–3,500 ppm); this is because of the presence of chrome spinels and chromite (Lightfoot et al., 1997a). High Cr rocks are unlikely to be produced by crystallization from evolved magmas approaching andesitic composition, although they may crystallize from tholeiitic magmas (Roeder and Campbell, 1985).

Important evidence for a mafic-ultramafic component comes from the abundance of Ni-Cu-PGE sulfide concentration. As summarized by Keays (1995), a fundamental requirement of magmas that form Ni-Cu-PGE sulfide deposits is that they are S undersaturated. This requirement stems from the extremely high partition coefficients of the PGE; for example, Peach et al. (1990) showed that partition coefficients for Pd between sulfide liquid and silicate melt are approximately 35,000. As a result of these very large partition coefficients, S-saturated magmas that have lost immiscible magmatic sulfide droplets will be very strongly depleted in the PGE and hence unable to form magmatic Ni-Cu-PGE sulfide deposits. The only mantle-derived magmas that are S undersaturated are generated by greater than 25 percent partial melting, such as picrites and komatiites or second-stage magmas such as boninites that were generated from residual upper mantle reservoirs from which substantial amounts of magma (and S) had previously been removed.

All known Ni-Cu-PGE sulfide deposits are associated with mafic and ultramafic rocks and are believed to have formed from the magma that formed these rocks. In particular, there are no known examples of such deposits having formed from andesitic magmas, as would have had to have been the case had the deposits formed from a crustal melt sheet. Although some authors (e.g., Golightly, 1994; Grieve, 1994) have pointed out that there may have been sufficient Ni and Cu in the impacted Archean rocks to supply the metals for the Ni-Cu-PGE sulfide deposits, we see three outstanding problems with this scenario:

1. Metal inventory of the Sudbury Complex ores. There is unlikely to have been enough base and precious metals to generate the observed ores unless the target rocks were particularly mafic in composition and hosted sulfides (e.g., Keays et al., 1995). For example, Table 2 shows the total amount of base metals mined in the Sudbury Complex (based on Ministry of Northern Development and Mines, 1994). These amounts are probably underestimates of the total metal inventory, because they do not take into account known disseminated sulfide mineralization or deposits that remain to be detected. For this reason, we have arbitrarily estimated that the true amount of metals is more than six times the known quantity. Grieve (1994) has estimated that the total volume of the Sudbury Complex is greater than 8,000 km^3. Taking an average density of the Sudbury Complex of 2.8 g/cc, this converts to greater than $2 \cdot 10^{19}$ g. Using the values for the total Ni-Cu-PGE resources in the complex from Table 2 multiplied by six, we can calculate the average concentration required of the impacted rocks, had these been the source of the metals. These values (e.g., 220 ppm Ni and 220 ppm Cu) are greater than those of average crust (20 ppm Ni and 25 ppm Cu). If derived from the crust, the target rocks would be required to contain ten times more Cu and Ni than that

present in average crust. Moreover, the granophyre and felsic norite contain substantial quantities of Cu and Ni (granophyre: 31 ppm Cu and 5 ppm Ni; felsic norite: 155 ppm Cu and 126 ppm Ni; Table 1), and these figures are higher than values for average crust. Our calculated weighted average for the Sudbury Complex composition in Table 1 excludes metal contributions from rocks with >5 percent sulfide, but demonstrates that the silicate rocks and disseminated sulfides in the Sudbury Complex reach elevated concentrations of 120 ppm Ni and 160 ppm Cu. Taking into account both the silicate and sulfide metal inventories requires the parental magma to have at least 246 ppm Ni and 325 ppm Cu. These are typical of the upper range of concentration in continental Mg-rich tholeiitic magmas (e.g., Lightfoot et al., 1994). Hence, either the impacted country rocks were very unusual in composition (i.e., have a significant contribution from Archean or Proterozoic mafic-ultramafic rocks) or they were not the source of the metals. The problem may be even worse for the element sulfur; the average S content of upper crust is 260 ppm, but the concentration required in the impacted country rocks is at least nine times this value to generate the Sudbury Complex which has a bulk average S content of ~0.25 percent. Estimates based on the PGE abundance of the ores are more open to question since we have only a rough estimate of the PGE tenor of the complex because PGE have been recovered from only a fraction of the sulfides. Assuming an average ore with 500 ppb Pd and 1,000 ppb Pt (e.g., Naldrett, 1989), then the amount of Pt and Pd in $1.5 \cdot 10^9$ metric tons (t) of reserves plus resources would be 750 t Pd and 1,500 t Pt. If derived from the main mass of the complex, this would require a parental magma with ~0.5 ppb Pd and ~1 ppb Pt. The main mass rocks have ~5 ppb Pt and 5 ppb Pd (Chai and Eckstrand, 1994) and therefore the amount of metals in the main mass would exceed abundance levels in average crust rocks by a factor of ~10.

2. Concentration of the metals. A second problem is that we have no satisfactory mechanism to account for the scavenging of the metals from the melt sheet to form the ores, had it been the source of the metals. Sulfur saturation of a previously S-undersaturated magma has long been the accepted model for the generation of Ni-Cu-PGE sulfide deposits (cf. Naldrett, 1989; Keays, 1995). Essentially, two components are required to form a major sulfide deposit: the first being a metal source and the second an S source or something that would drive the composition of the magma toward S saturation. In the case of the Sudbury Complex, Irvine (1975) has suggested that it was the addition of silica from the continental crust that drove the mantle-derived magmas toward S saturation and formation of immiscible magmatic sulfide droplets. This model requires that the metal source be a primitive mantle-derived magma. Although we have selected a picrite, it does not make a great deal of difference as far as PGE are concerned whether the magma was a komatiite, a picrite, or a high Mg tholeiite. The important point is that it was S undersaturated. Taking the average Pd of the picritic melt as 9 ppb (Keays, 1995), there would be 25 t of Pd in 1 km^3 of picritic magma with a density of 2.8 g/cc. Assuming that there is a total of 1,500 t of PGE metals in the magmatic sulfides of the Sudbury Complex, the total volume of picritic magma required to supply all of the sulfide-hosted Pd in the Sudbury Complex would be 62 km^3. This represents 0.78 percent of the total volume of the Sudbury Complex as estimated by Grieve (1994). We showed earlier that there would be no silicate geochemical signature if as much as 20 percent primitive mantle-derived magma was incorporated into the complex, and this is a factor of 30 times higher than the amount of picritic magma required to contribute the metals. On these grounds, the very small volume of primitive magma would have no detectable influence on the trace element signature of the resultant hybrid magma. Of course, collection processes would not have been 100 percent efficient, as indicated by the detectable levels of PGE in the main mass (0–7.4 ppb Pd and 0–12.4 ppb Pt: Chai et al., 1993), so more picritic magmas than calculated would have been required, but the models permit as much has 30 times more picritic magma.

3. Composition and age of the mafic-ultramafic inclusions. Lightfoot et al. (1995a,b,c) and Corfu and Lightfoot (1997) have shown that many of the ultramafic inclusions in the sublayer are fresh 1.85 Ga old rocks that have geochemical traits suggesting that they crystallized from a melt with a tholeiitic Mg/Fe ratio, yet an incompatible element abundance approaching that of the main mass of the Sudbury Complex. These inclusions as well as the mafic norite of the main mass and some of the sublayer contain olivine with Fo_{68-87} compositions and chrome-rich spinels and chromites; these compositions suggest that crystallization occurred in a magma with tholeiitic Mg/Fe and Cr abundance levels. Furthermore, the large number of fresh mafic-ultramafic inclusions in the sublayer and the offset dikes (Farrell et al., 1995) demand that crystallization occurred over a wide area from a magma with tholeiitic Mg/Fe. These inclusions cannot have come from the Archean, although some of the amphibolite inclusions in the Worthington offset quartz diorite have compositions and petrographic features consistent with derivation from a Nipissing diabase source (Lightfoot, unpub. data). Most of the 1.85 Ga inclusions are directly associated with the mineralized sublayer and with the mineralization; on this basis there is reason to suspect that more primitive magmas were involved than average upper crustal melts.

TABLE 2. Estimated Production from the Sudbury Mining Camp

Element	Production (t)	Grade
Ni	8,400,000	12 kg/t
Cu	8,200,000	11 kg/t
Au	101	0.13 g/t
Ag	3,184	4.11 g/t
Pt	279	0.36 g/t
Pd	284	0.37 g/t
Ir	10	0.015 g/t
Rh	34	0.05 g/t
Ru	23	0.03 g/t
Se	2,691	3.5 g/t
Te	308	0.4 g/t
Co	48,000	0.06 kg/t
Fe	13,400,000	
S	7,400,000	

Total value = $117 billion (Canadian) based on 1991 prices
Production given in metric tons
Data source: Ministry of Northern Development and Mines (1994)

It is suggested that the impact of the meteorite induced melting of the upper crust and generated a melt sheet. The composition of this melt sheet would have corresponded in part to that of the upper crust from which the melt sheet was derived. At the time of impact, the Huronian clastic sedimentary-volcanic package of rocks probably covered Archean shield over much of the target area. Although the Huronian is up to 10 km thick south of Elliot Lake, it may have been considerably thinner than this toward the northern margin of the Huronian. If the width to depth ratio of the impact crater was 10:1, then the depth of the crater would have been 9 to 12 km deep, depending on the diameter of the crater, which was probably 90 to 120 km (Golightly, 1994). Hence, if a melt sheet was formed, it would have incorporated far more material from the Archean greenstone-granite-migmatite terrane and Proterozoic intrusions than the Huronian epicontinental sequence.

Chai and Eckstrand (1994) suggested that the granophyre was generated by in situ melting of the upper crust (75% Archean rocks and 25% Huronian granite) as a result of impact-induced melting, whereas the norite was produced from a mantle-derived magma that had been contaminated with up to 60 percent Archean granulite facies rocks from the lower crust. We do not subscribe to this model because the ratios of incompatible elements in the granophyre are very similar to those in the felsic norite (Figs. 9 and 10); the only difference between the two is that the former contains one half of the heavy field strength elements when compared to the latter. Although we consider this type of coherence could not be possible if the two melts had contributions from essentially different crustal reservoirs, we cannot rule out completely Chai and Eckstrand's scenario because the crustal rocks involved, having a significantly higher incompatible element content than the mafic magma, could have a dominating influence on the resulting incompatible element content of the contaminated magma.

The meteorite impact event not only excavated a ca. 10-km-deep crater, but also produced the melt sheet and, apparently, produced significant breaking of the crust along Sudbury breccia zones, but more importantly along the lines of the offset dikes. Some of these dike are observed to penetrate for up to 25 km into the country rocks, and this is seen most spectacularly in the Foy offset dike, where mapping shows that it extends as a radial and concentric dike into the Archean gneisses and granitoids north of the complex (e.g., Lightfoot et al., 1997a and references therein). These cracks presumably not only radiated away from the center of the Sudbury structure but most likely also penetrated beneath the structure, and could be the cracks along which mantle-derived picritic magmas migrated to the surface to provide the inventory of Ni, Cu, and PGE. Presumably decompressive melting accompanying the meteorite impact event permitted magmas to be generated in the lithsopheric mantle and to be expelled from their source during the postimpact readjustment of the crater. The high Mg magmas rose from the mantle through the cracks beneath the crater and were injected into the melt sheet and mixed vigorously with the crustal melts, thereby forming a hybrid magma from which the main mass crystallized. The granophyre was presumably demarcated from the felsic norite at a stratigraphic position corresponding to the point at which a chemical break developed on the entry of augite as a cumulus mineral. Since the trace element contribution from the crustal source was an order of magnitude larger than that from the high Mg source, the injection of the high Mg magmas might simply have diluted, rather than altered, the chemical signature of the crustal melt sheet. However, as we have shown, the incompatible trace element data demand a 50 percent difference in abundance. Our models permit a maximum difference of 10 percent in the amount of mantle material added to the felsic norite relative to the granophyre, and therefore the entire compositional difference between the felsic norite and the granophyre is not explained by this process alone. However, the geochemical variations in the main mass do suggest that some in situ differentiation of the magma took place, and we believe that variations within the mafic norite, felsic norite, and transition zone quartz gabbro reflect a contribution from this process.

Mixing of the crustal- and mantle-derived magmas drove the high Mg magma toward S saturation because of the addition of silica as first suggested by Irvine (1975), and the addition of large amounts of crustal S. The net result was the production of immiscible sulfide droplets that were highly enriched in Ni, Cu, and PGE; having twice the density of their silicate hosts, the sulfide droplets sank to the temporary floor of the chamber ultimately to form the sublayer (Lightfoot et al., 1997a).

Summary and Conclusions

1. The norites and granophyres of the main mass of the Sudbury Complex are compositionally different with respect to their major element oxide abundances and trace element abundances. As Chai and Eckstrand (1994) pointed out, there is a compositional gap between them; however, the norites and granophyres retain essentially similar ratios of incompatible trace elements such as La/Sm, Gd/Yb, Th/Nb, etc. If, as Chai and Eckstrand (1994) suggest, the norites and granophyres represent different magmas derived from different sources, then this model must also explain the very similar ratios of the incompatible trace elements in the two different magmas. We suggest that it is more likely that the felsic norite and granophyre were derived from a common parental magma which was a melt of the upper crust that swamped any incompatible trace element contribution from the lower mantle or crust. These observations are inconsistent with both upper crustal contributions to the granophyre and lower crustal contributions to the norite magma. A maximum of 20 percent mantle contribution of primitive picritic magmas can be accommodated without changing the ratios of the incompatible trace elements. The compositional break between the felsic norite and the granophyre may be consistent with fractionation of the main mass magma, but we are performing more detailed studies of the chemostratigraphy to understand this process better.

2. The quartz diorite offset dikes and leucocratic norites of the funnel of the Whistle embayment are compositionally very evolved with respect to SiO_2 and MgO, and have elevated REE abundances and steep REE profiles. Traditionally, the offset quartz diorites and sublayer leucocratic norites have been grouped in with the sublayer (Souch et al., 1969) and considered part of the sublayer magma. The data presented

above suggest that the quartz diorites and leucocratic norites have a greater compositional affinity to the main mass magmas than to the sublayer magmas and were formed by the event responsible for the main mass rather than the one responsible for the sublayer. The similarity of the main mass felsic norite and the leuococratic norite at the end of the embayment and quartz diorite of the offset are consistent with a genetic link, but the intervening unit of sublayer norite is compositionally different and may have formed by a mechanism involving different chemical contributions compared with the main mass and the offsets.

3. There are broad compositional differences between the North and South Range offsets, and between mineralized and unmineralized offsets. The former differences may reflect assimilation of local crust that is broadly different in composition between the North and South Ranges. The Creighton offset quartz diorites have trace element compositions that approximate the composition of the local sublayer, and not that of the main mass. This may be a feature of quartz diorite that is developed proximal to the embayment structure.

Acknowledgments

The authors acknowledge the contributions made by Inco Exploration and Falconbridge Limited, without whose help and permission to access properties, this work would not have been possible. Specifically, we thank the following individuals at Inco Limited for thought-provoking discussions: Mars Napoli, Ed Pattison, Paul Golightly, Terry Little, Doug Goodale, Walter Peredery, Everett Makela, Richard Alcock, and Bob Martindale. We also thank the following individuals from Falconbridge Exploration Limited: Roger Poulin, Tony Green, Mike Sweeney, Fred Twilley, Peter Johansson, Paul Binney, and Ted Barnett. We have also benefited from discussions with Chris Hawkesworth, Tony Naldrett, Mei Fu Zhou, Steve Prevec, Dean Pekeski, and Zeljko Vujovic. We thank Gang Chai and Roger Eckstrand for providing a copy of their complete analaytical data. Analytical data were acquired through the skilled participation of the staff of the Ontario Geoscience Center's geoscience laboratories. We thank Roger Eckstrand and François Robert for reviews of an early version of this paper.

July 9, 1996; May 2, 1997

REFERENCES

Chai, G., and Eckstrand, R., 1994, Rare-earth element characteristics and origin of the Sudbury Igneous Complex, Ontario, Canada: Chemical Geology, v. 113, p. 221–244.

Chai, G., Eckstrand, R., and Gregoire, C., 1993, Platinum group element concentrations in the Sudbury rocks, Ontario—an indicator of petrogenesis: Canada Geological Survey Paper 93–1C, p. 287–293.

Cochrane, L.B., 1984, Ore deposits of the Copper Cliff offset: Ontario Geological Survey Special Volume 1, p. 347–360.

Corfu, F., and Lightfoot, P.C., 1997, U-Pb geochronology of the sublayer environment, Sudbury Igneous Complex, Ontario: ECONOMIC GEOLOGY, v. 91, p. 1263–1269.

Dickin, A.P., Richardson, J.M., Crocket, J.H., McNutt, R.H., and Peredery, W.V., 1992, Osmium isotope evidence for a crustal origin of platinum group elements in the Sudbury nickel ore, Ontario, Canada: Geochimica et Cosmochimica Acta, v. 56, p. 3531–3537.

Dickin, A.P., Artan, M.A., and Crocket, J.H., 1996, Isotopic evidence for distinct crustal sources of North and South Range ores, Sudbury Igneous Complex: Geochimica et Cosmochimica Acta, v. 60, p. 1605–1613.

Dietz, R.S., 1964, Sudbury structure as an astrobleme: Journal of Geology, v. 72, p. 412–434.

Ding, T.P., and Schwarcz, H.P., 1984, Oxygen isotope and chemical compositions of rocks of the Sudbury basin, Ontario: Canadian Journal of Earth Sciences, v. 21, p. 305–318.

Dressler, B.O., 1984a, General geology of the Sudbury area: Ontario Geological Survey Special Volume 1, p. 57–82.

——1984b,The effects of the Sudbury event and the intrusion of the Sudbury Igneous Complex on the footwall rocks of the Sudbury : Ontario Geological Survey Special Volume 1, p. 97–138.

Fairburn, H.W., Hurley, P.M., and Pinson, W.H., 1968, Rb-Sr whole-rock age of the Sudbury lopolith and basin sediments: Canadian Journal of Earth Sciences, v. 5, p. 707–714.

Faggart, B.E., Jr., Basu, A.R., and Tatsumoto, M., 1985,Origin of the Sudbury Complex by meteoritic impact: Neodymium isotopic evidence: Science, v. 230, p. 436–439.

Farrell, K.P.J., Lightfoot, P.C., and Keays, R.R., 1995, Mafic-ultramafic inclusions in the sublayer of the Sudbury Igneous Complex, Whistle mine, Sudbury, Ontario:Ontario Geological Survey Miscellaneous Paper 164, p. 126–128.

Gasparinni, E., and Naldrett, A.J., 1972, Magnetite and ilmenite in the Sudbury nickel irruptive: ECONOMIC GEOLOGY, v. 67, p. 605–621.

Golightly, J.P., 1994, The Sudbury Igneous Complex as an impact melt: Evolution and ore genesis: Ontario Geological Survey Special Volume 5, p. 105–118.

Grant, R.W., and Bite, A., 1984, Sudbury quartz diorite offset dikes: Ontario Geological Survey Special Volume 1, p. 275–301.

Grieve, R.A.F., 1994, An impact model of the Sudbury structure: Ontario Geological Survey Special Volume 5, p. 119–132.

Gupta, V.K., Grant, F.S., and Card, K.D., 1984, Gravity and magnetic characteristics of the Sudbury structure: Ontario Geological Survey Special Volume 1, p. 381–410.

Hearst, R.B., Morris, W.A., and Broome, H.J., 1994, Magnetic interpretation along the Sudbury structure LITHOPROBE transect: Ontario Geological Survey Special Volume 5, p. 33–44.

Hewins, R.H., 1971, The petrology of some marginal mafic rocks along the North Range of the Sudbury irruptive: Unpublished Ph.D. thesis, University of Toronto, 152 p.

Hurst, R.W., and Wetherill, G.W., 1974, Rb-Sr study of the Sudbury nickel irruptive [abs.]: American Geophysical Union Transactions, v. 55, p. 446.

Irvine, T.N., 1975, Crystallization sequences of the Muskox intrusion and other layered intrustions, II. Origin of chromitite layers and similar deposits of other magmatic ores: Geochimica et Cosmochimica Acta, v. 3, p. 991–1020.

Keays, R.R., 1995, The role of komatiitic and picritic magmatism and S-saturation in the formation of ore deposits: Lithos, v. 34, p. 1–18.

Keays, R.R., Vogel, D.C., James, R.S., Peck, D.C., Lightfoot, P.C., and Prevec, S.A., 1995, Metallogenic potential of Huronian-Nipissing magmatic province [abs.]: Canadian Mineralogist, v. 33, p. 932–933.

Krogh, T.E., and Davis, G.L., 1974, The age of the Sudbury nickel irruptive: Carnegie Institute of Washington Yearbook, v. 73, p. 567–569.

Krogh, T.E., McNutt, R.H., and Davis, G.L., 1982, Two high precision U-Ub zircon ages for the Sudbury nickel irruptive: Canadian Journal of Earth Sciences, v. 19, p. 723–728.

Krogh, T.E., Davis, D.W., and Corfu, F., 1984, Precise U-Pb zircon and baddeleyite ages for the Sudbury area: Ontario Geological Survey Special Volume 1, p. 431–447.

Kuo, H.-Y., and Crockett, J.H., 1979, Rare earth elements in the Sudbury nickel irruptive: Comparison with layered gabbros and implications for nickel irruptive petrogenesis: ECONOMIC GEOLOGY, v. 79, p. 590–605.

Lightfoot, P.C., 1996, The giant nickel deposits at Sudbury and Noril'sk [abs.]: Prospectors and Developers Association of Canada, Annual Meeting, 64th, Sudbury, September 1996, Abstracts, p. 57–58.

Lightfoot, P.C., and Hawkesworth, C.J., 1997c, Flood basalts and magmatic Ni, Cu, and PGE sulfide mineralization: Comparative geochemistry of the Noril'sk (Siberian Traps) and West Greenland sequences: American Geophysical Union Transactions (in press)

Lightfoot, P.C., and Naldrett, A.J., 1984, Chemical variation in the Insizwa Complex, Transkei, and the nature of the parent magma: Canadian Mineralogist, v. 22, p. 111–123.

Lightfoot, P.C., Naldrett, A.J., Gorbachev, N.S., Fedorenko, V.A., Hawkesworth, C.J., Hergt, J., and Doherty, W., 1994, Chemostratigraphy of the Siberian Trap lavas, Noril'sk district, Russia: Implications for the source of flood basalt magmas and their associated Ni-Cu mineralisation: Ontario Geological Survey Special Volume 5, p. 283–312.

Lightfoot, P.C., Farrell, K.P., Pekeski, D., Moore, M., and Keays, R.R., 1995a, Geochemical relationships among the main mass, sublayer and offsets of the Sudbury Igneous Complex, Ontario, Canada: Ontario Geological Survey Miscellaneous Publication 164, p. 116–121.

Lightfoot, P.C., Farrell, K.P., Moore, M., Pekeski, D., Crabtree, D., and Keays, R.R., 1995b, Geochemical relationships among the sublayer, main mass, and offsets: Constraints on the origin of the Sudbury Igneous Complex: p. 109–110.

——1995c, Geochemical variations within the sublayer and the mafic-ultramafic inclusions, Whistle mine, Sudbury Igneous Complex, Canada: International Geological Correlation Programme 336, Duluth Meeting, p. 111–112.

Lightfoot, P.C., Doherty, W., Farrell, K.P., Keays, R.R., Pekeski, D., and Moore, M., 1997a, Geochemistry of the main mass, sublayer, offsets, and inclusions from the Sudbury Igneous Complex, Ontario. Mineral Deposit Study: Ontario Geological Survey Open File Report 5959, 231 p.

Lightfoot, P.C., Hawkesworth, C.J., Olshefsky, K., Green, T., Doherty, W., and Keays, R.R., 1997b, Geochemistry of Tertiary tholeiites and picrites from Qeqertarssuaq (Disko Island) and Nuussuaq,West Greenland, with implications for the mineral potential of comagmatic intrusions: Contributions to Mineralogy and Petrology (in press).

McGrath, P.H., and Broome, H.J., 1994, A gravity model for the Sudbury structure: Ontario Geological Survey Special Volume 5, p. 21–32.

Milkereit, B., White, D., Adam, E., Boerner, D., and Salisbury, M., 1994, Implications of the LITHOPROBE seismic reflection transect for Sudbury geology: Ontario Geological Survey Special Volume 5, p. 1–20.

Ministry of Northern Development and Mines, 1994, Ontario mineral score 1994: Toronto, Ontario Ministry of Northern Development and Mines, 200 p.

Morrison, G.G., 1984, Morphological features of the Sudbury structure in relation to an impact origin: Ontario Geological Survey Special Volume 1, p. 513–522.

Moore, M., Lightfoot, P.C., and Keays, R.R., 1995, Geology and geochemistry of North Range footwall ultramafic rocks, Sudbury Igneous Complex, Sudbury, Ontario: Ontario Geological Survey Miscelaneous Publication 164, p. 122–123.

Muir, T.L., 1984, The Sudbury structure: Considerations and models for an endogenic origin: Ontario Geological Survey Special Volume 1, p. 449–490.

Naldrett, A.J., 1989, Magmatic sulfide deposits: Oxford Monographs in Geology and Geophysics, no. Naldrett, A.J., and Hewins, R.H., 1984, The main mass of the Sudbury Igneous Complex: Ontario Geological Survey Special Volume 1, p. 235–252.

Naldrett, A.J., Bray, J.G., Gasparinni, E.L., Podolsky, T., and Rucklidge, J.C., 1970, Cryptic variation and the petrology of the Sudbury nickel irruptive: ECONOMIC GEOLOGY, v. 65, p. 122–155.

Naldrett, A.J., Rao, B.V., and Evensen, N.M., 1986, Contamination at Sudbury and its role in ore formation, *in* Gallagher, M.J., Ixer, R.A., Neary, C.R., and Pritchard, H.M., eds., Metallogeny of basic and ultrabasic rocks: London, The Institution of Mining and Metallurgy, p. 75–92.

Pattison, E.F., 1979, The Sudbury sublayer: Its characteristics and relationships with the main mass of the Sudbury irruptive: Canadian Mineralogist, v. 17, part 2, p. 257–274.

Peach, C.L., Mathez, E.A., and Keays, R.R., 1990, Sulfide melt-silicate melt distribution coefficients for nickel and iron and implications for the distribution of other chalcophile elements:Geochimica et Cosmochimica Acta, v. 57, p. 3013–3021.

Peck, D.C., James, R.S., and Chubb, P.T., 1993,Geological environments for PGE-Cu-Ni mineralisation in the East Bull Lake gabbro-anorthosite intrusion, Ontario: Exploration and Mining Geology, v. 291, p. 85–104.

Pekeski, D., Lightfoot, P.C., and Keays, R.R., 1995, Geology and geochemistry of the Totten mine section of the Worthington offset, Sudbury Igneous Complex, Ontario: Ontario Geological Survey Miscellaneous Publication 164, p. 124–125.

Peredery, W.V., and Morrison, G.G., 1984, Discussion of the origin of the Sudbury structure: Ontario Geological Survey Special Volume 1, p. 491–512.

Prevec, S.A., Lightfoot, P.C., Moore, M.L., and Keays, R.R., 1996, Radiogenic isotopic evidence regarding the origins of the sublayer and offset environments of the Sudbury Igneous Complex, Ontario [abs]: Geological Association of Canada Program with Abstracts, p. A76.

Pye, E.G., Naldrett, A.J., and Giblin, P.E., 1984, The geology and ore deposits of the Sudbury structure: Ontario Geological Survey Special Volume 1, 603 p.

Rae, D.R., 1975, Inclusions in the sublayer from Strathcona mine, Sudbury and their significance: Unpublished M.Sc. thesis, University of Toronto, 207 p.

Roeder, P.L., and Campbell, I.H., 1985, The effect of postcumulus reactions on the composition of chrome-spinels from the Jimberlana intrusion: Journal of Petrology, v. 26, p. 763–786.

Scribbins, B.T., 1978, Exotic inclusions from the South Range sublayer, Sudbury: Unpublished M.Sc. thesis, University of Toronto, 213 p.

Scribbins, B., Rae, D.R., and Naldrett, A.J., 1984, Mafic and ultramafic inclusions in the sublayer of the Sudbury Igneous Complex: Canadian Mineralogist, v. 22, p. 67–75.

Souch, B.E., Podolsky, T., and the geological staff of the Internation Nickel Company of Canada, 1969, The sulfide ores of Sudbury: Their particular relation to a distinctive inclusion-bearing facies of the nickel irruptive: ECONOMIC GEOLOGY MONOGRAPH 4, p. 252–261.

Sun, S.-S., and McDonough, W.F., 1989, Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes: Geological Society Special Publication 42, p. 312–345.

Taylor, S.R., and McLennan, S.M., 1995, The geochemical evolution of the continental crust: Review of Geophysics, v. 33, p. 241–265.

Thomson, R., 1935,The "offset dikes" of the nickel intrusive, Sudbury, Ontario: American Journal of Science, v. 30, p. 356–367.

Walker, R.J., Morgan, J.W., Naldrett, A.J., Li, C., and Fassett, J.D., 1991, Re-Os isotope systematics of Ni-Cu sulfide ores, Sudbury Igneous Complex, Ontario: Evidence for a major crustal component: Earth and Planetary Science Letters, v. 105, p. 416–429.

Walker, R.J., Morgan, J.W., Hanski, E., and Smolkin, V.F., 1994, The role of the Re-Os isotope system in deciphering the origin of magmatic sulfide ores: A tale of three ores: Ontario Geological Survey Special Volume 5, p. 343–355.