Economic Geology
Vol. 97, 2002, pp. 1399–1418

Geology, Mineralization, and Emplacement of the Whistle-Parkin Offset Dike, Sudbury*

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Abstract

The Whistle-Parkin dike is a 12-km-long radial offset dike located in the northeast sector of the 1.85 Ga Sudbury impact structure. The dike is connected to the Sudbury Igneous Complex via a 0.5-km-long, 250-m-wide embayment. The Whistle segment of the dike narrows to a width of approximately 30 m and extends for about 1.5 km from the complex, where it is cut by the Post Creek fault zone. This fault displaces the dike 2 km to the northwest, beyond which it continues as the Parkin portion of the dike. The Parkin segment extends a further 10 km north-northeast. The dike and genetically associated embayment are comprised of numerous rock types. These include the sublayer, radial breccia, mafic sulfide-bearing breccia, inclusion-rich quartz diorite, and inclusion-poor quartz diorite. Economic Ni-Cu-PGE mineralization is found in association with the sublayer, mafic sulfide-bearing breccia, and inclusion-bearing quartz diorite phases. Rare earth element (REE) data reveal that the dike lithologies are representative of bulk Sudbury Igneous Complex melt.

We propose a multistage emplacement mechanism for the dike. The breccia units, including the inclusion-bearing quartz diorite phase, were forcefully injected laterally into an impact-generated radial crack during the excavation stage of crater formation. Subsequent early modification processes facilitated the intrusion of inclusion-poor quartz diorite, particularly along the dike margins. Inclusion-poor quartz diorite emplacement may have been gravitationally driven from the overlying impact melt sheet. Later stage modification (i.e., final transient cavity collapse) caused decoupling of the Whistle and Parkin dike segments via faulting. This occurred concurrently with the settling of the sublayer unit and associated economic sulfides into the embayment and main dike segments.

Introduction

The 1.85 Ga Sudbury structure of Ontario is one of the more intriguing geologic features on this planet. It is now widely accepted to be a 200- to 250-km multi-ring impact structure (Krogh et al., 1984; Grieve et al., 1991., Deutsch et al., 1995; Spray and Thompson, 1995). A major factor in the importance of the Sudbury structure is the presence some of the world's largest Ni- Cu-PGE deposits, as well as numerous relatively smaller, but similarly valuable, deposits. The Sudbury structure is located at the boundary between three major Precambrian terranes: the Archean Superior province, the Proterozoic Southern province, and the Grenville province.

The Sudbury Igneous Complex forms the present core of the structure. It is composed of norite at the base, a transition zone of gabbro, and granophyre at the top and is widely believed to be a differentiated impact melt sheet (Grieve et al., 1991). In plan view it is elliptical and approximately 27 by 60 km in size (Fig. 1). The overlying strata comprise the Whitewater Group of heterolithic fallback breccia, wacke, mudstone, and siltstone. Occurring beneath the complex are the footwall breccia and the Sudbury breccia (pseudotachylyte), the latter defining fault-related subconcentric and radial features; they are considered to be associated with the formation of the impact structure (Lakomy, 1990; Spray and Thompson, 1995; Scott and Spray, 2000).

The footwall rocks of the Sudbury structure consist of Archean greenstone, granitoid, and gneiss, Paleoproterozoic metavolcanic and metasedimentary rocks of the Huronian Supergroup, intrusive Nipissing metagabbro and diabase, and the Murray and Creighton granitic plutons.

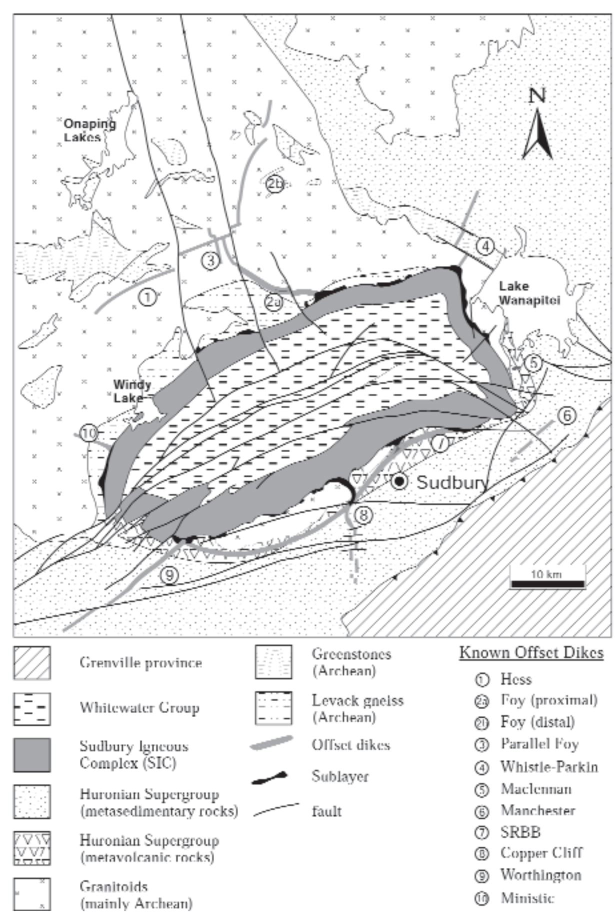

Fig. 1. Simplified geology of the Sudbury impact structure showing known offset dike locations and their names (modified after Wood and Spray, 1998).

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0361-0128/01/3292/1399-20 $6.00

The purpose of this study is describe the Whistle-Parkin offset dike system and the relationship it has with the Sudbury structure. The geology and geochemistry of the Whistle embayment has been previously reported in Lightfoot et al. (1997c). This study describes the variation of lithologies within the Whistle-Parkin offset dike and the relationships they have with each other. The study also shows how radial offset dikes can provide insight into the evolution of a complex multi-ring impact structure.

The offset dikes

The term "offsets" was first applied by Coleman (1905) to describe the melt-breccia dikes that emanate from the main mass of the Sudbury Igneous Complex. They have traditionally been referred to as the "offset sublayer" (Pattison, 1979; Giblin, 1984; Grant and Bite, 1984). However, this term is generally now restricted to the gabbro noritic inclusion- bearing unit found at the base of the Sudbury Igneous Complex within topographic lows in the footwall, referred to as "embayments" (Morrison, 1984; Lightfoot et al., 1997a). The offset dikes occur as radial, concentric, and discontinuous bodies around the complex. "Quartz diorite" is the local term for the rocks of the offset dikes, but most are granodioritic to monzodioritic in composition. They are important not only because of their economic value but also because of their role in the evolution of the cratering process (Wood and Spray, 1998).

There are ten known offset dikes: five radial dikes (Copper Cliff, Worthington, Whistle- Parkin, Ministic, and Foy), three concentric (South Range breccia belt, Manchester, and Hess), and two discontinuous (Creighton and Maclennan). The radial offset dikes are generally linked to the main mass via funnel-shaped embayments, which typically contain abundant sulfides associated with the sublayer unit.

Grant and Bite (1984) recognized three main petrographic types of quartz diorite and named them according to the dominant mafic mineral(s) present: (1) orthopyroxene (hypersthene)-, (2) clinopyroxene-, and (3) amphibole-biotite. The most common is amphibole-biotite quartz diorite which is the principal type in the radial offset dikes. It is medium grained and texturally subophitic to equigranular.

Geologic Setting of the Whistle-Parkin Offset Dike

The Whistle-Parkin offset dike extends from the northeast corner of the Sudbury Igneous Complex within Parkin and Norman Townships (Fig. 1). It originates as a 250-m-wide embayment and narrows to 30 to 50 m in width, extending for 12 km north-northeast into the country rock. The dike is cut and offset by at least three northwest-southeast-striking fault systems: the Post Creek fault zone 2 km from the Sudbury Igneous Complex, which displaces the dike 2 km to the northwest; the Milnet Mine fault zone 6 km from the complex, which displaces the dike approximately 250 m, again to the northwest, and an unnamed fault in the Distal Parkin segment, with a similar sense displacement of less than 50 m (Fig. 2). The Whistle- Parkin dike penetrates two major Precambrian tectonic units: the Archean Superior province and the Proterozoic Huronian Supergroup of the Southern province (Card and Innes, 1981; Jackson and Fyon, 1991). The contacts between the Archean Algoma and Levack crystalline rocks with the Benny greenstone belt metavolcanic rocks, and the Benny greenstone belt metavolcanic rocks with the Huronian Supergroup metasedimentary rocks, appear to be associated with the Post Creek and Milnet Mine fault zones, respectively.

The Benny greenstone belt rocks in the Parkin Township area consist of felsic to intermediate volcanic rocks, and feldspar and quartz-feldspar porphyritic rocks (Meyn, 1970; Tirschmann and Crawford, 1990). These units have an age of 2725 to 2703 Ma (Nunes and Pyke, 1980).

The Levack gneiss domain rims the northern margin of the Sudbury Igneous Complex. It is considered to be the basement to the Sudbury structure (Fueten et al., 1994) and seismic studies reveal that the Levack gneiss underlies much of the Sudbury structure (Milkereit et al., 1992). The Levack gneiss consists of supracrustal and intrusive rocks that have been deformed and metamorphosed to granulite facies conditions (Card, 1994). They are intruded by the Cartier batholith to the north and bounded by the Sudbury Igneous Complex to the south and are extensively cut by Proterozoic mafic dikes. A U/Pb zircon age of 2711 Ma has been established for the leucosome of a tonalitic gneiss in the Levack Complex (Krogh et al., 1984). In Norman Township the Levack gneiss consists of migmatitic tonalitic orthogneiss, biotite paragneiss, diatexitic granitoid rocks, mafic and intermediate gneiss, and foliated granodiorite bodies.

The Algoma gneiss domain, which underlies the Proterozoic Huronian Supergroup, consists of granitic and granodioritic gneiss and migmatite, with numerous enclaves of greenstone, syenite, granodiorite, and foliated granite (Jackson and Fyon, 1991). The Algoma plutonic domain constitutes one of the largest areas of felsic plutonic rocks in the Superior province. This batholithic complex consists mainly of coarse, porphyritic, leucocratic granite, or quartz monzonite, with subordinate granodiorite. The complex was intruded at intermediate levels into the gneiss and greenstone domain. The Cartier batholith, which crops out to the north of the Sudbury structure, is part of the Algoma suite of plutonic rocks and yields an age of 2642 ± 1 Ma (Meldrum et al., 1997). In Norman Township it consists of medium- to coarse-grained, subporphyritic granite and is the dominant rock type.

The Southern province rocks in the Sudbury region consist of the Huronian Supergroup. In Parkin Township, the offset dike penetrates the Bruce and Cobalt Groups (Meyn, 1970). The Bruce Group consists of quartzite, arenite, and conglomerate of the Mississagi Formation, conglomerate and quartzite of the Bruce Formation, carbonate and interbedded siltstone of the Espanola Formation, and quartzite of the Serpent Formation. The Cobalt Group consists of well- bedded siltstone, quartzite, and conglomerate of the Gowganda Formation and quartzite of the Lorrain Formation.

Dike Rock Types

Rock types within the Whistle-Parkin offset dike can be divided. Rocks of the Whistle embayment zone consist of norite, gabbro-norite, and gabbro of the Sudbury sublayer (Pattison, 1979; Lightfoot et al., 1997a, b); rock types within the rest of the offset dike consist of radial breccia, mafic sulfide-bearing breccia, inclusion-bearing quartz diorite, and

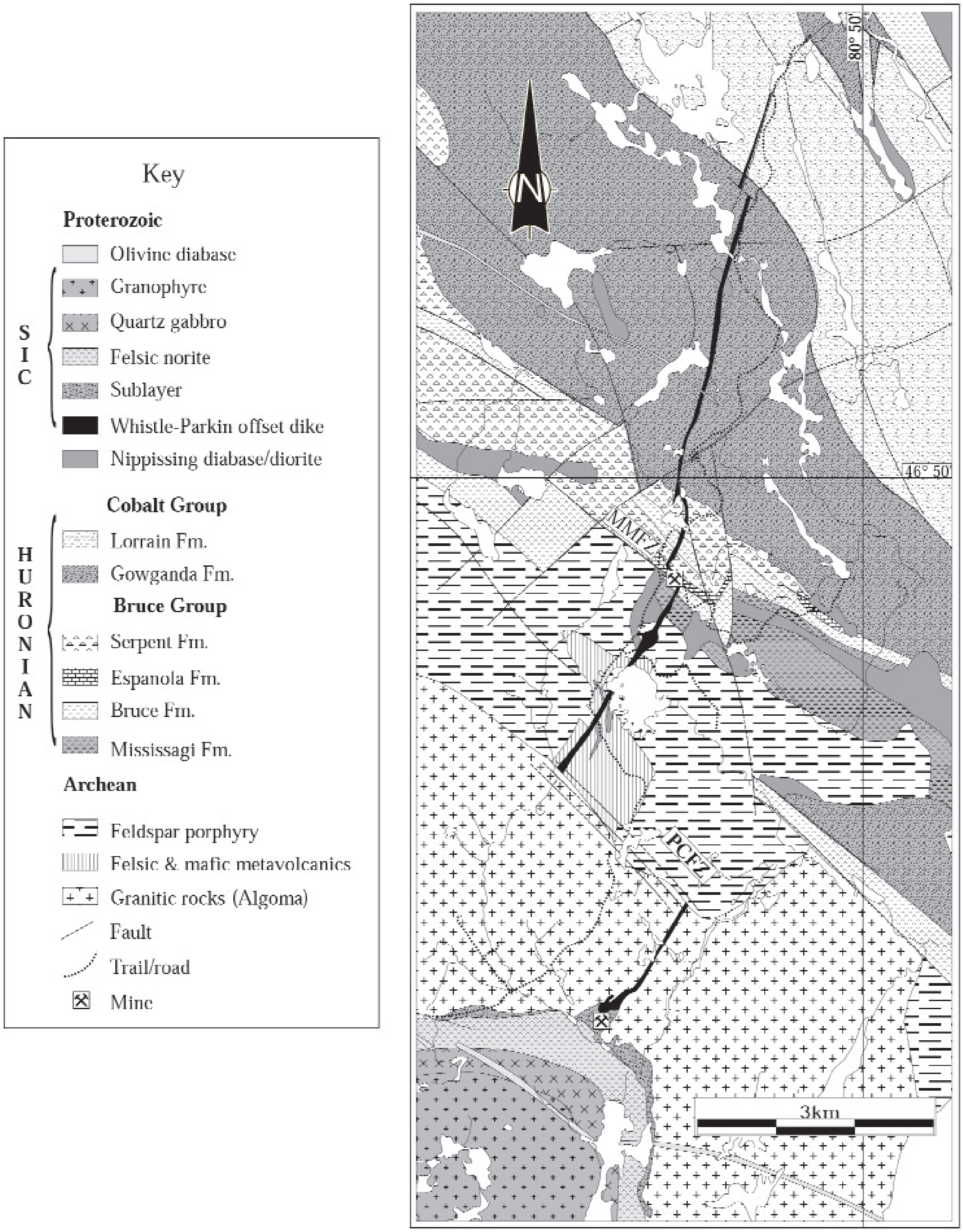

FIG. 2. Geology of the Whistle-Parkin offset dike system; MMFZ = Milnet Mine fault zone, PCFZ = Post Creek fault zone. Sources: Meyn (1970), Tirschmann and Crawford (1990), and field mapping as part of this study.

inclusion-poor quartz diorite. These units are classified on the basis of mappable field units, although contacts between them are typically gradational or diffuse.

The sublayer

The sublayer has been defined as a suite of sulfide- and inclusion-bearing norite, gabbro- norite, and gabbro (Souch et al., 1969; Pattison, 1979). The sublayer matrix is a dark, porphyritic- to poikilitic-textured, medium- to coarse-grained rock composed of unaltered clino- and orthopyroxene (10–40%), plagioclase (30–60%), variable amounts of quartz and quartz- feldspar intergrowths, and locally, primary biotite. Rare primary olivine has been reported within the Whistle embayment zone, but it is not a typical constituent of the sublayer at other localities (Pattison, 1979; Lightfoot et al., 1997a). The sublayer contains abundant inclusions dominated by melanorite, diabase, and pyroxenite. These inclusions yield ages similar to those of the sublayer and the

Sudbury structure as a whole, at approximately 1850 Ma (Corfu and Lightfoot, 1996). The sublayer is host to a major Ni-Cu sulfide deposit at the Whistle mine. The sulfides include disseminated and inclusion-bearing massive pyrrhotite with minor pyrite.

Radial breccia

The radial breccia is a heterolithic leucocratic breccia with a highly variable clast content. It is generally dark gray and siliceous (Fig. 3a). The term "radial breccia" is equivalent to the metamorphic-textured leucocratic breccia of Pattison (1979). It is also similar to the footwall breccia in appearance and has been referred to as "footwall breccia" by some workers (e.g., Grant and Bite, 1984; Lakomy, 1990). The matrix is extremely fine grained (0.01 to less than 1 mm) and is composed of predominantly feldspar and quartz (60–90%), with 10 to 40 percent biotite and other mafic minerals (pyroxene, amphibole), which are invariably altered to chlorite (Fig. 3b). This variation in mineralogy of the radial breccia matrix appears to be dependent on the local clast population.

Macroscopic clasts can make up 30 to 90 percent by volume of the radial breccia. The clast population is highly variable in both composition and shape. Clasts are angular to subrounded and vary in size from less than 10 μm (in thin section) to tens of meters. In the Parkin portion of the offset dike, 4 to 6 km from the Sudbury Igneous Complex, one gneissic clast measures at least 60 m in minimum length and approximately 25 m in maximum width. Assuming a thickness for the clast of at least 10 m and a density of 2,700 kg/m^3, the overall weight of this clast is at least 40,000 metric tons. The predominant clast composition is felsic and is generally gneissic and/or granitic, but mafic clasts are also present. Clasts typically do not represent the immediate wall-rock lithology. Fragments of the surrounding country rock occur in the radial breccia, but these make up a small percentage of the overall clast population.

Primary textures in the radial breccia are extensively obscured by secondary alteration; however, the dominant primary texture observed is fragmental. In thin section, the texture is dominated by cryptocrystalline interlocking feldspar and quartz with patches of mafic material. Partial melting can be observed, particularly at quartz and feldspar grain boundaries, resulting in the development of diffuse contacts and granophyric texture. Similar textures have been reported in the footwall breccia (Dressler, 1984; Lakomy, 1990). A number of shock features are seen in the clasts of the radial breccia, including decorated planar deformation features (DPDF) and mosaicism in feldspar.

Mafic sulfide-bearing breccia

The mafic sulfide-bearing breccia is a mesocratic heterolithic breccia. This unusual breccia is important in that it is associated with much of the sulfide mineralization in the Parkin portion of the offset dike. It is similar in appearance to the radial breccia. The matrix is very fine grained (0.01–0.2 mm) and dark gray in hand specimens. It is composed of 10 to 25 percent quartz, 30 to 45 percent feldspar, and 20 to 50 percent mafic minerals (typically amphibole), which are variably altered to biotite and/or chlorite. The mafic sulfide-bearing breccia may also contain up to 30 percent interstitial sulfides, which typically grade into more massive sulfide zones in the offset dike (Fig. 3c). The breccia matrix has a granoblastic metamorphic to subaphanitic igneous texture. This wide range in textures is due to extensive partial melting, later recrystallization, and subsequent alteration. Clasts in the mafic sulfide-bearing breccia are essentially the same as those in the radial breccia with granitic, gneissic, and mafic inclusions. They range from subangular to subrounded and are from centimeter to meter scale in size.

A suite of distinctive mafic inclusions occur in the mafic sulfide-bearing breccia. These are a feature of the mafic sulfide-bearing breccia and are rarely observed in the radial breccia. Locally they constitute 50 percent of the inclusion population. These inclusions are generally subrounded and are millimeter to approximately 30 cm in size. The majority of the inclusions are altered metapyroxenite. A similar clast population characterized by exotic mafic inclusions has been reported in the sublayer of the Whistle embayment (Farrell et al., 1995; Lightfoot et al., 1997a), but the relationship between the inclusions in the mafic sulfide-bearing breccia and the sublayer is not yet clear.

Inclusion-bearing quartz diorite

The inclusion-bearing quartz diorite has an equigranular, fine- to medium-grained matrix with a groundmass composed of 5 to 15 percent quartz, 25 to 45 percent feldspar, 30 percent hornblende (typically altered to biotite and/or chlorite), and approximately 10 percent sulfides and accessory minerals. On a fresh surface, the inclusion-bearing quartz diorite matrix is commonly dark gray in color and contains macroscopic inclusions that account for 10 to 40 percent of the rock volume (Fig. 3d). Inclusions consist predominantly of granitic and gneissic material and represent 65 to 100 percent of the total inclusion population. Other inclusions are mafic igneous, volcanic, and sedimentary fragments. The inclusions do not necessarily correspond compositionally with the country rock. They range in size from millimeter scale up to 50 cm in diameter and occur in a variety of shapes, from angular to rounded. The inclusion- bearing quartz diorite typically has a gradational relationship with the radial breccia and the mafic sulfide-bearing breccia but can also be observed in sharp contact with them. In general, the inclusion population in this quartz diorite is identical to that of the radial breccia where they are in proximity; however, the radial breccia clasts display a more brecciated texture, with fragmental clusters and higher clast concentration, whereas inclusions in the inclusion-bearing quartz diorite commonly occur isolated in the groundmass.

Inclusion-poor quartz diorite

The inclusion-poor quartz diorite is an equigranular, medium- to coarse-grained rock with a groundmass composed of 10 to 15 percent quartz, 25 to 45 percent feldspar, 30 percent hornblende (also altered to biotite and/or chlorite), 10 to 15 percent granophyre, and less than 5 percent opaques and minor sulfides (Fig. 3e). On a fresh surface, the inclusion-poor quartz diorite is typically dark gray in color and contains less than 5 percent inclusions. It is very similar to the inclusion-bearing quartz diorite matrix with respect to mineralogy and appearance; however, aside from containing few or no

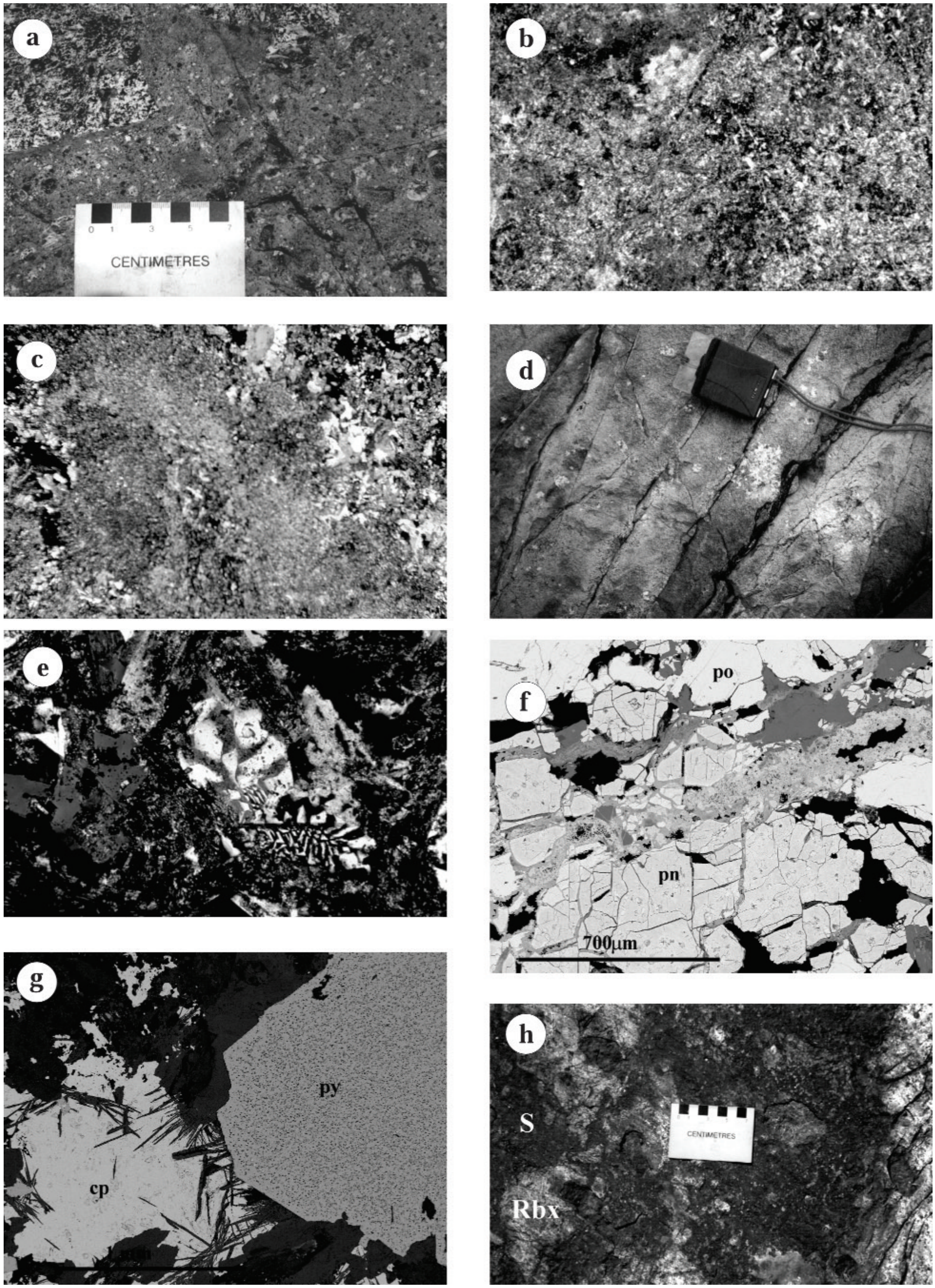

FIG. 3. a. Field photograph of the radial breccia from the Whistle zone. b. Photomicrograph of radial breccia (field of view = 2.5 mm). c. Photomicrograph of mafic sulfide- bearing breccia (field of view = 2.5 mm). d. Field photograph of inclusion-bearing quartz diorite from the Proximal Parkin zone. e. Photomicrograph of granophyric texture in altered inclusion- poor quartz diorite (field of view = 2.5 mm). f. Backscattered SEM image of fragmental sulfides in the mafic sulfide-bearing breccia; pn = pentlandite, po = pyrrhotite. g. Backscattered SEM image of sulfides in the inclusion-bearing quartz diorite; cp = chalcopyrite. h. Field photograph of sulfides (S) with clasts of radial breccia (Rbx) within sulfides from the Whistle zone.

inclusions, it does differ in a number of other respects: inclusion-poor quartz diorite contains up to 15 percent granophyric quartz-feldspar intergrowth, whereas inclusion-bearing quartz diorite contains very little or none. In general, the inclusion- poor quartz diorite is coarser grained than the inclusion-bearing quartz diorite. The inclusion- poor quartz diorite contains less than 10 percent blebby sulfides, whereas the inclusion-bearing quartz diorite contains up to 30 percent. The relationship between inclusion content and sulfides within the inclusion-bearing quartz diorite has been noted in other dikes (e.g., Copper Cliff; Grant and Bite, 1984). The inclusion-poor quartz diorite appears to crosscut most lithologies and has been seen to crosscut a clast within the radial breccia. The inclusion-poor quartz diorite has a chilled margin with the country rocks at a number of localities. This results in spherulitic textures with radiating, or sometimes aligned, laths of feldspar and chloritized amphibole. Alteration in both the inclusion-poor quartz diorite and inclusion-bearing quartz diorite is common. In general, the degree of alteration increases in the more distal portions of the dike. This alteration includes saussuritization, epidotization, and chloritization.

Whistle-Parkin Zonation

The Whistle-Parkin offset dike is divided into five zones on the basis of lithology: Whistle embayment, Whistle, Proximal Parkin, Middle Parkin, and Distal Parkin (Fig. 4). Major changes in the character of each zone are observed where the dike has been faulted. This is apparent at the Post Creek fault zone between the Whistle and the Proximal Parkin segments. The Whistle segment is dominated by fragmental breccias, whereas the Proximal Parkin is a mixture of all rocks found within the dike. Although differences between the Proximal and Middle Parkin zones are gradational, there are distinct differences between these two and the Distal Parkin zone. This difference coincides with the Milnet Mine fault zone, which has juxtaposed the two zones. To the south is the Middle Parkin zone, a mixture of all dike rocks, to the north is the Distal Parkin zone dominated by inclusion-poor quartz diorite and inclusion- bearing quartz diorite (Fig. 2).

Whistle embayment

The Whistle embayment, the site of the now defunct open-pit Whistle mine, occurs in the northeast corner of the Sudbury Igneous Complex (Fig. 4a). The open-pit excavation allowed for detailed study of the embayment environment (Farrell et al., 1995; Vujovic et al., 1995; Lightfoot et al., 1997a). The Whistle embayment is a funnel-shaped structure that is lined by footwall breccia and contains the sublayer. The country rocks at the Whistle embayment are pink porphyritic granites, migmatites, and gneisses of the Algoma terrane. The contact between the sublayer and the overlying felsic norite of the Sudbury Igneous Complex main mass is sharp. The footwall breccia is a heterolithic leucocratic breccia, similar in appearance to the radial breccia. Footwall breccia displays a variety of igneous textures that are the result of partial melting of the initial pulverized matrix, presumably due to the thermal effects of the immediately adjacent impact melt sheet (Lakomy, 1990). This melting of the footwall breccia allows for complex field relationships to be observed, where the remobilized footwall breccia intrudes the sublayer and vice versa.

Whistle zone

The Whistle zone of the dike is 2 km in length and begins at the northeast corner of the Whistle embayment (Fig. 4b). It is poorly defined spatially due to lack of exposure. Its contact with the Whistle embayment is no longer visible as it is overlain by tailings, but previous drilling by Inco Ltd. has provided information on the underlying geology. The rocks in the distal embayment consist of sublayer gabbro-norite and leucocratic gabbro-norite. Where the embayment joins the Whistle segment, inclusion-rich quartz diorite becomes the dominant rock type. Whether this is a sharp or gradational contact is not known (Lightfoot et al., 1997a). The country rock in the area consists of granitic and gneissic rocks of the Algoma and Levack terrane.

The Whistle segment north of this region is poorly exposed. It is dominated by radial breccia and mafic sulfide-bearing breccia. The radial breccia in the Whistle zone is clast choked. Clasts make up approximately 75 percent by volume of the dike at this location. The clast population can be divided into two groups: those containing exotic clasts that do not equate with the country rock, and those that equate with the country rock. Locally, clasts have been frozen during their incorporation into the radial breccia from the country rock (Fig. 5a). The contact between the radial breccia and the country rocks is gradational. This makes it difficult to establish where the Whistle segment begins or ends, and so its width can appear to range from 5 to 25 m. Pods of inclusion-bearing quartz diorite are seen in the Whistle zone, although they are not common.

The Proximal Parkin zone

The Proximal Parkin zone is located 3 to 4 km from the Sudbury Igneous Complex (Fig. 4c). It is the site of Falconbridge's Northbridge property (Tirschman and Crawford, 1990). The Proximal Parkin zone strikes at 035° and is 30 to 50 m wide. The country rocks at this location are Archean felsic and intermediate to mafic metavolcanics intruded by Nipissing metagabbro.

The dike here consists of radial breccia, inclusion-rich quartz diorite, inclusion-poor quartz diorite, and mafic sulfide-bearing breccia (Fig. 5b, c, d, e). The relationships among these rocks are chaotic and difficult to establish accurately in the field. The center of the zone is dominated by the inclusion-bearing phases—radial breccia, mafic sulfide-bearing breccia, and inclusion-bearing quartz diorite. Inclusion-bearing quartz diorite is the dominant rock type in this zone. It accounts for 30 to 50 percent of the zone and generally has a sharp contact with the inclusion-poor quartz diorite, although gradational contacts are seen locally. Inclusion-poor quartz diorite typically occurs at the edge of the dike in contact with the country rock, where it has a chilled margin, but it also occurs as isolated pods within the inclusion phases. Inclusion- bearing quartz diorite is sometimes in contact with the country rock, but where this is the case, a chilled margin is not observed. The radial breccia has a gradational relationship with the mafic sulfide-bearing breccia and the inclusion-bearing quartz diorite. Internal lithological contacts crudely

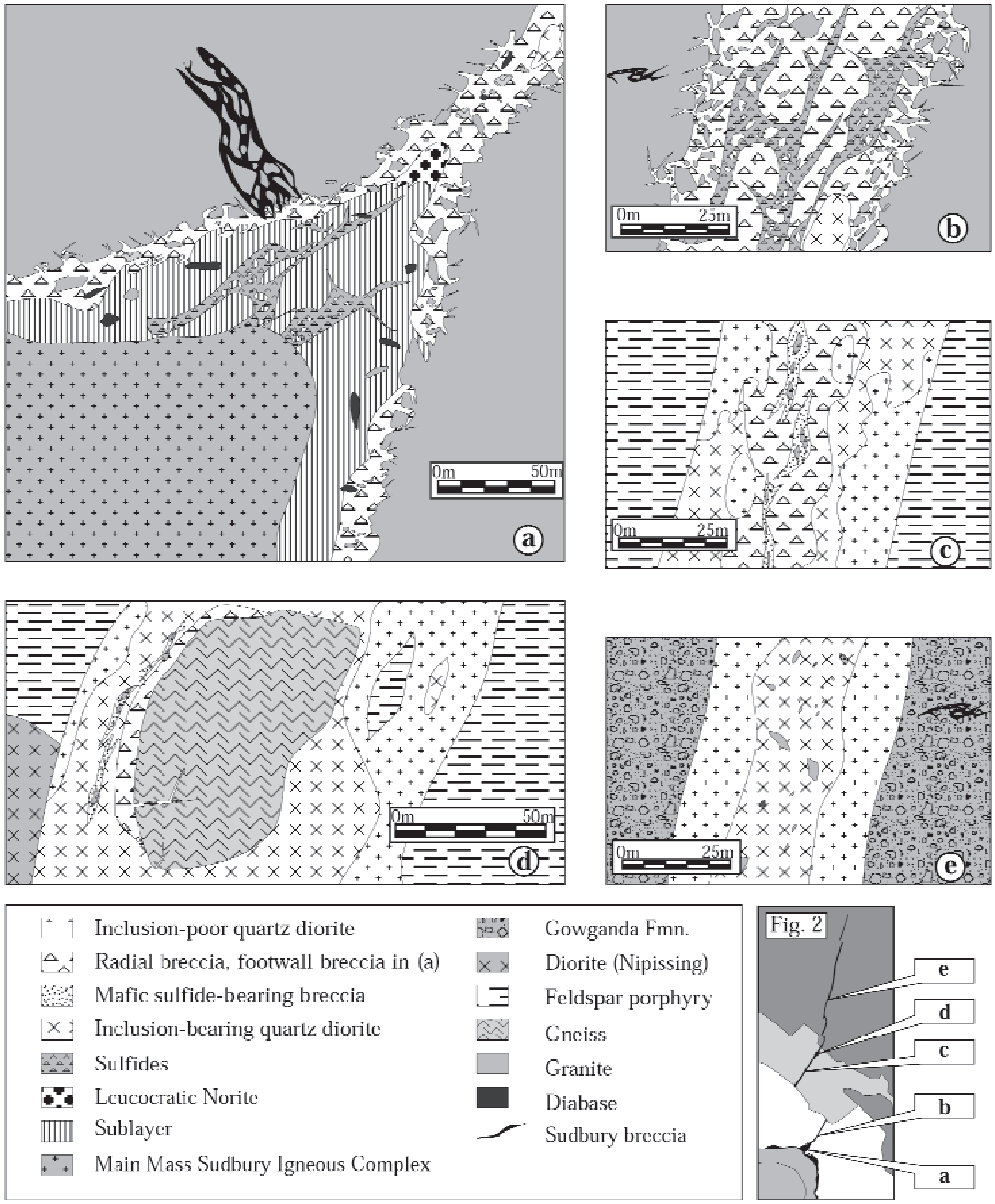

FIG. 4. Diagrammatic representation of lithological zonation in the Whistle-Parkin offset dike system. a. Whistle embayment zone (modified from Lightfoot et al., 1997a) showing the sublayer-filled embayment lined with footwall breccia. This footwall breccia grades into the radial breccia. b. Whistle zone, dominated by clast-rich radial breccia with local pods of inclusion-bearing quartz diorite. c. Proximal Parkin zone with a mix of all rock types of the dike. d. Middle Parkin zone with large gneissic megaclast. e.Distal Parkin zone with the consistent relationship of inclusion-poor quartz diorite at the edges and inclusion-bearing quartz diorite in the center of the dike.

follow the strike of the dike. Alteration in this zone is dominated by fracture-controlled epidotization. Primary mafic minerals are almost completely altered to actinolite, chlorite, and/or biotite. The feldspars display minor saussuritization.

The Middle Parkin zone

The Middle Parkin zone is located 5 km from the Sudbury Igneous Complex just north of Malbeuf Lake (Fig. 4d). Its geology is similar to that of the Proximal Parkin zone; however, it is characterized by a 65 × 35-m gneissic megaclast. The country rocks at this location consist of Archean feldspar porphyry and diorite. The dike at this location broadens to a width of over 100 m. The reason for this change in width is possibly related to the presence of the megaclast (Fig. 6). The gneissic megaclast is rimmed by a layer of radial breccia of variable thickness and is brecciated by it. The radial breccia is

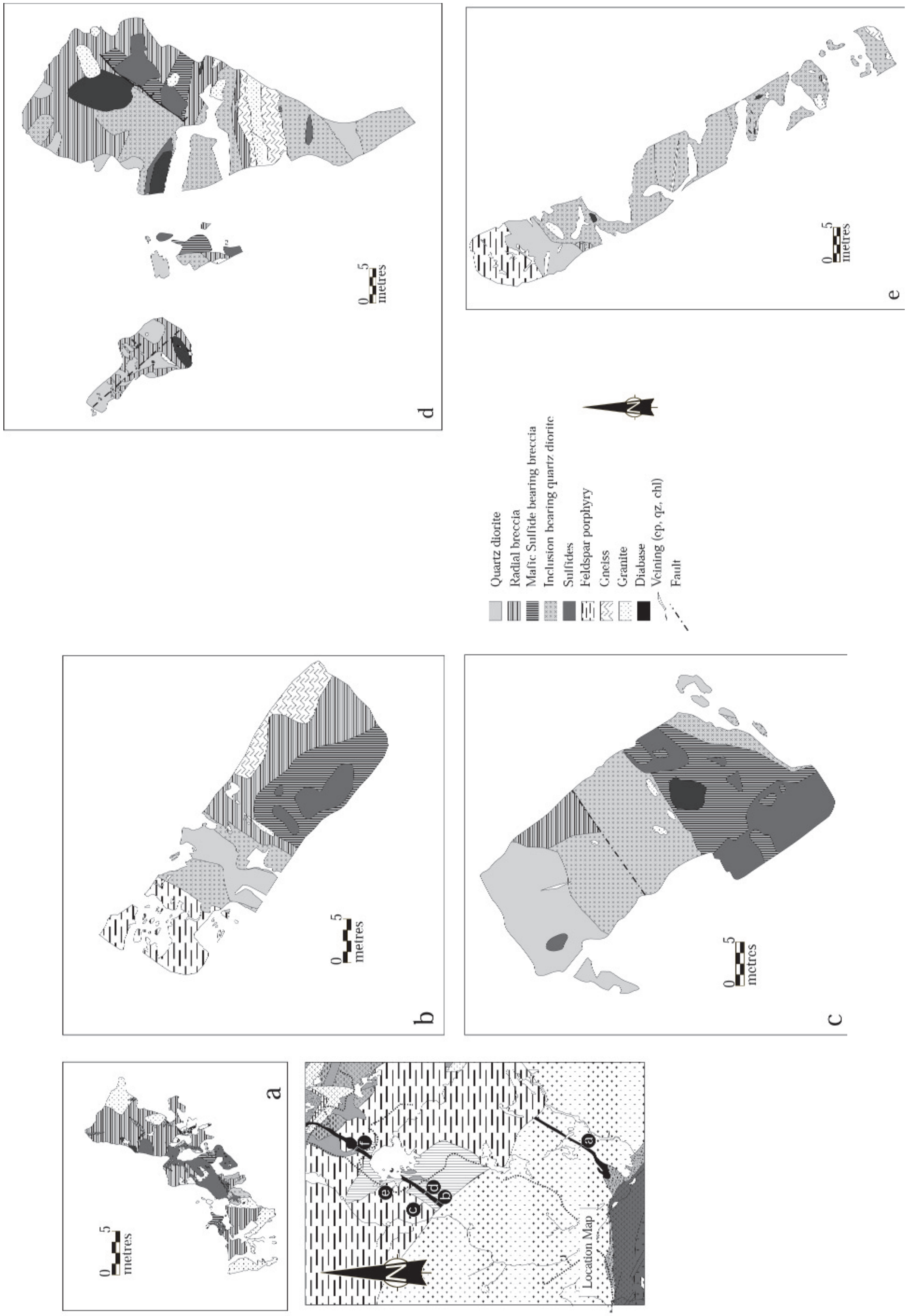

FIG. 5. Maps of trenches in Whistle zone (a) and in the Proximal Parkin zone (b, c, d, and e). The Middle Parkin zone is shown in Figure 6.

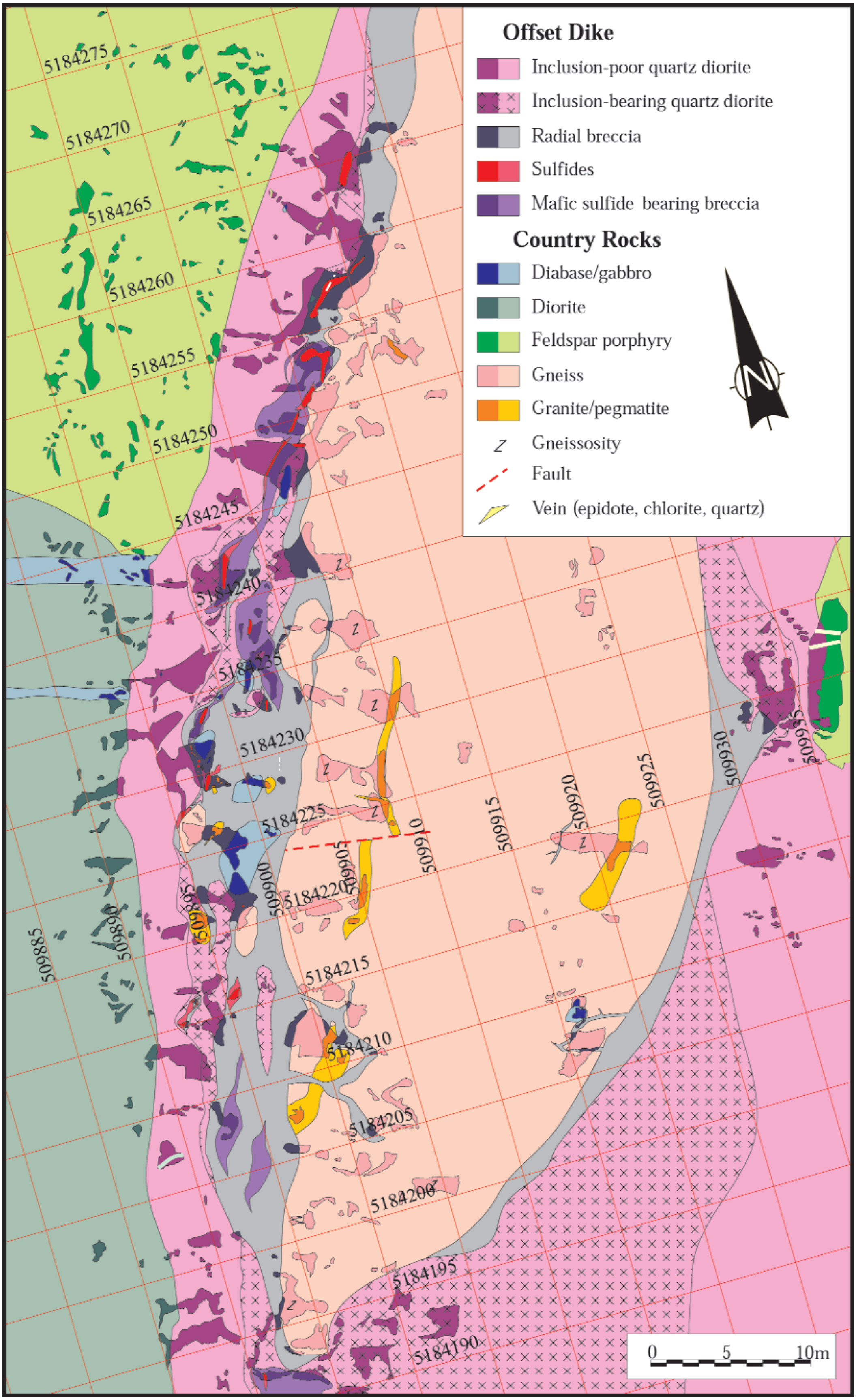

FIG. 6. Detailed geology of the Brady trench in the Middle Parkin zone. See Figure 5 for location map.

also seen as intrusive veins. Radial breccia, mafic sulfide-bearing breccia, and inclusion-bearing quartz diorite all occur between the megaclast and the inclusion-poor quartz diorite, the latter having a chilled contact with the country rock. The internal contacts between the inclusion-bearing phases are subparallel to the strike of the dike.

The Distal Parkin zone

The Distal Parkin zone is the least complex of all the dike segments (Fig. 4e). It has a width of 40 to 50 m, a dip of 80° E to subvertical, and a strike of 020°. The Distal Parkin zone penetrates several units of the Huronian Supergroup, namely Espanola Formation limestone, Serpent Formation quartzite and arenite, Gowganda Formation siltstone, and Lorrain Formation quartzite.

The Distal Parkin zone is composed of inclusion-bearing quartz diorite and inclusion- poor quartz diorite. In general the inclusion-bearing quartz diorite occupies the center of the zone, and the inclusion-poor quartz diorite occupies the margins (Fig. 7). This internal structure is consistent with what is reported in many of the other radial offset dikes (e.g., Worthington; Lightfoot et al., 1997a; Foy; Tuchscherer and

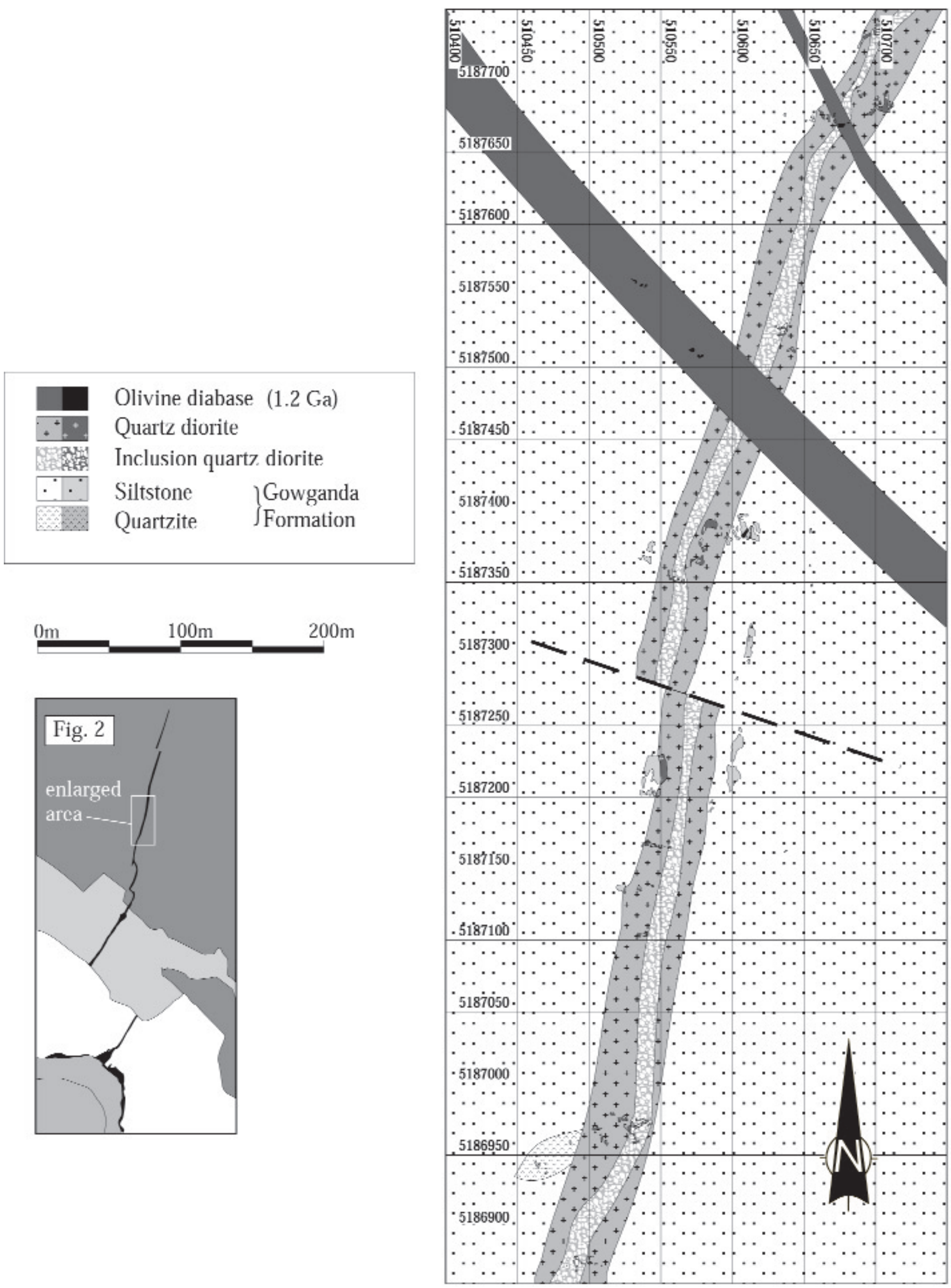

FIG. 7. Geology of the Distal Parkin zone.

Spray, 2002). There is a relative increase in abundance radially outward from the Sudbury Igneous Complex, with a relative decrease in inclusion-bearing quartz diorite. The clast population in the inclusion-bearing quartz diorite at the Distal Parkin is similar to that of the inclusion-bearing quartz diorite throughout the dike. Clasts are predominantly granitic and gneissic (accounting for approximately 70% of the clast population). Mafic igneous, metavolcanic, and locally derived clasts account for approximately 30 percent of the clast population. Clasts are rounded to subrounded and vary in size from submillimeter scale up to 50 cm. The majority of clasts show evidence of thermal erosion, with margins of clasts showing evidence of resorbtion into the inclusion-bearing quartz diorite melt. The contact of inclusion-poor quartz diorite with the country rock is sharp and typically chilled. The Gowganda Formation siltstone is hornfelsic where in contact with the inclusion-poor quartz diorite, making the contact in places difficult to define.

Alteration effects in the inclusion-bearing and the inclusion-poor quartz diorite in the Distal Parkin zone are ubiquitous. In some cases, all of the feldspars have been saussuritized; pyroxenes and amphiboles have been chloritized. Sericitization, epidotization, and carbonization are also common forms of alteration.

Geochemistry

Sampling and analysis

Out of a total of 319 samples collected over three field seasons, 30 were selected for geochemical analysis (Table 1). Major, trace, and rare earth element (REE) analysis was performed on all rock samples. Twenty-seven samples were lithologies from the offset dike (including a granitic clast in the radial breccia). Two samples of granite and one of feldspar porphyry were also analyzed from the country rock.

Samples of 1 to 2 kg were washed and crushed using a soft steel plate jaw crusher at the rock preparation laboratory at the University of New Brunswick. Care was taken in selecting chips for the inclusion-bearing rocks to ensure that matrix and not (obvious) inclusions were sampled. The chips were then powdered in a soft steel ring mill.

Samples AM13 to AM105 (excluding AM47) were analyzed at Memorial University, Newfoundland, whereas samples AM47 and AM161-289 were analyzed at XRAL Laboratories, Ontario. The major element oxides were analyzed using wavelength dispersive XRF on fused glass disks. Problems occurred with samples AM49, 55, 95, and 104 due to high sulfur levels. Trace element and REE analyses were performed using inductively coupled plasma-mass spectrometry (ICP-MS). Lead fire assays were performed on XRAL samples to determine Au, Pt, and Pd values.

Major elements

The major element data do not reveal distinct differences between the various dike lithologies. The SiO_2 contents of the inclusion-bearing quartz diorite matrix range from 55 to 61 wt percent, whereas the inclusion-poor quartz diorite contains 53 to 61 wt percent SiO_2. The radial breccia samples contain 60 to 71 wt percent SiO_2, somewhat higher than the values of the inclusion-poor and inclusion-bearing quartz diorite. The mafic sulfide-bearing breccia contains between 55 and 60 wt percent SiO_2. All rock types are intermediate in composition (Table 1). When the major element concentrations are averaged for specific dike lithologic units, values similar to the average of other offsets are obtained (see Lightfoot et al., 1997a). A bivariate plot for the major elements of the Whistle-Parkin offset reveals a decrease in Fe_2O_3, CaO, MgO, and TiO_2 and an increase in K_2O and Na_2O with increasing SiO_2 (Fig. 8).

On a quartz-alkali feldspar-plagioclase (QAP) diagram, the majority of dike rocks fall within the granodiorite field, as do rocks of many other offset dikes (e.g., Worthington, Lightfoot et al., 1997a; Hess, Wood and Spray, 1998; Foy, Tuchscherer and Spray, 2002). The radial breccia and mafic sulfide-bearing breccia samples plot as tonalites, along with one of the inclusion-poor quartz diorite samples. A single inclusion-bearing quartz diorite sample (AM46) plots as a quartz monzonite and two samples plot as a quartz monzodiorite (Fig. 9a). On an AFM diagram the majority of samples plot as a linear trend in the calc-alkali field, with three inclusion-bearing quartz diorite samples plotting in the tholeiitic field (Fig. 9b).

Rare earth elements

When the REE data are normalized to type 1 carbonaceous chondrite values (Taylor and McLennan, 1985), the profile for the dike lithologies exhibits a slight negative Eu anomaly (Fig. 10a). This is common for many offset dike lithologies (Lightfoot et al., 1997a; Wood and Spray, 1998). When normalized against average Sudbury Igneous Complex samples (Lightfoot et al., 1997a), the data show a slight positive Ce and Eu anomaly and a slight negative Tb anomaly (Fig. 10b). Overall, however, the Whistle-Parkin dike rocks, particularly the inclusion-poor and inclusion-bearing quartz diorite phases, show remarkable similarity to the average REE concentrations in Sudbury Igneous Complex samples. The REE profiles in the mafic sulfide- bearing breccia and radial breccia show an overall negative slope relative to those of average Sudbury Igneous Complex samples, but retain evidence of the Ce, Eu, and Tb anomalies (Fig. 10c). The inclusion-bearing quartz diorite samples show somewhat greater variation

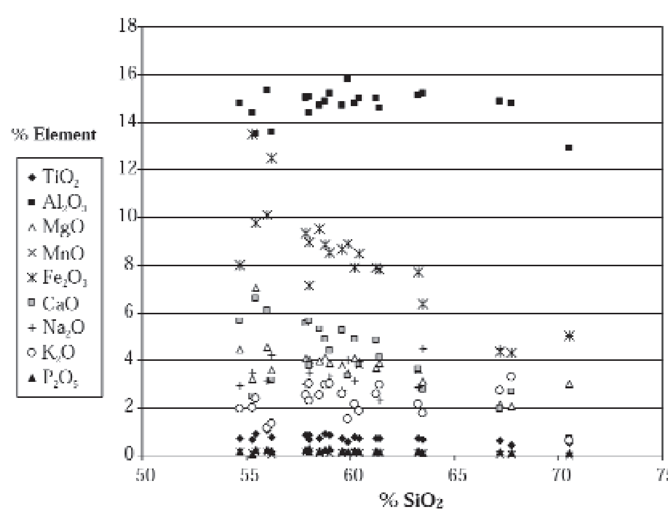

FIG. 8. Multi-element Harker plot for dike rock types.

Table 1. Geochemical Analyses of Selected Lithologies from the Whistle-Parkin Offset Dike

Sample no. Identity	AM47 RBX	AM161 IQD	AM164 IQD	AM165 QD	AM219 QD	AM229 IQD	AM231 QD	AM232 QD	AM257 RBX	AM261 RBX	AM264 QD	AM266 QD	AM273 MSBB	AM287 MSBB	AM289 QD
Wt %															
SiO_2	63.5	58	59	58.8	56.2	56	54.7	58	60.4	67.2	60.2	59.6	59.9	55.3	58.5
TiO_2	0.673	0.838	0.879	0.889	0.773	1.038	0.74	0.678	0.722	0.629	0.756	0.742	0.581	0.691	0.723
Al_2O_3	15.2	15.1	15.2	14.9	13.6	15.3	14.8	14.4	15	14.9	14.8	14.7	15.8	14.4	14.7
MgO	3.09	4	3.88	4.1	3.61	4.55	4.43	3.9	3.8	2.16	4.07	3.78	3.43	3.19	3.95
MnO	0.08	0.13	0.11	0.14	0.06	0.16	0.12	0.13	0.1	0.05	0.12	0.11	0.09	0.11	0.11
Fe_2O_3	6.39	8.95	8.51	8.85	12.5	10.1	8.01	7.14	8.48	4.34	7.9	8.65	8.91	13.5	9.52
CaO	2.78	5.67	4.4	4.88	3.15	6.07	5.65	3.77	3.82	1.97	4.86	5.25	3.37	2.5	5.3
Na_2O	4.49	3.5	3.28	2.98	4.21	3.13	2.94	2.48	3.92	4.48	3.12	2.72	4.02	3.5	2.52
K_2O	1.78	2.29	3	2.96	1.34	1.15	1.94	3	1.87	2.71	2.16	2.6	1.52	2.02	2.55
P_2O_5	0.1	0.3	0.28	0.24	0.18	0.24	0.18	0.15	0.15	0.13	0.2	0.2	0.15	0.06	0.19
L.O.I.	1.9	1.15	1.4	1.3	2.55	2.2	6.55	6.45	1.75	1.4	1.7	1.5	2.25	3.6	1.7
Sum	100.2	100.1	100.2	100.2	98.3	100.1	100.2	100.2	100.2	100.3	100.1	100.1	100.1	99.1	99.9
Ppm															
La	58.1	44	46.8	43.5	27	35.2	34.1	38.7	43.3	49.7	40.6	38.8	21.5	68.3	39.5
Ce	112	89.8	95.7	88.1	56.2	72.3	67.7	77.1	86.7	95.7	81.1	76.6	44.2	138	78.5
Pr	12.5	10.9	11.5	10.5	6.6	8.7	8	9	9.8	10.3	9.6	9.4	5.2	15.6	9.3
Nd	42.5	40.5	43	38.9	24.4	33.9	29.6	32.2	34.9	33.8	34.9	32.5	18.7	52.8	33.1
Sm	6.6	7.5	7.6	7.3	4.5	6.6	5.5	5.8	5.8	5	6.6	6.2	3.5	7.9	6.2
Eu	1.66	1.96	2.08	1.8	1.22	1.82	1.54	1.51	1.62	1.43	1.71	1.77	1.06	1.42	1.65
Gd	4.3	6	6.4	5.9	4.1	6.1	4.5	4.7	4.1	3.4	5.5	5.1	2.7	4.7	5
Tb	0.5	0.9	0.9	0.9	0.6	0.9	0.7	0.7	0.6	0.5	0.8	0.9	0.4	0.5	0.7
Dy	2.2	4.2	4.5	4.4	3.6	5.3	3.7	3.7	2.6	2	4.3	3.9	2	1.8	3.9
Ho	0.42	0.82	0.86	0.93	0.72	1.06	0.74	0.7	0.47	0.39	0.83	0.89	0.4	0.3	0.78
Er	1.1	2.2	2.5	2.5	2	3	2.1	2	1.4	1.1	2.4	2.2	1.1	0.8	2.2
Tm	0.1	0.3	0.4	0.4	0.3	0.4	0.3	0.3	0.2	0.2	0.3	0.4	0.2	-0.1	0.3
Yb	0.9	2	2.1	2.2	1.9	2.9	1.9	1.9	1.2	1.1	2.2	2	1	0.6	2
Lu	0.12	0.29	0.32	0.31	0.28	0.43	0.28	0.26	0.16	0.15	0.35	0.32	0.17	0.08	0.3
Th	19.2	7.7	8.2	8.9	9.1	6.8	7	8.9	14.3	22	9.6	8.7	4.2	27.5	8.5
U	1	1.2	1.4	1.6	1.5	1.2	1.4	1.7	1.1	0.9	2.1	1.9	0.8	1.1	1.8
Rb	40	64	85	75	82	34	67	89	57	49	62	84	52	85	92
Sr	428	511	459	433	169	426	449	232	389	322	483	455	395	332	448
Nb	11	10	9	10	12	9	10	10	10	11	11	10	7	16	10
Zr	187	173	191	184	155	154	135	181	207	519	162	164	132	226	154
Y	9	19	20	22	17	25	18	18	12	9	20	19	9	6	19
Ba	791	908	1,120	1,100	262	596	737	1,030	685	1,280	896	937	449	491	661
Ppb															
Au	6	14	4	2	278	5	3	2	34	1	15	37	85	275	334
Pt	14	27	12	<10	675	<10	<10	<10	78	<10	22	70	71	960	697
Pd	17	26	6	<1	658	1	<1	1	71	<1	77	168	86	996	724

with the average Sudbury Igneous Complex values (Fig. 10d). The inclusion-poor quartz diorite samples plot very close to the average REE concentrations in Sudbury Igneous Complex samples (Fig. 10e). Although there are significant variations among the various units in the dike, the average composition of these units is similar to that of average Sudbury Igneous Complex samples and suggests that they represent the bulk composition of the melt sheet as has been previously suggested in Lightfoot et al. (1997b). This is further supported by an Sm versus La plot of the dike lithologies (Fig. 11), which shows the Whistle-Parkin values plotting well within the array of the main mass of the Sudbury Igneous Complex, as defined by Lightfoot et al. (1997a); however, when the inclusion- poor quartz diorite is taken alone, it plots in the composition between the main mass mafic norite and the main mass granophyre. This is to be expected if we assume that the inclusion-bearing phases (inclusion-bearing quartz diorite, radial breccia, and mafic sulfide-bearing breccia) represent a heterogeneous mix of target lithologies, whereas the inclusion-poor quartz diorite represents a homogenized mix of the target lithologies (i.e., bulk impact melt).

Sulfides of the Whistle-Parkin Offset Dike

Sulfides in the radial breccia are composed of blebby and locally disseminated pyrrhotite, chalcopyrite, and pentlandite. These typically occur as fragmental sulfides within the breccia. Sulfides in the mafic sulfide-bearing breccia are composed predominantly of chalcopyrite, pyrrhotite, and minor pyrite. Pyrrhotite and pyrite occur as interstitial and fragmental sulfides (Fig. 3f), whereas chalcopyrite, pyrrhotite, and pyrite all occur as disseminated and stockwork vein sulfides. Sulfides in the inclusion-bearing quartz diorite are composed of blebby to disseminated chalcopyrite and pyrrhotite (Fig. 3g). Economic sulfides (1.9–3.9 wt % Ni,

TABLE 1. *(Cont.)*

Sample no. Identity	AM13 FP	AM17 RBX	AM20 QD	AM31 IQD	AM41 IQD	AM43 IQD	AM46 IQD	AM49 MSBB	AM53 GRT	AM55 QD	AM76 GRT	AM95 QD	AM100 GRT-CL	AM104 QD	AM105 RBX
Wt %															
SiO_2	70.03	63.25	61.27	61.39	55.44	57.86	67.72	0.00	77.66	0.00	71.85	0.00	70.61	0.00	70.55
TiO_2	0.44	0.74	0.73	0.72	0.89	0.86	0.43	0.00	0.03	0.00	0.17	0.00	0.15	0.00	0.52
Al_2O_3	15.94	15.14	14.99	14.60	13.52	15.05	14.80	0.00	12.14	0.00	14.20	0.00	15.07	0.00	12.93
MgO	2.23	3.60	3.67	3.88	7.02	4.05	2.06	0.00	0.15	0.00	0.69	0.00	0.57	0.00	3.00
MnO	0.03	0.11	0.12	0.11	0.16	0.12	0.05	0.00	0.01	0.00	0.02	0.00	0.02	0.00	0.02
Fe_2O_3	2.17	7.71	7.90	7.81	9.79	9.32	4.29	0.00	0.57	0.00	2.28	0.00	1.59	0.00	5.05
CaO	1.05	3.65	4.86	4.11	6.62	5.56	2.67	0.00	0.29	0.00	0.94	0.00	0.91	0.00	0.72
Na_2O	5.76	2.90	2.64	2.31	2.48	3.00	3.28	0.00	2.25	0.00	3.09	0.00	4.50	0.00	5.01
K_2O	1.30	2.14	2.58	2.96	2.39	2.52	3.29	0.00	5.05	0.00	4.34	0.00	4.13	0.00	0.64
P_2O_5	0.14	0.19	0.18	0.16	0.23	0.26	0.11	0.00	0.00	0.00	0.07	0.00	0.05	0.00	0.10
L.O.I.	1.51	2.65	1.92	2.15	1.65	1.35	0.99		0.64	1.55	0.96	5.52	0.51	2.44	1.47
Total	99.17	99.56	99.07	98.19	98.72	98.77	98.88	0.00	98.23	0.00	97.81	0.00	98.02	0.00	98.58
Ppm															
La	14.36	36.94	33.40	37.63	63.08	38.69	55.40	38.49	3.70	36.69	25.97	35.06	29.54	37.41	17.66
Ce	30.59	73.83	67.08	74.52	122.04	79.68	107.43	77.11	5.77	73.73	52.57	70.12	54.79	74.82	34.51
Pr	3.57	8.36	7.67	8.45	14.01	9.32	11.62	8.52	0.71	8.40	5.56	8.00	5.65	8.52	4.18
Nd	13.05	31.15	28.90	31.47	52.92	36.12	40.98	30.94	2.49	31.48	18.52	29.90	19.28	32.17	16.46
Sm	2.37	5.73	5.36	5.62	9.44	6.54	6.23	5.13	0.60	5.66	2.68	5.48	2.61	5.96	3.25
Eu	0.72	1.43	1.33	1.27	1.87	1.63	1.37	1.06	0.14	1.39	0.72	1.32	0.83	1.48	0.73
Gd	1.75	4.44	4.24	4.29	7.05	5.07	4.03	3.43	0.54	4.48	1.48	4.29	1.26	4.66	2.88
Tb	0.22	0.61	0.59	0.59	0.86	0.61	0.43	0.37	0.08	0.58	0.16	0.56	0.10	0.61	0.40
Dy	1.15	3.53	3.44	3.35	4.63	3.40	2.16	1.83	0.48	3.38	0.77	3.29	0.43	3.54	2.51
Ho	0.20	0.70	0.69	0.66	0.95	0.72	0.43	0.36	0.11	0.74	0.14	0.70	0.07	0.77	0.58
Er	0.57	2.16	2.08	1.99	2.79	2.12	1.21	0.99	0.32	2.23	0.39	2.12	0.18	2.31	1.85
Tm	0.08	0.29	0.28	0.26	0.36	0.27	0.15	0.12	0.04	0.30	0.05	0.28	0.02	0.31	0.26
Yb	0.46	1.83	1.76	1.64	2.24	1.69	0.95	0.68	0.27	1.86	0.27	1.75	0.14	1.96	1.69
Lu	0.07	0.28	0.26	0.25	0.32	0.25	0.14	0.11	0.04	0.28	0.04	0.26	0.03	0.29	0.26
Th	5.20	10.73	8.55	10.17	22.01	6.38	21.84	13.65	1.77	8.64	16.31	9.04	9.05	8.66	9.33
U	0.57	3.24	0.72	2.37	0.30	2.38	1.53	0.48	1.22	2.45	0.77	1.86	-0.87	0.38	4.88
Rb	43.57	52.14	90.91	100.97	87.27	76.19	88.86	80.82	116.61	101.04	131.23	70.31	44.05	62.53	30.93
Sr	341.53	505.14	479.30	445.93	448.12	526.01	465.70	340.80	140.41	411.23	480.66	208.32	343.81	382.57	61.25
Nb	3.69	9.94	9.45	9.17	11.76	8.49	7.05	8.65	2.59	9.77	1.72	8.94	0.69	9.15	5.74
Ta	0.26	0.59	0.54	0.52	0.52	0.40	0.33	0.31	0.21	0.56	0.07	0.55	0.03	0.54	0.66
Zr	121.63	200.87	162.85	157.60	187.66	177.42	156.98	177.22	6.31	171.92	131.96	159.30	171.94	174.10	146.10
Y	5.42	18.12	17.88	16.99	24.37	18.32	10.85	8.84	2.88	18.92	3.62	17.60	1.94	19.20	14.68
Ba	463.23	805.20	698.13	796.15	859.01	866.49	1,270.02	551.15	515.75	735.67	1,143.46	874.15	3,107.12	704.08	145.88
Ga	16.69	20.61	17.51	16.88	18.80	18.56	15.39	18.18	15.11	16.21	16.34	18.64	12.90	17.57	16.99
As	<1	2.25	7.02	0.18	<1	<1	<0.1	2.06	4.95	9.11	1.96	190.70	3.54	3.44	5.75
Hf	2.98	5.27	4.29	4.15	4.79	4.55	4.18	4.73	0.29	4.42	4.09	4.38	4.91	4.76	4.31
Pb	<1	3.96	4.31	9.52	9.33	9.44	27.08	125.24	29.37	11.95	4.37	37.02	16.82	7.45	<1
Cu	19.79	49.09	36.42	168.02	106.20	125.00	55.11	5,947.32	3.48	68.72	4.11	183.67	36.71	161.27	37.02
Cr	168.56	181.86	156.52	200.27	451.26	174.59	127.56	158.39	26.26	186.75	44.44	181.92	38.69	232.89	214.63
Ni	48.53	58.60	51.67	141.85	162.66	161.61	42.51	1844.40	<1	47.27	<1	284.79	31.52	207.61	50.17
Sc	9.71	8.94	13.05	12.17	26.13	19.99	9.41	7.29	3.34	19.44	3.72	16.06	<1	11.59	13.70
V	63.78	124.39	140.28	136.07	161.36	172.73	69.33	87.34	<1	135.62	23.52	140.82	14.65	132.26	91.16
Zn	14.23	42.64	38.71	47.68	73.94	50.98	21.22	89.20	<1	39.28	3.38	75.19	3.34	35.97	<1
S	1,213.62	365.71	370.87	824.72	1,066.21	1,435.52	554.25	23,989.00	120.18	256.61	94.06	1,821.57	98.33	565.44	1,332.07
Cl	95.48	128.69	468.86	403.93	429.70	529.22	427.60	684.23	224.08	670.66	350.43	74.78	208.39	240.06	153.42

Abbreviations: FP = feldspar prophyry, RBX = radial breccia, QD = quartz diorite, IQD = inclusion quartz diorite, MSBB = mafic sulfide bearing breccia, GRT = granite, GRT-CL = granite clast

0.06–0.3 wt % Cu; Lightfoot et al., 1997c) in the sublayer at the Whistle embayment zone occur as inclusion-bearing massive pyrrhotite with minor pyrite; they strike north-northeast as irregular wedge-shaped bodies. The Whistle zone shows a relative increase in Cu, with the dominant sulfides being chalcopyrite, pyrrhotite, and millerite. These occur as massive sulfide breccia and stockwork vein sulfides. The sulfides have been found to extend to a depth of approximately 500 m (Van Weichen, 1991). The radial breccia and mafic sulfide-bearing breccia are brecciated by the sulfides (Fig. 3h). Sulfides within the Proximal Parkin zone consist of blebby sulfides, dominated by pyrrhotite, in the inclusion-bearing quartz diorite and the radial breccia. The dominant sulfide-bearing rock type in this zone is the mafic sulfide-bearing breccia, with up to 30 percent interstitial, stockwork, and more massive sulfides. These sulfides are pyrrhotite and chalcopyrite with

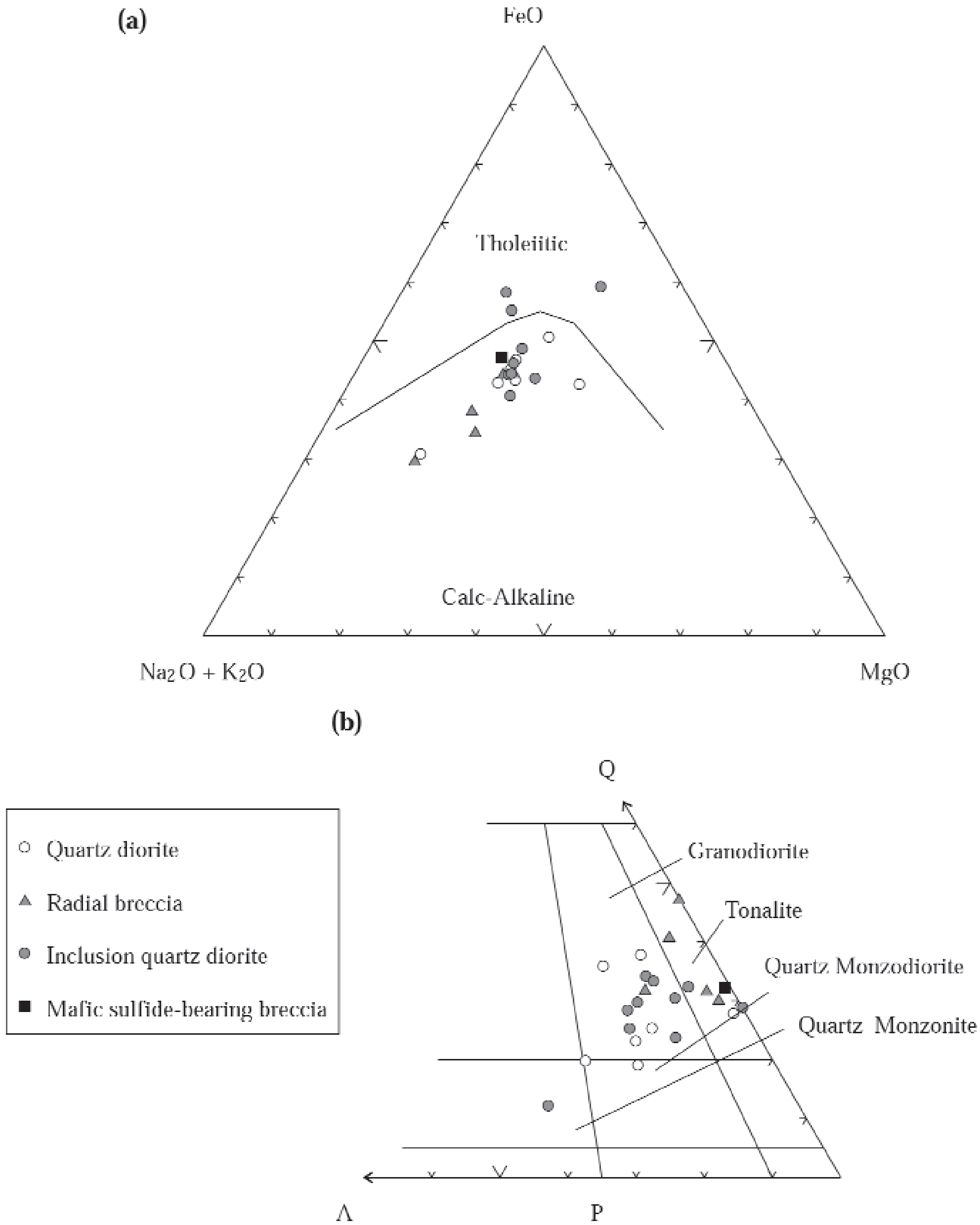

FIG. 9. AFM diagram (a) and QAP diagram (b) for dike lithologies.

minor pyrite. Sulfides in the Middle Parkin zone consist of blebby, disseminated, and stockwork pyrrhotite, chalcopyrite, and pentlandite. These occur in all the inclusion-bearing units. Considerable disseminated to massive pentlandite and pyrrhotite occur in the mafic sulfide-bearing breccia. Sulfides within the Distal Parkin zone consist of sparse blebby sulfides in the inclusion-bearing quartz diorite and inclusion-poor quartz diorite. The Distal Parkin zone is also the site of considerable quartz and ankerite veining. These veins contain disseminated chalcopyrite and pyrite that carry interstitial gold (Makela, 1989).

The blebby and disseminated sulfides that occur within the radial breccia and the mafic sulfide-bearing breccia in the Whistle and Parkin segments are commonly fragmental (i.e., they occur as fragments within the breccia), indicating early emplacement of sulfides within the inclusion-bearing phases. This is the first type of sulfides emplaced in the dike. The second type of sulfides, massive sulfides, which occur in the Whistle embayment and Whistle zones, brecciate the radial and mafic sulfide-bearing breccias, were emplaced later, and possibly settled from the main mass. The increase in Cu content moving from the Whistle embayment to the Whistle zone coincides with an increase in Cu at depth in the Whistle embayment zone (Van Weichen, 1991). Overall zoning of the sulfides in the Whistle environment indicates decreasing Cu toward the main mass. The recognition of two distinct types of sulfide ores is similar to observations in the Copper Cliff offset dike, where sulfides occur as disseminated blebs in the

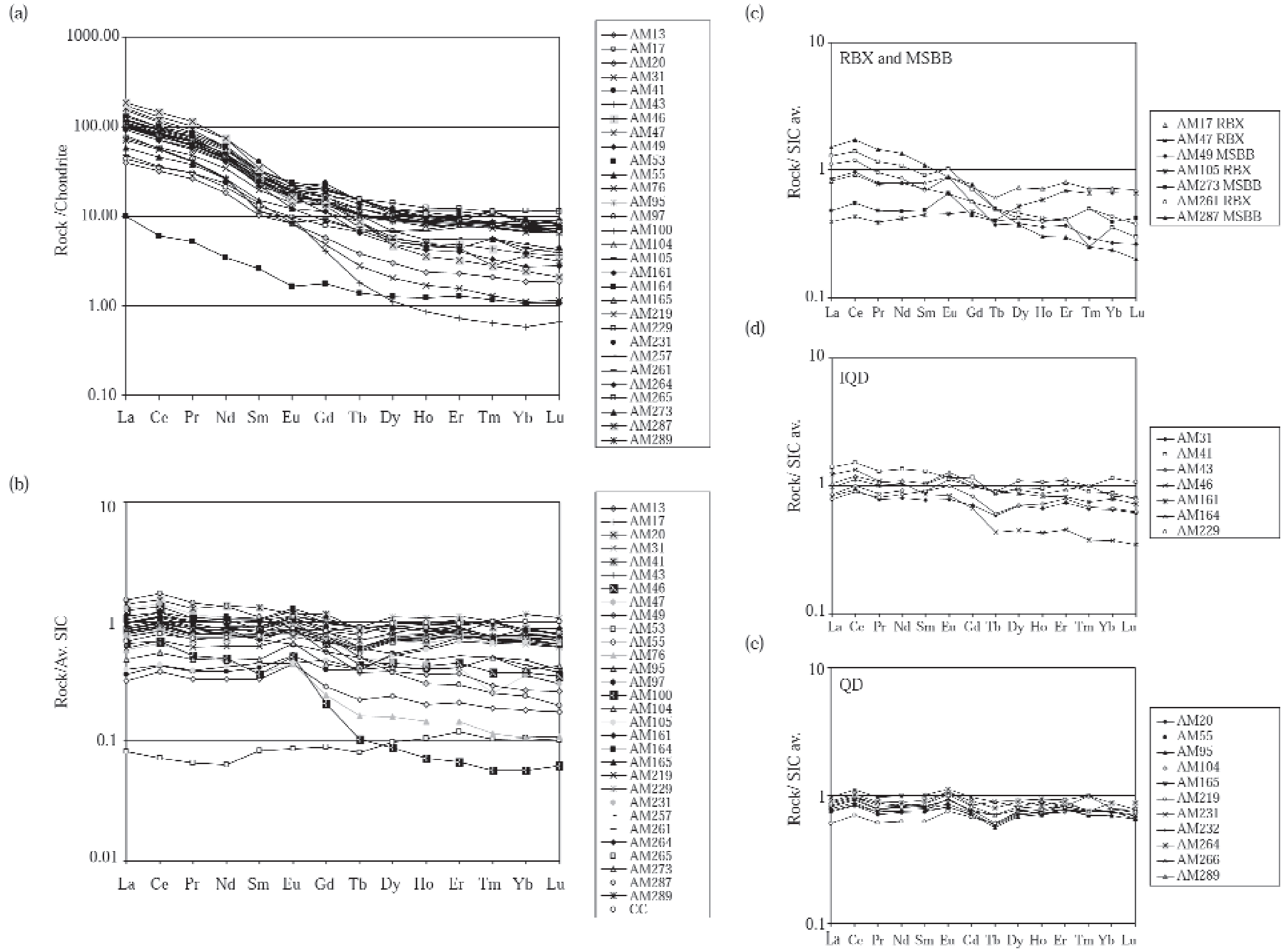

FIG. 10. a. Chondrite-normalized REE plot for all samples analyzed. b. Average Sudbury Igneous Complex (SIC)-normalized REE plot. CC = Copper Cliff offset dike c. Average Sudbury Igneous Complex-normalized REE plot for the radial breccia (RBX) and mafic sulfide-bearing breccia (MSBB). d. Average Sudbury Igneous Complex-normalized REE plot for inclusion- bearing quartz diorite. e. Average Sudbury Igneous Complex-normalized REE plot for inclusion-poor quartz diorite. Average Sudbury Igneous Complex and Copper Cliff values from Lightfoot (1997a).

quartz diorite matrix and as inclusion-bearing stringers that crosscut the quartz diorite (Cochrane, 1984).

The Whistle-Parkin offset dike has had two past producers: the Whistle mine, located within the Whistle embayment, and the Milnet mine, located within the Milnet Mine fault zone (Fig. 2).

The Whistle mine was operated, intermittently, via open-pit methods, from 1987 until 1997. During this decade of production approximately 7 Mt of ore was removed, typically grading 2 to 3 wt percent Ni, with greater than 0.2 wt percent Cu and less than 500 ppb Pt + Pd (Lightfoot et al., 1997c). The sublayer-type mineralization consisted of massive, inclusion-rich pyrrhotite ore with occasional pyrite and rare chalcopyrite stringers. The sulfides occurred in two main zones along the northwest and southeast margins of the embayment, varying in thickness from 1 to 150 m (Fig. 12). The massive sulfides contained rounded melanorite and pyroxenite inclusions (Farrell et al., 1995) and typically graded into the sublayer.

The Milnet mine was operated by Milnet Mines Ltd. from December 1952 to July 1954. During that period approximately 157,000 t of ore grading 1.5 wt percent Ni, 1.5 wt percent Cu, 800 ppb Au, and 2.4 ppm Pt + Pd was removed (Meyn, 1970). The sufides consisted of massive to disseminated pyrrhotite, pentlandite, pyrite, and chalcopyrite. The underground mine consisted of two orebodies. The orebody 1 was located about 70 m northwest of orebody 2 (Fig. 13). Both orebodies were located within brecciated and deformed limestone and quartzite of the Huronian Supergroup and Parkin inclusion-poor quartz diorite. The inclusion-poor quartz diorite at this locality is extensively deformed and altered; it is crosscut by numerous veins containing quartz, calcite, and ankerite. The Milnet Mine fault zone has apparently had an effect on the orebodies. From mine plans it can be seen that the ore and inclusion-poor quartz diorite-breccia are streaked out by the fault where the fault displaces the offset dike (Fig. 13).

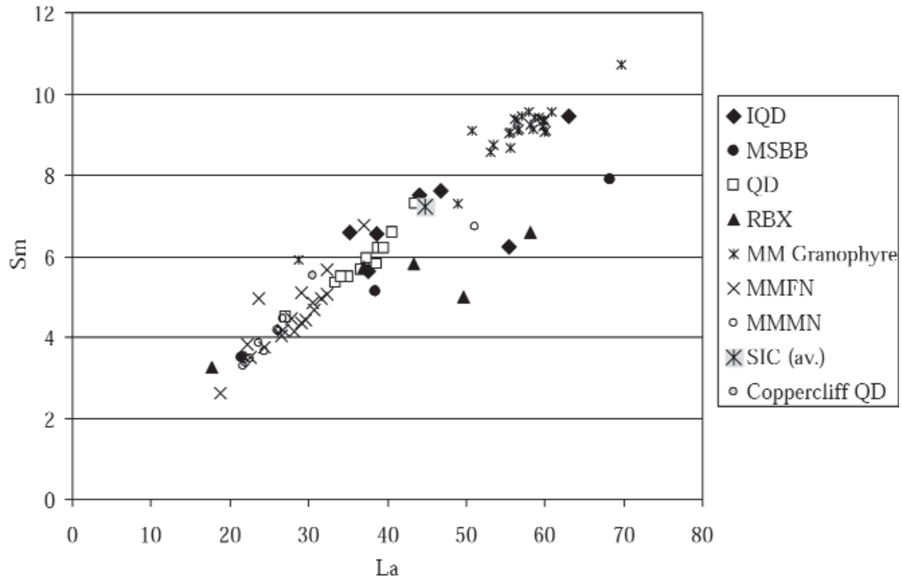

FIG. 11. Sm/La plot for different units of the Sudbury Igneous Complex and dike rocks from Whistle-Parkin. IQD = inclusion-bearing quartz diorite, MM = main mass, MMFN = main mass felsic norite, MMMN = main mass mafic norite, MSBB = mafic sulfide-bearing breccia, QD = inclusion-poor quartz diorite, SIC = Sudbury Igneous Complex. Sudbury Igneous Complex values taken from Lightfoot et al. (1997a).

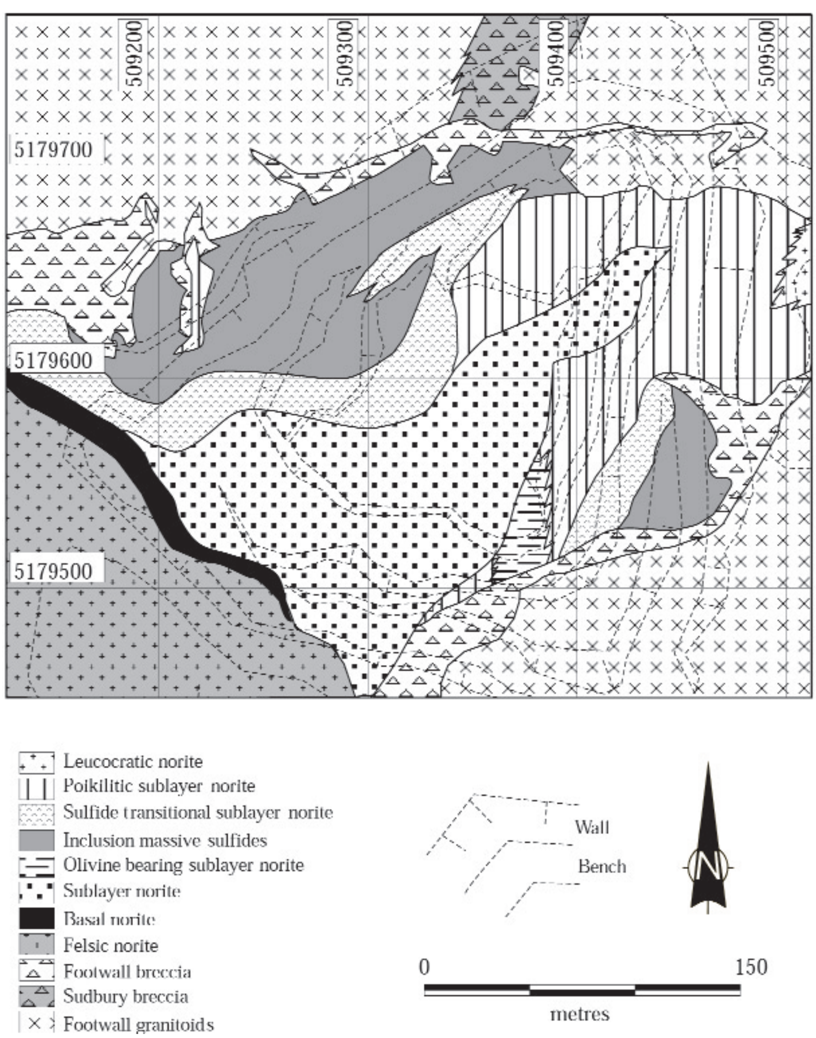

FIG. 12. Plan view of the geology and open-pit structure of the Whistle mine (modified from Lightfoot et al., 1997a).

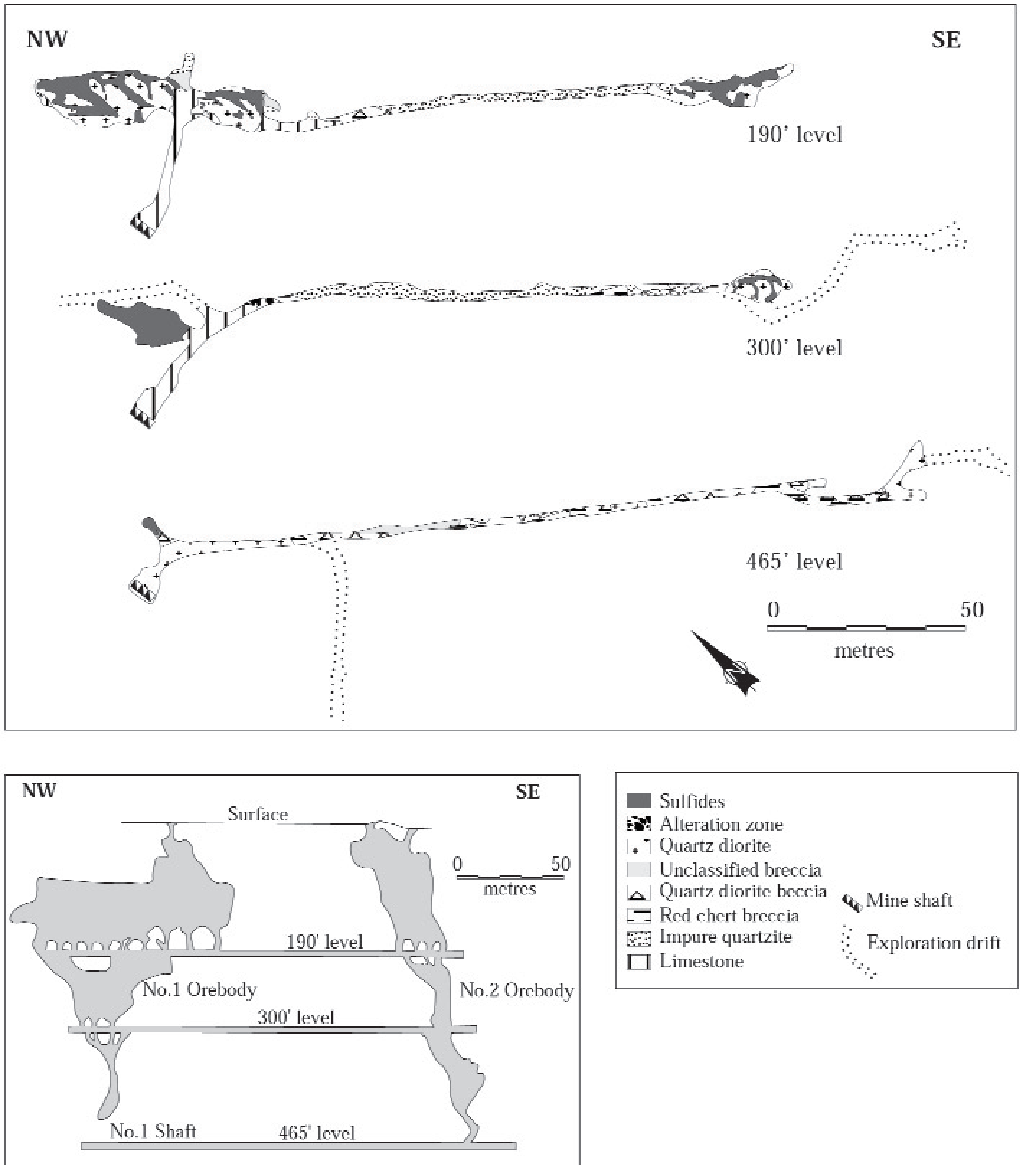

FIG. 13. Geologic cross section of the Milnet mine. Upper illustration shows simplified plan geology taken from mine plans. Lower illustration shows the shapes of the orebodies in vertical cross sectional view. Modified after Meyn (1970).

Discussion

The Whistle-Parkin offset dike, and indeed all radial offset dikes, offer unique insight into the mechanics of complex cratering. The offsets have traditionally been regarded as bodies intimately linked to the Sudbury Igneous Complex, primarily through melt descending from the overlying melt sheet while exploiting weaknesses created by the impact in radial and concentric fracture zones (Grant and Bite, 1984; Lightfoot et al., 1997a). However, detailed examination of the lithologies in the Whistle-Parkin environment reveals that the radial offsets are complex bodies.

The variable, almost chaotic, timing relationships between the inclusion-bearing dike rocks suggest that these lithologies were emplaced at the same time. This helps explain the variety and the often contradictory crosscutting relationships between them. Similarly, the fact that the clast content of the radial breccia is identical to that of the inclusion-bearing quartz diorite, where they are in proximity, is an indication that they were emplaced contemporaneously. The alignment of contacts within the dike parallel to strike represents an ordering of the dike moving radially outward and is coupled with a decreasing complexity of lithologies from the dike center to the margins. The clasts in the dike do not necessarily correspond to the wall rock in that area. The source material for these clasts is the target rock in the footwall of the crater complex, which, in the North Range, is the Levack Gneiss Complex and the Cartier granites. These rocks are found within 2 to 4 km of the Sudbury Igneous Complex in this area, yet similar clasts are found in the inclusion-bearing rocks up to 12 km from the complex. This implies considerable radial (outward and possibly downward) transport. Assuming that the megaclast at the Brady trench (Fig. 6) was transported in this manner, the sheer mass and volume (40,000 t) provides an indication of the enormous energies required to move it.

The inclusion-poor quartz diorite always has a clear, sharp contact with the other dike rocks. It crosscuts the other rock types and therefore postdates them, although by how much is unclear. The inclusion-poor quartz diorite has been observed chilled against the inclusion- bearing quartz diorite in the Foy offset (Tuchscherer and Spray, 2002); however, no such relationship was observed in the Whistle-Parkin offset dike. Isolated pods of inclusion-poor quartz diorite within the inclusion-bearing quartz diorite show an igneous contact, indicating that the inclusion-bearing quartz diorite was not solid when the inclusion-poor quartz diorite was emplaced.

The cooling history of the dike is also important in elucidating the relationships of each of the dike units. In the regions proximal to the Sudbury Igneous Complex, the lithologies display more gradational contacts and the inclusion-poor quartz diorite can occur in isolated pods, whereas in the more distal regions the only two lithologies, inclusion-poor quartz diorite and inclusion-bearing quartz diorite, are in sharp contact with each other and the inclusion-poor quartz diorite does not occur as isolated pods. This may be a function of the difference in temperature between the inclusion-poor and inclusion-bearing quartz diorite, where, in the proximal regions, there is far more mingling and possibly some mixing of the two magmas because of the relatively small temperature difference between them. In the distal regions there is very little mingling of the inclusion-poor and inclusion-bearing quartz diorites because of the larger temperature difference between them.

Conclusions

The above relationships indicate a possible multi-stage emplacement mechanism for the Whistle-Parkin offset dike (Fig. 14). Radial cracks are formed during the initial contact-compression stage of crater formation. These cracks act as zones of weakness during the excavation stage. We propose that all of the inclusion-bearing phases were emplaced simultaneously by means of preferential forceful injection into these radial cracks during the excavation stage of crater formation. This would account for the large amounts of energy required to transport megaclasts. The variation in rock types within the dike may be due to the nature of material being emplaced. It is common for melt, fragmental material, and vapor to be jetted from a cavity during crater excavation (Melosh, 1989). Some of this material would be injected into the radial crack since the excavating jet preferentially carves into the zones of weakness. The earliest injection material would be predominantly inclusion-bearing melt phases. This is due to the source of the injected material being closer to the point of impact and therefore subjected to higher shock pressures. As excavation continues, the injected material would become more fragmental in nature due to the source occurring farther from the point of impact and therefore subjected to lower shock pressures. The first types of sulfides were emplaced at this time. These were either fragmental sulfides emplaced with the breccias that were subsequently melted or blebs that came out of the injected melt.

The inclusion-poor quartz diorite is interpreted to have been derived from the melt sheet before any differentiation took place. This may have occurred during initial modification stage processes (e.g., central uplift); if so, the inclusion-poor quartz diorite in the Whistle-Parkin offset dike may be more closely related to inclusion-poor quartz diorite found in concentric dikes, such as Hess (Wood and Spray, 1998), than to the inclusion-bearing quartz diorite in the Whistle- Parkin. The REE patterns show less variation in the inclusion-poor quartz diorite than in the inclusion-bearing quartz diorite. This is probably the result of greater homogenization of the overlying impact melt sheet relative to initial injected melt. In the distal parts of the dike, the inclusion-poor quartz diorite exploited weaknesses between the dike and country rock and was injected. In the more proximal parts, the inclusion-poor quartz diorite mingled more intimately with the inclusion-bearing quartz diorite as it was injected.

Differentiation of the impact melt sheet (Sudbury Igneous Complex) to produce the sublayer followed, along with the segregation of sulfides from the melt. The sublayer rocks of the Whistle embayment zone represent the first mafic differentiate of the Sudbury Igneous Complex melt sheet. The large amount of contamination from the footwall and footwall breccia accounts for the felsic components within the sublayer. The sulfides then sink to the bottom of the melt sheet and infiltrate the offset dike and the footwall. A likely position for these sulfides to settle would be the troughlike embayment structures in the footwall, as described by Morrison (1984). This second type of sulfide derived from the melt sheet was emplaced at this time, descending as far as the Whistle zone and brecciating preexisting dike rocks. Fractionation of the sulfide melt resulted in the zonation of Cu-rich sulfides in the offset and distal footwall deposits, with the more Ni-rich sulfides located closer to the Sudbury Igneous Complex.

The sharp changes that occur in the dike across the fault offsets (i.e., the Post Creek and Milnet Mine fault zones) suggest that the main movement on these faults occurred after the emplacement of most, if not all, of the dike lithologies. These faults caused large amounts of movement, displaced the Whistle and Parkin segments, and possibly introduced the sulfides at the Milnet mine by tapping into sulfides at the base of the melt sheet, in a fashion similar to those of the South Range breccia belt (Scott and Spray, 2000).

Acknowledgments

This work forms part of a Ph.D. thesis by A.J.M. funded by a Falconbridge-Inco-Natural Science and Engineering Research Council of Canada Collaborative Research and Development grant awarded to J.G.S. The manuscript benefited from the helpful comments of Catharine Farrow, Kelli McCormick, and Phil Thurston. We are particularly grateful to Paul Binney, John Fedorowich, Tony Green, Dean MacEachern, and Mike Sweeny of the Sudbury Exploration Department of Falconbridge Ltd. and Chris Davis, Tim Lloyd, Emile Mailloux, and Bob Grant of Inco Ltd. for their guidance and encouragement during this project. The Ontario Geological Survey is thanked for logistical support. Colleen Lenehan and Derrick Budden (Geology Department, University of New Brunswick) provided excellent field assistance during the summers of 1999 and 2000, respectively.

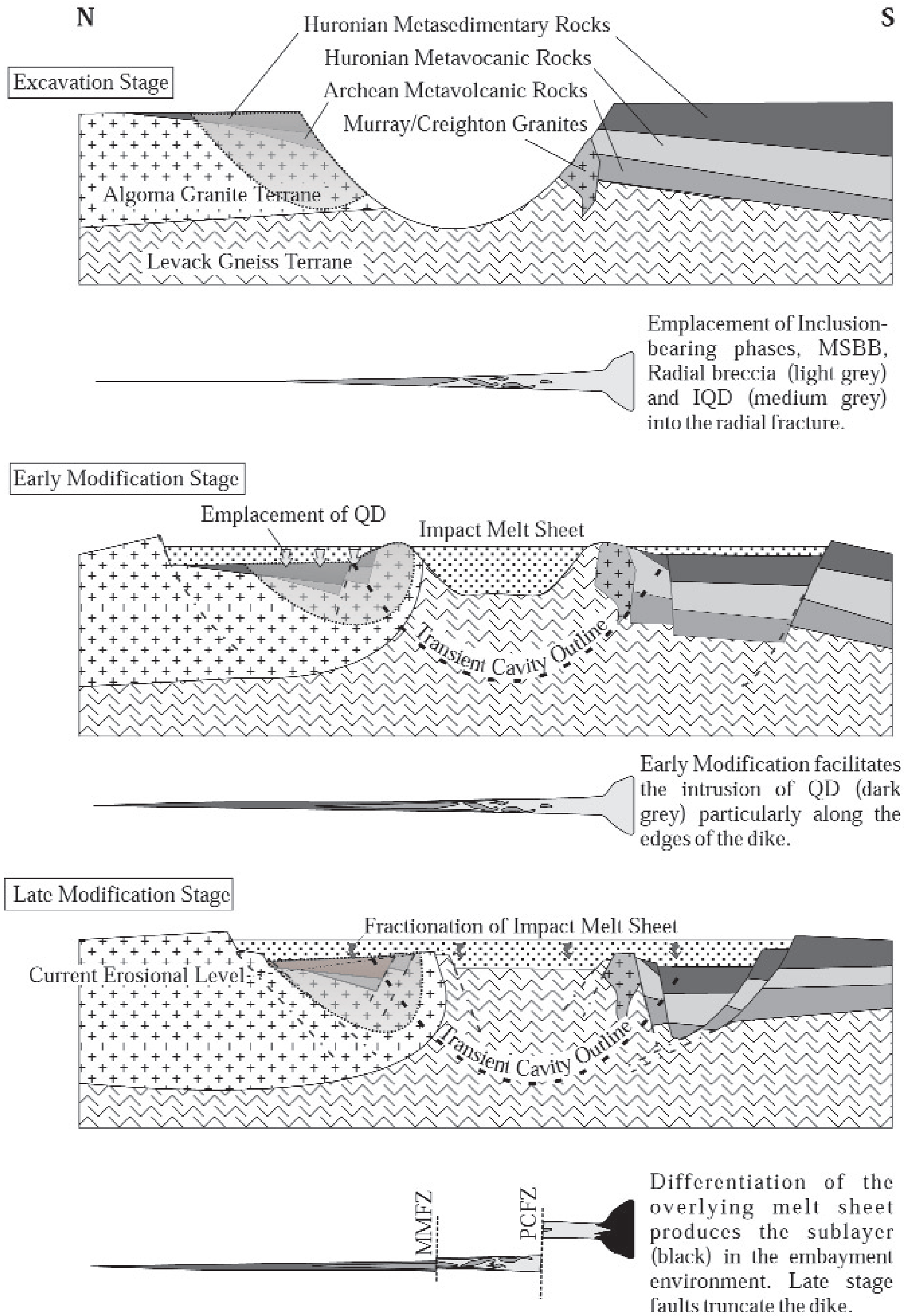

FIG. 14. Schematic diagram illustrating emplacement of the Whistle-Parkin offset dike. The dike is shown by a dotted line and highlighted in gray in cross sectional view. Beneath each cross section is the interpreted appearance of the current surface expression of the dike as it was being formed and modified during emplacement. Excavation stage shows the early emplacement of inclusion-bearing phases (mafic sulfide-bearing breccia, radial breccia, and inclusion-bearing quartz diorite). Early modification stage sees the emplacement of inclusion-poor quartz diorite, particularly along the margins of the dike concurrent with rebound of the transient cavity. During the late modification stage, as the crater is undergoing readjustments, the dike is cut by impact-related faults. The sublayer may have settled into the embayment at this time. MSBB = mafic sulfide-bearing breccia, IQD = inclusion-bearing quartz diorite, QD = inclusion-poor quartz diorite.

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