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Structural study of Sudbury breccia and sulphide veins, Levack embayment, North Range of the Sudbury structure, Ontario

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Abstract: The ca. 2.7 Ga Levack gneiss complex underlies the Levack embayment and northern part of the Sudbury structure. Sudbury breccia, a unit of centimetre- to metre-scale clasts and blocks in a fine-grained to aphanitic matrix, occurs as veinlets, veins, and irregular, disconnected, metre-wide massive bodies within wide breccia zones that cut the Levack gneiss complex. Sudbury breccia veins show no systematic orientations or displacements. Conjugate sets of chalcopyrite veins hosted by Sudbury breccia, and veins filled by hydrothermal minerals at the Barnet showing, were emplaced in tensile fractures perpendicular to the gneissic foliation. Observations suggest that the Sudbury breccia originated by in situ brecciation during propagation of impact shock waves, rather than by milling and friction melting along superfaults during collapse of impact crater walls. Sulphide veins were emplaced in tensile fractures that propagated perpendicular to gneissic foliation and coincided with hydrothermal activity.

Résumé : Le complexe gneissique de Levack, qui date d'environ 2,7 Ga, occupe le rentrant de Levack et la partie nord de la structure de Sudbury. La brèche de Sudbury, une unité formée de blocs et de clastes de dimensions centimétriques à métriques sertis dans une matrice à grain fin ou aphanitique, forme des veinules, des filons et des amas massifs (dont la taille se mesure en mètres) irréguliers et disjoints au sein de larges bandes bréchiques qui recoupent le complexe gneissique de Levack. Les filons de brèche de Sudbury ne montrent pas d'orientations ni de déplacements systématiques. Des ensembles conjugués de filons de chalcopyrite dans la brèche de Sudbury, ainsi que des filons remplis de minéraux hydrothermaux à l'indice de Barnet, sont contenus dans des fractures d'extension perpendiculaires à la foliation gneissique. Des observations laissent supposer que la brèche de Sudbury s'est formée par bréchification en place au cours de la propagation des ondes d'impact, plutôt que par broyage et fusion par friction le long de superfailles au cours de l'effondrement des parois du cratère d'impact. Les filons sulfurés ont été mis en place dans des fractures d'extension qui se sont propagées perpendiculairement à la foliation gneissique et leur formation a coïncidé avec l'activité hydrothermale.

INTRODUCTION

The Neoarchean Levack gneiss complex constitutes the footwall rocks of the Sudbury Igneous Complex (SIC) in the North Range of the Sudbury structure (Fig. 1). An impact caused extensive brecciation of the footwall rocks and produced irregular bodies of brecciated rocks, the Sudbury breccia, around the SIC (Dietz, 1964). The breccia formed either by shock waves travelling through the rocks upon impact (Kenkmann et al., 2000), by the elastic rebound of the crust after the initial impact excavation stage (French, 1998), by the collapse of crater rims along superfaults during the modification stage of the impact (Spray, 1997), or by a combination of these three processes.

The Sudbury Targeted Geoscience Initiative (TGI) is in the final year of a three-year program (2000–2003) designed to improve knowledge of the geological setting and processes involved in creating and modifying the world-renowned nickel–copper–platinum-group element (PGE) deposits of the 1850 Ma SIC (Ames et al., 2001). The PGE mineralization in Sudbury is the second most important in the world after Noril'sk, Russia (Farrow, 2001). Although exploration in Sudbury has historically focused on massive sulphide discoveries (Giblin, 1984), many new opportunities exist for Cu-PGE deposits.

Copper-PGE vein deposits (McCreedy West, McCreedy East, Strathcona deep copper zone) occupy fractures cutting through the Sudbury breccia and Levack gneiss (Morrison et al., 1994; Fedorowich et al., 1999) and are typically contained within a large zone of Sudbury breccia. Understanding the genesis and distribution of Sudbury breccia would provide useful tools and potential targets in the exploration for high-grade Cu-PGE mineralization in the footwall of the SIC. The sulphide veins 1) originated as Cu-PGE–rich sulphide melts due to sulphide immiscibility from the initial SIC sulphide melt (Li et al., 1992); or 2) they were deposited from hydrothermal fluids set into circulation by cooling of the SIC (Farrow and Watkinson, 1992); or 3) they more likely represent an integration of magmatic and high-temperature volatile activity with hydrothermal and structural modifications (Farrow and Lightfoot, 2002).

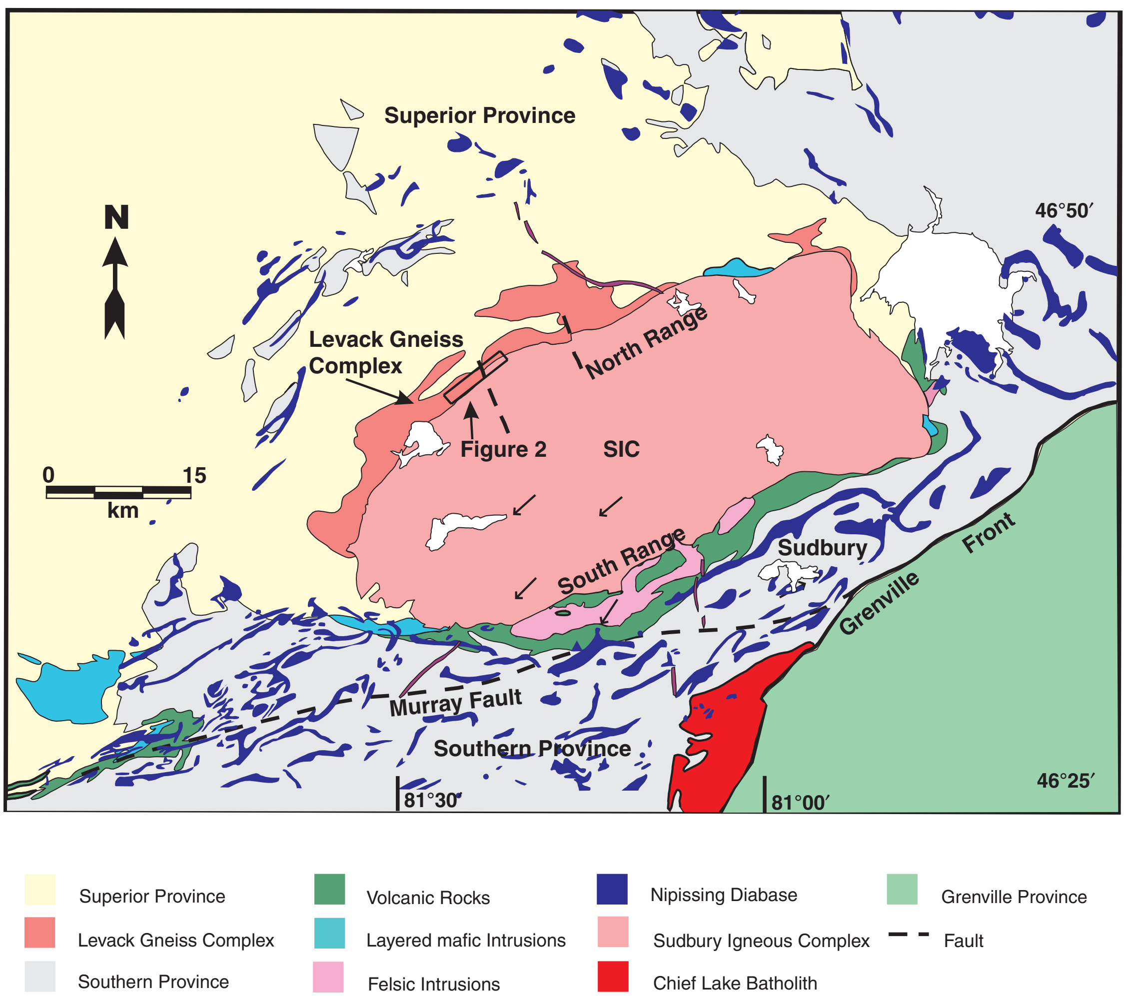

***Figure 1.** General geology of the Sudbury structure (*modified from *Rousell et al., 1997).*

The objectives of this subproject of the Sudbury TGI are to:

1. define the geometry, composition and spatial distribution of the Sudbury breccia and impact-related fractures in the Levack embayment; and
2. determine the geometry and relative timing of Cu-PGE sulphide-vein emplacement with respect to brittle deformation of footwall rocks and to the formation of epidote-chlorite±actinolite veins and potassic quartz veins.

To achieve these objectives, two summers of fieldwork were conducted to produce a 1:10 000 scale map of the footwall rocks, Sudbury breccia occurrences, and mineralized exposures of the Levack embayment, and to collect samples for geochemical analysis. Geochemical analysis of Sudbury breccia matrix and footwall rocks will be done in order to determine the relationship between host rock and Sudbury breccia, and also the association of volatiles, such as the halogens fluorine, chlorine, and bromine, with the footwall Cu-PGE veins within Sudbury breccia reported by numerous researchers (Farrow and Watkinson, 1992, 1997; Jago et al., 1994; Molnár et al., 2001; Hanley, 2002). Geochemical study of the halogen content of newly mapped (summer 2002) and already-known Sudbury breccia zones in the Levack embayment will be integrated with other studies of volatiles in the Sudbury TGI (Ames, 2002). This paper presents preliminary results from field observations of breccia zones and constraints on the Cu-PGE vein orientations.

GENERAL GEOLOGY

The Sudbury structure is at the junction of three structural provinces (Fig. 1): the Superior, Southern and Grenville provinces (Dressler, 1984; Rousell et al., 1997). The Superior Province, located north of the Sudbury structure, comprises Archean gneiss, metavolcanic and metasedimentary rocks, and granitic rocks. The Southern Province occurs northeast and south of the Sudbury structure. The rocks forming the Southern Province are low-grade metamorphic, Paleoproterozoic volcanic and sedimentary rocks intruded by the Creighton and Murray granitic plutons and deformed by the Penokean orogeny (Card et al., 1984; Dressler, 1984; Rousell et al., 1997; Riller et al., 1999). The Grenville Province is located 40 km south of the Sudbury structure and has a complex history of deformation and high-grade metamorphism. The southeastern corner of the Sudbury structure was strongly affected during the ca 1.0 Ga Grenville orogeny (Spray, 2001).

Geology of the Levack embayment

The immediate area of the Levack embayment (Fig. 2) is underlain by a 5 km wide part of the arcuate, ca. 2.7 Ga Archean Levack gneiss complex of the Superior Province (Dressler, 1984; Milkereit et al., 1992; Card, 1994). Three generations of Archean structures are observed in the map area (Fig. 3). A penetrative east-trending gneissic foliation (S_1) formed during a granulite-facies metamorphic event dated at 2647 ± 2 Ma (U-Pb; Krogh et al., 1984). Rare isoclinal and intrafolial F_1 folds are parallel to S_1. Both S_1 and F_1 are folded by map-scale, east-trending F_2 folds that plunge shallowly to steeply to the east and west. The F_2 folds are refolded by open to tight, northwest- to north-northeast-trending F_3 folds, which plunge shallowly to steeply to the northwest. The F_3 folds have a weak axial-planar cleavage, visible only in the hinge of the folds.

The Levack embayment is a semicircular trough at the base of the SIC. At surface, the embayment extends for more than 8 km from the Hardy pit in the west to the Longvack pit in

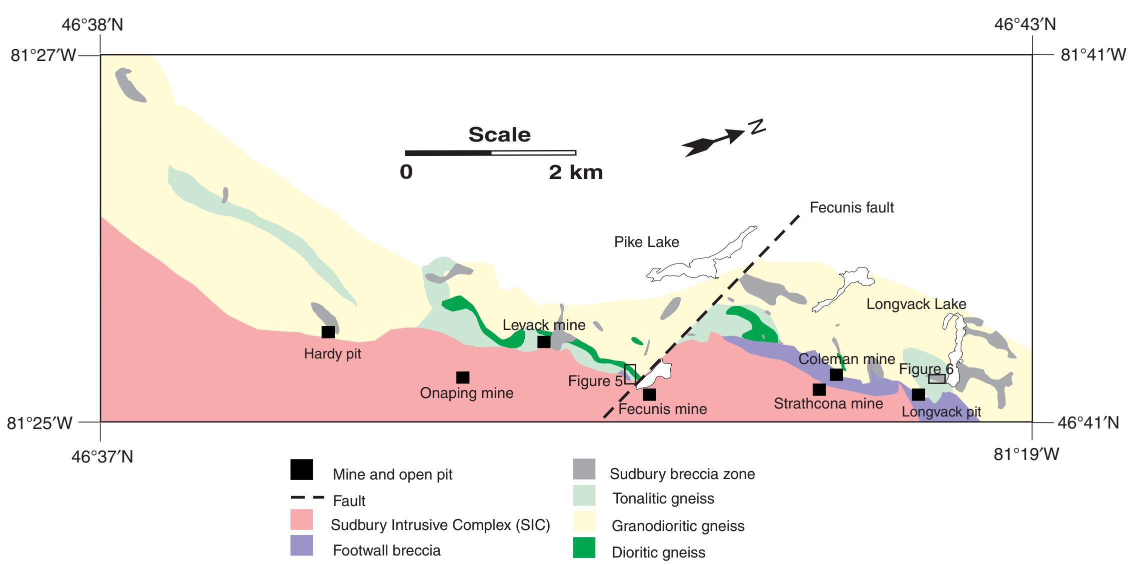

Figure 2. *Simplified geology of the Levack embayment, northern part of the Sudbury Igneous Complex, showing locations of detailed maps.*

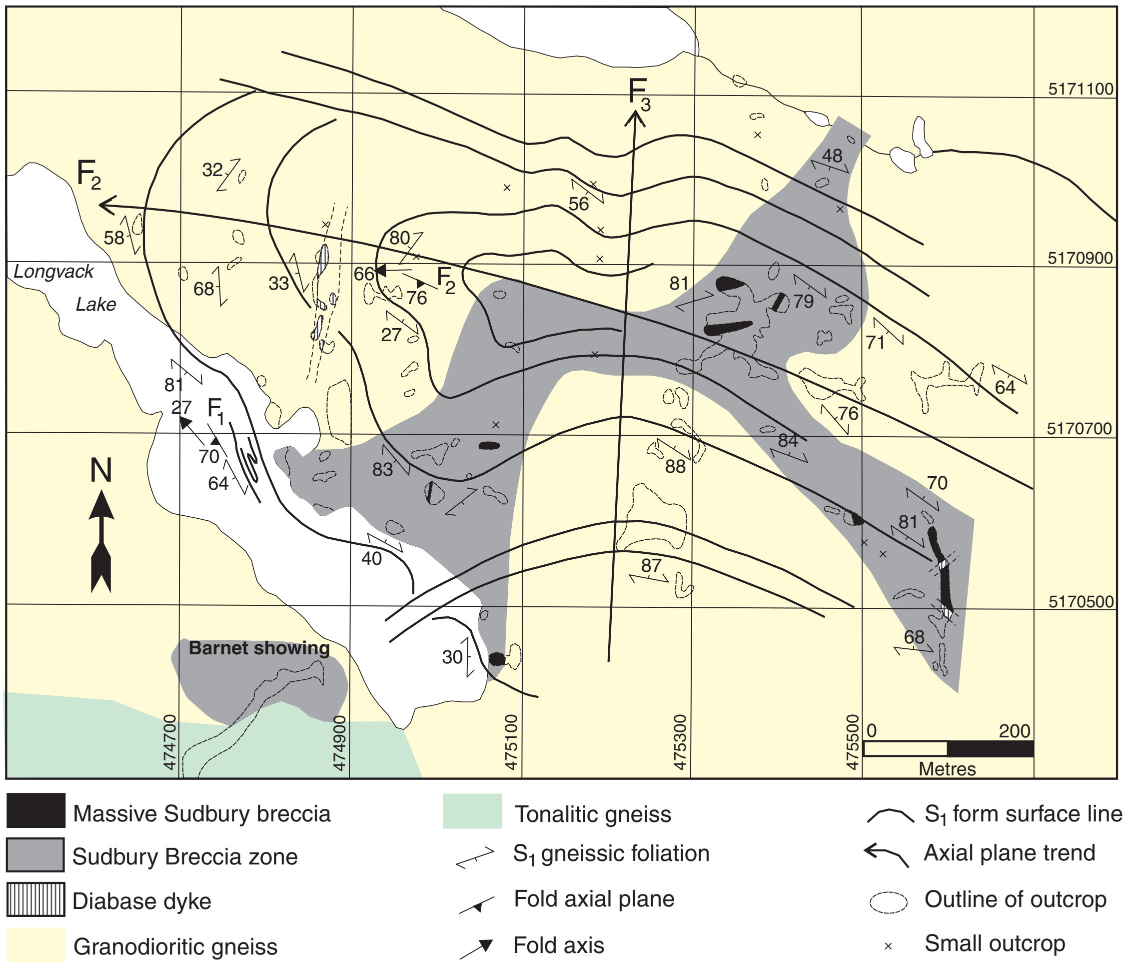

Figure 3. *Geology of Archean gneisses and Sudbury breccia zone, east of Longvack Lake.*

the east (Fig. 2). The Levack embayment corresponds to a depression in the footwall, plunging south-southwest at an average of 20º, in which the sublayer rests and is overlain by mafic norite of the SIC. The sublayer consists of mafic inclusions in a fine-grained noritic or sulphidic matrix. The sulphidic matrix constitutes the massive orebodies in embayment. The thickness of sublayer and mafic norite is greater at the centre of the depression and thins toward the margins. As with all other embayments around the Sudbury structure, the Levack embayment is interpreted as a slump structure that formed during collapse of the crater wall shortly after the 1850 Ma meteorite impact (Morrison, 1984; Fedorowich et al., 1999; McCormick et al., 2002). The Sudbury breccia, the most conspicuous impact feature in the northern part of the Sudbury structure, is cut by minor faults and fractures filled by chlorite-epidote±actinolite and/or sulphide minerals, which likely formed later during the modification stage of the impact. A late regional structure, the Fecunis Fault (Fig. 1, 2), sinistrally offsets the SIC by 800 m (Rousell et al., 1997). The fault strikes 160º and dips 80ºW. Two slickenside orientations, one pitching 10 to 15ºN and the other 24 to 29ºN, are observed on the chlorite- and calcite-coated fault plane.

Levack gneiss complex

The Levack gneiss complex is a polymetamorphic assemblage of rocks that was deformed and metamorphosed in the lower to middle crust during the Archean and probably exhumed during the Neoarchean, as suggested by Card et al. (1984) and Card (1994), due to late-orogenic extension. Its arcuate position around the northern SIC was due to the 1850 Ma impact event (Card, 1994; Grieve et al., 1991). In the 2 km by 10 km study area, the felsic and mafic gneiss that make up the complex are crosscut by northwest-trending diabase dykes.

The felsic gneiss, which underlies 80% of the study area, is subdivided into two units based on its mineral composition. Tonalitic gneiss is a foliated, greyish white, medium- to coarse-grained rock consisting of plagioclase, quartz (>5%), hornblende (<5%), and chlorite±orthopyroxene±clinopyroxene ±magnetite. The pyroxene is altered to amphibole, which is, in turn, partly altered to chlorite. The gneissic foliation is defined by quartzofeldspathic bands, varying in width from 5 to 25 cm, alternating with mafic bands of chloritized amphibole, varying in width from 3 to 12 cm. Granodioritic gneiss differs from the preceding unit by the presence of biotite and

K-feldspar. It is a weakly foliated, pinkish white, medium- to coarse-grained rock consisting of felsic bands of plagioclase, quartz (>5%), K-feldspar, and minor mafic minerals, alternating with fine-grained mafic bands of biotite, pyroxene, chlorite, and hornblende.

Mafic gneiss makes up the remaining 20% of the Archean rocks. Dioritic gneiss is a homogeneous, light yellowish brown, medium-grained rock composed of plagioclase, quartz (5%), hornblende (>15%), and chlorite±clinopyroxene. Amphibolite is a fine-grained green rock, containing hornblende (>20%), plagioclase, pyroxenes, and chlorite, but no quartz. The unit is discontinuous and varies in width from 1 m to more than 30 m. Thin injections (1 to 2 cm wide) of plagioclase and quartz are parallel to a gneissic foliation (S_1) defined by the preferred orientation of hornblende. Metapyroxenite is a massive, medium-grained, homogeneous rock composed almost exclusively of pyroxene, partially replaced to hornblende, with minor plagioclase and magnetite. The rock is greenish black on altered surfaces. Leucocratic injections of plagioclase and quartz are aligned and define a local foliation.

Northwest-trending diabase dykes, ranging in width from 0.3 to 8 m, cut across the Levack gneiss. They are uniformly fine grained, with phenocrysts of plagioclase in the case of the wider dykes. Overprinting of the dykes by the Sudbury breccia suggests that the dykes likely belong to the 2450 Ma Matachewan dyke swarm (Buchan et al., 1990; Card, 1994).

Sudbury breccia

On a regional scale, the Sudbury breccia occurs as far as 80 km from the SIC contact (Thompson and Spray, 1994). It is generally more abundant near the SIC contact (Dressler, 1984), especially in the vicinity of the embayments (Fedorowich et al., 1999). The Sudbury breccia is also localized along contacts between rock units with high competency contrast, such as diabase-gneiss contacts. The matrix of the Sudbury breccia is aphanitic to fine grained, dark grey on fresh surfaces, and greenish grey on altered surfaces. Structures associated with the Sudbury breccia vary with the width of the breccia, as follows:

1. **1 to 20 mm wide veinlets:** Numerous randomly oriented veinlets are observed in all rock units of the Levack gneiss. The matrix contains less than 5% angular to subangular clasts, ranging in size from 5 to 10 mm. The clasts reflect the composition of the host rocks. Where the veinlets are orthogonal or suborthogonal to the foliation of the host rock, ductile dragging of the gneissic foliation is locally observed along the veinlet margins (Fig. 4A). Late epidote and chlorite are commonly found within the veinlets or along their margins.
2. **2 to 100 cm wide veins:** Veins can often be traced for metres to tens of metres along strike. They occur close to massive breccia zones, where they are oriented subparallel to the contact between the massive breccia and the gneiss. The matrix contains subrounded to subangular clasts that represent the host-rock types cut by veins of Sudbury breccia. The clasts are either randomly oriented or they define a flow banding that becomes more pronounced along the margins of the veins. The character of the vein margins can change both across and along their strike. The veins commonly have a sharp, well defined margin and an opposite, more diffuse and irregular margin that gradually fades into the host rock (Fig. 4B). Dragging of the gneissic foliation and displacement of compositional markers by as much as 10 to 15 cm occur along a few veins, but there is generally no change in the orientation of the gneissic foliation across most of them. Tensile gashes, filled with matrix only, occur along the sharp margins of a few veins. Movement directions were recorded along several veins, but no consistent pattern emerged.
3. **Massive breccia:** Massive breccia forms 1 to 100 m wide, irregularly shaped bodies that cut across the gneissic foliation. It is clast-supported, with an average of 10 to 15% matrix. Only clasts of the host rocks are found in the massive breccia. The shape of the clasts is a function of their size: centimetre-wide clasts are generally angular to subangular, whereas metre-wide clasts are generally subangular to rounded. The latter commonly contain veinlets of Sudbury breccia.

East of Longvack Lake, a zone of Sudbury breccia that appears on company maps was remapped this past summer (Fig. 3). The zone comprises a few outcrops of massive breccia, shown in black in Figure 3. Most outcrops in the zone generally contain less than 5% breccia as veins and veinlets. Thus, this zone, which continues west to the Levack mine and includes the Barnet showing (Fig. 2), is a zone of disconnected breccia occurrences.

Footwall breccia

A second type of breccia, the footwall breccia, occurs in footwall rocks immediately below the SIC (Mitchell and Mutch, 1957). Exposures of footwall breccia are located on the east, north, and west margins of the SIC. It forms a discontinuous unit with irregular orientation of contacts, its thickness varying from 1 to 150 m (Coats and Snajdr, 1984; McCormick et al., 2002). In the study area, footwall breccia is exposed and increases in thickness toward the eastern sector, along the contact with the SIC (Fig. 2). The contact with the SIC is sharp, and becomes gradually diffuse as it gets further into the footwall rocks. The breccia contains clasts of Levack gneiss, diabase, and Sudbury breccia in a fine-grained matrix of plagioclase, quartz, and K-feldspar. The diabase clasts are more abundant close to the SIC contact and decrease rapidly toward the footwall contact. Clasts of Levack gneiss lose their gneissic foliation due to recrystallization along the clast margins. Clasts of Sudbury breccia that vary in size from 10 to 20 cm commonly have a diffuse, recrystallized margin that is coarser grained than the clast matrix. Porphyroclasts of K-feldspar, up to 2 to 3 cm in diameter, are surrounded by the quartzofeldspathic matrix. Blebs of epidote and sulphide minerals are randomly distributed in the matrix of the footwall breccia.

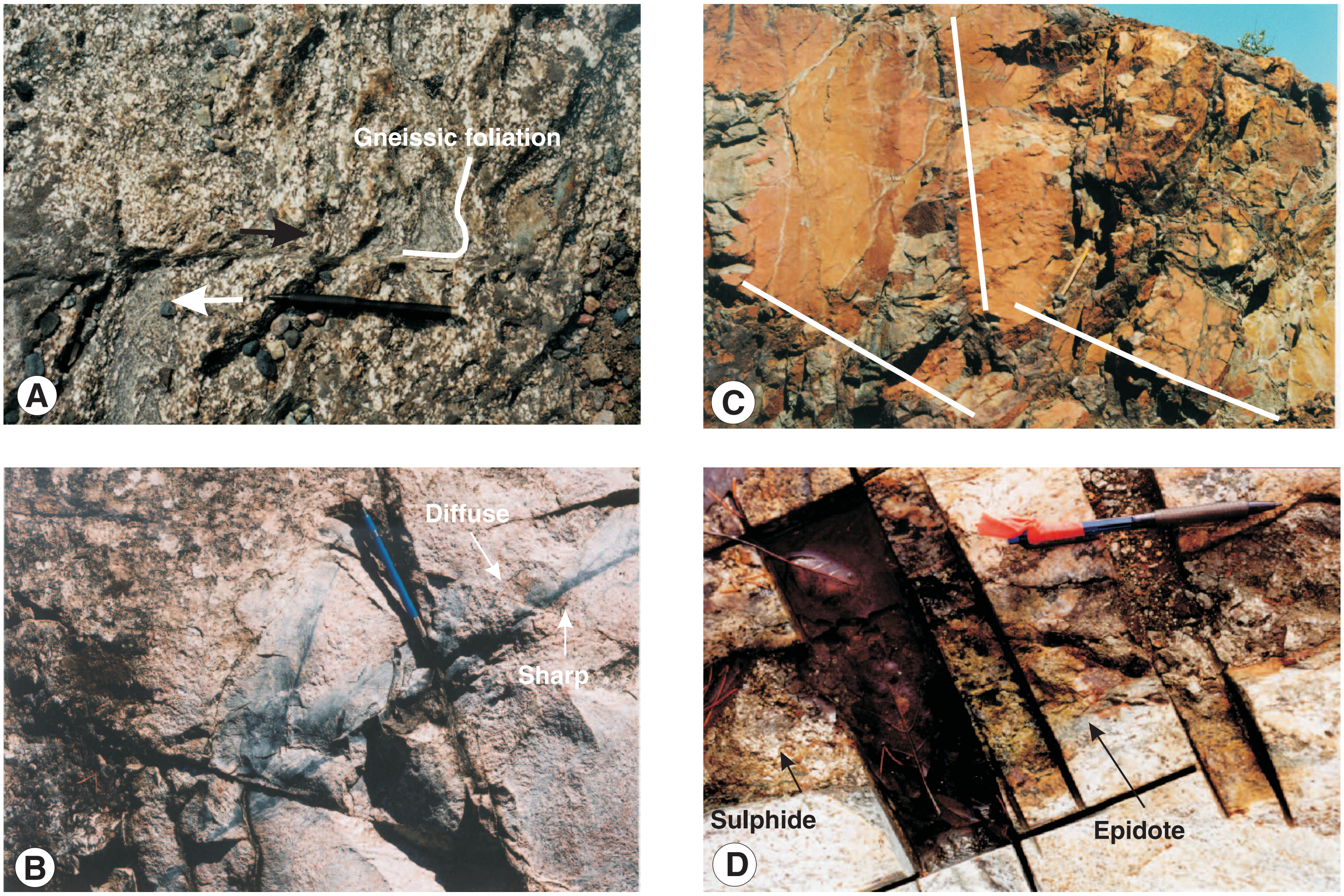

Figure 4. *A) Veinlet of Sudbury breccia showing dextral movement by dragging of gneissic foliation; pencil for scale.* ***B)*** *Sharp and diffuse margin on a vein of Sudbury breccia; pencil for scale.* ***C)*** *Sulphide veins in the Levack adit; black lines emphasize the sulphide veins; sledgehammer for scale.* ***D)*** *Sulphide vein with epidote at the Barnet showing.*

Sulphide veins

Sulphide mineralization exposed in the study area occurs as veins cutting through the Sudbury breccia and Levack gneiss, and as disseminated and semimassive sulphide pockets in the matrix of the Sudbury breccia and footwall breccia. There are two vein-mineralized exposures in the North Range: the Levack adit and the Barnet showing (Fig. 5, 6). The Levack adit (Fig. 5) is located 75 m west of the Fecunis Fault and is less than 100 m from the SIC contact. Pyrrhotite-pentlandite-chalcopyrite veins cut across the gneissic foliation of the host biotite quartzofeldspathic gneiss (Fig. 4C). The veins have two dominant orientations: one set strikes 025º to 045º and dips 75º to 85º S, and a second set strikes west and dips shallowly to the north. The two vein sets are linked by veinlets branching off the main veins. The veins have an average width of 15 cm. They merge on the west wall of the adit to form an oxidized, semimassive mineralized zone (Fig. 5).

The Barnet showing, mapped with a plane table (Fig. 6), is the surface expression of the Strathcona mine, which hosted Cu-PGE–rich sulphide veins (Fedorowich et al., 1999). Tonalitic gneiss is cut by a massive breccia zone consisting of gneiss and diabase clasts, surrounded by a fine-grained matrix. The

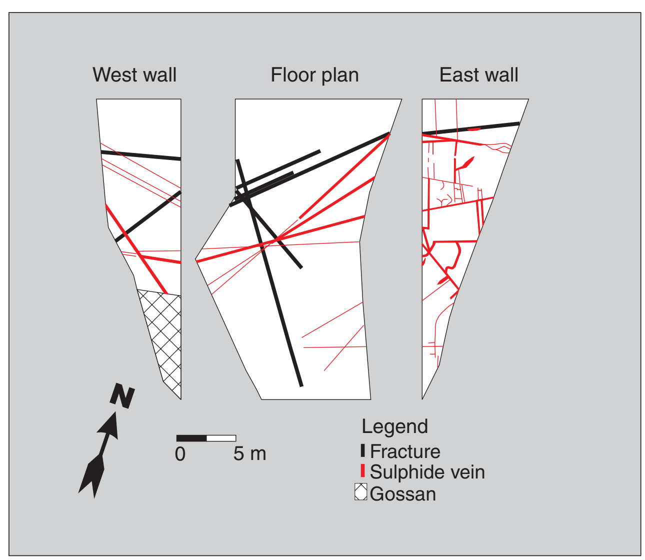

Figure 5. *Map of the Levack adit showing mineralized veins and fractures. Adit location in the Levack embayment shown on Figure 1.*

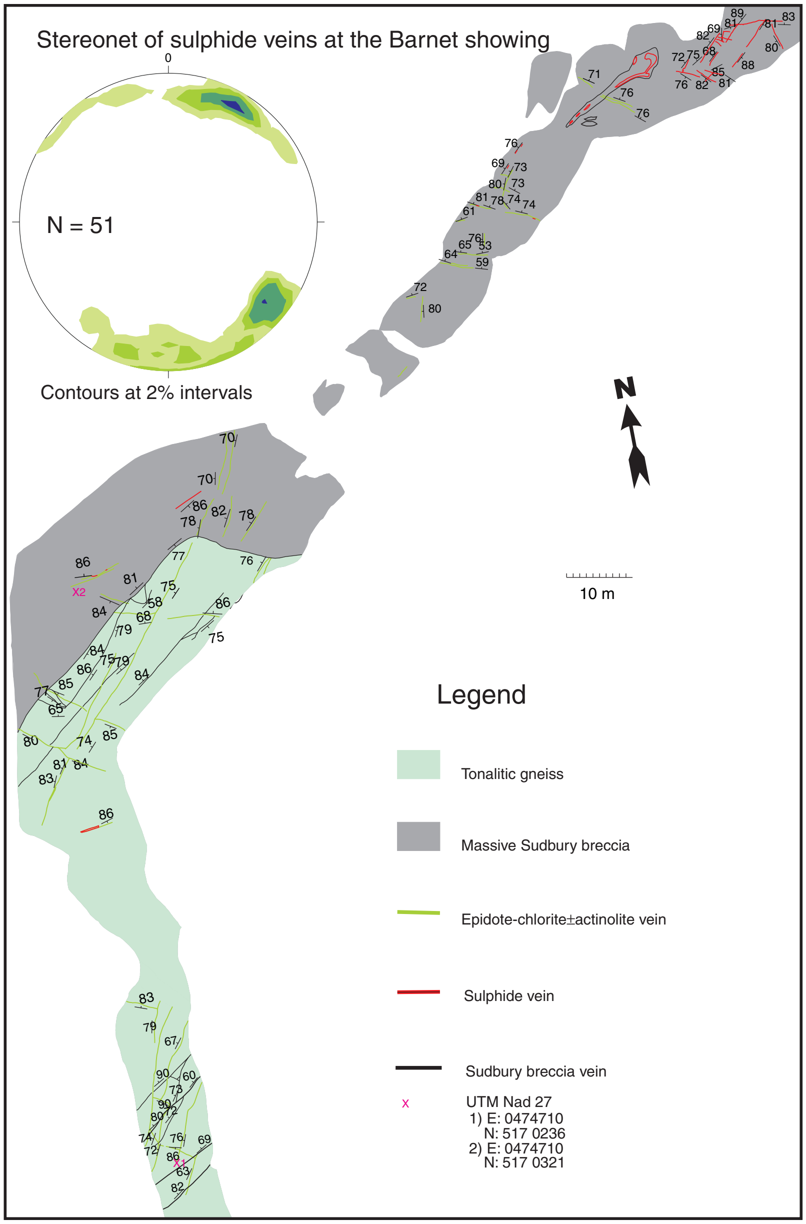

Figure 6.

Simplified map of the Barnet showing with mineralized veins and alteration-filled veins. Stereonet represents poles of sulphide veins. See *Figure 3 for location.*

contact between the massive Sudbury breccia and the tonalitic gneiss trends west on the east side of the outcrop and southwest on the west side of the outcrop. Sulphide veins and epidote-chlorite±actinolite veins occupy late fractures that cut through both the tonalitic gneiss and the Sudbury breccia (Fig. 6). The epidote-chlorite±actinolite veins have two dominant orientations: one set strikes 230º to 250º and dips 65º to 90ºN, and a second set strikes 190º to 210º and dips 70º to 90ºW. At the north end of the showing, a conjugate system of sulphide veins passes from the matrix of the breccia into a large block of Levack gneiss set within the Sudbury breccia. The veins contain chalcopyrite, pyrite, and minor bornite and pyrrhotite. One vein set, striking 90º to 120º and dipping 65º to 85ºS, mimics and follows the gneissic foliation in the block of Levack gneiss. The second vein set strikes 230º to 250º, approximately perpendicular to the gneissic foliation, and dips 60º to 80ºN (Fig. 6). The second vein set is commonly associated with epidote-chlorite±actinolite (Fig. 4D). Dextral displacements of 2 to 5 cm are observed along these veins, but the veins generally show no displacement.

DISCUSSION AND CONCLUSIONS

The geometry and distribution of the Sudbury breccia, as well as structures associated with the breccia, are all factors that relate to the understanding of the formation of the Sudbury structure and its world-class ore deposits. Three concentric zones of Sudbury breccia have been reported around the Sudbury structure to define the size of the crater (Thompson and Spray, 1994). The present study, in a 10 km wide section, shows that the distribution of the breccia is sporadic and does not define concentric zones, as maintained by Thompson and

Spray (1994), but is more abundant in the vicinity of the Levack embayment (Fedorowich et al., 1999), especially along rock units with high competency contrasts (Fairbarn and Robson, 1942). Massive breccia occurs as disconnected, irregular bodies and veins within wide zones that contain less than 5% breccia. The clasts in the massive breccia are all derived from the local host rocks. Little or no displacement is observed along the margins of massive and vein breccia. Where centimetre-scale displacements occur along the smaller breccia veins, no systematic kinematic pattern could be determined. These observations are more consistent with in situ brecciation of the Levack gneiss during the propagation of shock waves, rather than with milling and friction melting of the rocks along superfaults that formed during rim collapse (Thompson and Spray, 1994). If the Sudbury breccia were to have formed along superfaults, it should define continuous planar zones with an easily recognizable pattern of fractures and contain clasts other than the local host rocks. Geochemical analysis of the Sudbury breccia, matrix and clasts, and host rocks will provide more information in the attempt to verify this preliminary interpretation.

Sulphide veins at the Levack adit and Barnet showing differ both in their orientations and sulphide mineralogy. Sulphide veins at the Barnet showing are Cu-PGE rich, dominated by chalcopyrite (Farrow and Watkinson 1992, 1997; Jago et al., 1994; Hanley 2001), and locally associated with hydrothermal minerals (epidote-chlorite±actinolite). A first set of veins simply exploited the pre-existing gneissic foliation. The second set of veins shows no or little displacement and is oriented perpendicular to the gneissic foliation. The hydrothermal minerals are found in this second set but are not mixed with the sulphide minerals. This suggests that the sulphide veins were emplaced in tensile fractures that propagated perpendicular to the gneissic foliation and coincided with hydrothermal activity (Farrow and Lightfoot, 2002). Sulphide veins at the Levack adit are dominated by pyrrhotite. The veins were likely emplaced in a different system of fractures that formed during or immediately after the segregation of sulphide minerals from the cooling SIC.

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REFERENCES

Ames, D.E.
2002: Sudbury Targeted Geoscience Initiative (TGI) (2002–2003): overview and update; *in* Summary of Field Work and Other Activities 2002; Ontario Geological Survey, Open File Report 6100, p. 17-1 to 17-10.

Ames, D.E., Galley, A.G., Legault, D., LaFrance, B., Dubois, A, Parker, J., Benn, K., Kjarsgaard, I., and Zierenberg, R.
2001: Sudbury Targeted Geoscience Initiative (TGI): role of volatiles, structure and host rocks in the evolution of Sudbury ores; *in* Summary of Field Work and Other Activities 2001; Ontario Geological Survey, Open File Report 6070, p. 25-1 to 25-9.

Buchan, K.L., Neilson, D.J., and Hale, C.J.
1990: Relative age of Otto stock and Matachewan dykes from paleomagnetism and implications for the Precambrian polar wander path; Canadian Journal of Earth Sciences, v. 27, no. 7, p. 915–922.

Card, K.D.
1994: Geology of the Levack gneiss complex, the northern footwall of the Sudbury structure, Ontario; *in* Current Research 1994-C; Geological Survey of Canada, p. 269–278.

Card, K.D., Gupta, V.K., McGrath, P.H., and Grant, F.S.
1984: The Sudbury Structure: its regional geological and geophysical setting; *in* The Geology and Ore Deposits of the Sudbury Structure, (ed.) E.G. Pye, A.J. Naldrett, and P.E. Giblin; Ontario Geological Survey, Special Volume 1, p. 25–44.

Coats, C.J.A. and Snajdr, P.
1984: Ore deposits of the North Range, Onaping-Levack area, Sudbury; *in* The Geology and Ore Deposits of the Sudbury Structure, (ed.) E.G. Pye, A.J. Naldrett, and P.E. Giblin; Ontario Geological Survey, Special Volume 1, p. 327–346.

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

Dressler, B.O.
1984: The effects of the Sudbury event and the intrusion of the Sudbury Igneous Complex on the footwall rocks of the Sudbury Structure; *in* The Geology and Ore Deposits of the Sudbury Structure, (ed.) E.G. Pye, A.J. Naldrett, and P.E. Giblin; Ontario Geological Survey, Special Volume 1, p. 97–136.

Dupuis, L.H.
1979: The nature and origin of Sudbury breccia near Lake Laurentian; M.Sc. thesis, Laurentian University, Sudbury, Ontario, 149 p.

Fairbarn, H.W. and Robson, G.M.
1942: Breccia at Sudbury; Journal of Geology, v. 50, p. 1–33.

Farrow, C.E.G.
2001: Sudbury: PGE mineralization and environments; Canadian Institute of Mining, Metallurgy and Petroleum, 103rd Joint Annual Meeting, Program with Abstracts, p. 58.

Farrow, C.E.G. and Lightfoot, P.C.
2002: Sudbury PGE revisited: toward an integrated model; *in* The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements, (ed.) L.J. Cabri; Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 54, p. 483–506.

Farrow, C.E.G. and Watkinson, D.H.
1992: Alteration and the role of fluids in Ni, Cu and platinum-group element deposition, Sudbury Igneous Complex contact, Onaping-Levack area, Ontario; Mineralogy and Petrology, v. 46, p. 67–83.

Farrow, C.E.G. and Watkinson, D.H.
1997: Diversity of precious-metal mineralization in footwall Cu-Ni-PGE deposits, Sudbury, Ontario: implications for hydrothermal models of formation; Canadian Mineralogist, v. 35, no. 4, p. 817–839.

Fedorowich, J.S., Roussel, D.H., and Peredery, W.V.
1999: Sudbury breccia distribution and orientation in an embayment environment; Geological Society of America, Special Paper 339, 305–315.

French, B.V.
1998: Traces of catastrophe: a handbook of shock-metamorphic effects in terrestrial meteorite impact structures; Lunar and Planetary Institute, Houston, LPI Contribution No. 954, 120 p.

Giblin, P.E.
1984: History of exploration and development, of geological studies and development of geological concepts; *in* The Geology and Ore Deposits of the Sudbury Structure, (ed.) E.G. Pye, A.J. Naldrett, and P.E. Giblin; Ontario Geological Survey, Special Volume 1, p. 3–23

Grieve, R.A.F., Stoffler, D., and Deutsch, A.
1991: The Sudbury Structure: controversial or misunderstood? Journal of Geophysical Research, v.96, p. 22,753–22,764.

Hanley, J.J.
2002: The distribution of the halogens in Sudbury breccia matrix as pathfinder elements for footwall Cu-PGE mineralization at the Fraser Cu zone, Barnet main copper zone, and surrounding margin of the Sudbury Igneous Complex, Onaping-Levack area, Ontario, Canada; M.Sc. thesis, University of Toronto, Toronto, Ontario, 255 p.

Jago, B.C., Morrison, G.G., and Little, T.L.
1994: Metal zonation patterns and microtextural and micromineralogical evidence for alkali- and halogen-rich fluids in the genesis of the Victor Deep and McCreedy East footwall copper orebodies, Sudbury Igneous Complex; *in* Proceedings of the Sudbury-Noril'sk Symposium, (ed.) P.C. Lightfoot and A.J. Naldrett; Ontario Geological Survey, Special Volume 5, p. 65–75.

Kenkmann, T., Hornemann, U., and Stöffler, D.
2000: Experimental generation of shock-induced pseudotachylites along lithological interfaces; Meteoritics and Planetary Science, v. 35, p. 1275–1290.

Krogh, T.E., Davis, D.W., and Corfu, F.
1984: Precise U-Pb zircon and baddeleyite ages for the Sudbury area; *in* The Geology and Ore Deposits of the Sudbury Structure, (ed.) E.G. Pye, A.J. Naldrett, and P.E. Giblin; Ontario Geological Survey, Special Volume 1, p. 431–446.

Li, C., Naldrett, A.J., Coats, C.J.A., and Johannessen, P.
1992: Platinum, pallladium, gold and copper-rich stringers at the Strathcona mine, Sudbury: their enrichment by fractionation of a sulphide liquid; Economic Geology, v. 87, p. 1584–1598.

McCormick, K.A., Fedorowich, J.S., McDonald, A.M., and James, R.S.
2002: A textural, mineralogical and statistical study of the footwall breccia within the Strathcona embayment of the Sudbury Structure; Economic Geology, v. 97, p.125–143.

Milkereit, B., Green, A., and Sudbury Working Group
1992: Deep geometry of the Sudbury structure from seismic reflection profiling; Geology, v.20, p. 807–811.

Mitchell, G.P. and Mutch, A.D.
1957: Hardy mine; *in* Structural Geology of Canadian Ore Deposits, Volume 2; Canadian Institute of Mining and Metallurgy, Congress Volume, p. 350–363.

Molnár, F., Watkinson, D.H., and Jones, P.C.
2001: Multiple hydrothermal processes in footwall units of the North Range, Sudbury Intrusive Complex, Canada, and its implications for the genesis of vein-type Cu-Ni-PGS deposits; Economic Geology, v. 96, p. 1645–1670.

Morrison, G.G.
1984: Morphological features of the Sudbury Structure in relation to an impact origin; *in* The Geology and Ore Deposits of the Sudbury Structure, (ed.) E.G. Pye, A.J. Naldrett, and P.E. Giblin; Ontario Geological Survey, Special Volume 1, p. 513–520.

Morrison, G.G., Jago, B.C., and White, T.
1994: Footwall mineralization of the Sudbury Igneous Complex; *in* Proceedings of the Sudbury-Noril'sk Symposium, (ed.) P.C. Lightfoot and A.J. Naldrett; Ontario Geological Survey, Special Volume 5, p. 57–64.

Riller, U., Schwerdtner, W.M., Halls, H.C., and Card, K.D.
1999: Transpressive tectonism in the eastern Penokean orogen, Canada: consequences for Proterozoic crustal kinematics and continental fragmentation; Precambrian Research, v. 93, p. 51–70.

Rousell, D.H., Gibson, H.L., and Jonasson, I.R.
1997: The tectonic, magmatic and mineralization history of the Sudbury Structure; Exploration and Mining Geology, v. 6, no. 1, p. 1–22.

Thompson, L.M. and Spray, J.G.
1994: Pseudotachylitic rock distribution and genesis within the Sudbury impact structure; *in* Large Meteorite Impacts and Planetary Evolution, (ed.) B.O. Dressler, R.A.F. Grieve, and V.L. Sharpton; Geological Society of America, Special Paper 293, p. 275–288.

Spray, J.G.
1997: Superfaults; Geology, v. 25, no. 7, p. 579–582.

Spray, J.G.
2001: Geology of the Sudbury Structure with emphasis on shatter cones, Sudbury breccia and pre-impact folded marbles; Canadian Tectonics Group Annual Meeting, Sudbury 2001, Field Trip Guidebook, 24 p.

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