

# Deformation of the Sudbury Structure: Paleomagnetic evidence from the Sudbury breccia

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Received 15 June 2005; received in revised form 1 July 2006; accepted 6 July 2006

## Abstract

Paleomagnetic results from fine-grained samples of Sudbury breccia, collected from 28 sites around the northern half of the 1.85 Ga Sudbury Igneous Complex (SIC), reveal the existence of two major components of magnetization, *A* and *B*. *A*, carried by magnetite, was formed close to the time of the SIC and has a direction that is related to the dip of the norite unit within the different ranges of the SIC. Component *B*, mainly carried by pyrrhotite, is a younger, secondary magnetization of more problematical origin, in part related to heating during the 1.24 Ga Sudbury magmatic event. In the northwest part of the SIC, *A* is found in breccia clasts, intermediate norite, sublayer, Levack Gneiss and Matachewan diabase, indicating that it is due to baking by the SIC. Tilt-correcting the West range by 36°, the North range by 22° and the northern East range by 36°, about axes parallel to local strike of the norite, minimises the dispersion of the paleomagnetic data to give a pre-folding direction of 199.4°/78.8°. The paleomagnetic data are similar to those obtained by Morris [Morris, W.A., 1984. Paleomagnetic constraints on the magmatic, tectonic, and metamorphic history of the Sudbury basin region. In: Pye, E.G., Naldrett, A.J., Giblin, P.E., (Eds.), *The Geology and Ore Deposits of the Sudbury Structure*, Special vol. 1. Ontario Geological Survey, pp. 411–427] on the SIC, suggesting for the first time that the SIC and the surrounding basement were deformed (probably during the 1.9–1.7 Ga Penokean Orogen) as a single unit. The un-folding of the paleomagnetic directions indicates that SIC limbs were already inclined, a result of the original intrusion configuration, or a syn-folding remanence. It is possible that the SIC was originally flatter if the distribution of paleomagnetic directions is the result of flexural flow folding. This explanation could also produce a similar distribution of paleomagnetic directions across the basin, but cannot be quantified due to the lack of measurable fold-related strain in breccia and SIC units around the northern half of the basin. © 2006 Elsevier B.V. All rights reserved.

**Keywords:** Sudbury breccia; Sudbury Structure; Deformation; Paleomagnetism; Rock magnetism

## 1. Introduction

Hosting the largest Ni–Cu deposits in the world, the Sudbury Structure (Fig. 1) still remains enigmatic, despite the considerable scientific attention given to it in the last century. Its origin, size, geometry and type

of deformation continue to be debated among geologists. Initially thought to have formed exclusively as the result of endogenic processes, the Sudbury Structure is now recognized as one of the largest impact structures on Earth (Peredery and Morrison, 1984; Grieve, 1994; Spray and Thompson, 1995).

The Sudbury Structure is a  $\sim 27 \times 60$  km oval-shaped basin with an original diameter estimated to be 190–260 km (Peredery and Morrison, 1984; Grieve, 1994; Spray and Thompson, 1995; Spray et al., 2004). The oval shape is believed by Shanks and Schwerdtner (1991a,b) to be the result of deformation during late

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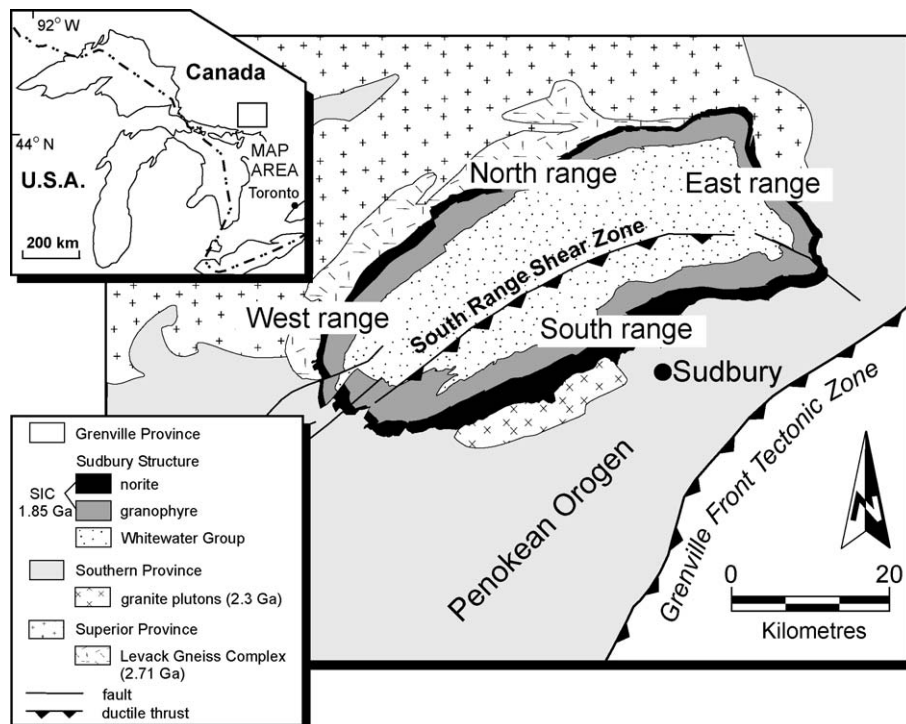


Fig. 1. Regional location of the Sudbury Structure and generalized geology of the Sudbury area (SIC, Sudbury Igneous Complex). After [Riller et al. \(1996\)](#) modified after [Thurston \(1991\)](#).

stages of the Penokean orogeny (1.9–1.7 Ga). The South range exhibits steeper contact dips with the basement when compared to the North range which seems to have been less deformed and to have preserved its initial geometry ([Rousell, 1984](#)). If the original shape of the Sudbury basin was once circular, the North and South ranges of the basin have been subsequently rotated relative to each other in order to get the variation in attitude that we see today. Paleomagnetism is a method that is potentially able to give a quantitative solution to the amount and variability of this deformation.

Early paleomagnetic studies in the Sudbury area were done mainly in the Sudbury Igneous Complex (SIC) units by [Hood \(1961\)](#), [Sopher \(1963\)](#), and [Laroche \(1969\)](#). Their conclusions closely resemble those of [Morris \(1980, 1981, 1982a,b, 1984\)](#) who conducted the most complete paleomagnetic research of the SIC. His measurements on norite, granophyre, sublayer, and offsets from all four ranges of the SIC revealed a total of seven different remanence directions, each remanence component being related to different intrusion, mineralization, and metamorphic events in the area. Two and possibly three components show directional differences

between the various ranges of the Sudbury Structure and were interpreted as predating the deformation episodes that produced the rotations of the limbs towards the interior of the basin. The combined Types 2 and 1 remanence components show total rotations inward towards the centre of the basin of  $61^\circ$ ,  $24^\circ$ ,  $42\text{--}47^\circ$ , and  $55^\circ$ , for the East, North, West, and South ranges, respectively ([Morris, 1980](#)). However, this model of tectonic deformation is not supported by structural studies in the northeast part of the SIC ([Cowan et al., 1999](#)). The objective of this current study was to compare the paleomagnetic response of the Sudbury breccia with that of the SIC units to test if the basement has been involved in the same deformation as the SIC units. Sudbury breccia has the advantage of being the first-formed rock of the Sudbury impact event, having essentially the same age as the SIC (1.85 Ga). The breccia pervades basement lithologies all around the SIC and occurs up to 80 km from it. Any tectonic rotations involving the ranges of the Sudbury basin should be recorded in the basement (and hence in the Sudbury breccia) if no faults intervene. Consistent remanence directions observed in a pilot study of breccias in the northwest corner of the Sudbury Structure ([Smethurst, 1997](#)), when compared to

scattered directions that characterize the breccia remanence in the South range (Scott, 2001), directed this study to breccias in the northern part of the Sudbury Structure.

## 2. Regional geology

Situated at the intersection of the Superior, Southern, and Grenville provinces of the Canadian Shield (Fig. 1), the Sudbury Structure includes the SIC, the Sudbury sedimentary basin (Whitewater Group) and brecciated basement rocks surrounding the igneous complex (Krogh et al., 1984; Dressler, 1984b; Dressler et al., 1991a,b). The 2.5 km thick SIC is composed of four distinct units. From bottom to the top, they are contact sublayer, norite, gabbro and granophyre. U–Pb dating of zircon and baddeleyite from norite and granophyre gives a precise age of  $1850 \pm 1$  Ma (Krogh et al., 1984). Modern ideas for the origin of the Sudbury Structure range from an exclusively impact melt origin, an intrusive origin, possibly triggered by the Sudbury impact event, and a combination of the two (Faggart et al., 1985; Deutsch et al., 1989, 1995; Chai and Eckstrand, 1993; Grieve et al., 1991; Grieve, 1994; Norman, 1994; Mungall et al., 2004).

The northern part of the Sudbury Structure is bordered by the 0.5–5 km wide Levack Gneiss Complex. Its granulite facies assemblages recorded near the SIC are dated at  $2711 \pm 7$  Ma (U–Pb on zircon, Krogh et al., 1984). The  $2642 \pm 1$  Ma (U–Pb on zircon; Meldrum et al., 1997) monzogranite to granodioritic Cartier Batholith intrudes the Levack Gneiss Complex, forming a north–northwest dipping contact as suggested by gravity models (McGrath and Broome, 1994). Clastic metasedimentary and metavolcanic rocks of the Huronian Supergroup (2450 and 2219 Ma, U–Pb on baddeleyite; Krogh et al., 1984; Corfu and Andrews, 1986) characterize the Southern Province that borders the Sudbury Structure to the south.

Archean rocks around the northern half of the Sudbury Structure were intruded at  $\sim 2473 + 16/-9$  Ma (U–Pb on baddeleyite; Heaman, 1997) by Fe-rich quartz tholeiites of the NNW-trending Matachewan dyke swarm (Ernst, 1982; Siddorn and Halls, 2002). They were followed by the  $2219 \pm 4$  Ma Nipissing intrusions (U–Pb on baddeleyite; Corfu and Andrews, 1986) which form mafic dykes, sills and cone sheets intruding the Paleoproterozoic Huronian metasediments. They consist mainly of pyroxene and hornblende gabbro (Card, 1978). The youngest intrusive events in the Sudbury area are the  $1238 \pm 4$  Ma (U–Pb on baddeleyite; Krogh et al., 1987) west–northwest-trending olivine diabase dykes of the Sudbury swarm (Card and Innes, 1981; Choudhury,

1984) and the  $\sim 600$  Ma east-trending diabase dykes of the Grenville swarm (e.g. Murthy, 1971).

## 3. Deformation and metamorphism in the Sudbury area

Proponents of an initial circular shape for the Sudbury Structure (e.g. Morrison, 1984; Roest and Pilkington, 1994; Morris, 2002) suggest that the oval shape we see today is the result of subsequent deformation. The most important stage in the deformation of Sudbury Structure is attributed to Penokean large-scale shortening that included reverse faulting and transpression along the South range shear zone (SRSZ) (Fig. 1). As a result, the South range of the Sudbury basin was displaced more than 8 km to the northwest (Shanks and Schwerdtner, 1991a), transforming the original Sudbury basin to the oval structure we see today. This deformation occurred under conditions of greenschist facies metamorphism. Finite strain and anisotropy of magnetic susceptibility (AMS) studies done in the Whitewater Group indicate increasing deformation from northwest towards southeast that produced a shortening of the Sudbury basin along a northwest–southeast directed axis (Brocoum and Dalziel, 1974; Kligfield et al., 1977; Clendenen et al., 1988; Hirt et al., 1988, 1993). The original shape of the Sudbury Structure was found to be either near circular (Brocoum and Dalziel, 1974; Hirt et al., 1993) or less elliptical than it is today (Clendenen et al., 1988). Based on radiometric data, Fueten and Redmond (1997) and Bailey et al. (2004) argue that Penokean deformation had ended before the Sudbury event took place, and that the southeast-over-northwest-directed ductile deformation of the Southern Province rocks was caused either by a 1450 Ma old deformation event that resulted in local metamorphism in the area (e.g. Dudas et al., 1994; Davidson and van Breemen, 1994) or by the 1.7–1.6 Ga Mazatzal/Labradorian orogenies that affected the southeastern part of Laurentia and the SIC (Gibbins and McNutt, 1975; Bailey et al., 2004). They further suggest that these events are also responsible for the formation of the SRSZ and the current elliptical shape of the Sudbury Structure. The later Grenville orogeny (1.1–0.9 Ga) also imprinted a regional metamorphism in the area. Based on paleomagnetic overprints in Huronian rocks exposed  $\sim 60$  km northeast of Sudbury, Hyodo et al. (1986) estimated that the temperatures of this metamorphic event decreased to less than  $400^\circ\text{C}$  beyond a distance of 2 km from the Grenville Front. Remagnetization of Sudbury dykes in the Sudbury area (Palmer et al., 1977) and of Gowganda sediments and Nipissing diabase in the Southern Province (Stupavsky

and Symons, 1982) occurs mainly within 2 km and as far as 8 km from the front. These arguments indicate that the Grenville orogeny had a minimal effect on the shape and metamorphism of the Sudbury basin. Apart from the regional metamorphism, the SIC imprinted a contact metamorphism on the rocks adjacent to it. Field studies (Coats and Snajdr, 1984; Dressler, 1984a; Lakomy, 1990) and thermal modeling (Naldrett and Kullerud, 1967; Ivanov and Deutsch, 1999) revealed that the contact metamorphism around the SIC recorded temperatures above the magnetite Curie point of  $\sim 580^\circ\text{C}$ , out to distances of about 2 km, that lasted for hundreds of thousand years. Contact metamorphism reached pyroxene hornfels facies close to the SIC, fading to quartz and plagioclase recrystallization  $\sim 2$  km away from the SIC (Dressler, 1984a). A 1–3 km wide high-grade metamorphic aureole in the Levack Gneiss occurs beneath the north and northwest margin of the Sudbury Structure (McGrath and Broome, 1994; Hearst et al., 1994; Morris et al., 1992a,b) and around the northern SIC it is older than a sub-greenschist (probably Penokean) regional metamorphism (Card, 1978; Fleet et al., 1987).

#### 4. Sudbury breccia

Sudbury breccia occurs as  $<1$  mm thick veinlets to large dyke-like bodies that are several hundred metres thick. Most authors document a limit of within 50–80 km of the SIC for Sudbury breccia occurrences (Dressler, 1984a,b) which seem to be more common in concentric zones around the SIC that are interpreted as original rings of the Sudbury impact structure (Spray et al., 2004). Field evidence places the age of the Sudbury breccia as pre-SIC (Speers, 1957; Peredery and Morrison, 1984). Sudbury breccia bodies are associated with structural weaknesses such as lithological contacts (e.g. between mafic dykes and gneisses), faults, joints and foliations (Dressler, 1984a,b; Rousell et al., 2003). Subangular to angular fragments of a few millimeters to hundreds of meters in size, are incorporated in a dark matrix in most Sudbury breccias. With the exception of the injected types, the breccias have  $\sim 40$ – $60\%$  clast content, mainly derived from basement host rocks (Dressler, 1984a,b; Thompson and Spray, 1996; Rousell et al., 2003). Laser-probe Ar–Ar ages of 2.7–2.2 Ga for breccia clasts from the North range of the Sudbury Structure are similar to ages reported for nearby basement rocks (Krogh et al., 1984; Thompson and Spray, 1996). The matrix is composed of neomorphic crystallites of biotite, plagioclase, orthoclase, sanidine, and quartz, in a cryptocrystalline and micro-igneous texture (Thompson and Spray, 1996).

Red, light grey and flow-foliated matrices occur in which clasts are typically elongated and oriented parallel to the flow layers of the matrix. Breccia matrix from the North range of the Sudbury Structure yielded similar ages ( $\sim 1.85$  Ga by the Ar–Ar method; Thompson et al., 1994) to that of the impact event as given by SIC emplacement (Krogh et al., 1984). Post-impact secondary minerals such as biotite, actinolite, albite, titanite, epidote, clinozoisite, chlorite and prehnite were formed as a result of retrogression to greenschist and lower grade facies, and were due to metamorphism that occurred as a result of post-impact tectonothermal events (e.g. Penokean and Grenvillian; Thompson et al., 1998). Multiple laser-probe Ar–Ar ages between  $\sim 1000$  and  $\sim 1850$  Ma that may date the alteration, were reported for samples from the North range of the Sudbury Structure (Thompson et al., 1998). The low-grade metamorphism that affected the Sudbury breccias in this area indicates that impact-related magnetizations in the breccia, carried by magnetic minerals with high unblocking temperatures such as magnetite and hematite, may survive.

In the past, the origin of Sudbury breccia was attributed to magmatic/tectonic events (Fairbairn and Robson, 1942; Speers, 1957; Dupuis et al., 1982; Dressler, 1984a). Planar deformation features in quartz, feldspar, and zircon and the abundant development of shatter cones in the basement suggest that the Sudbury breccia is a shock-induced feature, resulting from high-velocity impact (Dietz and Butler, 1964; Krogh et al., 1984; Dressler et al., 1991a; Lakomy, 1990; Spray and Thompson, 1995). Accordingly, the different types of breccias recognized at Sudbury are attributed to multiple brecciation processes occurring throughout the various stages of meteorite impact crater formation (Peredery and Morrison, 1984; Müller-Mohr, 1992; Thompson and Spray, 1994). Chemical composition of the matrix and the clasts in the Sudbury breccia as well as the host rocks favour in situ brecciation as the major process of breccia formation (Rousell et al., 2003; Legault et al., 2003). Thompson and Spray (1996) define the Sudbury breccia as a pseudotachylite that was formed mainly “by frictionally induced comminution and partial melting of wall rocks during high-speed (seismogenic) slip”.

#### 5. Experimental procedure and methodology

For the present study, 28 breccia sites were sampled, covering an area along the North range of the Sudbury Structure from the southwest shore of Wanapitei Lake in the east to Armstrong Lake in the west (Fig. 2). Normally,

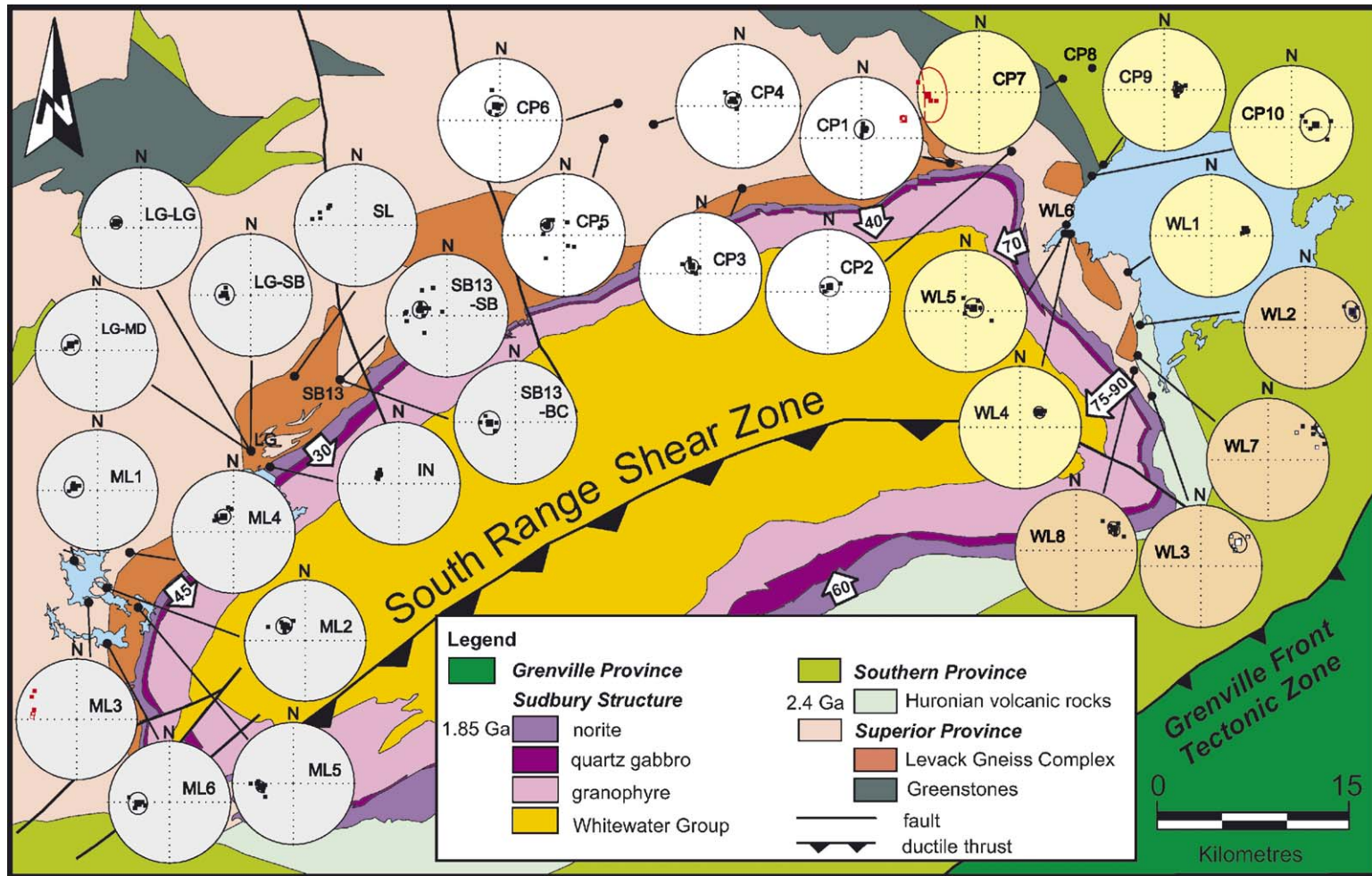


Fig. 2. Equal area stereographic projections of the site paleomagnetic directions in Sudbury breccia and site means with their  $\alpha_{95}$  circles of confidence from the northern side of the Sudbury Structure. Open/closed squares correspond to upward/downward pointing magnetizations, and black/red squares indicate A/B magnetizations. Data from the West range is shown in light gray stereonets, white stereonets represent data from the North range, light yellow stereonets represent data from the northern East range, and light orange stereonets are based on data obtained in the southern East range. See text for discussion. Map adapted from Wood and Spray (1998).

at least six samples were collected from each site. Both veins of breccia and breccia bodies of tens to hundreds of metres in lateral dimensions were sampled. Emphasis was placed on fine-grained veins of breccia containing few clasts, because previous experience (Smethurst, 1997) suggested that they more often preserved a stable, coherent remanence. A total of 140 field-drilled cores and 80 block samples, later cored in the laboratory, were oriented using magnetic and sun compasses. The 2.5 cm diameter cores were then cut into specimens 2.4 cm in length. Their remanent magnetization was measured in the Paleomagnetism Laboratory at the University of Toronto at Mississauga (UTM) with a modified DIGICO spinner magnetometer, with repeatability in measurement of natural remanent magnetization (NRM) intensities down to 1 mA/m. From all samples, at least one specimen (a total of 250) was treated by stepwise alternating-field (AF) demagnetization up to 100 mT using a Schonstedt GSD-1 instrument. Specimens with low NRM intensities of <1 mA/m were demagnetized in the paleomagnetic laboratories at the University Western Australia using a 2G Enterprises superconducting magnetometer and a two axis Magnetic Measurements (MM) tumbler, and at the University of Windsor (Canada) using an automated CTF DRM-420 cryogenic magnetometer and a Sapphire SI-4 AF demagnetizer. Stepwise thermal demagnetization was applied to 48 specimens, at least one per site, using a Schonstedt TSD-1 furnace to a maximum temperature of 600 °C. Paleomagnetic directions for the individual specimens were obtained by Principal Component Analysis (Kirschvink, 1980) with a maximum angular deviation of 10° using a computer program developed by Enkin (1994).

Investigations of magnetic mineralogy to identify possible magnetic remanence carriers were done on at least one specimen from each site using two methods. The variation of magnetic susceptibility with temperature ( $k$  versus  $T$ ) up to 700 °C was measured using a low-field automated Sapphire SI-3 magnetic susceptibility meter at the UTM Paleomagnetism Laboratory. We also performed isothermal remanent magnetization (IRM) acquisition measurements to reach saturation of the IRM (SIRM), which was then AF demagnetized in 12 steps up to 140–150 mT. These experiments were done using a Sapphire Instruments SI-4 AF demagnetizer, a Sapphire Instruments SI-6 pulse magnetizer, and a vertically configured 2G cryogenic magnetometer with a lower sensitivity limit of  $\sim 2 \times 10^{-6}$  A/m at the University of Windsor. The Anisotropy of Magnetic Susceptibility (AMS) was measured using a Sapphire susceptibility meter at the UTM laboratory. Polished thin sections

of 20  $\mu\text{m}$  thickness were also analyzed in both reflected and transmitted light to determine the type of breccia, the opaque mineralogy and the degree of alteration.

## 6. Optical microscopy observations

Using reflected and transmitted light microscopy, breccia samples were examined to obtain their composition, fabric and alteration, with particular attention paid to those opaque minerals such as pyrrhotite, magnetite and hematite that carry the remanent magnetization.

Clasts are represented by both monomineralic (i.e. quartz, plagioclase, microcline, minor pyroxene) and lithic fragments (gneiss, diabase) within various degrees of roundness. In a few sites (LG, WL6) clast alignment is present and in one site (WL2) there are flow structures. In general the clasts have been variously altered through quartz recrystallization, feldspar sericitization, and formation of secondary biotite (Fig. 3A), actinolite (Fig. 3B), muscovite, epidote, chlorite, and calcite. The matrix is crystalline in most sites, cryptocrystalline in a few sites (LG4, CP1, ML3), and in only one site clastic (WL2). Matrix recrystallization is represented by secondary plagioclase, epidote, quartz, biotite, and actinolite (see Fig. 3). Epidote (Fig. 3C), chlorite (Fig. 3D), quartz and calcite veins are present in a few samples and are post-brecciation as they both cut and include clasts. The assemblage of secondary minerals indicates a low to medium greenschist facies of metamorphism that affected both clasts and matrix. An attempt was made to relate the breccias with one of the four types defined by Müller-Mohr (1992) for the Sudbury breccia. Most are early frictional breccias, di- to polymictic dyke breccias, and dyke breccias with crystalline matrix (Table 1).

The opaque mineralogy is dominated by pyrrhotite (Fig. 3E), commonly accompanied by hypidiomorphic pyrite (Fig. 3F and G) and small amounts of chalcopyrite (Fig. 3E). Individual crystals of magnetite were found in the western, northwestern, and eastern samples located closer to the SIC that are characterized by the presence of fine-grained magnetite in the matrix of the breccias (Fig. 3G). This magnetite may be the result of norite contact metamorphism; secondary plagioclase with magnetite occurs in the footwall rocks around the North range of the SIC (Dressler, 1984a). Hematite is also found with magnetite in a few samples as discrete crystals (Fig. 3H) or as rims around grains of pyrite or pyrrhotite (Fig. 3F), possibly representing an oxidation stage in the process of brecciation or of later heating by the norite. Alteration of these iron oxides to hydroxides is also present to various degrees in the samples.

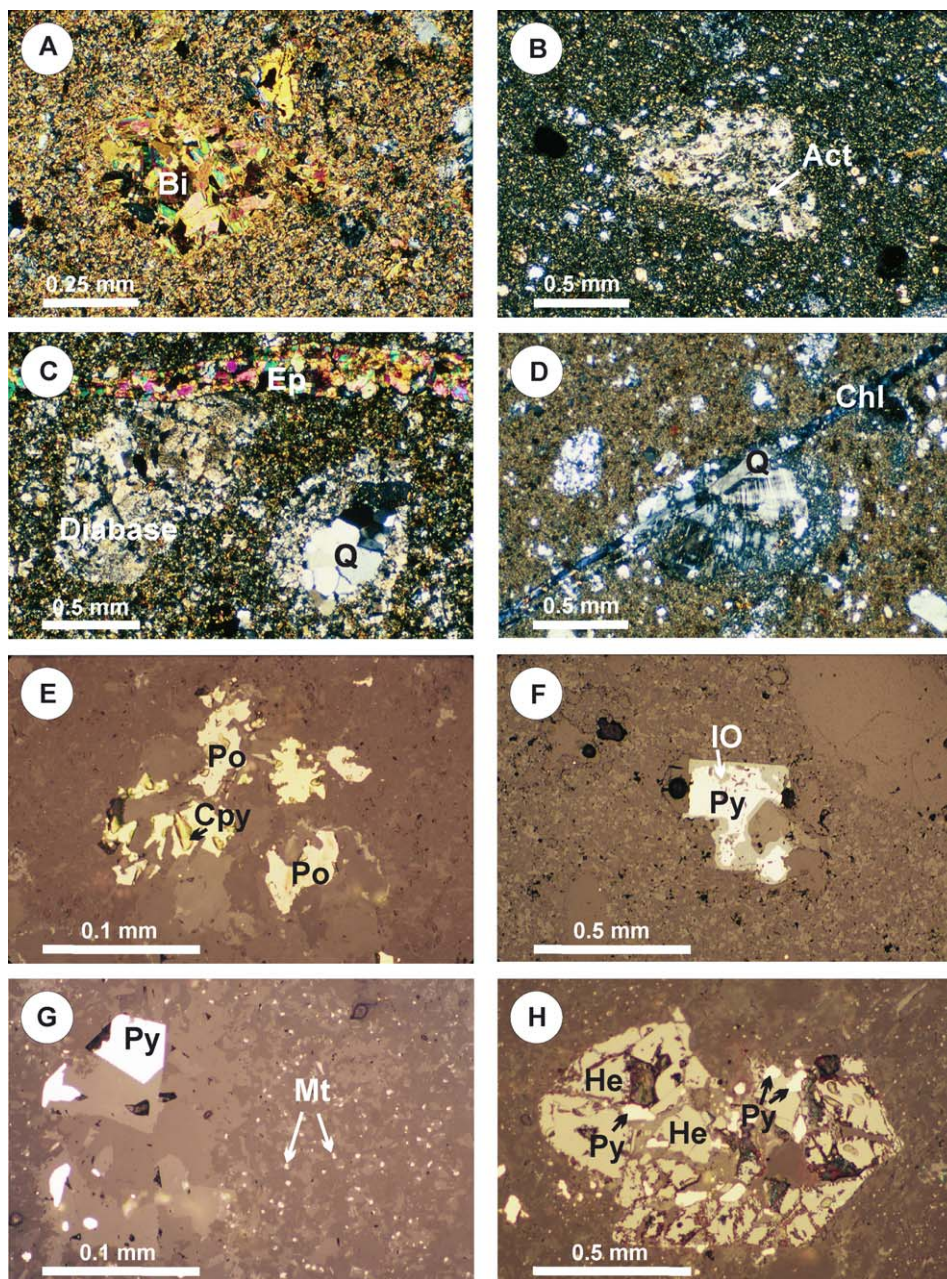


Fig. 3. Petrographic observations of alteration under crossed nicols and opaque mineralogy in Sudbury breccia: (A) biotite (Bi) in clasts and matrix; (B) actinolite (Act) in clasts and matrix; (C) epidote (Ep) vein; (D) chlorite (Chl) and quartz (Q) vein; (E) pyrrhotite (Po) and chalcocopyrite (Cpy); (F) pyrite (Py) with rims of iron oxides (IO); (G) pyrite and fine-grained magnetite (Mt); (H) hematite (He) with pyrrhotite.

## 7. Characteristics of Sudbury breccia remanence

The natural remanent magnetization (NRM) of the Sudbury breccia around the northern half of the Sudbury Structure varies in intensity from less than one to thousands of mA/m. The NRM intensity and susceptibility decrease away from the SIC, defining two zones of

mixed higher and lower values, between 0 and 1 km and around 2 km away from the SIC (Fig. 4). The higher values of susceptibility and NRM intensity recorded within about 2 km from the SIC contact suggest some enhancement due to contact metamorphism. Higher susceptibility values close to the norite/basement contact have also been documented south of the SIC within a

Table 1  
Summary of petrographic and paleomagnetic data

| Site        | Lithology <sup>a</sup> | N <sup>b</sup> | Site mean <sup>c</sup> |       | k <sup>d</sup> | $\alpha_{95}$ <sup>e</sup> (°) | Magnetic carrier <sup>f</sup> | Remanence type <sup>g</sup> |
|-------------|------------------------|----------------|------------------------|-------|----------------|--------------------------------|-------------------------------|-----------------------------|
|             |                        |                | D (°)                  | I (°) |                |                                |                               |                             |
| North range |                        |                |                        |       |                |                                |                               |                             |
| NW          |                        |                |                        |       |                |                                |                               |                             |
| ML1         | 3                      | 3              | 279.0                  | 57.2  | 80.7           | 13.8                           | –                             | A                           |
| ML2         | 3                      | 6              | 305.4                  | 54.7  | 36.5           | 11.2                           | mt                            | A                           |
| ML4         | 1                      | 7              | 325.8                  | 65.1  | 39.8           | 9.7                            | –                             | A                           |
| ML5         | 3                      | 8              | 264.9                  | 44.9  | 70.6           | 6.6                            | mt                            | A                           |
| ML6         | 3                      | 4              | 267.8                  | 46.2  | 46.0           | 13.7                           | mt                            | A                           |
| SB13-BC     | BC                     | 4              | 268.0                  | 54.7  | 38.4           | 15.0                           | mt                            | A                           |
| SB13-SB     | 1                      | 13             | 283.4                  | 53.3  | 15.4           | 10.9                           | mt                            | A                           |
| LG-LG       | LG                     | 3              | 282.2                  | 55.1  | 223.2          | 8.3                            | –                             | A                           |
| LG-MD       | MD                     | 3              | 282.4                  | 54.4  | 87.2           | 13.3                           | –                             | A                           |
| LG          | 1                      | 3              | 271.9                  | 54.4  | 84.2           | 13.5                           | –                             | A                           |
| IN          | IN                     | 7              | 295.8                  | 60.6  | 279.4          | 3.6                            | mt                            | A                           |
| N           |                        |                |                        |       |                |                                |                               |                             |
| CP1         | 3                      | 3              | 15.7                   | 77.4  | 90.2           | 13.1                           | –                             | A                           |
| CP1         | 3                      | 3              | 65.2                   | –25.8 | 999.9          | 3.6                            | po                            | B                           |
| CP2         | 3                      | 4              | 18.8                   | 83.0  | 52.7           | 12.8                           | –                             | A                           |
| CP3         | 3                      | 6              | 310.3                  | 74.7  | 53.5           | 9.2                            | mt                            | A                           |
| CP4         | 3                      | 5              | 318.6                  | 79.3  | 54.0           | 10.5                           | po                            | A                           |
| CP5         | 3                      | 5              | 301.0                  | 63.6  | 78.8           | 8.7                            | –                             | A                           |
| CP6         | 1                      | 5              | 343.4                  | 70.1  | 32.2           | 13.7                           | –                             | A                           |
| East range  |                        |                |                        |       |                |                                |                               |                             |
| NE          |                        |                |                        |       |                |                                |                               |                             |
| CP7         | 3                      | 3              | 266.4                  | 17.3  | 18.5           | 29.5                           | po                            | B                           |
| CP8         | 3                      | 5              | 64.4                   | 85.1  | 16.6           | 19.3                           | –                             | PEF                         |
| CP9         | 2                      | 7              | 85.6                   | 71.1  | 80.0           | 6.8                            | mt                            | A                           |
| CP10        | 3                      | 5              | 84.8                   | 57.5  | 14.6           | 20.7                           | low-Ti mt                     | A                           |
| WL1         | 1                      | 5              | 80.1                   | 43.0  | 341.8          | 4.1                            | mt                            | A                           |
| WL4         | 3                      | 4              | 52.4                   | 57.2  | 147.8          | 7.6                            | mt                            | A                           |
| WL5         | 3                      | 7              | 69.9                   | 78.0  | 23.7           | 13.7                           | mt                            | A                           |
| WL6         | 1                      | 4              | 283.1                  | 84.2  | 36.2           | 15.5                           | –                             | PEF                         |
| WL2         | 2                      | 4              | 70.6                   | 18.6  | 62.5           | 11.7                           | mt                            | A                           |
| SE          |                        |                |                        |       |                |                                |                               |                             |
| WL3         | 3                      | 5              | 56.6                   | –28.8 | 39.4           | 12.3                           | –                             | A                           |
| WL7         | 3                      | 7              | 60.3                   | –1.6  | 12.0           | 18.5                           | –                             | A                           |
| WL8         | 3                      | 7              | 59.7                   | 28.7  | 52.0           | 8.4                            | –                             | A                           |

<sup>a</sup> Numbers for lithology represent either breccia types as defined by Müller-Mohr (1992) (1, early frictional breccia; 2, di- to polymictic dyke breccia; 3, dyke breccia with crystalline matrix) or rock lithology (BC, Sudbury breccia clasts; LG, Levack Gneiss; MD, Matachewan dyke diabase; IN, intermediate norite).

<sup>b</sup> Numbers of samples used for calculating site means.

<sup>c</sup> Declination (*D*) and inclination (*I*) of paleomagnetic direction mean.

<sup>d</sup> Fisher precision parameter.

<sup>e</sup> Half-angle of the cone of 95% confidence about the mean direction.

<sup>f</sup> Magnetic carrier as determined from thermal demagnetization data; symbols for magnetic carriers are mt for magnetite and po for pyrrhotite; dash for magnetic carrier indicates no specific data.

<sup>g</sup> A and B stand for types A and B components; PEF, present Earth's magnetic field. All paleomagnetic directions are recalculated for a common location at 46.6°N latitude and 278.8°E longitude.

500 m-wide contact metamorphic zone with the Murray granite pluton (Riller et al., 1996). Susceptibility appears positively related to NRM intensity, but exceptions exist.

### 7.1. Paleomagnetic components

Generally, AF demagnetization revealed two or three remanence components with more-or-less overlapping

coercivity spectra. After first removing a viscous component of low coercive force, a second higher-coercivity component was observed in the specimens from each site, i.e. component A, that could be isolated on vector diagrams (Table 1). Component A is characterized by high coercivities of  $\sim 60$ – $100$  mT and by high unblocking temperatures in the range of  $540$ – $590$  °C (Fig. 5a). Together with drops at  $580$ – $590$  °C on the susceptibility curves (e.g. SB13-5-1, Fig. 6), all of these parameters indicate that the resolved A magnetization is carried by magnetite.

One of the main characteristics of the A remanence was that, usually, it did not yield stable end points on AF demagnetization because another component (B) with higher coercivity ( $>100$  mT) was present (Fig. 5b). An important observation is that B sometimes is related to low-unblocking temperatures of around  $320$ – $370$  °C (Fig. 5b). Low unblocking temperatures of about  $\sim 340$ – $370$  °C were also found through susceptibility measurements (e.g. CP9-5-2 and CP7-4-1, Fig. 6). A pyrrhotite sample from Sudbury (courtesy of Özden Özdemir) gave the expected unblocking temperature of  $320$  °C, based on the results of Schwarz (1975). The Curie temperature of pyrrhotite and the broad range of Curie temperatures specific to titanomagnetites are the closest match for the  $\sim 320$ – $370$  °C temperature values obtained through thermal demagnetization and susceptibility measurements from this study. When heated above  $500$  °C, pyrrhotite transforms irreversibly, usually to magnetite (Bina and Daly, 1994), and at higher temperatures to hematite, either directly or by oxidation of magnetite (Dekkers, 1990). For specimens where the low unblocking temperature magnetic phase is present, the cooling curve records an increase in susceptibility, thus supporting the presence of some kind of pyrrhotite (Fig. 6). Thin sections, particularly those from specimens that only show the  $320$ – $370$  °C drop, contain pyrrhotite. All these observations suggest that some form of pyrrhotite carries the B remanence. Similar susceptibility drops at  $350$ – $370$  °C and enhanced values during subsequent cooling have been found in other samples from magnetically reset dykes that were measured with the same instruments (Halls et al., 2001; Halls and Wingate, 2001). High unblocking temperatures up to  $350$  °C for natural pyrrhotite were obtained experimentally by heating in air and argon (Rochette et al., 1990), and the presence of oxygen which diffuses easily through the pyrrhotite crystal lattice (Graham and Bennett, 1987) was inferred to explain such high unblocking temperatures.

SIRM crossover plots (Symons and Cioppa, 2000) generated two distinct groups of points: one group of

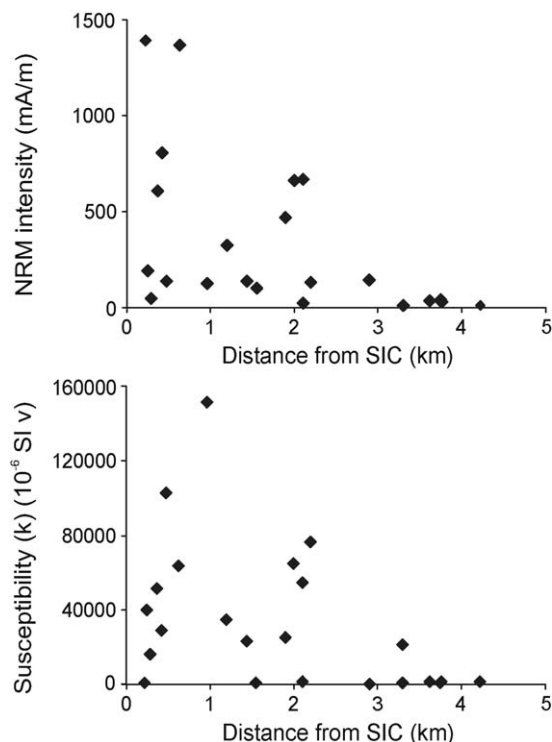


Fig. 4. NRM average intensity and susceptibility ( $k$ ) values as a function of distance from the SIC/basement contact. Note the overall positive correlation between the NRM and  $k$ , and the higher intensities between  $\sim 0$  and  $1$  km, and at  $\sim 2$  km beyond the SIC/basement contact.

less interactive magnetic grains (values just below 0.5) of single domain magnetite and a more interactive cluster (values significantly lower than 0.5) probably representing mixed single domain and pseudosingle domain magnetite (Fig. 7). How much the presence of pyrrhotite influences these data is hard to assess; only one crossover point was found to indicate the presence of single domain pyrrhotite in one specimen, suggesting that the SIRM data are mainly the reflection of the domain state of magnetite in the breccia (Symons, D.T.A., 2004. Personal communication). Three points greater than 0.5 indicate that some samples contain a higher coercivity magnetic mineral, hematite or goethite, which influences the position of the crossover points for these samples (Szabó and Cioppa, 2004). However, most samples saturated at about  $400$  mT, a sign that magnetite dominates the magnetic phase in the breccia.

## 7.2. Origin of the B remanence component

Remanence B differs from A in having a higher coercivity spectrum, generally lower unblocking tem-

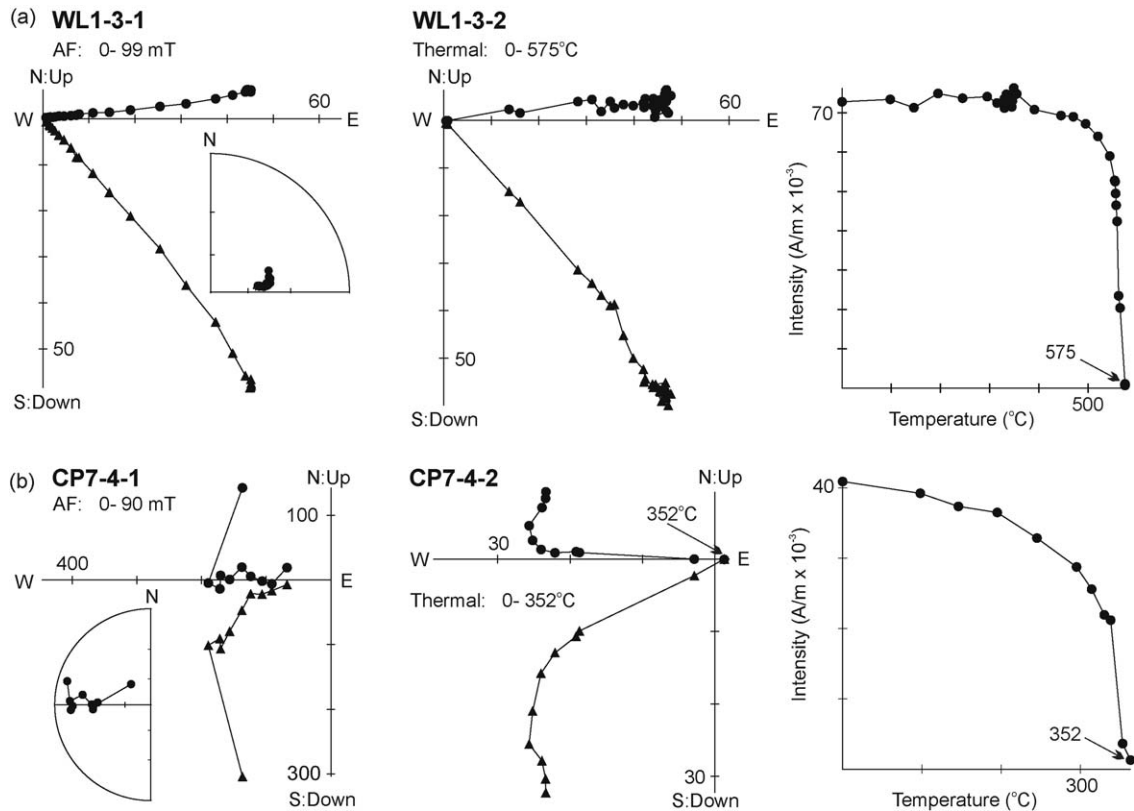


Fig. 5. Characteristic demagnetization behaviours of the *A* and *B* components for the northern side of the Sudbury Structure. Each row presents data based on AF and thermal demagnetization from two specimens of a common sample. From left to right they are: a vector diagram and equal angle stereographic projection based on alternating field demagnetization, followed by vector diagrams and intensity decay plots obtained through thermal demagnetization. Scale is in units of mA/m. In the stereographic projections, open/closed circles correspond to upward/downward magnetizations. In the vector diagrams, solid circles/triangles represent projections of the tip of the magnetization vector on the horizontal/vertical plane.

peratures and a distinctly different remanence direction. These observations suggest that *B* reflects a younger metamorphic overprint. Sometimes low-unblocking temperature components were found with similar directions to *A*, suggesting that the remanence was not affected by remagnetization events. In other cases the higher coercivity component entirely overprinted the breccia remanence (CP7-4-1, Fig. 5b). The identification of *B* magnetizations with post-Penokean geological events is difficult because they do not always correspond with previously recognized paleomagnetic directions. Candidates include the “normal polarity” 1.2 Ga Sudbury dyke direction ( $\sim 266^\circ/0.8^\circ$ , Palmer et al., 1977), a possible reversed polarity Sudbury dyke suite known as the McGregor Bay dykes (mean  $\sim 100^\circ/23^\circ$ , Palmer et al., 1977),  $\sim 1000$  Ma Grenville Province resetting ( $\sim 111^\circ/27^\circ$ , Palmer et al., 1977; Larochelle, 1967), a  $\sim 600$  Ma Grenville dyke event ( $\sim 119^\circ/45^\circ$ ; Murthy, 1971), and Type 3 ( $209^\circ/31^\circ$ ) and Type 4 ( $323^\circ/31^\circ$ ) directions identi-

fied with pyrrhotite mineralization events by Morris (1981).

Different directions of *B* magnetization were obtained (Fig. 8): Sudbury dyke directions (CP7-4-1, Fig. 5b), a remanence with shallow negative inclination and east–northeast declination, not recorded before but whose nearest neighbour in terms of direction comes from the McGregor Bay dykes and the Sudbury dykes within the Grenville Province (CP1, Fig. 9a), Type 3 reversed and Type 4 normal directions found by Morris and Pay (1981), various other directions of unknown nature in the south and southwest quadrant, many with directions intermediate between that of the Sudbury dykes and the Type 3 direction found by Morris and Pay (1981). If the shallow northeast overprints are related to fluid movement accompanying the Sudbury (dyke) igneous event, then the reversed direction, being closer to the suspected source of the magma, may be younger than the normal one. However, clearly reversed Sudbury dyke directions were not found in the Sudbury

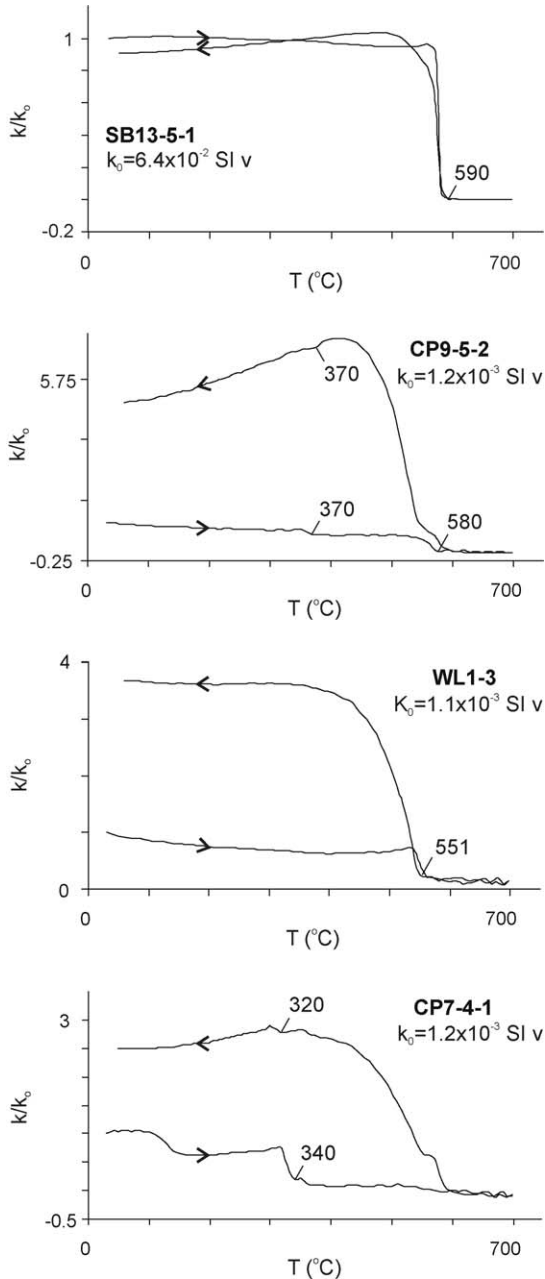


Fig. 6. Susceptibility ( $k$ ) as a fraction of initial susceptibility ( $k_0$ ), plotted against temperature in °C, during both heating and cooling cycles. Note the two major drops of  $k$  intensity at around 350–370 and 580 °C that correspond to pyrrhotite (?) and magnetite, respectively. The two minerals can appear together or by themselves. Also note the increase of the susceptibility in the cooling process showing magnetite and low-Ti magnetite formation at the expense of the low temperature component.

area, the olivine diabase McGregor Bay dykes being the only possible candidates (Palmer et al., 1977) and so this is only a hypothesis. Alternatively, other metamorphic events such as those documented at ~1660 and

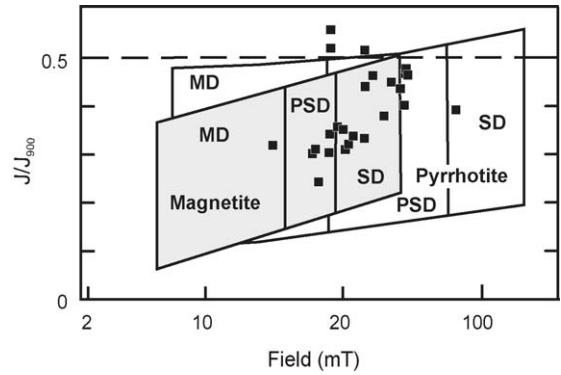


Fig. 7. SIRM crossover points in the Sudbury breccia plotted against theoretical domains for magnetite and pyrrhotite (Symons and Cioppa, 2000).  $J_{900}$ , magnetization intensity at 900 mT; MD, multidomain grain size; PSD, pseudosingle domain grain size; SD, single domain grain size.

~1450 Ma (e.g. Fueten and Redmond, 1997; Bailey et al., 2004), although lacking paleomagnetic data, might be responsible for these  $B$  pyrrhotite magnetizations in the Sudbury breccia. Other components of low coercivity and low unblocking temperature were also present,

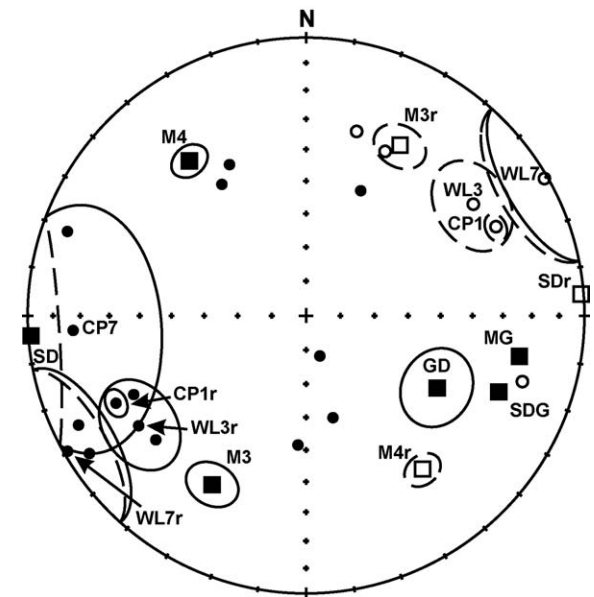


Fig. 8. Equal area stereographic projection of various Sudbury breccia  $B$  specimen directions (circles) and site means (labelled circles with 95% level of confidence) compared to known paleomagnetic directions from the Sudbury area (large squares) for: Sudbury dykes (SD); McGregor Bay dykes (MG); Grenville overprints in Sudbury dykes (SDG) (Palmer et al., 1977; Larochelle, 1967); Grenville dykes (GD; Murthy, 1971), M3 and M4 (Types 3 and 4 components; Morris, 1984). WL3 and WL7 type A and CP1 type B as well as SD, M3, and M4 magnetizations are plotted in both polarities (i.e. WL3 and WL3r). Open/closed symbols correspond to upward/downward magnetizations.

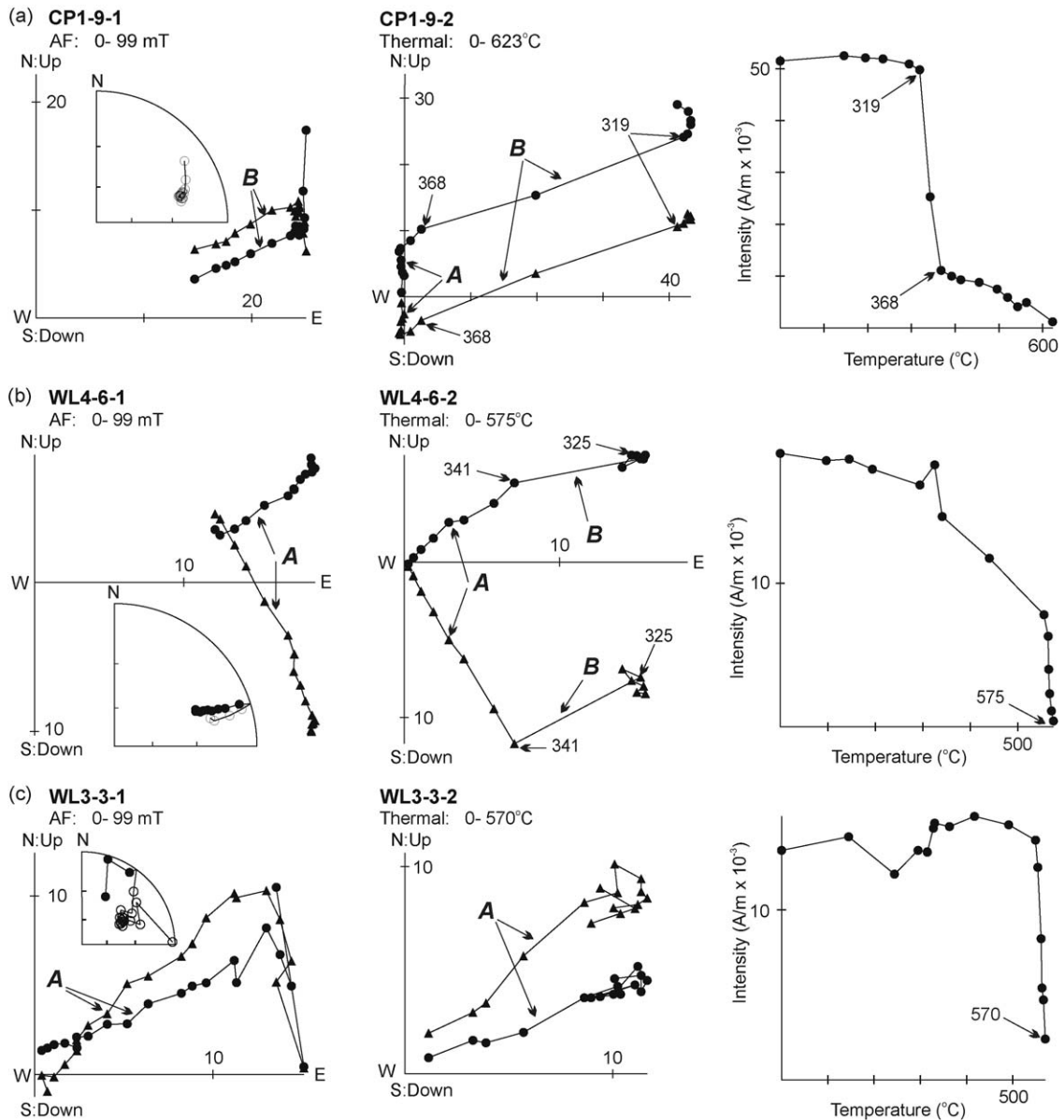


Fig. 9. Characteristic demagnetization behaviour of the *A* and *B* components in the north (a), northeast (b), and southeast (c) segments of the Sudbury Structure. Note the directional similarity for the *B* component in the north (a) and northeast (b) and the *A* component in the southeast (c), which is in contrast to their coercivity and unblocking temperatures. Explanation of plots as in Fig. 5.

some of them being viscous present Earth's field (PEF) components and others similar to *A* in direction (Table 1).

### 7.3. Variation of the *A* component around the northern part of the Sudbury Structure

The characteristics of the *A* remanence around the North range of the Sudbury basin, show systematic differences. The western and northwestern directions (Fig. 2) are consistent in direction both at the within-

site and between-site level, having westerly declinations and downward inclinations. The only exception is site ML3 where a ~50 m-wide Sudbury dyke occurs about 20 m away (OGS Map Number 2491, Dressler, 1984b) and may have reset the breccia remanence. A mean was not defined for this site because of clear streaking in the remanence directions. The same observations seen in the western sites are also found for the northern data (Fig. 2), the difference being the more northerly declinations and steeper inclinations. At site CP5 a coherent *A*

direction with steep inclination and northerly declination was found, but other samples, closer to a shear zone were more scattered (Fig. 2). Along the eastern range site mean distributions become more scattered (Fig. 2), but they are broadly divisible into northern and southern groups (Fig. 2). With the exception of one site (CP7) which displays a clear pyrrhotite-carried *B* component with a typical Sudbury dyke direction (Fig. 8), the remaining sites (WL1, 4 and 5, CP9, 10) all show a steep to intermediate down *A*-type component with a northeast to easterly declination, carried by magnetite. Even sites CP8 and WL6, although showing scattered directions dominated by low coercivity components, include samples of higher coercivity with the same direction. The northeast corner therefore is characterized by an *A* component direction that is similar to that from the adjacent North range, except that the declination is more easterly.

Paleomagnetic results from breccias in the southern East range (sites WL2, 3, 7, 8) differ markedly from all others in having the majority of samples showing a shallow positive to negative inclination and east–northeasterly declination. These sites are characterized by demagnetization paths with a northeasterly movement to shallower inclinations followed by movement back towards steeper inclinations, which sometimes continue towards the westerly Sudbury dyke direction. Samples at both sites WL7 and 8 show a high coercivity steep down direction to the north similar to that found in the North and northern East ranges. This behaviour of a northeasterly movement to shallower inclinations upon demagnetization also characterises some sites (e.g. WL4, 5) from the northern East range (Fig. 9b). An important link between the two components is provided by site WL4 (Fig. 9b), which shows a sample in which the shallow inclination component is virtually untouched by AF demagnetization but is completely removed by a temperature of 340 °C, suggesting that it is carried by pyrrhotite. In accordance with our earlier findings, this component would be interpreted as a secondary *B* component along a direction closest to that found in the McGregor Bay dykes. Farther south along the East range, at sites WL2, 3, 7 and 8, a component with virtually the same shallow direction, dominates over the steeper component but its nature is problematical. It appears to be carried by magnetite and has coercivity and unblocking temperatures similar to that of the *A* component (Fig. 9c). Petrographic thin sections and *k* versus *T* plots from these sites all identify magnetite rather than pyrrhotite. We will provisionally include this shallow component as an *A* remanence while recognizing that its direction is virtually identical with components, interpreted as overprints that are close in age to reversed

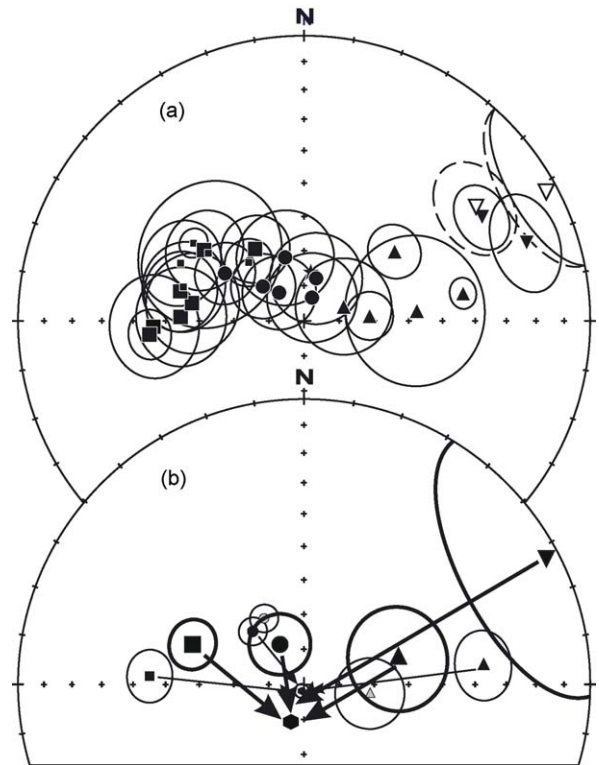


Fig. 10. (a) Equal area stereographic projection of Sudbury breccia site means and their  $\alpha_{95}$  confidence circles for the *A* component in the West (this study, larger squares; Smethurst, 1997, smaller squares), North (circles) and East (triangles and inverted triangles) ranges of the Sudbury Structure. Note the broad east–west streaking, the scattered data in the east and the well grouped means in the west and north. The star illustrates the present Earth's magnetic field direction. Solid/open symbols indicate positive/negative inclinations. (b) Comparison between Sudbury breccia directions (larger symbols), norite directions (smaller black symbols; Morris, 1980), and granophyre (gray smaller symbols; Morris, 1981) in the West (squares), North (circles), and East (triangles) ranges of the Sudbury basin. There is an obvious correspondence between the east–west streaking of the Sudbury breccia directions and the norite and granophyre directions from the same sides of the North range. Partial untilting brings the Sudbury breccia directions for the different ranges into a common direction ( $199.4^\circ/78.8^\circ$ ), close to the norite one ( $199^\circ/88^\circ$ ).

Sudbury (McGregor Bay) dykes that occur in sites CP1 and WL4 (Fig. 9).

A summary of site data for the *A* remanence is shown in Fig. 10a. The data to the west, northwest, north and northeast of the SIC are represented by well-grouped sites with steep inclinations that toward the east vary progressively in declination, whereas southeast of the SIC, inclinations are much less and have east–northeast declinations. Consequently there is a strong east–west streaking of site means.

The broad east–west streaking in Fig. 10a could be interpreted as a sign of unremoved magnetic overprints

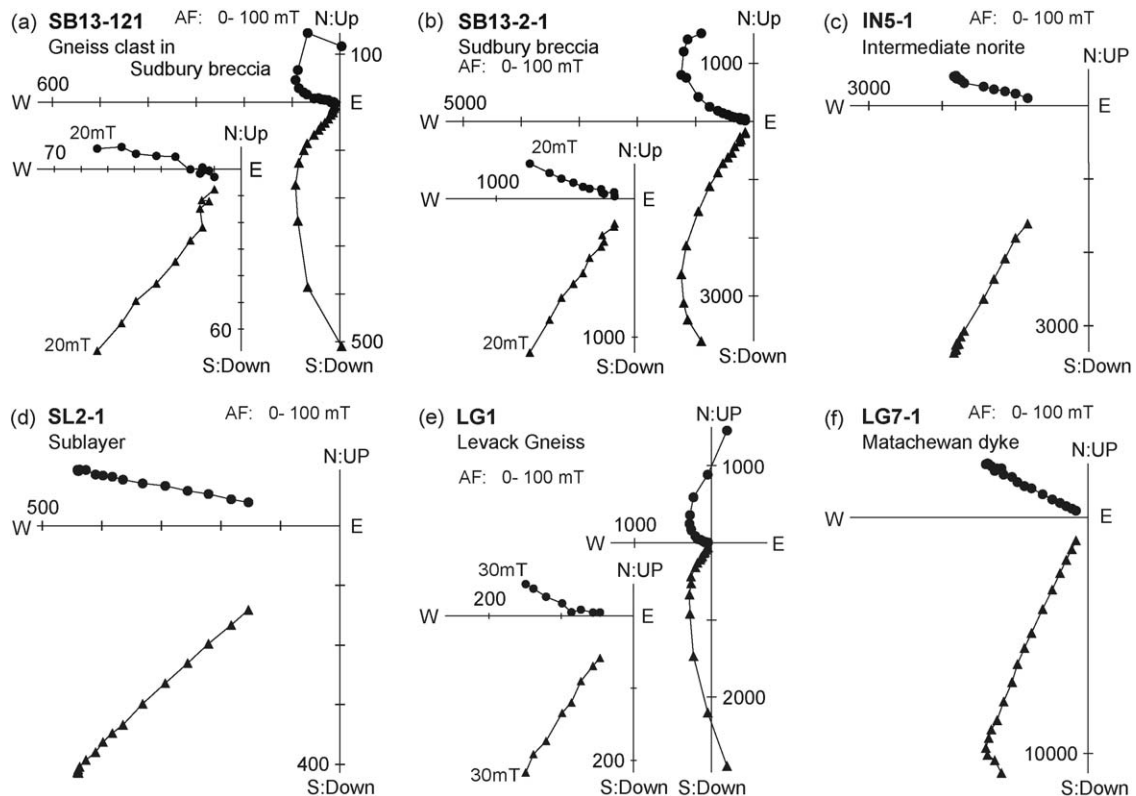


Fig. 11. Vector diagrams for clast (a) and matrix (b) of Sudbury breccia, intermediate norite (c), Sublayer (d), Levack gneiss (e) and Matachewan dyke diabase (f) from the northwest part of the Sudbury Structure (based on AF demagnetization data). Note the similarity in the direction exhibited by both the matrix and the clast of the breccia and also the host rock lithologies. Scale is in units of mA/m. Solid circles/triangles represent projections of the tip of the magnetization vector on the horizontal/vertical plane.

such as those from the Sudbury dyke event that are known to affect the data. However, the  $\alpha_{95}$  confidence ovals of the calculated means from regions around the northern half of the SIC do not overlap (Fig. 10b), are relatively small (Table 1) and show essentially no within-site or within-group streaking. Also, *A* components defined by stable end points as revealed by AF and thermal demagnetization procedures (Fig. 5a), are clearly separated from coexisting *B* components (e.g. WL4-6-1 and WL4-6-2 in Fig. 9b). However, we cannot completely rule out that secondary overprints such as those related to Sudbury and McGregor Bay dykes are contaminating the data. The southern East range for example is dominated by a conspicuous low inclination component that looks like *A* in its coercivity and thermal characteristics and yet occurs with another component that also is carried by magnetite and has high coercivities, but yields a steep *A*-like direction! If the shallow component is indeed close to a reversed Sudbury dyke age, then an interesting observation can be made: the Sudbury dyke direction occurs pervasively around the SIC where many sites (e.g. ML3, WL6, WL4, CP7) show movement towards shallow

westerly or west-southwesterly declinations at the highest demagnetizing fields, but it is only in the east where the reversed Sudbury dyke-like component dominates.

#### 7.4. Origin of the *A* remanence component

Within site SB13, both clasts (SB13-BC, Fig. 2) and matrix (SB13-SB, Fig. 2) carry the *A* remanence (Fig. 11a and b). This could indicate that (a) the magnetization in Sudbury breccia was acquired during breccia formation as a fault frictional melt at high temperatures (800–900 °C, Thompson and Spray, 1996) so that clast heating reset any remanence carried by magnetite, (b) it was acquired as an overprint remanence during subsequent heating by the norite or (c) it is a post-SIC overprint. In the northwest, three sites were sampled with the purpose of testing the magnetic remanence present in Levack Gneiss (LG–LG in Fig. 2, site LG), Matachewan dykes (LG–MD in Fig. 2, site LG), intermediate norite (site IN), and sublayer (site SL) (Figs. 2 and 11). All four rock types gave a virtually single-component *A* direction similar to that

carried by Sudbury breccia (LG–SB in Fig. 2, site LG) in the same area (Fig. 2). Sample directions at the sublayer (SL) site exhibit an unexplained streaking in their distribution from 278.1°/28.8° to 307.6°/46.3° and therefore no mean was calculated in this case. For these samples thermal demagnetization showed discrete drops in remanence intensity at 550 and 590 °C, demonstrating that the magnetic carrier is magnetite or low-Ti titanomagnetite. A low unblocking temperature at ~360–370 °C was found only through susceptibility measurements but the overall susceptibility spectrum is dominated by magnetite. The fact that these different lithologies are characterized by such similar magnetic remanence directions indicates that all these rocks of different ages were subject to the same magnetization event and consequently that the Sudbury breccia may not carry a primary TRM but a thermo-chemical overprint.

Four post-SIC events could have affected the magnetic remanence in the Sudbury area: the Grenville orogeny (1.1–0.9 Ga), the 1.2 Ga Sudbury and 0.6 Ga Grenville intrusive events, and the Penokean orogeny (1.9–1.7 Ga). Grenville directions were not recorded in the studied Sudbury breccias. The metamorphic temperature recorded for the Grenville Front decreases to less than ~400 °C beyond a distance of 2 km (Palmer et al.,

1977; Hyodo et al., 1986). The closest sampled sites in this study are more than 20 km away from the Front. Similarly, Grenville dykes may be present in the Sudbury Structure, most lie to the south of the Front and are unlikely to have affected the breccias.

The intrusion of Sudbury diabase dykes locally overprinted the remanence of the Sudbury breccia, usually in cases where the breccia was in contact (e.g. CP7) or located within the reheated zone of the dyke (e.g. ML3). Overall, Sudbury dyke-like remanences have low-unblocking temperatures and the highest coercivities, corresponding to perhaps a particular phase of pyrrhotite. A frequent observation throughout the entire study area was that at the highest coercivity directions progressively moved towards shallower westerly declinations. Only in the extreme east do directions shallow more commonly towards the east. However, we should stress that the absence of east–west streaking at the within-site level for the A remanence directions, suggests that the Sudbury dyke and other overprints have been effectively removed by our demagnetization procedures.

Metamorphic studies indicate only a low to middle greenschist facies related to the Penokean orogeny in the North range of the Sudbury basin (Card, 1978; Fleet et al., 1987; Easton, 2000). In order to completely

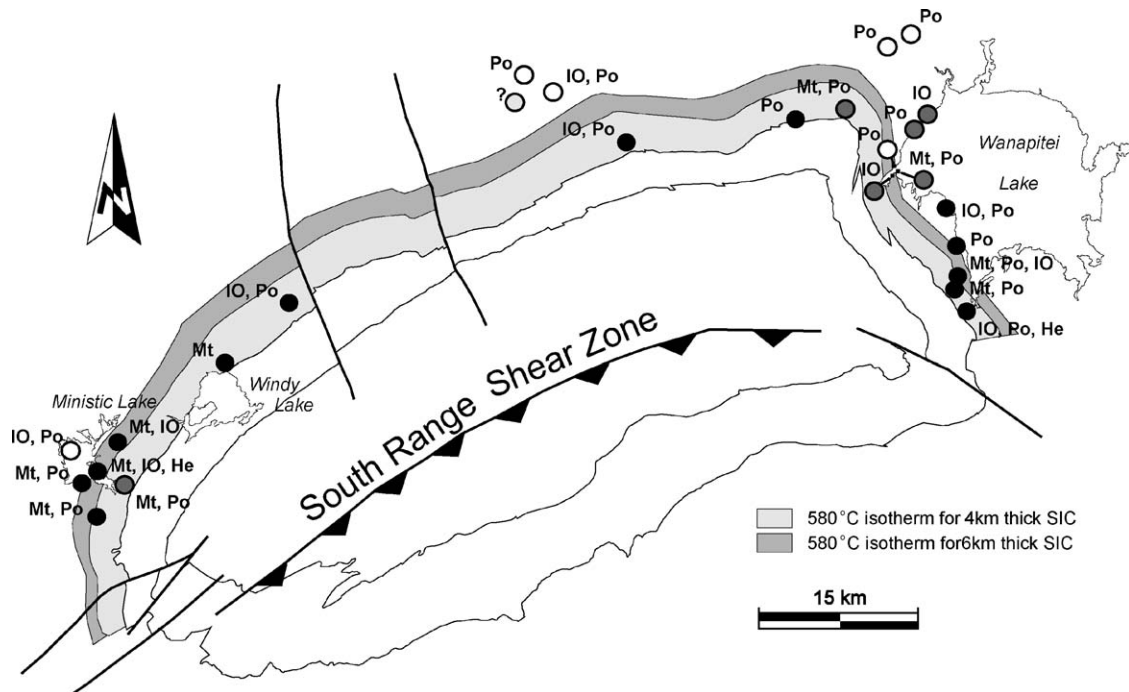


Fig. 12. Susceptibility (*k*) characteristics (circles) and magnetic mineralogy (characters) around the North range of the Sudbury Structure. Mt, fine-grained magnetite; IO, iron oxides (magnetite and/or hematite); Po, pyrrhotite; He, hematite. Circles represent the magnetic minerals as obtained from *k* vs. *T* data. Black circles show the exclusive presence of magnetite, darker gray circles illustrate dominance of magnetite over pyrrhotite, lighter gray circles show dominance of pyrrhotite over magnetite, whereas white circles indicate the presence of only pyrrhotite.

reset magnetite remanences, unblocking temperatures of  $\sim 550\text{--}590^\circ\text{C}$  would require exposures to temperatures of more than  $500^\circ\text{C}$  acting over hundreds of millions of years as shown by blocking temperature curves as a function of time (Pullaiah et al., 1975). Based on these figures, Dunlop and Buchan (1977) indicate that a magnetization with a blocking temperature of  $500^\circ\text{C}$  should survive greenschist metamorphism. A positive contact test in the North range confirmed that the paleomagnetic remanence found in the offset dykes shows similar paleomagnetic directions with those in the North range norite and has not been overprinted by later remagnetization events (Morris, 1982b). These arguments support the idea that the *A* remanence recorded in the Sudbury breccia represents a pre-Penokean magnetization.

Overall, the distribution of site mean *A* directions (Fig. 10a) bears some relationship with the structure of Sudbury basin. A compilation of the breccia directions from this study and from previous work from the northwest side of the Sudbury basin (Smethurst, 1997) as well as norite and granophyre means from the North range (Morris, 1980, 1984) is presented in Fig. 10b. The breccia directions exhibit the same distribution from west to east as those from the norite and granophyre (Fig. 10b). Also, in the northeast the breccia directions are located between the directions found in the norite and the granophyre, whereas in the north the difference between the three lithologies is less distinct. For the North and northern East ranges, the  $\alpha_{95}$  confidence circles of the mean directions from the three different rock types overlap and their means are not distinctly different at the 95% confidence level. The norite mean in the East range was calculated from five sites and the granophyre only from three (Morris, 1980, 1981). In the southern East range the norite and granophyre directions are as steep as the ones in the northern East range and therefore the difference between the norite and the breccia is anomalously large here, a difference that could be explained if the breccia remanence is younger.

The overall similarity in the distribution of mean *A* directions from the norite, granophyre and breccia implies that they carry the same remanence signature, and that the breccia was either overprinted by norite/granophyre heating or being broadly contemporaneous, recorded a similar field direction. Thermal modelling of the Sudbury Structure suggests that the  $580^\circ\text{C}$  (the unblocking temperature of magnetite) isograd occurred at a depth of one-half of the assumed SIC thickness, about 2–3 km below the SIC (Ivanov, B.A., 2001. Personal communication; see Ivanov and Deutsch, 1999 for more details). Most of the studied breccias are located within 2–3 km from the SIC bound-

ary (Fig. 12). In this scenario, the E–W streaking in the breccia-remanence directions around the northern half of the Sudbury basin can be explained in the same way as the norite remanence distribution. Morris (1984) observed that the scatter of norite directions decreased upon unfolding of the Sudbury Structure. Thus, the breccia and the norite both may have acquired their remanences at more or less the same time and before the Sudbury basin achieved its present form.

Susceptibility versus temperature (*k* versus *T*) measurements clearly exhibits the presence of magnetite and pyrrhotite in the Sudbury breccia (Fig. 6). These two minerals can dominate individually the susceptibility curve, but they can also coexist, confirming the thermal demagnetization results from the same samples that show unblocking temperatures of both  $\sim 360$  and  $\sim 580^\circ\text{C}$ . In samples close to the Sudbury basin, high susceptibility and remanence intensity are caused by magnetite rather than pyrrhotite, but further away the reverse is true (Fig. 12). The relative abundance of these two minerals could not be confirmed from the thin sections because only the monoclinic pyrrhotite ( $\text{Fe}_7\text{S}_8$ ) is ferrimagnetic and a distinction between different types of pyrrhotite cannot be made using standard optical microscopy. Rims of iron oxides were found to replace pyrite and pyrrhotite in many of the studied samples. A possible explanation for these observations is that the breccia closer to the norite has been subsequently heated to the extent that much of magnetic pyrrhotite converted to magnetite, thus supporting the premise that the *A* remanence in the Sudbury breccia has been produced substantially by SIC heating along with associated mineralogical changes, and thus being of a thermochemical origin. Increased susceptibility values close to the norite/basement contact have been documented south of the SIC, at the contact with the Murray granite pluton. They were also explained by the production of magnetite during norite contact metamorphism (Riller et al., 1996).

## 8. Discussion and conclusions

The distribution of the *A* remanence direction of the Sudbury breccia around the northern half of the Sudbury Structure exhibits a west–east streaking as one moves from west to east. The same applies for the norite unit of the SIC (Morris, 1980). From the present and previous studies around the northern margin of the SIC, both the geological strike and the paleomagnetic declination change in a clockwise manner towards the east, which is in agreement with an inward tilting of different sides of the SIC about axes parallel to the local strikes of the SIC/basement contact (Morris, 1984).

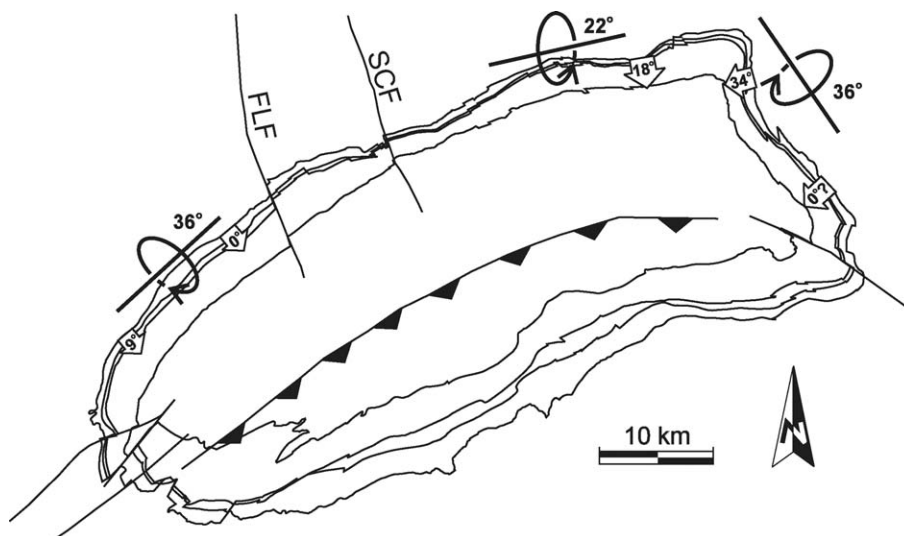


Fig. 13. Geological history of the northern part of the Sudbury Structure in the light of Sudbury breccia paleomagnetic results. Local dips are illustrated by numbers in white arrows. Inward rotations about axes parallel to the local strikes are shown by black arrows and the numbers associated with them define the amount of these rotations. FLF, Fecunis Lake Fault; SCF, Sandcherry Creek Fault.

A reduced streaking in the paleomagnetic directions found in the norite is observed when the ranges are rotated outwards by values of 42–47°, 24°, and 61° for the western, northern and eastern margins, respectively (Morris, 1984). The result is an initially more open Sudbury basin, plunging gently to the southwest. The inward dip of the North range had a value of 20°, the East range dipped 14° to the southwest, whereas the West range was subhorizontal. In Fig. 10b the same procedure was applied to the Sudbury breccia remanence directions. As one can see, unfolding about axes parallel to local strike moves site means towards a common direction at 199.4°/78.8°, close to that (199°/88°) estimated by Morris (1980) for the norite. Inward rotations for the west–northwest, north, and northeast areas, respectively, are 36°, 22°, and 36°, respectively. This leaves initial dips around the basin of 0–9°S in the west–northwest, 18°S in the north, and 34°W in the northeast (Fig. 13). The above partial untilting is supported by a McFadden and Jones (1981) statistical fold test at a 95% level of confidence.

Despite this broad agreement with the interpretation of Morris, a major dilemma remains, and concerns the data from the southern half of the East range. In order to bring the interpreted *A* directions into the pre-folding magnetization direction, the southern East range must be tilted westwards about 90°, which would immediately flatten the SIC/basement contact, causing a 50° difference in rotation between the north and south segments of the East range, which cannot be readily reconciled with the 5–20° difference in the dip of the SIC/basement contact (Fig. 2).

Another problem is that Morris's norite and granophyre remanence directions from the southeast segment of the SIC are relatively steep (Fig. 10b, norite: Dec = 84°, Inc = 37°,  $\alpha_{95}$  = 9°,  $N$  = 5; granophyre: Dec = 98°, Inc = 71°,  $\alpha_{95}$  = 10°,  $N$  = 3; Morris, 1980, 1981) and do not require significant unfolding. The breccia sites appear to lie within the expected metamorphic aureole of the SIC and yet have a completely different direction. One way out of the problem is that the entire basement and southern East range was rotated through 90°. The breccia remanence was acquired rapidly after impact and suffered the full rotation, but the SIC was sufficiently hot that most of its magnetization was acquired after the rotation. Compatible with this interpretation is that the breccias contain a steep down component which may represent the later heating by the SIC. However, this extreme deformation contrasts with the relative modest rotations farther north. Several faults are shown near or along the SIC/basement contact along the southern East range (Dressler, 1984b) and it is possible that the SIC and basement were decoupled at the time of deformation. This could lead to a scenario by which the southeastern SIC suffered a tilting comparable to that farther north, but the basement underwent a more extreme tilting. A major constraint on the amount of basement tilting is that vertical, northwest-trending dykes occur in the Archean terrain east of the SIC (Dressler, 1981). West of sites WL1 and WL6 the dykes contain irregular feldspar phenocrysts, resembling the 2.47 Ga Matachewan swarm farther north, and are observed by us to be vertical, but it is a general feature of basement dykes

along the East range (Dressler, 2004. Private communication). Although their exact correlation is uncertain they are older than the Sudbury impact event because we observed west-pointing shatter-cones in them. This would imply that the basement has suffered little rotation, allowing the case to be made that the shallow magnetization directions found in the breccias are secondary and related to the Sudbury dyke or other overprints. Sudbury dykes do not occur near breccia sites (OGS Map 2451, Dressler, 1981) but chemically active fluids associated with this intrusive episode may have utilised the breccia zones.

An important consideration is whether fabric, original or metamorphic, has in any way affected the paleomagnetic directions. Macroscopically, the breccia fragments show weak to random orientations in the Archean rocks in the West and North range, respectively (Cowan et al., 1999; Rousell et al., 2003) or their long axes are aligned parallel to the walls of the breccia bodies, attributed to flowage of the breccia prior to consolidation (Rousell et al., 2003). The average degree of sample AMS ( $k_{\max}/k_{\min}$ ) based on measurements of about 150 samples is about 6–7%, with a maximum of 20%, a minimum of 2%, and with less than 20% of the samples having anisotropies greater than 10%, so that any paleomagnetic deflection will only be a few degrees (Janak, 1967).

Flexural flow folding has been shown to rotate paleomagnetic directions in the opposite sense to rigid body rotation of fold limbs leading to a primary remanence having the appearance of a syn-folding one (e.g. Stamatakos and Kodama, 1991). This is an important consideration in the Sudbury basin because as a result of Penokean orogenesis a well-defined foliation with overall steep inclination to the south and more or less east–northeast strike is well developed in the Whitewater Group but less obviously in the more competent SIC (Ames et al., 2005). Brocoum and Dalziel (1974) claim that it is absent in the northern one third of the basin, Rousell (1975) mentions a local weak foliation in the North range of the Whitewater Group and Cowan et al. (1999) show from AMS data that the fabric in the SIC along the northern range was primary rather than secondary. However, the presence of the foliation shows that the Sudbury basin has not deformed in a rigid body fashion. We have tried to minimise any effects of flexural flow folding by only taking samples from sites that are situated around the northern half of the basin, where foliation is minimal and where metamorphic overprinting is no higher than sub-greenschist (Card, 1978; Fleet et al., 1987). Where the foliation is well-developed, AMS studies show a  $k_{\min}$  direction more or less within a NNW–

SSE vertical plane normal to foliation (Hirt et al., 1988, 1993; Kligfield et al., 1977). If this foliation was developed throughout the basin it might also be expected in the surrounding basement rocks giving rise to similar  $k_{\min}$  orientations. However, we have AMS results from 23 sites in breccias showing that  $k_{\min}$  directions are widely dispersed both within and between sites and provide no evidence that a fabric similar to that in the interior of the Sudbury basin exists. Of more relevance is that we have no evidence that passive flow folding has significantly affected magnetization orientations and therefore have proceeded to analyse the paleomagnetic data on the assumption that flow folding has not affected the data. The similarity of our data to that obtained by Morris from the SIC itself indicates that the SIC and immediate adjacent basement have been deformed in a similar manner, whether it be rigid body which provides a more tractable analysis or passive flexural folding which requires knowledge of variations in finite strain. We have not attempted the second analysis because the rocks are not obviously internally deformed.

However, despite weak strain seen in the North range of the SIC and Whitewater Group, the norite and gabbro in the East range, and the Sudbury breccia in the surrounding basement, a flexural flow folding type of deformation could explain why the paleomagnetic directions in the different parts of the Sudbury Structure make different angles with the local SIC/basement contact and more specifically it could account for the smear of directions shown in Fig. 10a. Such a mechanism could probably argue for a layering of the SIC that was more horizontal prior to deformation, but with the available data from the Sudbury breccia, we cannot test this mechanism, only argue qualitatively that it may explain our results.

In conclusion, paleomagnetic data from impact-induced Sudbury breccia around the northern margin of the SIC support earlier paleomagnetic results on the SIC by Morris that suggest the original Sudbury Structure was deformed by folding, probably during the Penokean Orogen. As indicated by Morris (2002), deformation probably took place along some of the Onaping faults that cross the Sudbury Structure such as the Fecunis Lake Fault and Sandcherry Creek Fault in the North range (Fig. 13). We believe that many of the breccia sites within about 2 km of the SIC contact have been magnetically reset by the SIC because more proximal sites tend to be more magnetic and contain magnetite. However, even if the breccia was not reset, it still would be expected to carry a remanence with a direction similar to that of the SIC, unless rapid basement rotation preceded the acquisition of remanence in the norite. Either way, our results suggest for the first time that the basement, all around the

northern half of the Sudbury Structure, from the western to the northeastern margins of the SIC, appears to have also been involved in the tilting. The paleomagnetic results from the southern East range argue for either a more extreme basement tilting or virtually none at all, depending upon whether or not the breccia remanence is primary. Flexural flow folding could have produced the distribution of the paleomagnetic *A* component in the northern part of the Sudbury Structure, but a quantitative solution is not possible due to lack of measurable strain in the Sudbury breccia.

## Acknowledgements

This paper is based on the research done by ES for her M.Sc. thesis and was financed from NSERC Discovery Grant A7824 awarded to HCH. We want to thank: Prof. Dan Schulze for sharing his expertise in optical mineralogy, Jacob Hanley for recognition of opaque and metamorphic phases in breccia samples, and for providing sampling locations, Dr. Özden Özdemir for help in interpreting magnetic susceptibility data, Prof. David Symons for permission to use his laboratory at the University of Windsor where Dr. Philip McCausland and Dr. Mike Harris provided helpful practical advice, and where Dr. Maria Cioppa guided us in the use of the SIRM method and analysis; Prof. David Dunlop and Prof. Alexander Cruden, M.Sc. thesis committee members, for useful comments and suggestions; Dr. Nicolae Har, Dr. Marcel Benea and Dr. Carmen Chira for advice and logistical support for the optical microscopy work; Bodgan Nițescu and Jaime Estrada for field assistance; Michelle Scioritino for AMS measurements; Paul Binney of Falconbridge Ltd. for giving permission to sample and for introducing us to the geology of the Sudbury area, and Peter Recollet who gave us permission to sample within the precincts of the Wahnapiet First Nation. HCH would like to thank the Tectonics Special Research Centre, University of Western Australia, the former director, the late Chris Powell and Dr. Z.-X. Li, Director of the Paleomagnetism Laboratory, for access to the Centre's Superconducting magnetometer, during the time that HCH was a Visiting Research Fellow in 2000. Prof. David Symons and Dr. Maria Cioppa critically reviewed an earlier draft of the paper. Three anonymous reviewers are thanked for their constructive comments.

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