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PSEUDOTACHYLITES ASSOCIATED
WITH THE SUDBURY STRUCTURE

A PETROGRAPHIC, CHEMICAL AND PALEOMAGNETIC STUDY OF PSEUDOTACHYLITES ASSOCIATED WITH THE SUDBURY STRUCTURE

BY

JULIE BLONDÉ

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ABSTRACT

Pseudotachylites within the Levack Gneisses of the North Range Sudbury Structure were studied, with an emphasison petrography, major oxide chemistry, and paleomagnetism.

The pseudotachylites are present as dark greyish green veins and larger scale breccia zones. The matrix is glassy and aphanitic and the fragments, mostly quartz and feldspar are subangular to subrounded. The larger fragments and the wall rock contain kink bands in biotites and planar features in feldspars and quartz. The planar features are defined by rows of parallel inclusions and are diagnostic of shock metamorphism when parallel to specific crystallographic orientations of quartz. The major oxide chemistry shows the pseudotachylites are enriched in total iron, magnesia and lime. This corresponds to other impact-generated pseudotachylite chemistries. Thus, these rocks are not a product of pure wall rock and either the mafics were selectively melted out or added from an external source.

Paleomagnetic analysis confirms the age of the pseudotachylite is approximately the same as the North Range of the Sudbury Structure, the least deformed component. Thus whatever the event was it also formed the pseudotachylite. The fact that the pseudotachylite contains shock metamorphic features, supports that the event was likely an impact, as of yet the only known process capable of producing the required pressures, temperatures and strain rates.

ACKNOWLEDGEMENTS

There are so very many people to whom I owe great thanks. Firstly, I wish to thank my thesis supervisor, Dr. Brian Burley, for all of his help, advice and knowledge, and without whom this thesis would not have been possible. I also wish to thank Mrs. Burley for her help on the sample-collecting trip to Sudbury, and Dr. Alan Dickin for the use of his samples of Sudbury Breccia.

Many thanks go to all of the technicians in the Geology Department, namely, Len Zwicker, Jack Whorwood and Jim McAndrew, for the thin sections, photography and slides, and XRF analyses, respectively.

I thank George LeBlanc and Ken Versteeg, for helping me with the spinner magnetometer and especially Dr. Bill Morris, for obtaining a BIG pseudotachylite sample suitable for paleomag, for processing my paleomag data, for his extremely helpful discussions and explanations about Sudbury, and for his valuable advice and support regarding the thesis presentation, and for the many "proof-reads" of my thesis.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

with the Sudbury breccia, pseudotachylites and wall rock added.

LIST OF PLATES

INTRODUCTION

Since its discovery in the late 1800's, the Sudbury Structure has been and remains a geological enigma. With the construction of the Canadian Pacific Railway through the Sudbury region a century ago, came the discovery and subsequent exploitation of the largest copper-nickel deposit in the world. Such a find fueled the need to understand its origins and perhaps find more sites of this sort. A century of study has revealed the uniqueness and complexity of the Sudbury Structure.

The modern understanding of the Sudbury morphology is well-established. Roughly elliptical, with a 60 km long major axis trending SW-NE and 27 km long minor axis, the Sudbury Structure is a layered, and funnel shaped intrusion located at the junction of three structural provinces of the Canadian shield: the Superior, the Southern and the Grenville (Figure 1). The Structure, contains within it, several accepted examples of shock features, such as shatter cones (Dietz, 1964), breccia (Dietz, 1964), pseudotachylites (Dressler, 1984), and microscopic planar features (French 1968, 1972, Dence 1972), which have come to be interpreted as evidence for the impact origin of the Sudbury Structure.

Pseudotachylites and Sudbury Breccia are essentially the same unit, the former being a finer and smaller scale version of the latter. Both have been proposed as evidence for impact, on their own, but more importantly when accompanied by other features of shock metamorphism as mentioned previously. This thesis examines at several aspects of the pseudotachylite to determine if their formation is consistent with an impact origin. Petrographic, chemical and paleomagnetic, analyses of the pseudotachylite are compared to those of other units of the Sudbury Structure and to a similar proposed impact site, the Vredefort Structure in South Africa.

The pseudotachylite samples were obtained from the North Range of the Sudbury Structure, just north of Windy Lake, within the Levack region (Figure 2).

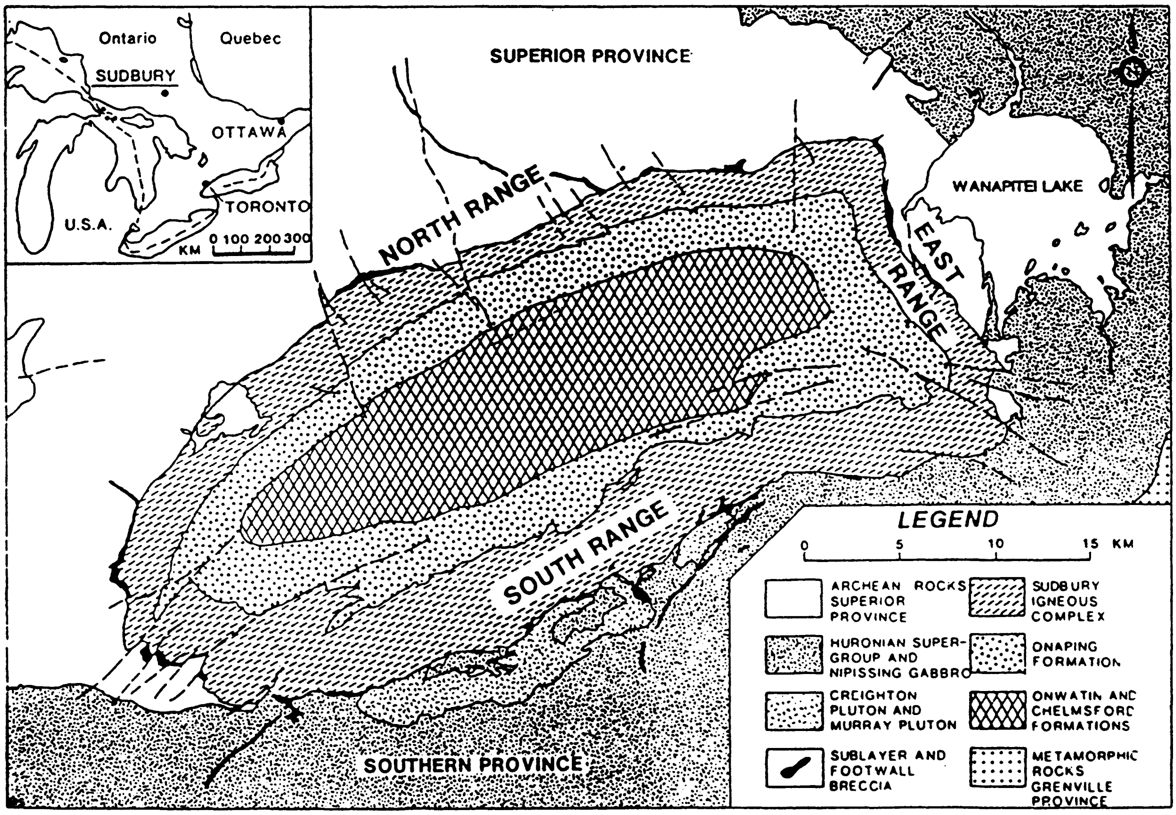


Figure 1: Geologic Map of the Sudbury Structure (from Lowman, P.D., 1992, p. 229)

Sample Locations
(1-chemical,petrographic, 2-paleomag.)

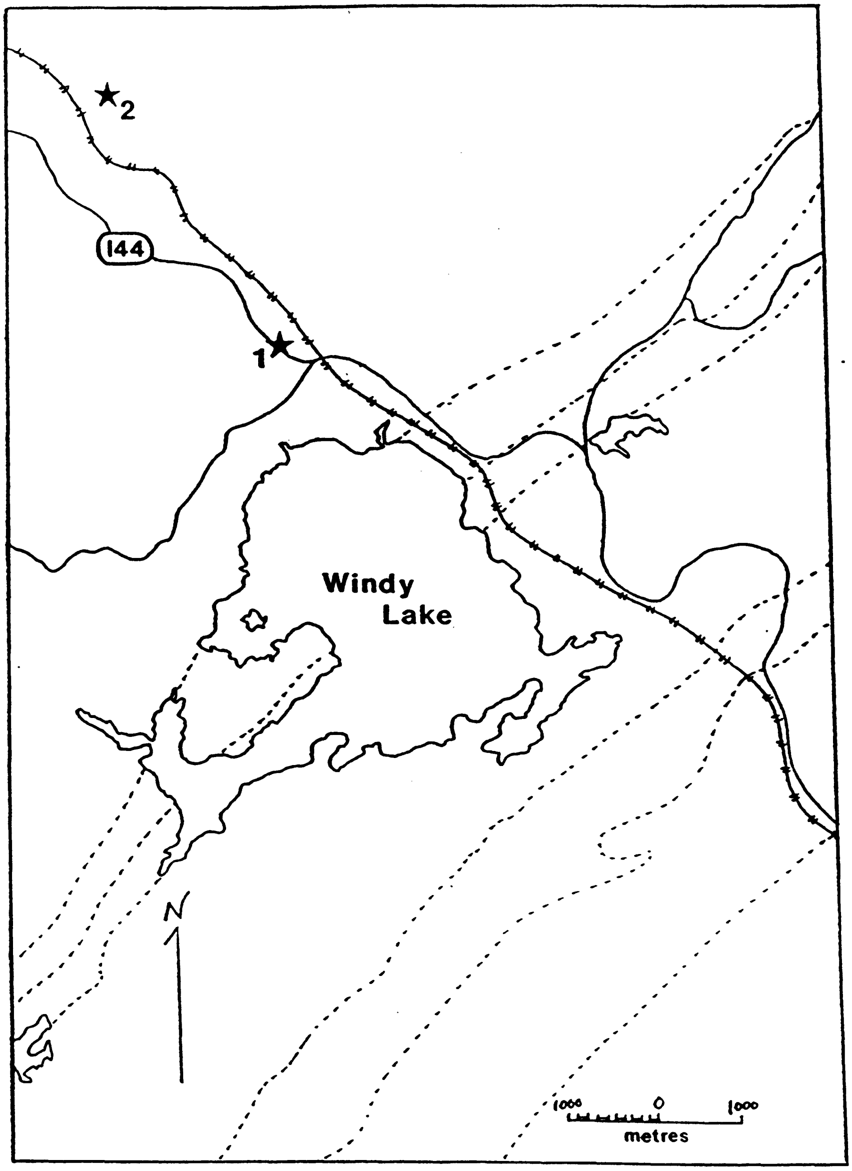


Figure 2: Sample Locations (site 1: chemical and petrographic analysis; site 2: paleomagnetic analysis) based on : Dressler, B.O., 1984: Sudbury Geological Compilation; OGS Map 2491, Precambrian Geology Series, scale 1:50 000, geological compilation, 1982-83.

The outcrops consist of massive pink and grey gneisses and granites, which provide a complementary background for the dark gray-green veins of pseudotachylite.

The analyses are based on the paleomagnetic declination and inclination of eight cores, from sample site 2, and from sample site 1, a major oxide XRF analysis of four powdered samples and a petrographic analysis of three thin sections of pseudotachylite, Sudbury breccia and their respective wall rocks (Figure 2).

PREVIOUS WORK ON PSEUDOTACHYLITES

Definition of Pseudotachylites

The origin and significance of pseudotachylites are difficult to explain, as the very definition of pseudotachylites remains obscure. The term "pseudotachylyte" was originated by Shand (1916) to describe,"... dark, aphanitic rock found as veins and networks in granite in the neighbourhood of Parijs, South Africa. He used this term because of the rocks strong resemblance to tachylite." (Shand, p. 199, cited in Philpotts, 1964, p. 1089). A tachylite is a dark, basaltic volcanic glass, associated with chill margins (Bates and Jackson, 1980, p. 636). Shand (1916) described the veins as utterly irregular in form, thickness, direction, and strike, as being sinuous, thickening and thinning, anastomosing and terminating blindly (Figure 3). According to Shand, the matrix or groundmass of these pseudotachylites is microcrystalline or aphanitic, and surround in the larger veins, a wide range of fragments, which are more rounded than angular. The contact between the vein and the wall rock is abrupt with no evidence of shearing in the wall rock parallel to the vein and no indication of fault displacement greater than "two inches".

Most definitions describe pseudotachylite as an extreme form of mylonite or cataclasite that shows some fusion (Philpotts, 1964, Suppe, 1985). Bates and Jackson (1980, p. 507) define two types of pseudotachylite:

> 1) "A dense rock produced in the compression and shear associated with intense fault movements, involving extreme mylonitization and/or partial melting. Similar rocks, such as the Sudbury Breccias, contain shock metamorphic effects and may be injection breccias emplaced in fractures formed during meteorite impact."

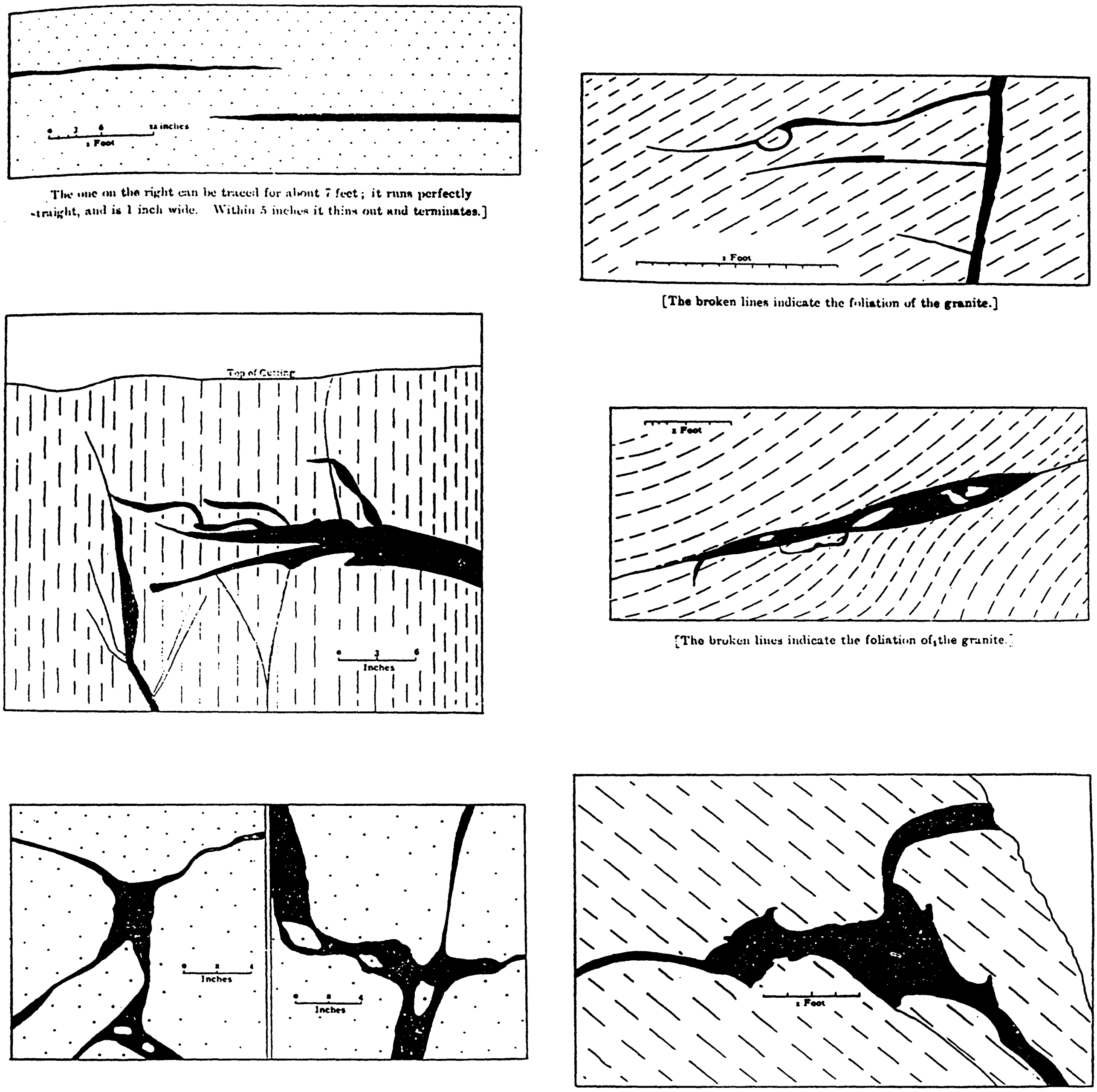


Figure 3: Sample drawings of Vredefort pseudotachylites in outcrops, source: Shand, S.J., 1916, p. 201-203.

2) "A dark grey or black rock that resembles tachylyte and that typically occurs in irregularly branching veins. The material carries fragmental enclosures, and shows evidence of having been at high temperatures. Miarolitic and spherulitic crystallization has sometimes taken place in the extremely dense base. Some pseudotachylite has behaved like an intrusive and has no structure obviously related to local crushing."

Ultimately the difficulty arises in distinguishing the difference between fault-generated and shock-generated pseudotachylite, which brings us to define cataclasite and mylonite.

Suppe (1985) recognizes mylonites as fine grained, laminated rocks occurring in plastic fault zones, and pseudotachylites as extremely fine grained mylonites having undergone frictional melting.

Fletcher and Reimold (1989) attempt to clarify the difference between pseudotachylites, cataclasites and mylonites based on the nature of the matrix and the mode of formation. Mylonites and cataclasites have clastic matrices while pseudotachylites have an aphanitic or crystalline matrix. **Cataclasites** are formed in **brittle deformation** regimes, experiencing mechanical deformation by fracturing, rotation, and crushing. **Mylonites** are formed in **ductile and thermal** regimes showing evidence of flow and a lamellar texture. All three, pseudotachylites, mylonites and cataclasites are fragment-laden.

Passchier, Myers and Kröner, (1990) in their study of high grade gneiss terrains, indicate that very low grade metamorphic conditions in gneisses will cause brittle deformation, manifested as stick-slip motion with total movement of the order of millimetres to metres per year, ultimately forming cataclasite and pseudotachylite.

The former resulting from brecciation of the host with abundant fluid access, and the latter, "..forms by local melting of the rock along a brittle fault plane due to heat generated by frictional sliding (Philpotts, 1964; Francis and Sibson, 1973; Sibson, 1974, 1975, 1977; Grocott, 1981; Maddock, 1983, 1986; Maddock *et al.*, 1987) or, possibly in some cases by intense cataclasis (Wenk, 1978) ... Melting is thought to occur at temperatures exceeding 1000 °C in a zone a few mm wide called the `generation surface'." (Passchier *et al.*, 1990, p. 43).

In general, cataclasites and mylonites have clastic matrices and are formed in fault zones. Cataclasites have experienced brittle deformation, and laminated mylonites ductile deformation. Pseudotachylites generated in fault zones are an extremely fine-grained version of either a cataclasite or mylonite that has experienced melting. Pseudotachylites generated by meteorite impact, are a result of, " ...the passage of a shock wave through the host material." (Spray, 1993, p. 1335), occurring as, ".. sub-millimetre thick veinlets to dyke-like bodies up to 1 km or more thick. It is the latter, larger occurrence which has been referred to as `breccia'." (Spray, 1993, p. 1335).

Other criteria for the definition of pseudotachylites have been proposed by some authors. Philpotts (1964) notes that pseudotachylites require the presence of abundant quartz, as it resists granulation. Passchier *et al.* (1990), state that in order to generate the frictional heat required, the host rock must be massive, dry and have low porosity, as, "... fluid present in porous rocks lowers the effective normal stress over a fault plane upon heating and, consequently, not enough frictional heat can be produced to cause local melting." (p. 44).

Pseudotachylite Paragenesis

Shand proposed two possible pseudotachylite origins: (1) as the end product of the sequence, mylonite--fritted mylonite or flinty crush rock -- fused mylonite or pseudotachylite -- recrystallized pseudotachylite: and (2) as an igneous intrusion. The latter origin was supported by, according to Shand (1916), the sharp contacts with the host rocks, the lack of shearing in the wall rock and the blind intrusive nature (pertaining to the difficulty in seeing the depth, extent, and source, and the cross-cutting of existing fabrics) and the mylonitic origin, by the similarity of the chemical compositions of the host rocks to the accompanying pseudotachylite. Shand (1916) concluded that, the material of the pseudotachylite is melted granite (wall rock) with the appearance of an igneous intrusion, and that: "...the source of the heat and the mechanics of the intrusive process remain obscure." (p.217). In this paper, Shand further proposed that, "...the form of the pseudotachylite veins indicates that the granite was shattered by a sudden gigantic impulse or series of impulses. If this impulse were of the nature of an explosion in the sub-crust, it would have as a necessary consequence, the out rush of incandescent gases through all the fissures of the granite." (p. 216). Is this perhaps the first indication of a possible impact origin?

Philpotts (1964) studied pseudotachylite veins in the Belleau-Desaulniers area, Quebec, and concluded that two types of formational processes were at their origin: (1) frictional fusion in a fault zone and (2) extreme mylonitization and the "injection of finely pulverized material into fractures" (p. 1008). He notes the difficulty in determining the pseudotachylite origin due to the extremely fine grained nature, and the lack of evidence for fusion in the pseudotachylite. Philpotts (1964) also discussed the origin of the heat causing fusion, noting that the displacement of the pseudotachylite is too small to generate enough frictional heat, and that as suggested by Shand (1916), the heat may rather arise from hot gases, generated with the fault action and supported by the presence of amygdules and vesicles. Moreover Philpotts (1964) indicates that it would require less energy to raise the temperature of the rock to fusion if the rock were already hot, due possibly to close association with an intrusive body or igneous activity in general.

GEOLOGICAL SETTING

The Sudbury "structure" includes the surrounding Sudbury Breccia, the Sudbury Igneous Complex and the central Whitewater group (Figure 1). The Sudbury breccia is found in a zone several kilometres wide, surrounding the Sudbury Igneous Complex, and consists of irregular bodies of breccia within the Archean and footwall rocks. The Sudbury Igneous Complex is approximately 1.85 billion years old (Krogh, 1984) and can be divided into three units: an outer norite layer, a middle gabbro layer and the innermost micropegmatite or granophyre. The dip of the complex varies but is primarily in towards the centre of the basin. The copper-nickel sulfide ore is located in three major areas: (1) the outer, lower edge of the norite, (2) as dike-like bodies radiating outwards, and (3) the footwall rocks parallel to the main complex (Giblin, 1984, p. 6). The Whitewater Group consists of the innermost Onaping Formation (interpreted as a volcanic tuff or fall back breccia), the Onwatin mudstone, and finally the Chelmsford sandstone wackes.

The samples obtained are from the North Range of the Sudbury Structure which refers to the least deformed, north-easterly trending limb of the Sudbury Igneous Complex and the immediately adjacent host rocks to the north-west. Here the host rocks are those of the Levack region and consist of granites, migmatites and the Levack Gneisses. These gneisses have been described by Dressler (1984) as being very inhomogeneous in composition and texture, consisting of medium to fine grained mafic-rich and felsic-rich bands ranging in width from a few millimetres to tens of metres. As one proceeds away from the Sudbury Igneous Complex the Levack Gneisses decrease in grade from granulite to amphibolite facies. The specimens collected are from the pseudotachylite veins within the Levack Gneisses of the North Range of the Sudbury Structure. As seen in Figure 2, the pseudotachylite veins, and its associated wall rock were sampled from an outcrop along Hwy 144 located approximately 700 metres from the turn off to the Windy Lake Provincial Park. The Sudbury breccia and wall rock were sampled from an outcrop 128 metres further north along Hwy 144.

PETROGRAPHY

The thin sections are from the same samples as those used for chemical analysis, and it is important to note once again that the Sudbury breccia and the pseudotachylite veins are essentially the same unit although the latter is a smaller scale and finer version of the former.

Macroscopic Description

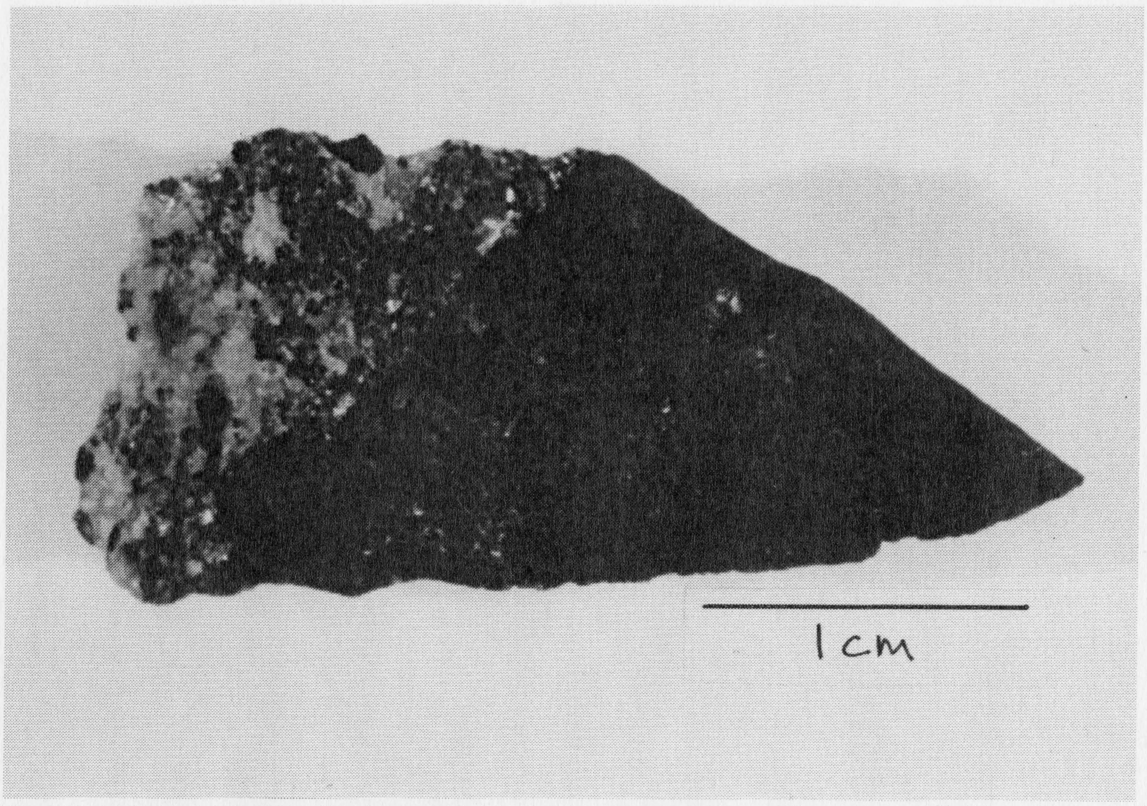
In hand specimen, the pseudotachylite veins studied are aphanitic, dark grey to black, massive, and show no cleavage or structure but contain abundant fragments (Plate 1).

The fragments, within the fine matrix, appear to make up about five percent of the vein. They are too small to be further described accurately, but appear to include anhedral quartz and feldspars, less than one millimetre in size and sulfides less than 0.1 millimetres in diameter. The weathered surface of the pseudotachylite is mostly greyish-green, and yellow-orange in places. The contact between the wall rock and pseudotachylite is fairly sharp and smooth but not perfectly straight. The vein itself in the outcrop, varies in width, thickening and thinning and eventually pinching out (Figure 3). No evidence of obvious lateral displacement are observed on either side of the vein inrelation to the host rock.

The gneissic wall rock immediately adjacent to the pseudotachylite is mesotypic, and medium grained (between 0.5 and 2 mm). The essential minerals consist of equal portions of white and vitreous quartz, feldspar, black prismatic amphibole and biotite. Any accessory minerals are too fine to be seen in hand specimen.

Plate 1 : Pseudotachylite hand specimen (note the sharp contact with the coarser wall rock.)

Plate 2 : Sudbury Breccia hand specimen (note the larger and more abundant fragments).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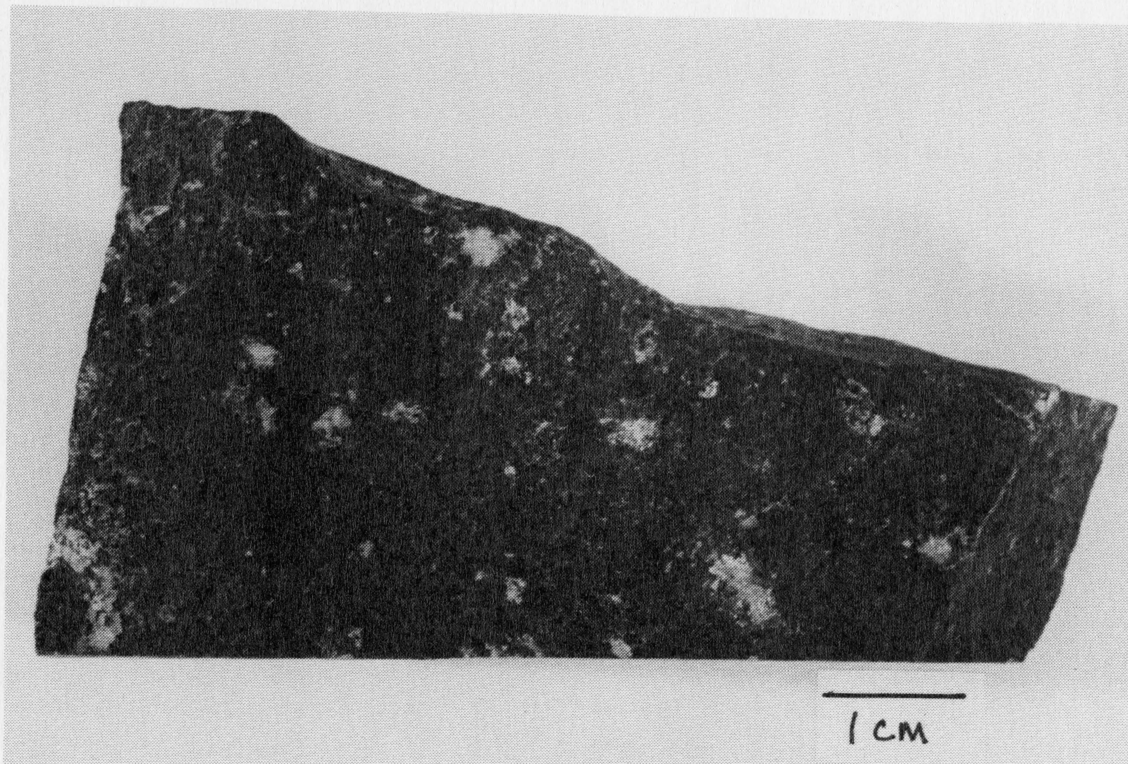
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The Sudbury breccia (Plate 2) is basically the same as the pseudotachylite but has a dark grey matrix with a higher content of fragments (up to 40 %), which are also larger. The breccia is massive with no structure and a random distribution of fragments. The fragments are polymineralic and monomineralic consisting of quartz, feldspar, biotite and amphibole.

Microscopic Description

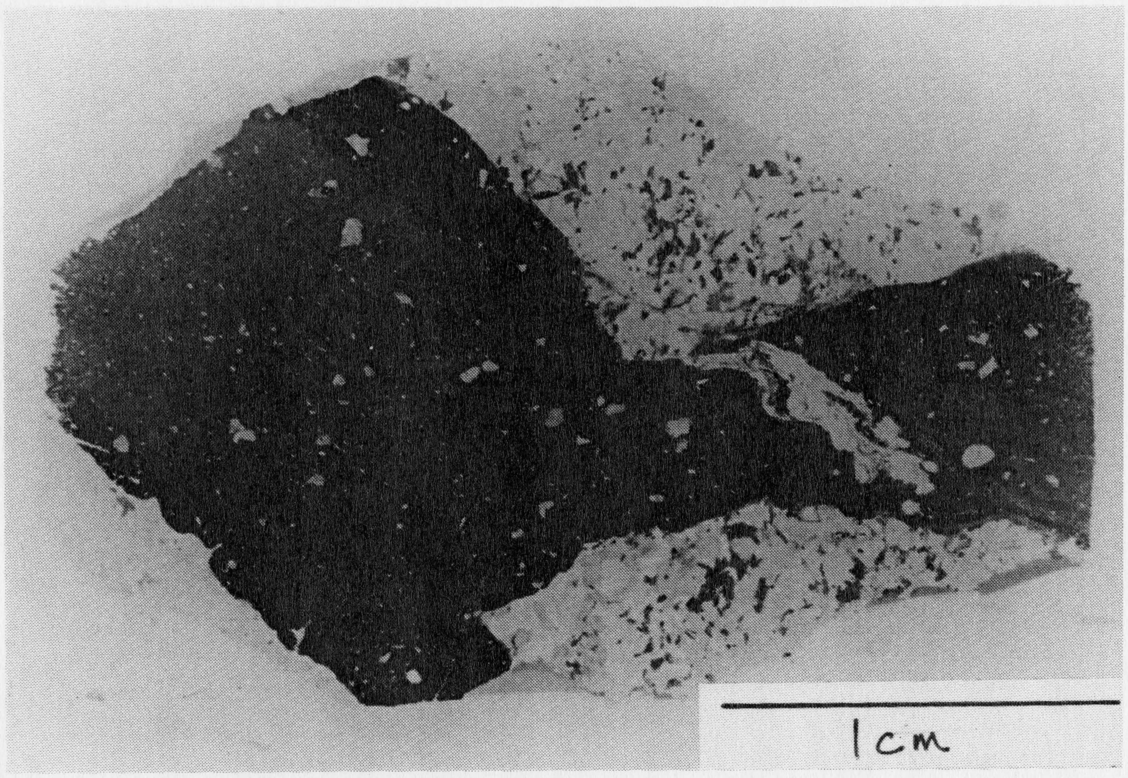
The pseudotachylite is extremely fine grained, grey-brown under plain light and isotropic under crossed polars (Plates 3 and 4). However the colour is not uniform, being more reddish-brown along the wall rock contact and grading into a more greyish brown towards the centre of the vein. There are also undulating bands of darker and lighter pseudotachylite which seems to be associated with the swirl of wall rock caught up in it (Plates 3 and 4). The fragments are now be seen to make up about 15 to 20 % of the vein, are less than 1 mm in size and vary from subrounded to subangular. Finer details are not observed with the sole use of the transmitted light microscope.

The largest proportion of the fragments, about 80 %, consists of monomineralic and polymineralic quartz and feldspar. The size of the fragments prevents the possibility of distinguishing twinning or biaxial interference figures indicative of feldspars, and thus, render the determination of the exact proportions of quartz and feldspar difficult. The fragments occur as discrete grains and as irregular aggregates which appear as subrounded conglomerates and as xenomorphic and granoblastic quartz and feldspar (Plates 5 and 6).

Next in abundance are opaque sulfide fragments whose exact mineralogy is not known due to their small size. They make up approximately 70 % of the fragments and are less than 0.1 mm in size.

Plate 3 : Pseudotachylite vein, plane polars (note the variations in darkness in the vein, in particular at the contact with the wall rock).

Plate 4 : Pseudotachylite vein, crossed polars.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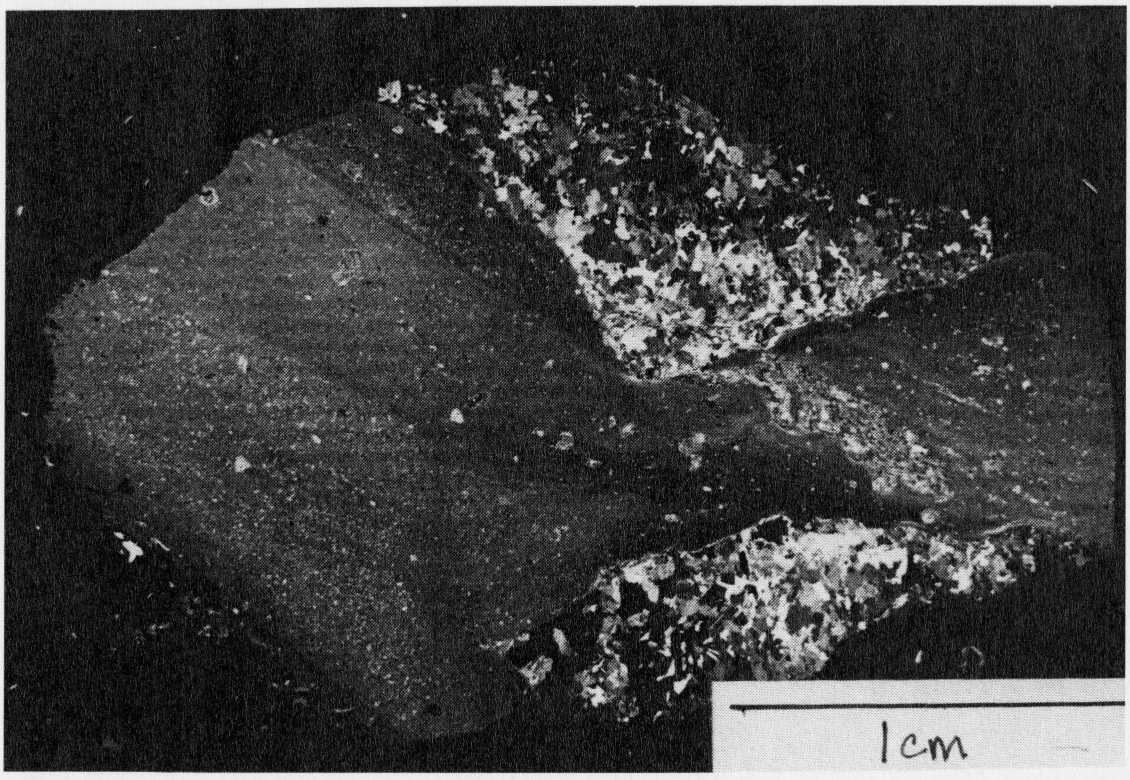
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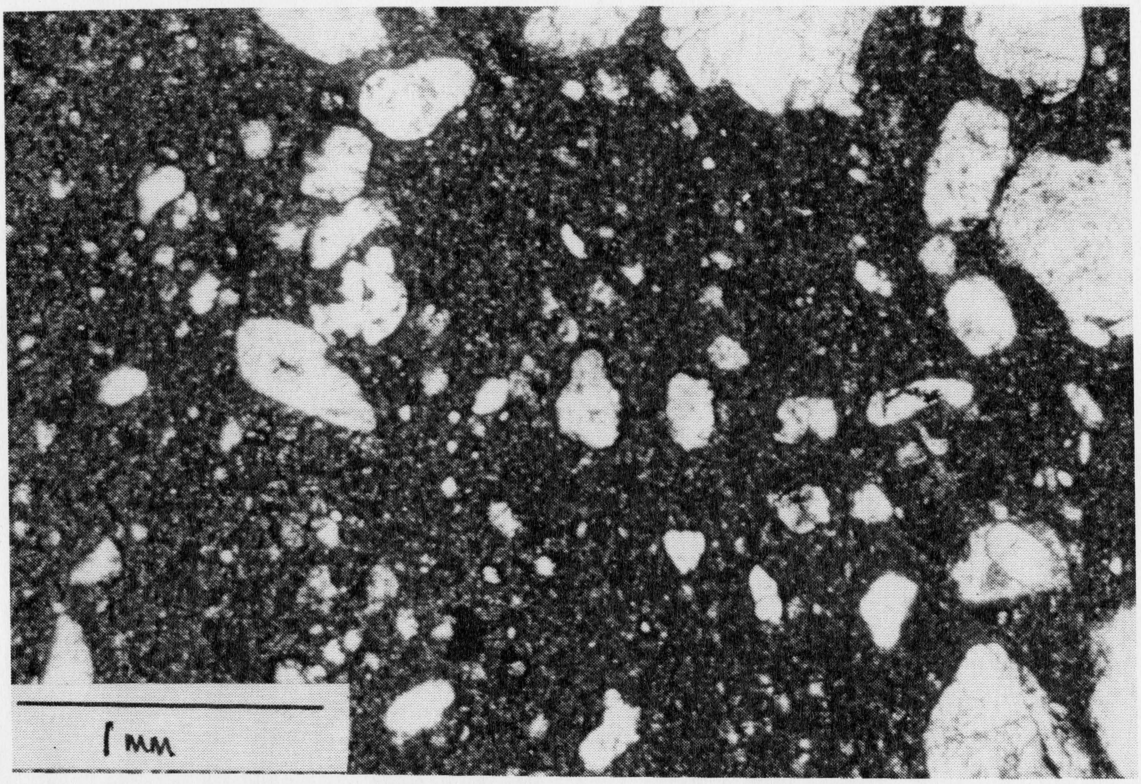
Plate 5 : Pseudotachylite, plane polars (note the aphanitic matrix and the subangular to subrounded fragments).

Plate 6 : Pseudotachylite, crossed polars.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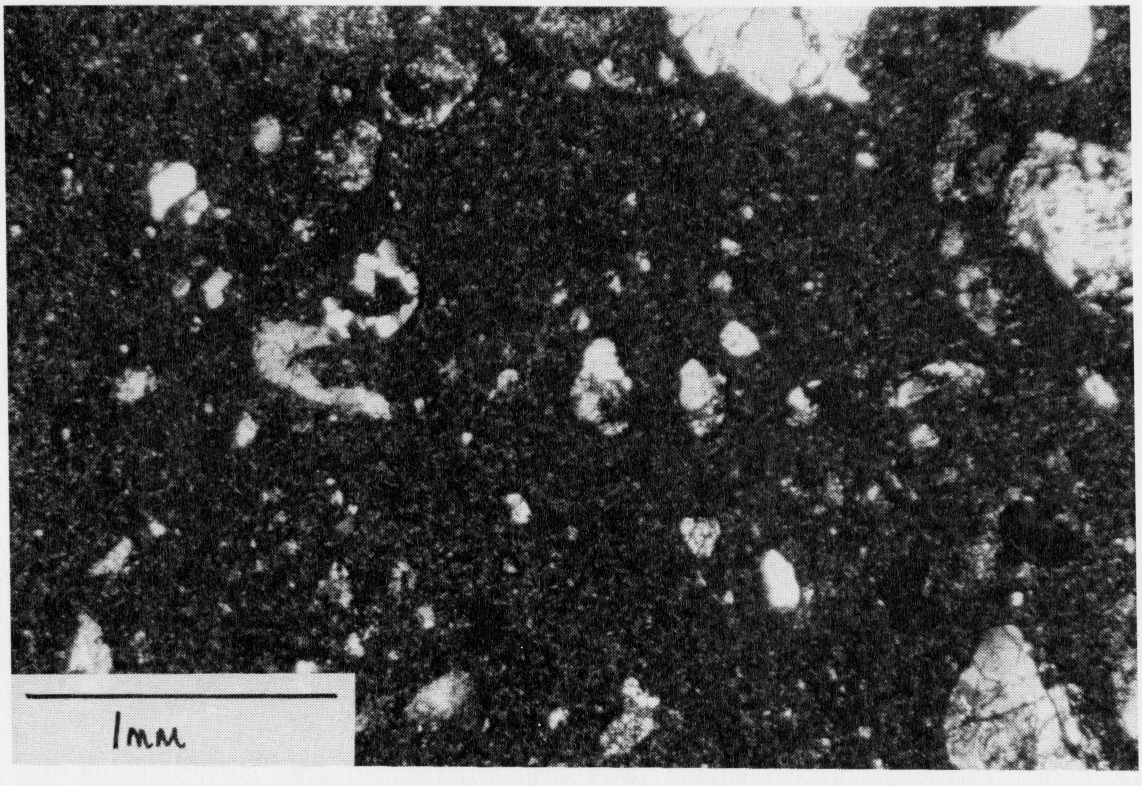
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Making up less than 0.5 % of the fragments are amphiboles and biotites distinguished by their higher birefringence and pale brown colour, respectively. Further identification of these last two types of fragments is rendered difficult by their small grain size.

The larger fragments, those greater than 0.5 mm, (mainly quartz and feldspar) have relatively sharp outlines whereas the smaller fragments have fuzzy, indistinct outlines which appear to grade into the fine matrix (Plates 5 and 6).

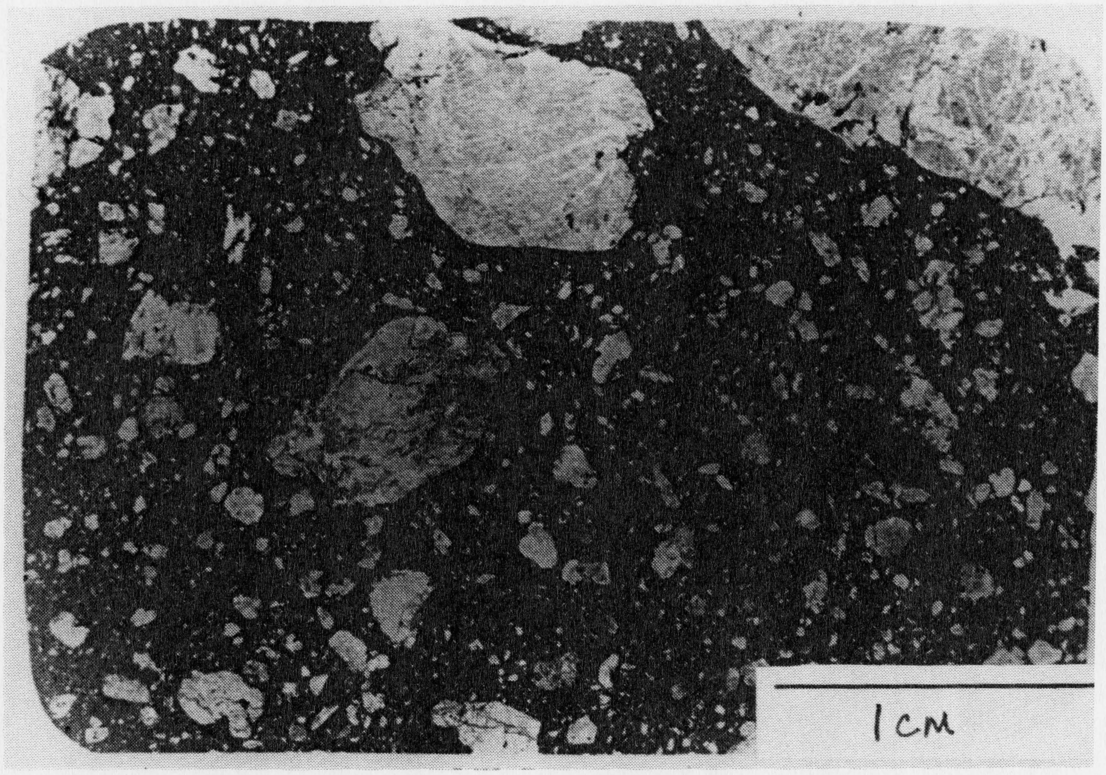
The wall rock immediately adjacent to the pseudotachylite is relatively coarse grained and made up of 70 % quartz and feldspar and 25 % amphibole and biotite. The quartz and feldspar present in approximately equal proportions are large, up to 0.5 mm, anhedral, subrounded and show a granoblastic texture. Some quartz grains have sutured contacts with neighbouring quartz grains indicative of annealing. The 15 % amphiboles are obvious by their 60° - 120° cleavage, and greenish-brown colour. The 10 % biotites are reddish-brown with typical birds-eye texture and perfect basal cleavage, and pleochroism and birefringence being less than usual.

The remaining rock consists of roughly 3 % opaques, possibly sulfides, but cannot be definitely identified without a polished thin section. The opaques are larger and more abundant near the pseudotachylite contact. Many of the opaque grains are surrounded by a red-brown rim. The wall rock also contains less than 1 % apatite, which occurs as hexagonal and isotropic grains less than 0.01 mm in size.

The Sudbury Breccia matrix is more brown and slightly coarser than that of the pseudotachylite and shows no flow structures, bands or colour variations on the scale observed (Plates 7 and 8). The abundant fragments are again largely quartz and feldspar, greater than 2 mm in size, and subrounded to subangular. Many of the fragment boundaries are surrounded by a dark fuzzy outline, other boundaries are less distinct and grade into the matrix. There are not only monocrystalline, but also

Plate 7: Sudbury Breccia, plane polars.

Plate 8: Sudbury Breccia, crossed polars (note the large turbid feldspars in the upper right hand corner, and the clearer, fractured quartz grain in the upper centre of the thin section).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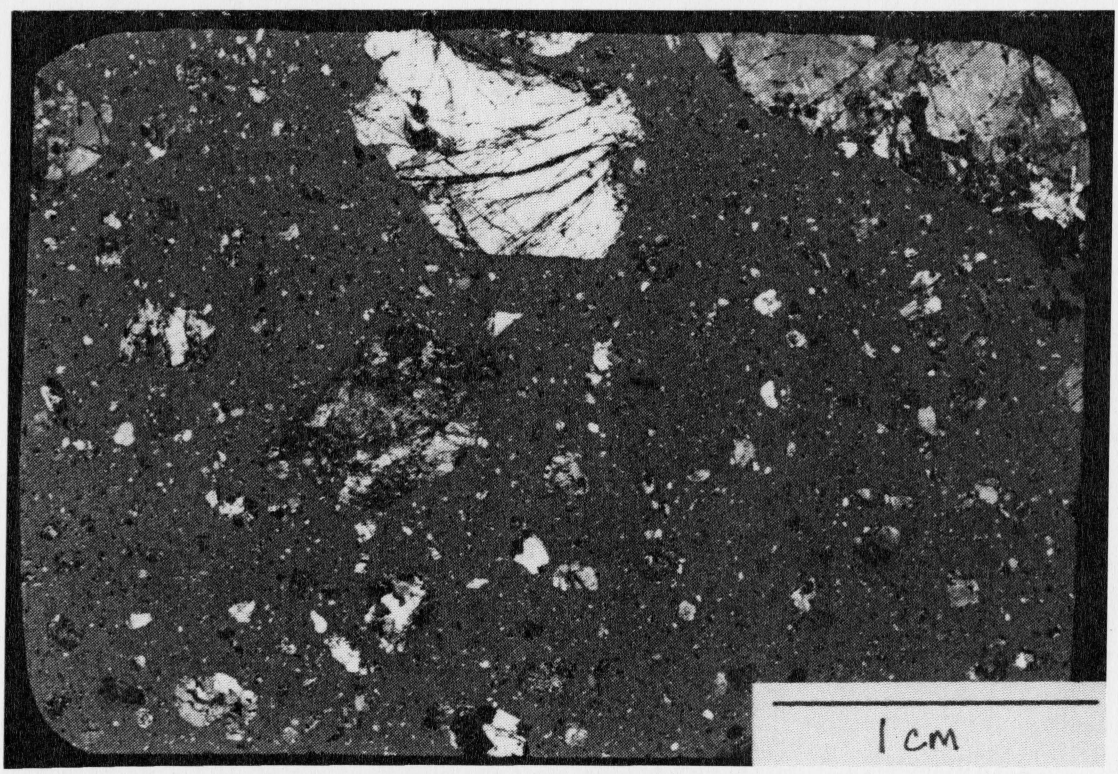
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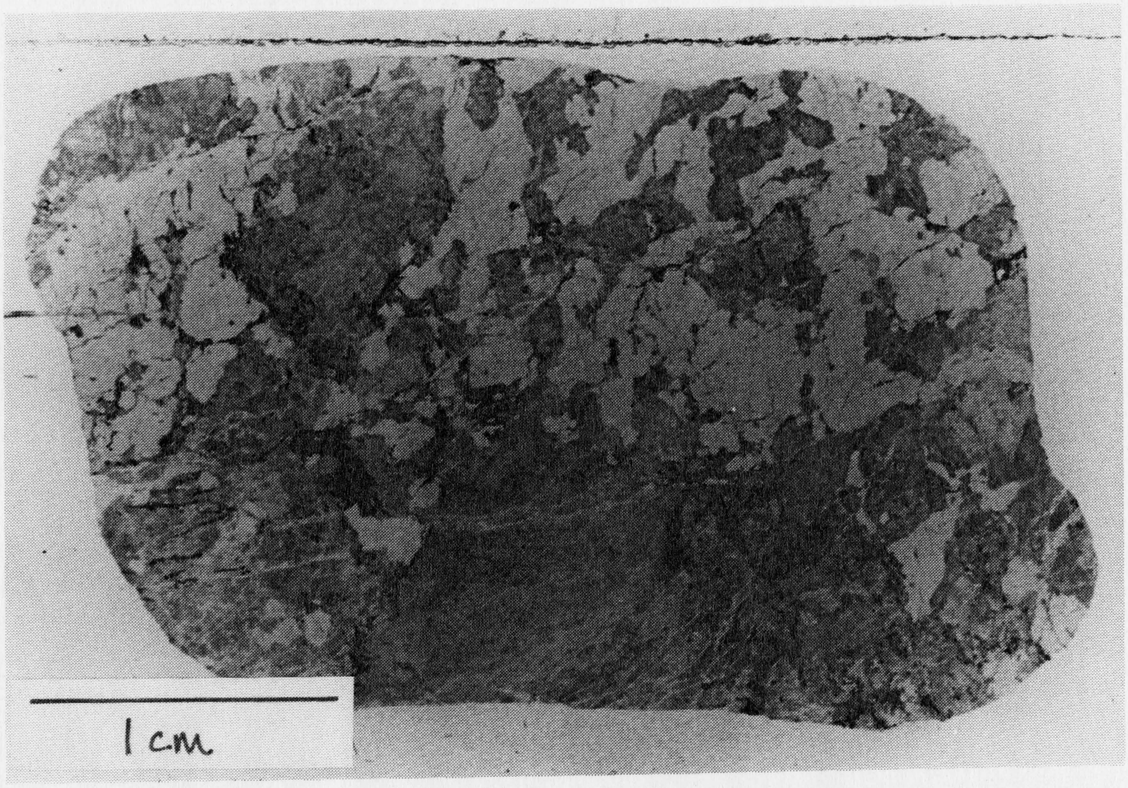
xenomorphic polycrystalline aggregates of more rounded grains. Blebby glass is found in fractures of quartz grains which also have planar features. The feldspars are too cloudy and turbid to enable the observation of many features. Both quartz and feldspar fragments are very fractured. Other fragments include sulfides and epidote (distinguished by its very high relief and birefringence) which are generally in close association.

The Sudbury Breccia wall rock (Plates 9 and 10) mineralogy differs from that of the pseudotachylite wall rock by the presence of approximately 10% pale green chlorite, showing a perfect basal cleavage, an anomalous blue interference colour, and no kink bands, and about 2% epidote and 0.5% sphene, showing a very high relief. No grains of amphibole or biotite were observed.

Plate 9 : Sudbury Breccia wall rock, plane polars (note the darker grey turbid grains are feldspar and the lighter grey, clearer grains of quartz).

Plate 10 : Sudbury Breccia wall rock, crossed polars.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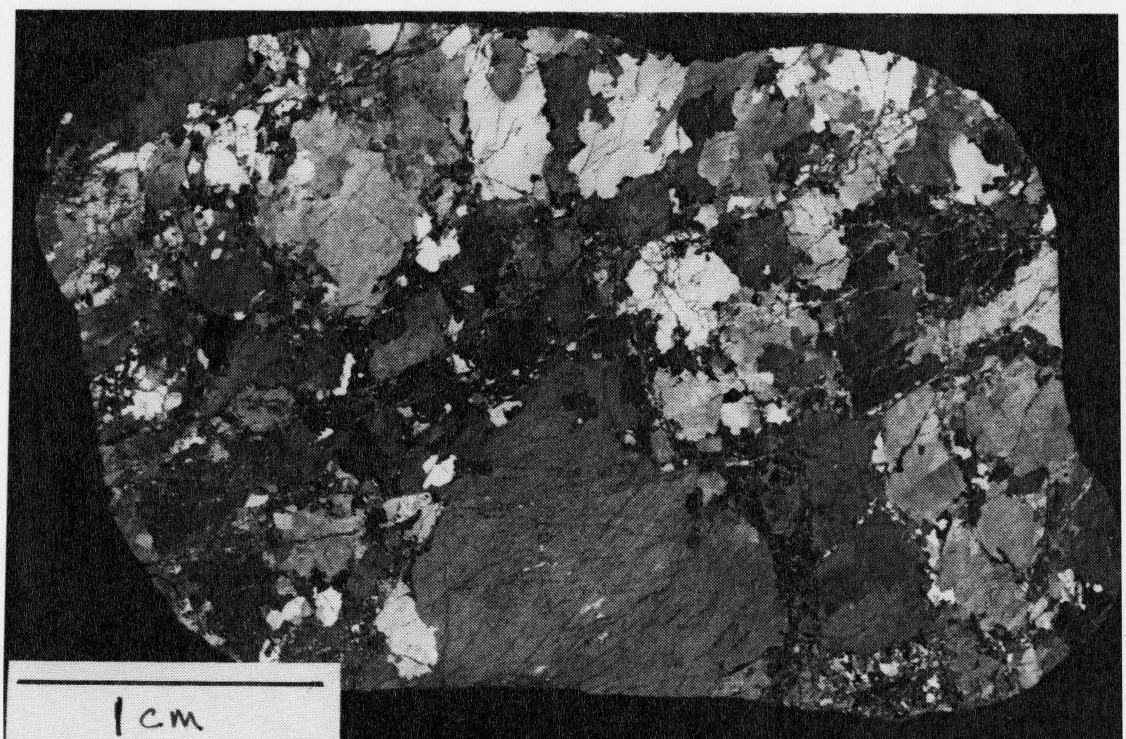
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Shock Metamorphic Features

The presence of shock features at known impact sites and nuclear explosion experiments is well-established. Impact metamorphism has become aligned with shock metamorphism, as meteorite impacts are the only known natural agent/means by which shock features can be produced (French, 1968). As defined by Chao (1967), impact metamorphism, "...describes the changes in minerals and rocks resulting from the hypervelocity impact of a body such as a meteorite." (p. 192). French (1968) expands on this to say how a hypervelocity impact induces the passage of transient high-pressure shock waves which result in the instantaneous transfer of the kinetic energy of the meteorite into the surrounding rocks. Both French (1968) and Stöffler (1971) compare the conditions of normal and endogenic metamorphism to those established for shock metamorphism (Stöffler, 1971, specifies that his shock features are in non-porous rocks).

Very basically, the differences seem to lie in the temperatures, pressures and strain rates generated (Table 1).

Table 1: Comparison of the conditions of shock and endogenic metamorphism

Conditions	Endogenic/Normal	shock
pressures	< 50 kb	10-100 kb to some megabars
temperatures	800 - 1000 °C	several thousands of degrees
duration	0.1 to 10 millions of years	instantaneous, nanoseconds to seconds
range	3 to 7 km depth widespread in crust	surface to subsurface
reactions	attain/approach equilibrium	rapid disequilibrium
rate of pressurization	extremely low	extremely high

(derived from Stöffler (1971, p. 88) and French (1968, p. 2))

Stöffler describes several distinctive shock features: both macroscopic, such as, shatter cones (Dietz, 1947, 1960 in Stöffler, 1971), and microscopic, such as high pressure polymorphs of quartz (*i.e.*, stishovite and coesite). Based on studies of nuclear experimental impacts, Stöffler devised a set of stages, or zones, proceeding outwards from the impact centre, ie., stages 0 through stage 5. Murtaugh (1976) added shock effects on amphibole and biotite to Stöfflers stages.

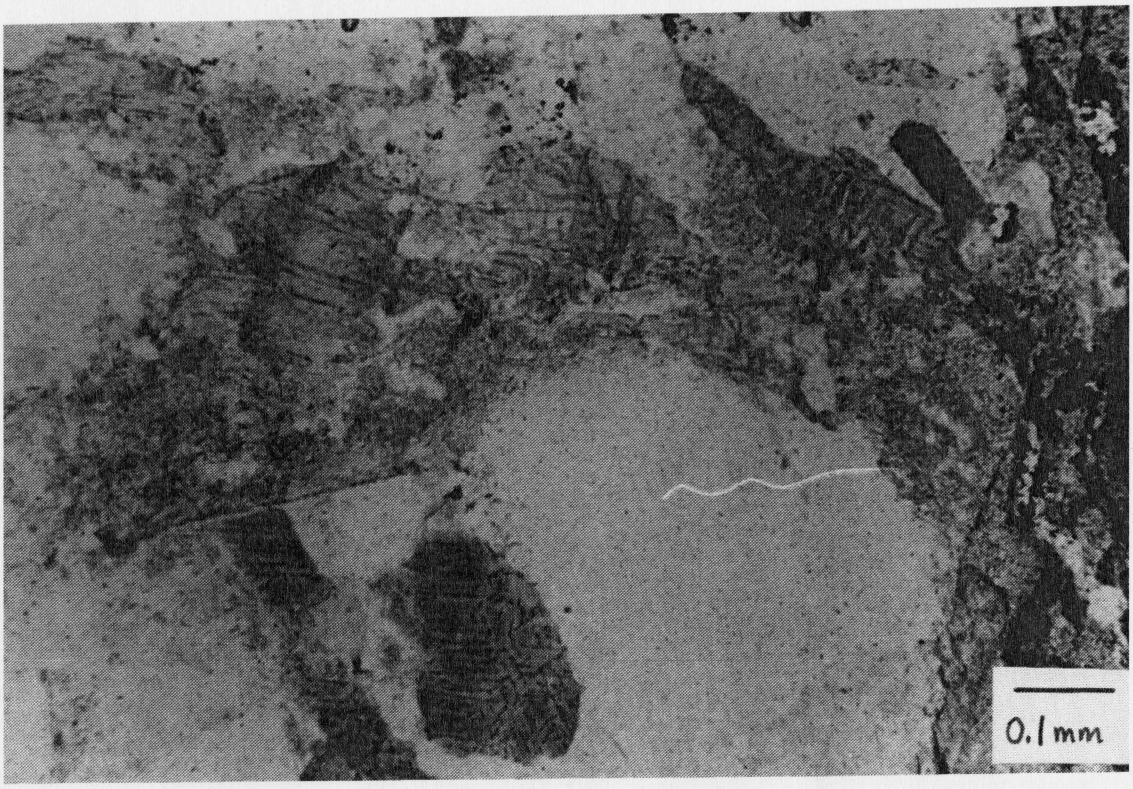
French (1968) studied granitic inclusions in the Onaping Formation of the Sudbury Structure. He established the presence of features akin to ones found at known impact sites, citing the Meteor Crater (Arizona), Wabar (Arabia) and Harburg (Australia). In the same paper, French lists the following shock features: formation of high pressure polymorphs, high-temperature fusion and decomposition reactions among opaque minerals, widespread cleavage in quartz, planar features in quartz and feldspar and the formation of thetomorphic glasses. Chao (1967) notes that the denser minerals are typically less deformed and that there are few detectable changes in apatite, sphene, ilmenite, rutile and zircon.

Kink Bands

Kink bands are structural features found in biotites. They appear as bends, or wrinkles, chevron-like irregular undulations at a high angle to the basal cleavage, seen in the wallrock of the pseudotachylite (Plates 11 and 12). Also characteristic of shocked biotites is reduced birefringence and pleochroism (Chao, 1967).

Plate 11: Kink bands in biotite, plane polars (the kink bands are the folds at a high angle to the cleavage, best seen in the biotites in the upper portion of the plate, being the grey, tabular grains).

Plate 12 : Kink bands in biotite, crossed polars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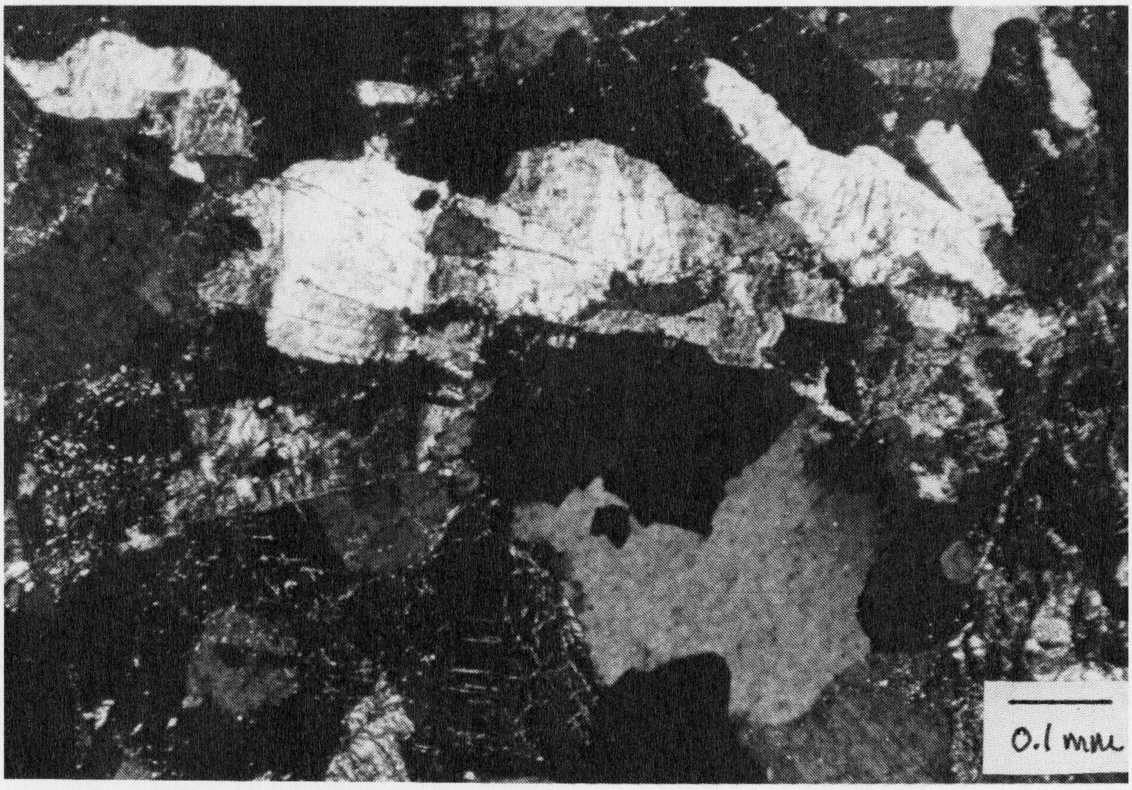
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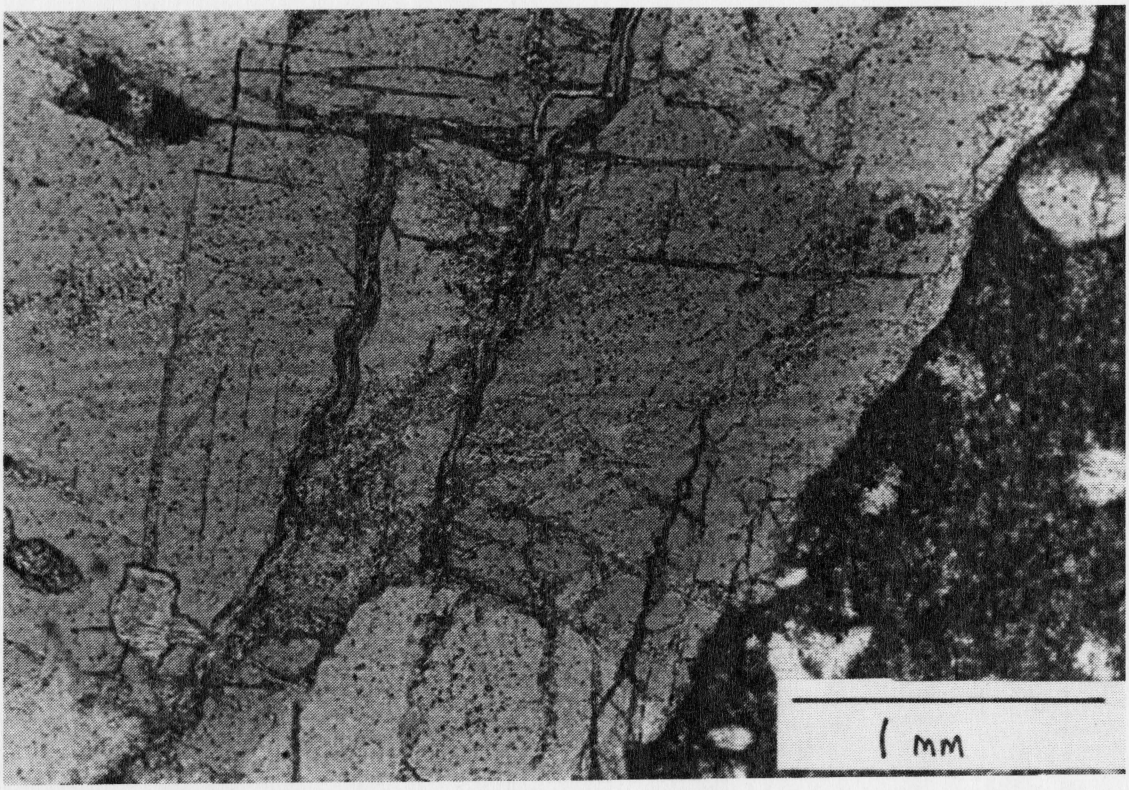
Planar Features

The wall rock associated with the Sudbury breccia shows the most and the clearest planar features due to the larger and less altered nature of the grains. Planar elements is a," ...collective term for the parallel set of deformation structures that are closely spaced and crystallographically oriented .." (Carter, 1965; Von Englehardt and Bertsch, 1969; Stöffler, 1972 cited in Fricke *et al.*, p. 176-7, 1990). According to Fricke *et al.* (1990), planar elements are a result of fluid penetration into fissures opened up in shocked and shattered grains. They occur as fractures or rows of aligned, "dust-like" (Fricke *et al.*, 1990) inclusions, 1-2 microns wide and 2-5 microns apart (Grieve *et al.*, 1990) and vary in continuity across the grain (Plates 13, 14, 15, 16). When fresh, the planar features are filled with diaplectic glass. Older ones are filled with inclusions or decorations (Grieve, 1990). The planar features, in feldspars (Plates 17 and 18), are less easily distinguished due the turbid, altered surface of the feldspars, and are seen most clearly in grains of quartz (Plates, 13, 14, 15, 16, 19, 20).

Plate 13 : Planar features in quartz, plane polars

Plate 14: Planar features in quartz, crossed polars.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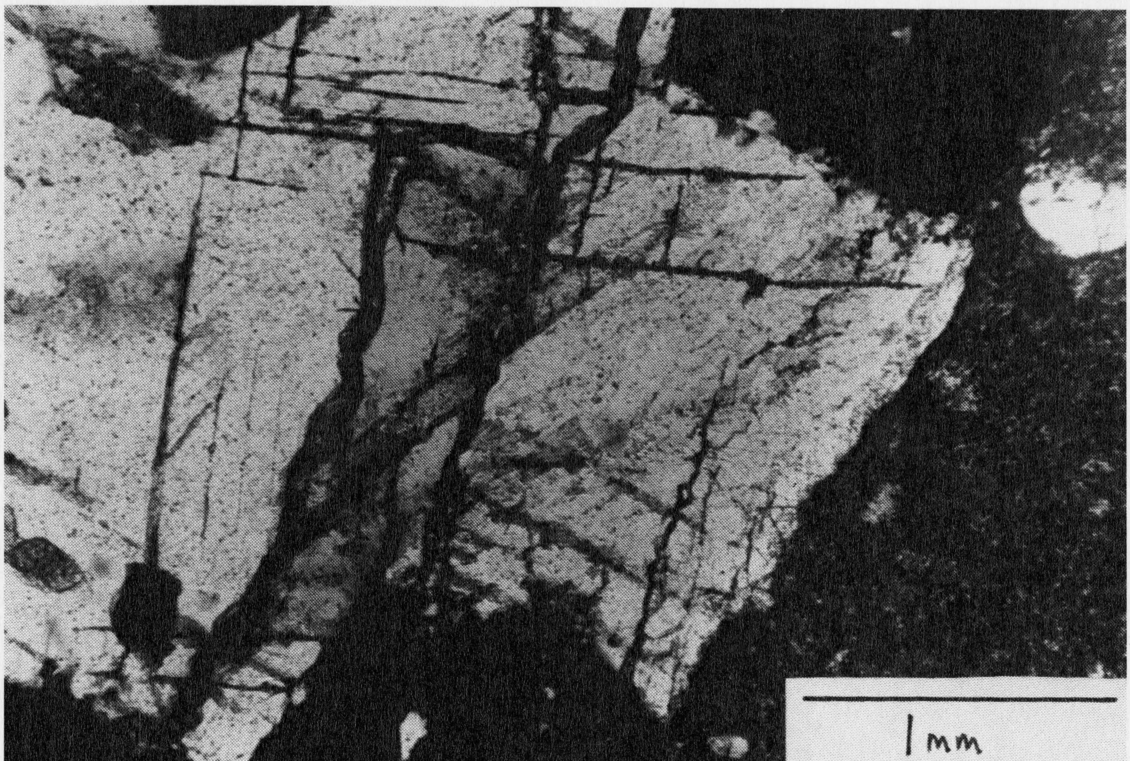
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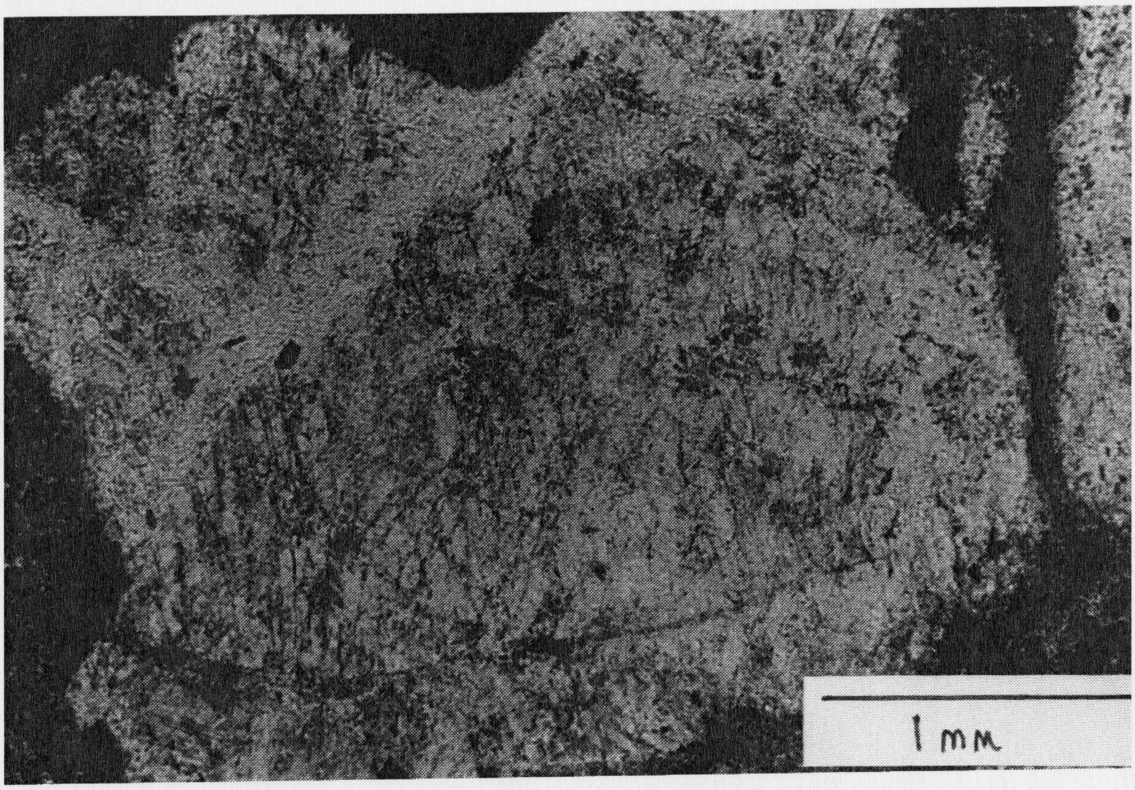
Plate 15: Planar features in feldspars, plane polars

Plate 16: Planar features in feldspars, crossed polars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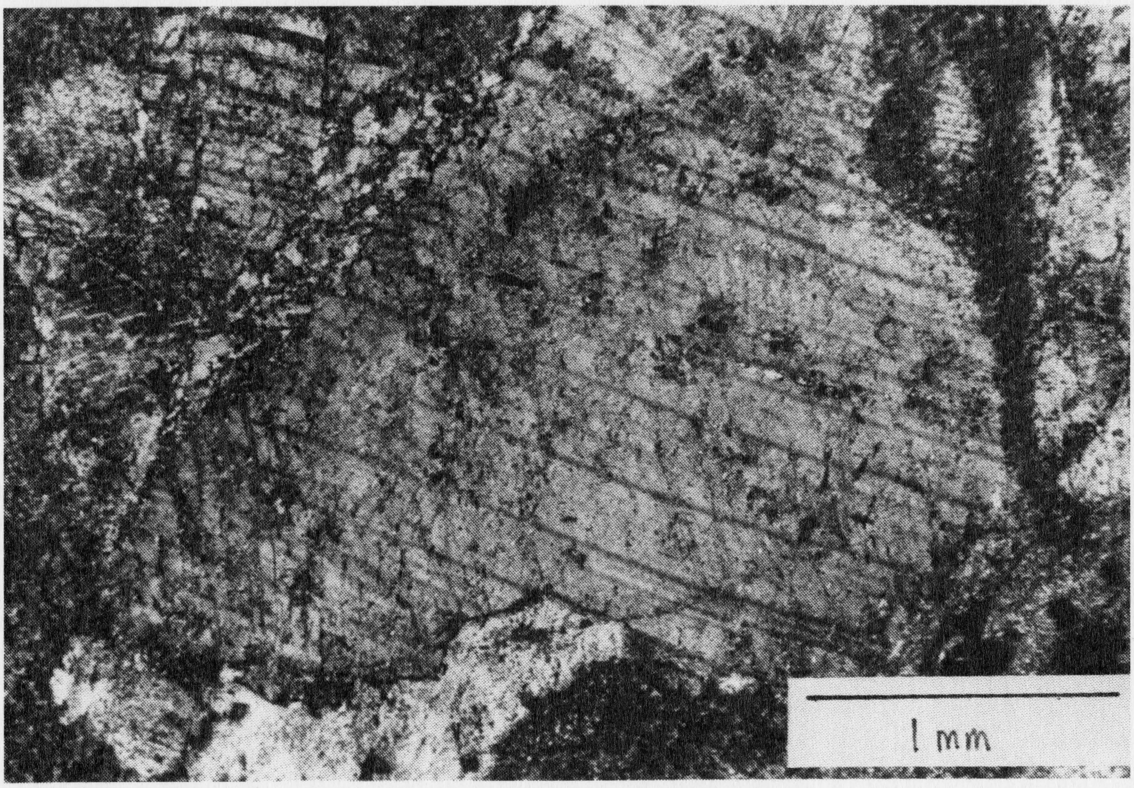
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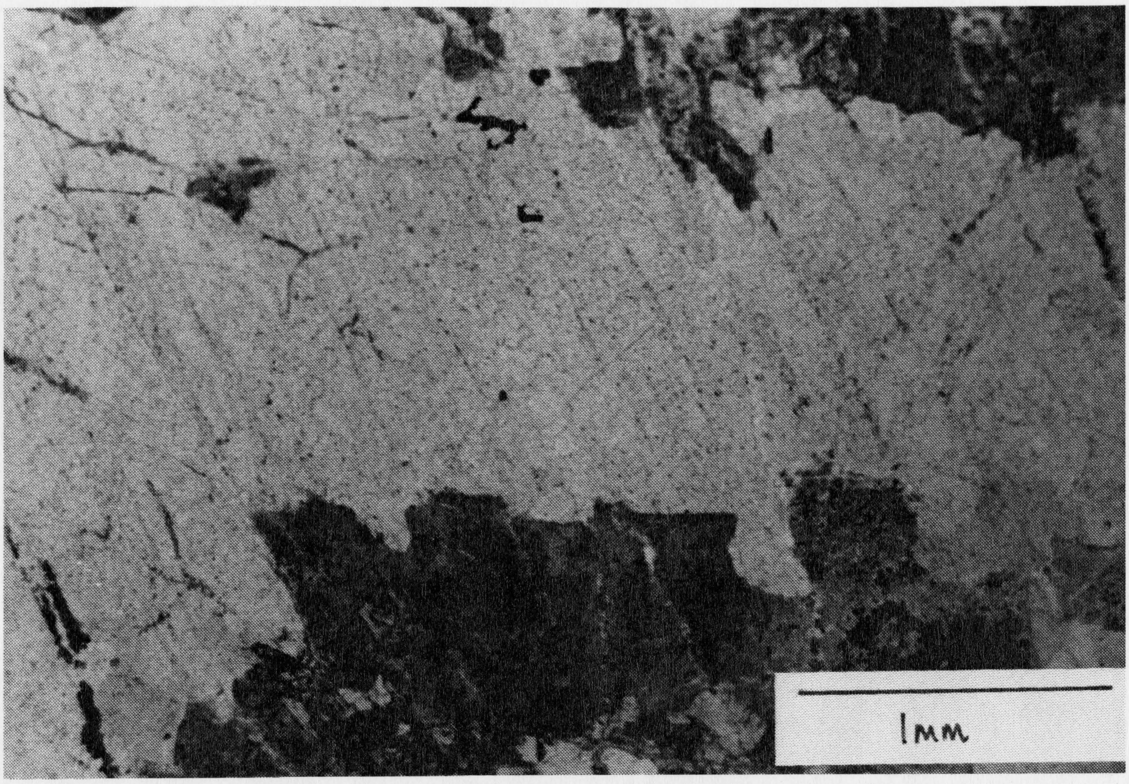
Plate 17: Planar features in quartz, plane polars.

Plate 18: Planar features in quartz, crossed polars.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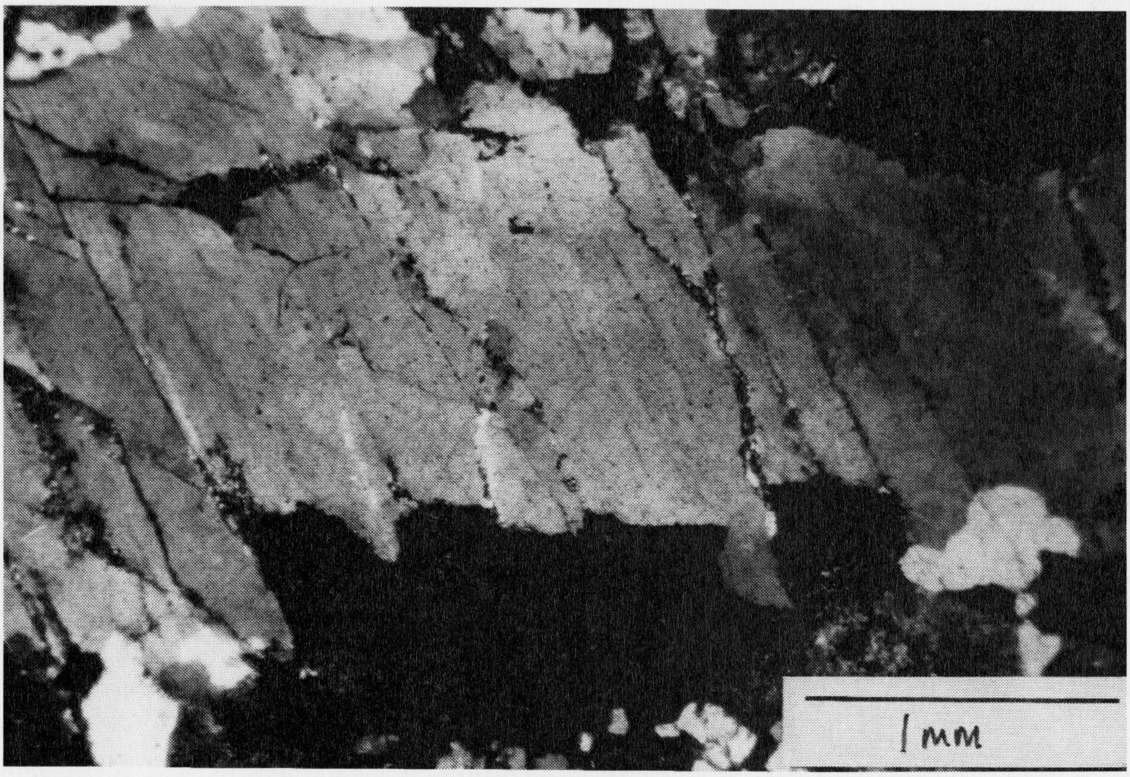
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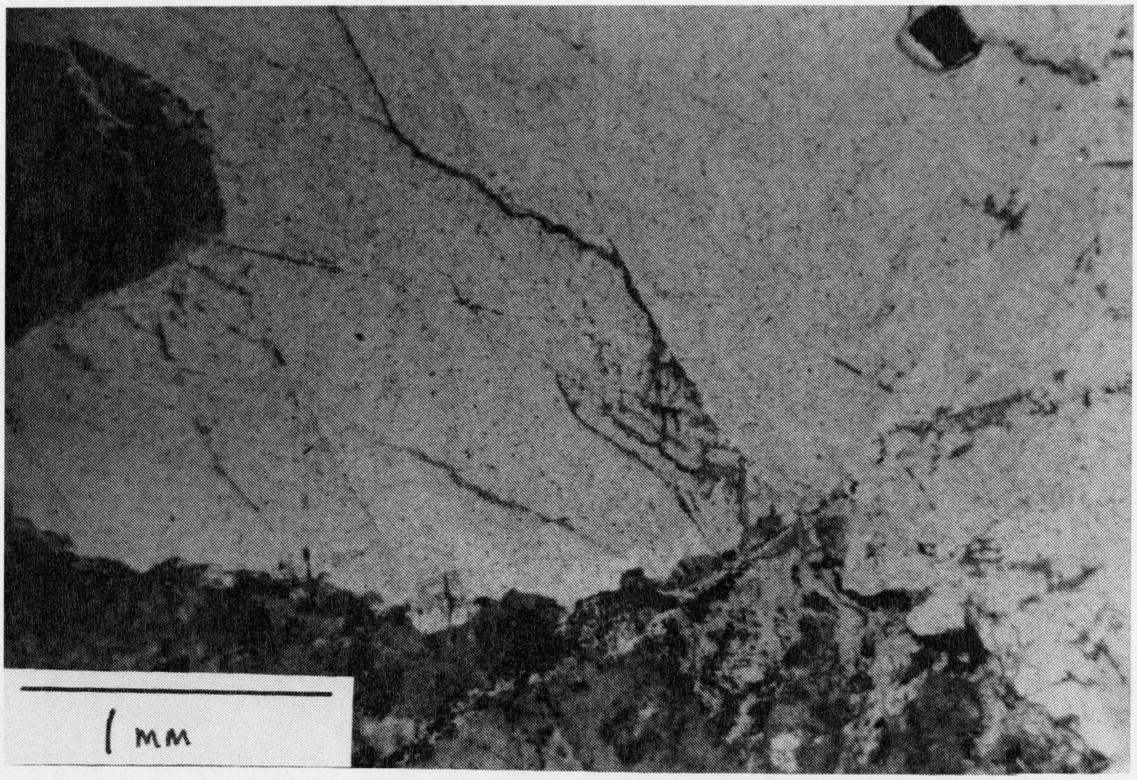
Plate 19: Planar features in quartz, plane polars.

Plate 20: Planar features in quartz, crossed polars.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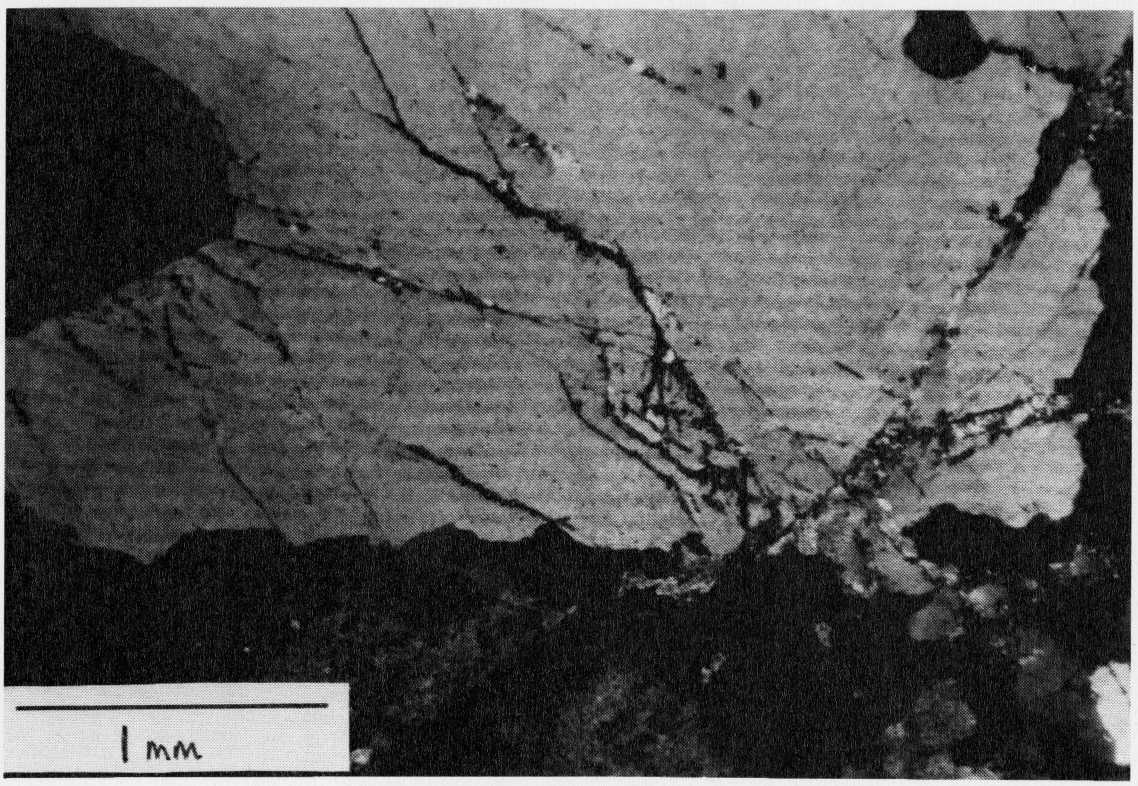
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The presence of kink bands and planar features are not distinctive of shock on their own as they can also form in tectonically deformed rocks (Chao, 1967). However, multiple sets of features and certain orientations of these features are diagnostic of shock. Using standard universal stage techniques, the orientation of the planar features was measured relative to the c-axis of the quartz grain (Table 2), and subsequently plotted on a stereonet (Figure 4).

When compared to a stereonet of the crystal faces of quartz, the planar features seemed to cluster about specific faces, which are more readily observed when plotted on a histogram (Figure 5) showing the predominance of the orientations, parallel to the basal plane, $\{0001\}$, the omega $\{10\bar{1}3\}$ and the pi $\{10\bar{1}2\}$.

These particular orientations are diagnostic shock planar features (Grieve, *et al.*, 1990, Fricke *et al.*, 1990) and thus indicate, they were not formed as a result of endogenic metamorphic processes. The petrographic analysis establishes that the samples are definitely pseudotachylite and contain features of shock metamorphism.

Table 2: Crystallographic Orientations of 14 Quartz Grains

specimen	grain	c-axis orientation	sets and orientation
Sudbury Breccia	1	316.5 / 26.5 S	1) 45.5 / 10 S
			2) 125.5 / 24 N
			3) 89 / 8 N
			4) 75.5 / 7.5 S
	2	350 / 0	1) 83.5 / 2 N
	3	162.5 / 1 N	1) 78.5 / 5 N
Sudbury Breccia wall rock	1	152 / 0	1) 354.5 / 4 N
			2) 53.5 / 2 N
	2	119.5 / 0	1) 88.5 / 7 S
	3	58.5 / 0	1) 65 / 17.5 N
	4	77.5 / 21 N	1) 91.5 / 13 S
	5	107 / 8 N	1) 85.5 / 7 S
			2) 178.5 / 12 S
	6	170.5 / 5 N	1) 85 / 1 N
			2) 132 / 3 S
	7	250 / 5.5 S	1) 81.5 / 3 N
	8	145.5 / 4.5 N	1) 84.5 / 3.5 N
			2) 139.5 / 3 S
			3) 201 / 7.5 S
	9	239 / 0	1) 175.5 / 12.5 N
	10	83.5 / 0	1) 85.8 / 1.5 N
			2) 159.5 / 0
Pseudotachylite	1	185.5 / 14.5 N	1) 82.5 / 5 S

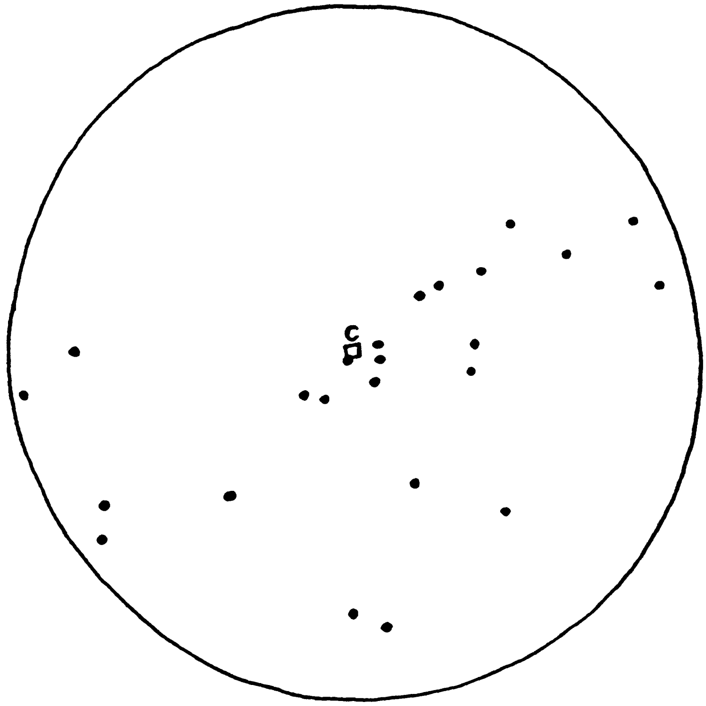


Figure 4: Equal angle stereonet plot of the orientations of planar features of 14 quartz grains, represented by the dots, shown relative to the c-axis.

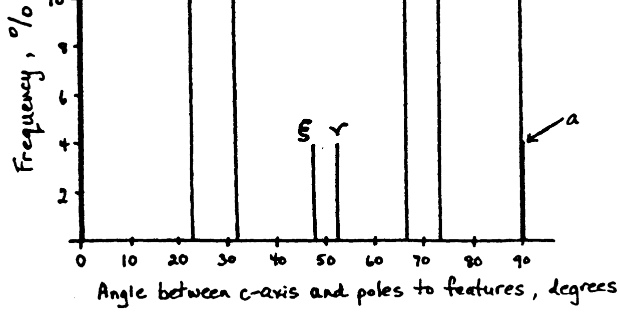


Figure 5: Histogram plot of the orientations of the planar features of the quartz grains as they correspond to thte crystallographic orientations of quartz.

CHEMISTRY

The XRF chemical analyses were performed at McMaster University in the X-Ray Fluorescence Lab. Using a Phillips Fluorescent 1480 instrument, one gram of powdered sample was mixed with six grams of spectrograph flux 1A and fused to a glass at 1100 °C in a platinum-gold crucible. The XRF analyses are based on four pseudotachylite specimens taken from the Levack region in the North Range of the Sudbury Structure.

The major oxides obtained were compared to McMaster standard values which were corrected for volatile loss as compiled from the Geostandards News Letter vol. 13, Special Issue, July 1989. The values obtained have standard deviation of error of at most 0.65.

The analyses aid in the clarification of the Sudbury origin only so far as to verify that they are pseudotachylites in comparison to other pseudotachylite samples. The results seem to raise more questions about the actual formational process, showing some interesting discrepancies or possible trends in major oxide contents, discussed below.

A comparison of the pseudotachylite composition to that of the wall rock (table 3) shows that the silica, alumina, potash and P2O5 weight percent contents decrease, whereas the manganese oxide, magnesia, lime, titania, soda and iron contents increase. The most drastic changes are the decrease in silica content by 8.67 weight percent and potash content by 4.32 and the increase in magnesia content by 6.25, lime content by 4.43 and iron content by 6.45 weight percent.

TABLE 3: XRF Major Oxide Analyses

oxides	pseudo-tachylite wall rock 1	pseudo-tachylite wall rock 2	pseudo-tachylite wall rock 3	pseudo-tachylite wall rock average	pseudo-tachylite vein	Sudbury Breccia	Sudbury Breccia wall rock
SiO_2	68.1	66.8	67.5	67.47	58.8	61.6	78.3
Al_2O_3	16.0	15.6	15.8	15.8	12.7	15.7	10.4
MnO	0.032	0.031	0.033	0.032	0.159	0.087	0.034
MgO	0.668	0.655	0.685	0.673	6.927	3.621	1.19
CaO	2.77	2.76	2.79	2.776	7.21	3.67	1.6
Na_2O	3.37	3.38	3.42	3.39	4.47	4.17	3.24
K_2O	5.61	5.58	5.6	5.597	1.28	2.49	0.96
TiO_2	0.41	0.40	0.41	0.407	0.95	0.75	0.24
P_2O_5	0.41	0.40	0.41	0.407	0.16	0.12	0.02
Fe_2O_3	2.1	2.04	2.15	2.097	8.55	6.82	2.45

C.I.P.W. Norms

quartz	21.2	20.1	20.3	20.5	7.7	15	50.6
corund	0.3	0	0	0.1	0	0	1.2
zircon	0	0	0	0	0	0	0
orthoc	33.2	33.0	33.1	33.1	7.6	14.7	5.7
albite	28.5	28.6	28.9	28.7	37.8	35.3	27.4
anorth	11.1	10.9	11.2	11.1	10.8	16.8	7.8
leucite	0	0	0	0	0	0	0
nephel	0	0	0	0	0	0	0
kalioph	0	0	0	0	0	0	0
acmite	0	0	0	0	0	0	0
Na-met	0	0	0	0	0	0	0
diopside	0	0	0	0	16	0	0
wollast	0	0	0	0	0	0	0
hyperst	1.7	1.6	1.7	1.7	9.8	9.0	3.0
olivine	0	0	0	0	0	0	0
Ca-orth	0	0	0	0	0	0	0
magnet	0	0	0	0	0	0	0
chromite	0	0	0	0	0	0	0
hematite	2.1	2.0	2.2	2.1	8.6	6.8	2.5
ilmenite	0	0	0	0	0	0	0
sphene	0	0.1	0	0	2.3	0.5	0
perovsk	0	0	0	0	0	0	0
rutile	0.4	0.4	0.4	0.4	0	0.6	0.2
apatite	0.9	0.9	0.9	0.9	0.4	0.3	0
fluorite	0	0	0	0	0	0	0
pyrite	0	0	0	0	0	0	0
calcite	0	0	0	0	0	0	0
sum norm	99.4	97.6	98.8	98.6	101.0	98.9	98.4

Chemical analysis of the Sudbury breccia sample was complicated by presence of fine-grained inclusions/fragments. The resulting analyses are considered contaminated and less representative of the brecciation process. As evidence, going from the wall rock to the Sudbury Breccia samples, with the exception of silica, all oxide contents are increased.

The data suggest that the pseudotachylite is not the product of 100% wallrock assimilation, as indicated by the higher mafic content of the pseudotachylite compared to the wall rock. By which mechanism were the mafics introduced? A plot of the normative quartz, orthoclase and albite+anorthoclase (Figure 6) shows the trend from the granitic-granodioritic composition of the wall rock, towards a more dioritic-gabbroic composition of the pseudotachylite and Sudbury Breccia.

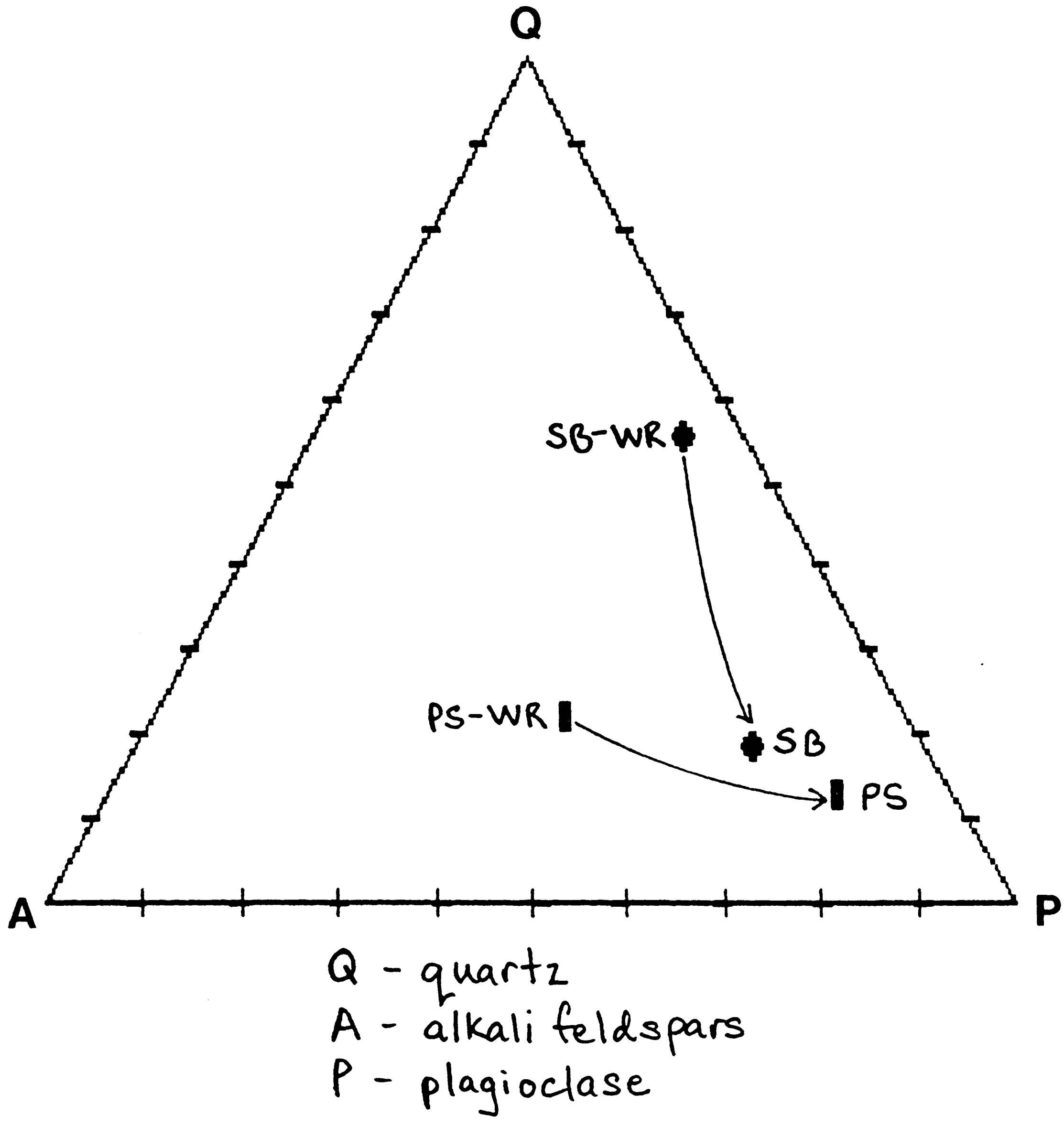


Figure 6: QAP plot of the, pseudotachylite = PS, Sudbury breccia = SB, pseudotachylite wall rock = PS-WR and the Sudbury breccia wall rock = SB-WR.

Variability in the compositions of the respective wallrocks is not identical either. The Sudbury breccia wall rock is higher in silica, magnesia and iron contents, lower in alumina, lime, potash, titania and P2O5 contents, and very similar in magnesia and soda contents, compared to the pseudotachylite wall rock. The variability of the wall rock itself between these two nearby samples makes it difficult to make any definitive statements about the observed distinctive chemical changes.

Comparison to other Pseudotachylite Chemistry

Chemical analyses performed by Shand (1916) on Vredefort pseudotachylites showed a direct correlation between the pseudotachylite and its wall rock. From this, he concluded that the pseudotachylite is melted wall rock. However, Shand (1916) acknowledged this correlation may be purely the result of failing to remove the fragments from the pseudotachylite matrix. Shand (1916) further noted the difficulty in establishing a definite correlation as the granite-gneiss wall rock is extremely variable in composition over small areas, with more mafic and more felsic bands.

In fault-generated pseudotachylite of the Belleau-Desaulniers area, Quebec, Philpotts (1964), observed an increase in silica, alumina and potash contents and a decrease in lime, magnesia, titania and iron contents in the network dikes of pseudotachylite. His purity of samples are based on an approximately 95% pure pseudotachylite matrix sample obtained by, first, crushing the sample to 60 mesh size, and removing the fragments by hand sorting, then by further crushing to 300 mesh size, and finally, immersing the sample in a heavy liquid to remove the remaining fragments by gravity settling.

Philpotts (1964) concluded that the pseudotachylite resembles its host rock chemically, however the significant differences can be explained by selective melting of specific fractions of the country rocks. Quartz and potash feldspar, for example, being the lowest melting components, will be preferentially melted leading to an increased content of silica and potash in the resulting pseudotachylite (Philpotts, 1964).

An analysis of the pseudotachylite of Vredefort by Reimold *et al.* (1990) showed that the pseudotachylite was much more mafic than its alkali granitic host counterpart. They concluded that the pseudotachylite had been formed by injection and not in situ. Dressler (1984) who considers the Sudbury breccia to be a pseudotachylite, analysed the matrix and compared it to its host rock. He found that silica, magnesia, lime and iron contents increased in the matrices which had diabasic host rocks, while content of the same oxides decreased in matrices with arkosic and granitic hosts. He then concluded: ".. the chemical characteristics of the breccia matrices can be explained by assuming that the breccia-forming process not only affected the immediate host rocks,but also some other 'foreign' material. " (p. 115). Thus the incorporation of allochthonous granitic fragments in mafic host rocks and allochthonous mafic fragments in granitic host rocks is part of the formational event.

In conclusion, it seems difficult to derive a definite correlation between the Sudbury pseudotachylite chemistry and those of other sites due primarily to the variable wall rock composition, the sample contamination and the relatively few analysed samples. If any "trends" do exist, they can only be better substantiated by the analysis of many more samples.

PALEOMAGNETISM

The paleomagnetic analysis was undertaken as a means of determining a relative age for the pseudotachylite, with respect to the age of the rest of the Sudbury Structure. The feasibility of such a study is based on the fact that most authors believe the North Range to be the least deformed and least metamorphosed component of the original structure and on the results of a paleomagnetic analysis performed by Morris (1984) on the rocks of the Sudbury Igneous Complex.

The paleomagnetic method determines the orientation of the magnetic remanence vector in the samples. The natural remanent magnetization represents the magnetism of the earth at the time of the formation of the rock, or a reset magnetic orientation imposed on the sample by subsequent deformational, metamorphic or mineralization processes. From a study of over 2000 samples from the norite, granophyre layers, the offsets and sublayer of the Sudbury Igneous Complex, Morris (1984) concluded the Sudbury Igneous Complex contained evidence for seven different remanence acquistion events. He indicates that these remanence directions, are a record of, "...multiple intrusive pulses, multiple mineralization events, and multiple periods of deformation." (Morris, 1984, p. 425), that have occurred in the Sudbury area, between 2200 to 1250 Ma ago. Morris (1984) further states that in the North Range segment, "... both the declination and the geological strike change in a clockwise manner around the Basin." (p. 417), thus, " The present configuration, then, best describes the shape of this part of the Sudbury Igneous Complex at the time of norite intrusion." (p. 417).

Paleomagnetic Method

Five cores were drilled into the pseudotachylite specimen, yielding eight samples, A1, A2, B1, B2, C1, C2, D1,and E1 (Plate 21). These cores which were 2.5 cm in diameter and ranged between 2.1 to 2.4 cm long, were heated in a furnace over a range of temperature increments: 0, 200, 250, 300, 350, 400, 450, 500, 530, 550, 570, 590, and 610 °C. After each heating event, the remanent magnetization remaining in the sample was measured using a spinner magnetometer. The spinner magnetometer spun each sample in three mutually perpendicular axes in both clockwise and counter-clockwise directions, to obtain the declination, inclination and the intensity of the remanent magnetism after each heating event. Figure 7 shows a plot of intensity versus temperature, showing how with increased heating, the strength of the remanent magnetization reduces, until it reaches 580 °C, the Curie point for magnetite, after which a great deal of scatter occurs.

Plate 21: Paleomagnetic pseudotachylite sample, with the 5 cores, clockwise, A, B, C, D, E.


1 cm

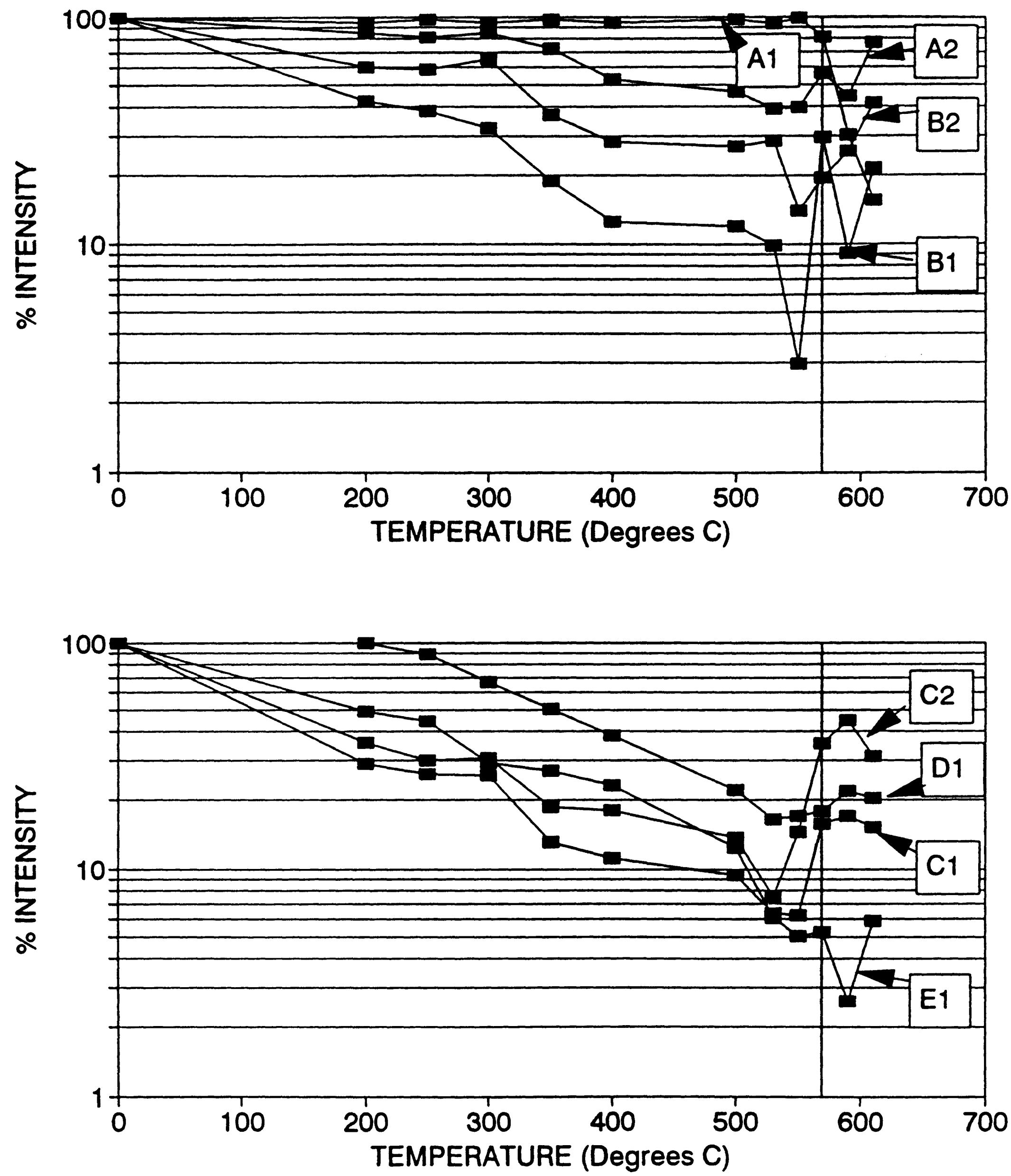


Figure 7: Paleomagnetic plots of % intensity of the magnetic remanence direction versus temperature.

Results

The final orientations that resulted are listed in table 4, and plotted in figure 8.

Table 4 : Mean Remanence Poles for the Pseudotachylite Samples

sample	declination, inclination (degrees)
A1	311.0, 64.0
A2	324.2, 71.3
B1	350.7, -69.6
B2	001.1, 32.0
C1	311.7, 55.6
C2	354.6, 55.8
D1	077.5, -61.1
E1	309.8, -40.5

Table 5: Mean Remanence Directions and Poles for the Sudbury Igneous Complex (after Morris, 1984, p. 417)

type	D, I (degrees)	alpha95 (degrees)	event
N1, N2	330, 68	6	norite intrusion, granophyre-1 intrusion
N3	309, 31	7	mineralization/intrusion?
N8	250, 70	7	granophyre-2 intrusion and mineralization
N6	032, 65	4	dike intrusion-middle zone quartz diorite
N4	323, 31	5	mineralization
N7	111, 38	13	Grenville Front metamorphism

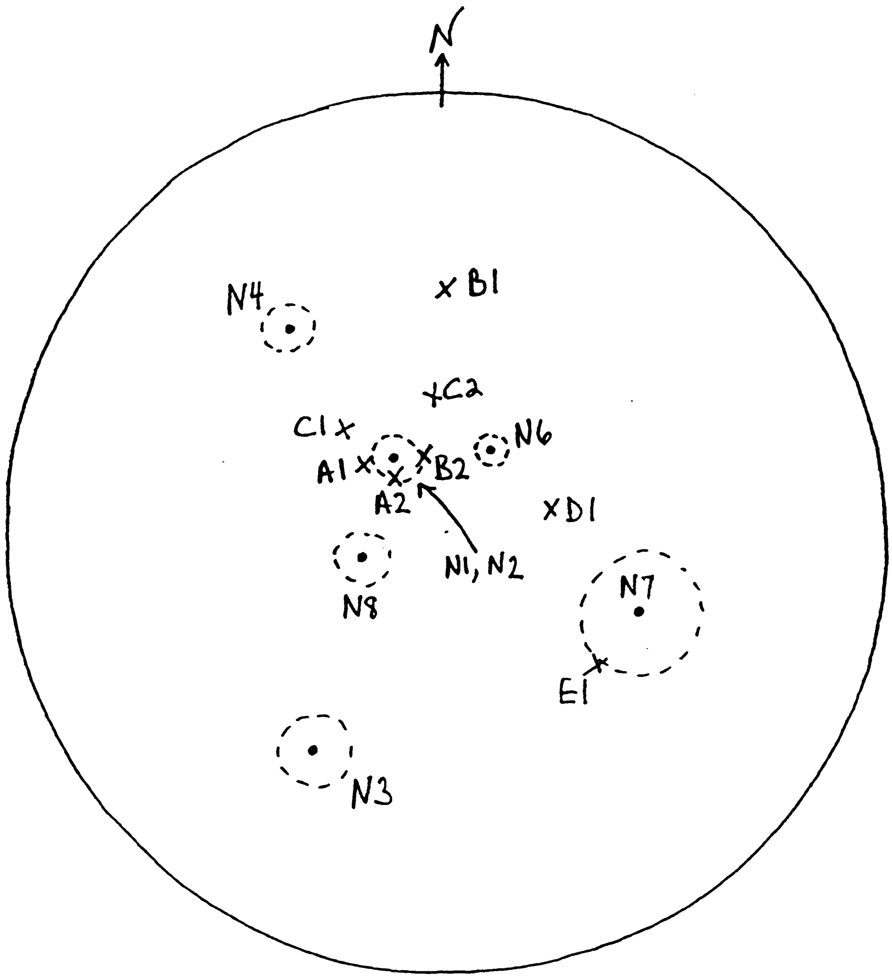


Figure 8: Equal angle stereonet plot of the pseudotachylite remanence directions, indicated by the X's, A1, A2, B1, B2, C1, C2, D1, E1, and those obtained by Morris, 1984, for the Sudbury Igneous Complex, N1, N2, N3, N4, N6, N7, N8, represented by the dots.

The paleomagnetic plot shows how the majority of the samples, namely A1, A2, B2, C1, and C2, cluster around Morris' N1, N2 remanence directions for the Sudbury Igneous Complex. There is a high degree of human error associated with this method however, the results show fairly well that the remanence direction of the pseudotachylite/granitic mobilizate is approximately the same as the oldest remanence direction of the Igneous Complex.

DISCUSSION

The work performed for this thesis permits the author to determine that the pseudotachylite is impact and not fault-generated. In fact, that the distinctive "intrusive" appearance of the pseudotachylite veins in the outcrop, are not associated with any fault surface or large displacement is one of my strongest arguments. Typically fault-generated pseudotachylite is characterized, as previously described, by the presence of displacement and sheared wall rock, whereas impact-generated pseudotachylite shows no or little evidence of displacement and has a more intrusive appearance.

Can fault and impact generated pseudotachylite also be distinguished by their chemistry?

Philpott's (1964) study of the pseudotachylites which he believes are products of fault movement, show distinct differences in the chemistry of the wall rock and the vein, namely an increase in silica, alumina and potash and a decrease in magnesium, total iron and calcium. These trends are almost opposite to those of other studies of impact-generated pseudotachylites, which are marked by an increase in iron and magnesium in the pseudotachylite relative to its wall rock. To come to a conclusion regarding the mafic enrichment requires a great deal more sampling and analysis to ensure it is not just a local anomaly. The extreme local variability of mafic and felsic chemistry in the typically gneissic host rocks also makes it difficult to make generalities between impact sites, *i.e.*, Sudbury and Vredefort. Hyndman (1985) compiled average chemical compositions from 257 granitoid rocks worldwide and plotted the silica values against the major oxides (Figure 9). When the silica values obtained for Sudbury are indicated on Hyndman's plot, one can see that the pseudotachylite vein is anomalously high in magnesium and iron, exceeding the maximum and minimum values as determined by Hyndman (Table 6, Figure 9). The Sudbury breccia is also higher in magnesium and iron, but lies, within the maximum-minimum range, while the wall rock shows typical major oxide values for its determined silica content.

The question that arises from the above comparison is, where does the enrichment in mafics come from? There are two possibilities: 1) mafic fragments were preferentially melted during formation of the pseudotachylites, or 2) the mafics were introduced from an external source. The former is supported by the lack of mafic fragments (biotite and amphibole) in the pseudotachylite vein and the Sudbury breccia compared to their respective wall rocks. The latter hypothesis is viable if the impact, or explosion, occurred, as suggested by, French, 1979 and Guy-Bray, 1979, close to a preexisting magma source, possibly associated with the Nipissing diabases and gabbros. The increased mafic content in the pseudotachylites could have resulted from mafic material from this remobilized magma. However the age of the Nipissing, based on U-Pb baddeleyite ages, obtained by Noble and Lightfoot, ranges between 2217.2 ± 4 and 2209 ± 3.5 Ma , thus the explosion or impact would have had to occurred much earlier than the intrusion of the 1.85 Ma Sudbury Igneous Complex. An alternative explanation is that mafics originated from mafic rich gases associated with an impact event. Shand (1916), for example, proposed that the heat source generating the pseudotachylites at Vredefort maybe the result of hot gases released by the explosive event which formed the structure.

	Diorite and quartz diorite		Tonalite		Granodiorite and quartz monzodiorite		Granite and quartz monzonite	
	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range
SiO_2	54.31	49.75–60.8	64.82	58.70–72.49	66.37	55.81–73.00	71.93	62.0 –77.48
TiO_2	0.95	0.5 – 1.3	0.62	0.25– 1.04	0.53	0.12– 0.98	0.26	0.04 – 0.73
Al_2O_3	17.76	15.68–20.4	16.5	14.44–19.18	15.90	13.63–20.49	14.58	12.44 –17.95
Fe_2O_3	2.27	0.1 – 4.83	1.30	0.34– 2.54	1.07	0.02– 3.46	0.78	0.05 – 4.0
FeO	5.31	3.3 – 6.9	3.47	1.60– 6.18	2.87	0.76– 4.71	1.42	0.34 – 3.78
MnO	0.13	0.08– 0.21	0.09	0.04– 0.17	0.08	0.02– 0.13	0.05	0.01 – 0.15
MgO	4.62	2.2 – 5.8	2.28	0.59– 4.26	1.66	0.14– 3.97	0.66	0.02 – 2.70
CaO	7.8	6.0 – 8.79	4.78	2.40– 6.69	3.42	1.37– 7.42	1.86	0.34 – 4.7
Na_2O	3.83	2.2 – 4.67	3.50	2.17– 5.12	3.51	2.05– 5.4	3.57	2.62 – 4.73
K_2O	1.06	0.3 – 2.20	1.74	0.17– 2.84	2.91	1.14– 5.10	4.02	2.7 – 5.41
P_2O_5	0.25	0.06– 0.39	0.18	0.10– 0.35	0.15	0.04– 0.28	0.08	0.005– 0.4
CO_2	0.04	0.0 – 0.2	0.75	0.01– 0.2	0.07	0.03– 0.3	0.05	0.0 – 0.2
H_2O	1.09	0.4 – 1.9	0.83	0.05– 1.3	0.68	0.2 – 1.2	0.545	0.12 – 1.47
Rb, ppm			96	10–154	123	40–202	225	71–532
Sr, ppm			283	170–490	282	118–690	109	0–359
No. of analyses	22		33		105		97	

Table 6: Averaged chemical compositions of 257 common granitoid rocks from worldwide localities, from Hyndman, 1985, p. 307.

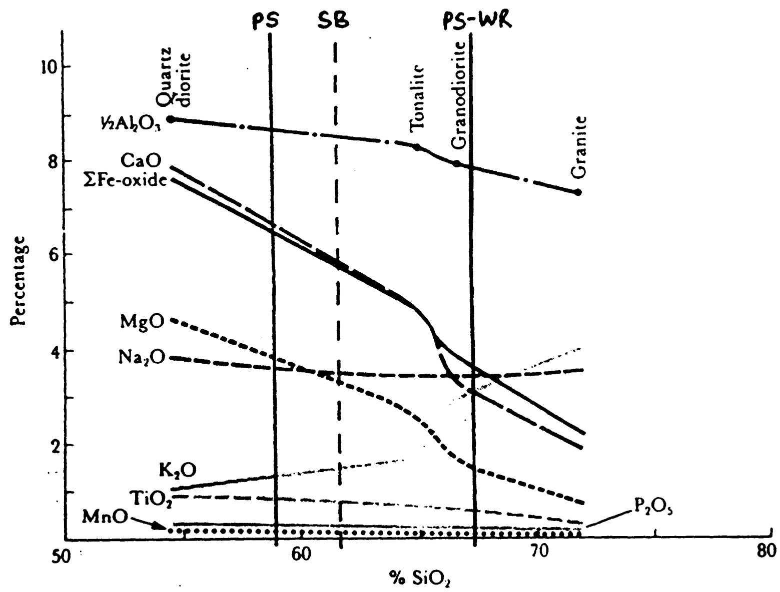


Figure 9: Plot of % silica versus % major oxides of generalized worldwide granitoid compositions, from Hyndman, 1985, p. 308, with the Sudbury breccia, SB, pseudotachylite, PS, and wall rock, PS-WR, silica values, indicated.

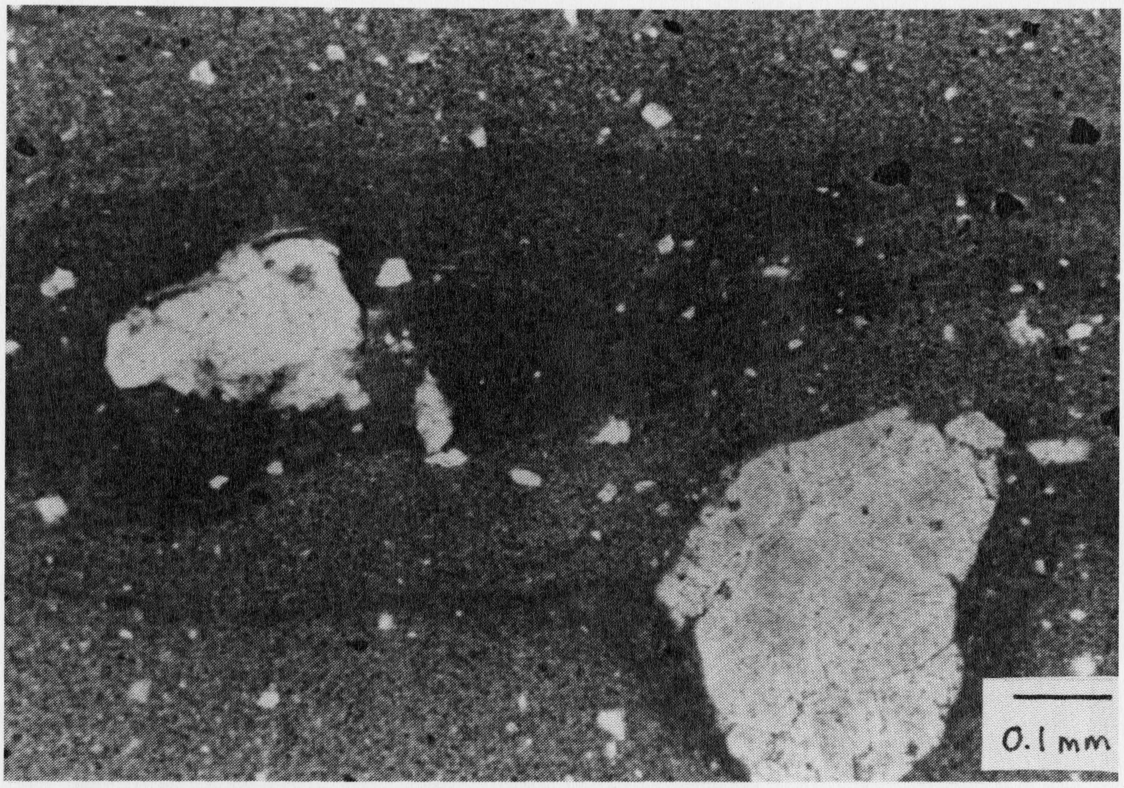
Can fault and impact pseudotachylite be distinguished petrologically?

The petrographic analysis clearly shows the distinctive aphanitic, glassy nature of the pseudotachylite matrix. By definition, fault-generated pseudotachylites should have a clastic matrix. Also of interest are the flowage features (Plates 22 and 23), wavy undulations of darker bands in the pseudotachylite matrix, perhaps indicating more than one episode of formation, which is more likely the cause of endogenic processes, or multiple volcanic explosion events.

Diagnostic, multiple and specifically oriented, **shock-induced** planar features are present in quartz grains of the wall rock and in the fragments of pseudotachylite, and Sudbury breccia. These diagnostic shock features are the best petrographic indication of impact rather than fault origin.

Plate 22 : Flowage structures in pseudotachylite, plane polars.

Plate 23 : Flowage structures in pseudotachylite, crossed polars.


0.1mm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Can the genesis of pseudotachylites be determined by establishing their age relative to large scale regional structures?

Reimold *et al.* (1990), published results of a 40Ar - 39Ar dating which revealed a series of ages for the Vredefort pseudotachylite between 2.2 and 1.1 Ma, and concluded that they indicate either a series of pseudotachylite forming events, or thermal overprinting. These authors based their dating study exclusively on the Vredefort pseudotachylites and on the premise that their formation age would be close or simultaneous, to a Vredefort impact event.

The paleomagnetic analysis reported here provides only a relative age for the Sudbury pseudotachylite which coincides with the event forming the Sudbury Igneous Complex. There is a problem with viewing these results as conclusive arguments for impact-produced pseudotachylites, as the origin of the Sudbury Igneous Complex is, itself, questionable. The Sudbury Igneous Complex is believed to be either the result of 1) impact/explosion-triggered igneous intrusion (French, 1979), 2) impact melt sheet, (Grieve *et al.*, 1991), or 3) an igneous intrusion occurring much later than the event creating the structure. If one assumes that the event which initiated the intrusion of the Igneous Complex occurred relatively soon after the event which created the Sudbury Structure, than the age of the pseudotachylite is close to that of the intrusion. With the time span resolution of the paleomagnetic method, this would be characterised by the two lithologies having the same primary magnetization. Which is exactly what we see in this limited collection. This is a preliminary report. For a more definitive assessment between the pseudotachylites and the Sudbury Igneous Complex it will be necessary to examine many more samples and use a number of other age-dating methods.

Origin of the Sudbury Structure

The enigmatic nature of the Sudbury Structure persists. As of present, there are two main theories: endogenic cryptoexplosion and meteorite impact.

Endogenic Hypothesis

Endogenic origin advocates use paleocurrent data of theWhitewater Group as proof that the Sudbury Structure was not originally circular. Muir (1984) notes the similarities of some of the features of diatremes, kimberlites, tuff rings, resurgent çalderas and ring-like complexes to features of Sudbury. However, Muir (1984) also indicates that all of these processes are on a much smaller scale than Sudbury, and that no single process can account for the origin of the Sudbury Structure. Although the exact non-impact mechanism, which must be capable of generating the great shock pressures, temperatures, and strain rates, remains a puzzle. Muir (1984) proposes two possible mechanisms for the origin of the Sudbury Structure: (1), a confinement and strain, and (2) fluid (liquid or gas) pressure creating an explosion.

Impact Origin

Grieve (1987) describes the basic characteristics of terrestrial impact structures: circular form; evidence for intense, localized, near-surface structural disturbance and brecciation, leading to associated low seismic velocities and residual negative gravity anomalies (Pohl *et al.*, 1977, cited in Grieve, 1987); no deep-seated roots; a low magnetic signature (Dabizha and Ivanox, 1978, cited in Grieve, 1987); and most importantly shock-metamorphic effects (French and Short, 1968, cited in Grieve, 1987). Grieve (1987) goes on to divide impact structures into two basic types: simple and complex. Simple structures like the Meteor Crater, Arizona, have an uplifted rim area, "...in the freshest examples ... overlain by an overturned flap of near-surface target rocks with inverted stratigraphy which is in turn overlain by fallout ejecta..." (p. 246), a crater floor, "...underlain by a lens of allochthonous unshocked and shocked target-rock breccia. Bounding the breccia lens are autochthonous brecciated and fractured target rocks..." (p. 246). Complex structures have diameters between 2 and 4 km, " The freshest examples are characterized by a structurally uplifted central area, exposed as a central peak and/or rings, surrounded by a peripheral depression and a faulted rim area. The peripheral depression is partly filled by allochthonous breccia and/or an annular sheet of so-called impact melt rocks." (Grieve, p. 248).

The possibility of Sudbury being an impact site was first proposed by Dietz (1964) based on the presence of shatter cones, and the Sudbury breccia, occupying tension cracks and fissures and showing no displacement, thus not fault generated.

Foremost for impact evidence is the presence of shock features, such as macroscopic shatter cones and microscopic planar lamellae in quartz and feldspar, kink bands in biotite and glass formation. Endogenic advocates have yet to devise a natural process which can produce the conditions required to create such features. The main features against an impact origin are the elliptical shape of the Sudbury Structure, the zonal nature of the Onaping Tuff, and the vast amounts of igneous rocks associated with it (Naldrett, 1984), the apparent lack of a central uplift (McCall, 1979), and the variable orientation of shatter cones (Muir, 1984). The elliptical shape is cited most often against impact. However, recent seismic and structural evidence for intensive deformation of the South Range indicates this is no longer a serious criticism (Milkereit and Green, 1992, Sharks and Schwerdtner, 1991). The proposal of Sudbury's impact origin is due mainly to comparisons to the features found at established impact sites. Most impact sites being roughly circular. Lowman (1992) claims that the elliptical shape of the Sudbury structure is not a problem, as elliptical impact craters are possible and can be seen on the moon, therefore, "... the elliptical shape of the present structure may be understandable if an obliquely impacting body hit an active orogenic belt." (Lowman, 1992, p. 238). The long axis of the Sudbury Structure is parallel to the Penokean fold trends, and paleomagnetic evidence does indicate the basin was being deformed at the time of the intrusion of the Sudbury Igneous Complex. The ambiguous abundance of igneous rocks associated with the Sudbury structure is another factor against impact. French (1979) and Guy-Bray (1979) both propose that the age of the Sudbury event is older than the presently accepted age of 1.85 billion, and in fact, closer to the age of the Nipissing diabases, gabbros and their Fe-Ni-Cu sulfides. Thus the impact either hit this preexisting Nipissing-related magma pool, and remobilized it, or it struck an area of anomalously high thermal gradient, offloading and fracturing, ultimately producing magma.

CONCLUSIONS

Petrographic analysis of the pseudotachylite veins, Sudbury Breccia and associated wall rocks has revealed the aphanitic, glassy nature of the pseudotachylite vein and the Sudbury Breccia matrix, and confirmed the presence of diagnostic shock metamorphic planar features in the quartz grains of the fragments within the pseudotachylite and wall rock.

Chemically the pseudotachylite has an anomalously high mafic content compared to the composition of the immediate wall rock and to Hyndman's (1985) chemically averaged granitoid rocks with the same silica content. This is contrary to Philpott's (1964) analysis of fault-generated pseudotachylite showing an increase in silica and potash. The pseudotachylite is, thus, not fault-generated nor is it the product of 100 % assimilation of its host or wall rock.

The paleomagnetic data supports a syngenetic relationship between the pseudotachylite and the intrusion of the Sudbury Igneous Complex. The paleomagnetic orientation of the pseudotachylites is the same as that of the least deformed component of the Sudbury Structure, as determined by Morris (1984), which is the orientation corresponding closest to that formed by the event.

Proponents for an endogenic origin of the Sudbury Structure most often cite its elliptical shape as a factor against the impact theory. This is explained usually by deformation of the original crater by subsequent tectonism, Morris (1984) does not invoke a meteorite impact for Sudbury, but states that, " If such a meteorite event occurred in the Sudbury region, it probably formed only a small part of along and complex geological history." (p. 412). However an endogenic origin cannot account for the presence of the diagnostic shock metamorphic features. As of yet meteorite impacts are the only known means by which shock metamorphism can be produced (French, 1979).

Unless a comparable endogenic process can be discovered to produce shock, the fact that Sudbury pseudotachylites are concluded to be impact-produced and the same age as the Sudbury Igneous Complex, supports the theory of an impact origin for the Sudbury Structure.

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