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Order or chaos? Origin and mode of emplacement of breccias in floors of large impact structures

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Abstract

Breccias in the crater floor of large impact structures are pseudotachylites (sensu largo), authigenic monomict and polymict clastic-matrix breccias, so-called footwall breccias, and impact melt breccias. Pseudotachylite bodies in the center of large impact structures (e.g., Vredefort Dome, South Africa) appear to have a random distribution and orientation, but most dip steeply or vertically. Large bodies of pseudotachylite in the more distal sectors of the >200-km-diameter Sudbury Structure have been interpreted as ring and terrace collapse features. In the Vredefort Dome, networks of randomly distributed pseudotachylite veins accompany large (“mother lode”) pseudotachylite dikes. In general, pseudotachylites in the floors of central parts of impact craters may form through explosive transfer of thermal shock energy, in a process that could be termed “flash replacement melting”, whereas pseudotachylites at large distances from the centers of large impact structure are believed to have formed through friction leading to partial or complete melting, similar to the formation of tectonic pseudotachylites. In smaller structures (e.g., Ries and Slate Islands), clastic-matrix breccias instead of pseudotachylites occur as the most common breccias in the crater floors. They have a chaotic distribution pattern. Their dips are commonly also steep to vertical. Melt breccia dikes in the target rocks of the crater floor are associated with melt sheets that fill the lower part of the excavation cavity. At Vredefort, erosion has removed the coherent melt sheet, but melt breccia dikes (Vredefort Granophyre) in the crater floor are preserved. They are characterized by a remarkably homogeneous chemical composition and are believed to represent the initial, undifferentiated impact melt. Near the Vredefort collar, the Granophyre forms more or less concentric dikes. In the more central parts of the Dome, their orientation is more random, but, in places, may be controlled by the Archean fabric of the crater basement. The “Offset” dikes of the Sudbury Structure are associated with the Sudbury Igneous Complex that represents, in total or in part, a differentiated impact melt sheet. The dikes, in many aspects, are similar to Vredefort Granophyres, but their interpretation as undifferentiated bulk melt is problematic on geochemical and structural grounds. Chemically, these dikes are not homogeneous and, in places, they contain massive sulfide deposits that are unlikely components of an undifferentiated impact melt. Differentiation and precipitation of massive sulfides are slow processes compared with the presumably high energy and fast emplacement of a supposedly undifferentiated melt.

Pseudotachylites of the central impact crater apparently are mainly produced in the compression phase of the impact process, whereas clastic-matrix breccias form during the uplift and crater modification phases. Impact melt breccia dikes

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contain pseudotachylite-bearing inclusions and cut across pseudotachylite bodies. Such impact melt breccia dikes were probably emplaced during uplift and crater modification.

Keywords: impact breccia emplacement; pseudotachylite; clastic-matrix impact breccias; impact melt breccia dikes

1. Introduction

Asteroid and comet impact is a fundamental planetary process. Since the observation of the spectacular impacts of the fragments of comet Shoemaker–Levy on Jupiter in 1994, even the most reluctant geoscientist has had to acknowledge that impacts are not only a phenomenon of the geologic past. Planetary impacts still occur and pose a potential threat to the survival of life on Earth. This is not the only reason why the geoscience and planetary science communities have an ongoing responsibility to study terrestrial impact structures. Research on more than 170 known impact structures on Earth, as well as impact ejecta layers, also provides essential insight on the development of the planets of the solar system and even the development of life on Earth (e.g., Alvarez et al., 1980, 1982; Sharpton and Ward, 1988; Kring, 2000; Koeberl and MacLeod, 2002, and references in these publications). It has even been suggested—although controversially—that plate tectonic forces rely to significant degrees on energy input from large impact events (Price, 2001).

It is our intention to provide a comprehensive account on what is known about a particular aspect of impact cratering, namely, the formation of breccias in and below the crater floor and in country rocks in the terrain surrounding the excavation cavity of impact craters. This paper is based largely on our experience gained from 4 months of fieldwork on pseudotachylites of the Vredefort Structure, many years of earlier field studies in the Sudbury Structure, and our first-hand knowledge of the Ries, Manicouagan, Slate Islands and several other impact structures. Our presentation and the comprehensive reference list are intended to serve as a foundation for future investigations that will hopefully lead to a better understanding of the impact process.

It has been shown that different types of breccias are formed during distinct phases of the impact process (e.g., Lambert, 1981; Bischoff and Oskierski, 1987; Hilke, 1991; Müller-Mohr, 1992a,b; Dressler and Sharpton, 1997; Dressler et al., 1999). Here we wish to refine earlier observations on this aspect of impact research. In addition, we present extensive, new results of a recent field investigation on the distribution and orientation of major pseudotachylite occurrences in the Vredefort Dome—the central uplifted area of the Vredefort impact structure in South Africa. These observations are compared with those made at other impact structures, amongst them the very large Sudbury and Manicouagan structures in Canada. Clastic-matrix breccias, another major type of impactite, may form polymict dikes or authigenic, monomict, irregularly shaped bodies in rocks of the crater floor. The authigenic, monomict breccias commonly have transitional contacts with their host rocks. These clastic-matrix impact breccias have not been found in all well-exposed crater floors, and we provide some tentative interpretations as to why this could be the case. Finally, we provide a short review of occurrences of impact melt breccia dikes known to occur in the crater floors of some of the large impact structures such as Manicouagan, Sudbury and Vredefort.

Interpretations are often based on relatively limited observations. The present publication includes a large number of photographs and figures. Not all of them are described in great detail. We encourage the reader to study our illustration in detail. In combination with the text, they hopefully will substantiate our interpretations of the formation of the various breccia in the floors of impact structures, or, if we cannot convince our colleagues, will encourage discussion and further research. The following account will show that there still remain many open questions on how, in what specific impact environment, and in what three-dimensional arrangement breccias are formed—or emplaced—in the crater floor and the surrounding terrain of the target area. Are we dealing with chaotic processes leading to random distribution and orientation of impact breccia bodies or can we see some geometric order?

2. Terminology of impactites in crater floors

Stöffler and Grieve (1994), on behalf of the Subcommission on the Systematics of Metamorphic Rocks of the International Union of Geological Sciences, proposed a classification and nomenclature for impact metamorphic rocks. This classification is not uncontroversial. In this paper, we deal with impact-generated breccias in rocks of the crater floor and surrounding country rocks. For breccias, which are exclusively formed from clastic components, the 1994 nomenclature recommends the term "fragmental breccia". We have decided not to apply this term. It is unfortunately redundant—breccias, by their nature are fragmental rocks. Descriptive terms are employed where no generally accepted terms exist.

The first chapter of our review deals with pseudotachylites. For the sake of brevity, we use this term and not the term "pseudotachylitic breccia" that would be more appropriate as a "catch all" for the various types of clastic or melt-bearing breccias that have been collectively called "pseudotachylite" and that can form by a number of processes such as friction or shock melting, cataclasis leading to melting, or a combination of these effects (for a review of the problematics, cf. Reimold, 1995, 1998). Almost 100 years ago, these enigmatic rocks were first described from the Vredefort Structure by Shand (1916), who named these rocks "pseudotachylytes". This structure is now generally accepted as the largest or at least, one of the largest terrestrial impact structures (Gibson and Reimold, 2001).

There is still some controversy on a generally acceptable definition of the term pseudotachylite. The Glossary of Geology (Bates and Jackson, 1987) defines "pseudotachylite" as: (1) "dense rocks produced in the compression and shear associated with intense fault movements" and similar rocks "such as Sudbury breccias" that "contain shock metamorphic effects" that "formed during meteorite impact"; and (2) "dark grey or black rock that externally resembles tachylyte and that typically occurs in irregularly branching veins. The material carries fragmental enclosures..." Such definitions are unfortunate. The second example applies also to rocks of the first definition, namely, those associated with intense fault movement or meteorite impact. Structural geologists commonly apply the term "pseudotachylite" only to rocks generated by friction in fault or shear zones. The problem is—as so often—that a term originally used as descriptive term for some observations in the field slowly gains a different, sometimes wider, more specific or genetic meaning.

Macroscopically, pseudotachylite may closely resemble other tectonic breccia types such as cataclasite and ultramylonite, aphanitic or microcrystalline magmatic intrusions, and also impact melt injections. This fact has led to a multitude of misclassifications of such vein or dike breccias as documented and discussed in detail by Reimold (1995, 1998). This author promoted careful laboratory-based identification of the true identity of a pseudotachylite, in order to be able to better constrain the origin and timing of formation of such breccias. He suggested using the field term "pseudotachylitic breccia" for breccias for which an origin by frictional melting cannot be established.

Unfortunately, the general impact community has not accepted this proposal. Even detailed laboratory investigations do rarely result in a clear statement regarding the origin of such breccias. The term pseudotachylite is still indiscriminately being used in the literature dealing with impact sites. Whenever we are confident about the impact mode of origin of "pseudotachylite" occurrences described by us, we will say so.

We use the rather generic and descriptive terms "polymict, clastic-matrix breccia" and "authigenic, monomict, clastic-matrix breccia" for two common rock types that have been described from many impact sites. These terms are easily applicable in the field and laboratory situations and should not lead to any misinterpretations. Rondot (1989) introduced the term "mylolisthenite" for clastic-matrix impact breccias without or with minor glass fragments. The term did not gain general acceptance. For a specific breccia type found in impact crater floors immediately below the crater cavity, the term "Footwall Breccia" has been coined. It describes a polymict breccia deposit at the interface of impact melt sheets and the crater floor, as observed, e.g., in the Sudbury Structure, where this term was originally used (Langford, 1960).

Impact melt rocks may form sheet-like bodies in the excavation cavity of impact craters as well as veins and dikes within the crater floors. In this paper, we deal with impact melt dikes only and concentrate on their distribution within several of the largest terrestrial impact structures. Dressler and Reimold (2001) provided a still up-to-date review on impact glasses and impact melt rocks. The reader is also referred to this publication for more detail on definitions and terminology of impact melt rocks.

3. Pseudotachylites

3.1. Introduction

Shand (1916) introduced the term "pseudotachylyte" (modern spelling "pseudotachylite") for dark-colored, glassy-looking, branching, and dike- and vein-like rocks of the Vredefort area that contain inclusions mainly derived from the nearby country rock and that resemble tachylite, a volcanic glass formed from basaltic magma found as chilled margins of dikes, sills, and flows. Shand came to the conclusion that "...the pseudotachylyte has originated from the granite itself through melting, caused not by shearing but by shock, or alternatively, by gas fluxing." Since Shand's work, the enigmatic pseudotachylites have been described from numerous sites of tectonic deformation in the world, and also from a number of impact structures, and they still are the subject of intensive research by both structural geologists and impact researchers. Pseudotachylites occur at faults and shear zones and in rocks of the floor of impact structures and even in rock fragments ejected from impact craters. Many pseudotachylite occurrences are located in areas affected by regional metamorphism and, therefore, it is not surprising that there is no general agreement on the character of the matrix of pseudotachylite breccias and their origin. Philpotts (1964) stated that (tectonic) pseudotachylites were formed by frictional fusion, a view also held by Higgins (1971), Maghloughlin and Spray (1992), and Reimold and Colliston (1994; and references therein). Maddock et al. (1987) investigated fault-generated pseudotachylites from Greenland and Scotland. The Greenland carbonate and associated phases filling the amygdules were used to estimate shallow paleoseismic depths of vesiculation, whereas in the case of the Outer Hebrides Thrust, amygdules are filled with K feldspar, titanite, epidote and quartz suggesting that these pseudotachylites were tectonically transported to greater depths subsequent to their formation. Others, in the older (Waters and Campbell, 1935) and in more recent (Weiss and Wenk, 1983; Dressler, 1984a; Müller-Mohr, 1992a) literature argued for an origin by cataclasis as result of milling—without or with involvement of fusion. Spray (1992, 1998) provided experimental and physical constraints on pseudotachylite formation and concluded that cataclasis preceded frictional melting. He proposed that frictional melting was dependent on the physical characteristics (shear strength, fracture toughness) of the various rock-forming minerals present and that the presence of hydrous mineral phases enhanced melting.

Some workers have distinguished various types of pseudotachylites. "A-type" and "B-type" pseudotachylites were distinguished in the Vredefort Structure by Martini (1991, 1992). A-type occurrences were designated as thin veins characterized by dark gray, aphanitic material with fluidal melt textures. B-type pseudotachylites, according to Martini, form large bodies and long dikes and are composed of dark, very fine-grained, clastic material. They supposedly represent early compressional and later extensional phases, respectively, formed during the formation of large impact structures. This classification was challenged by Reimold et al. (1992) who pointed out the lack of convincing field evidence for this distinction. Spray (1998) introduced the terms endogenic (E)- and shock (S)-type pseudotachylites. S-type occurrences were associated with initial friction and shock melting during the compression phase of the impact process, and E-types formed during the crater modification phase by a process analogous to the formation of other endogenic pseudotachylites from tectonic settings.

Fiske et al. (1995) generated pseudotachylite in shock experiments, and Kenkmann et al. (2000) advocated an origin for pseudotachylite in impact settings through a combination of friction and shock melting, as deduced from shock experiments. Reimold (1995, 1998) provided a detailed review of the arguments presented on the origin of impact pseudotachylites by friction melting and/or shock brecciation and, as stated above, advocated to reserve the term "pseudotachylite" for rocks formed by friction melting only.

Masch et al. (1985) described rocks similar to pseudotachylites from landslides in Nepal and Austria. They applied the term “hyalomylonite” to these rocks and provided evidence for their generation by frictional melting. Black melt veinlets are also known from many meteorites and from some lunar rocks. So-called shock veins in the Martian meteorite Zagami were formed by rapid shear melting and solidified in extremely short times. The melts crystallized under high pressures and very high temperatures as suggested by the presence of high-pressure minerals such as stishovite, silicate hollandite, akimotoite and amorphous perovskite (Langenhorst and Poirier, 2000). Very thin pseudotachylite veins associated with terrestrial impact structures have also been shown to be associated with high-pressure minerals, e.g., stishovite and coesite found associated with pseudotachylites in the collar rocks of the Vredefort Dome (Martini, 1978, 1991, 1992).

In the following, we concentrate on (1) a short review on what is known about pseudotachylites (or pseudotachylitic breccias) in the rocks of three impact structures we are familiar with (namely, Ries, Manicouagan, and Sudbury) and (2) the new results of recent field investigations of pseudotachylites in the Vredefort Dome. In a summary, we attempt an interpretation of our observations. We are aware that our ideas will probably not become accepted by all impact researchers. However, we hope that our observations will be taken in consideration in future research efforts.

3.2. Ries crater, Germany

The Ries crater is a 24-km-diameter and ~ 15-Ma-old impact crater in southern Germany. The target rocks consist of Middle Triassic to Upper Jurassic sedimentary rocks overlain by Oligocene and Miocene clays and sands. These units, as well as Hercynian granodioritic and granitic rocks and gneisses from the crystalline basement are found as fragments in allogenic fallback and fallout breccias. The crater floor is not exposed anywhere, but has been reached by 1206-m-deep scientific drilling. The borehole Nördlingen 1973 penetrated 324 m of postimpact crater-filling sediments, and ~ 400 m of fallback suevite, a glass-rich and shock metamorphosed clast-bearing fallback breccia, before reaching the impact-deformed and brecciated basement

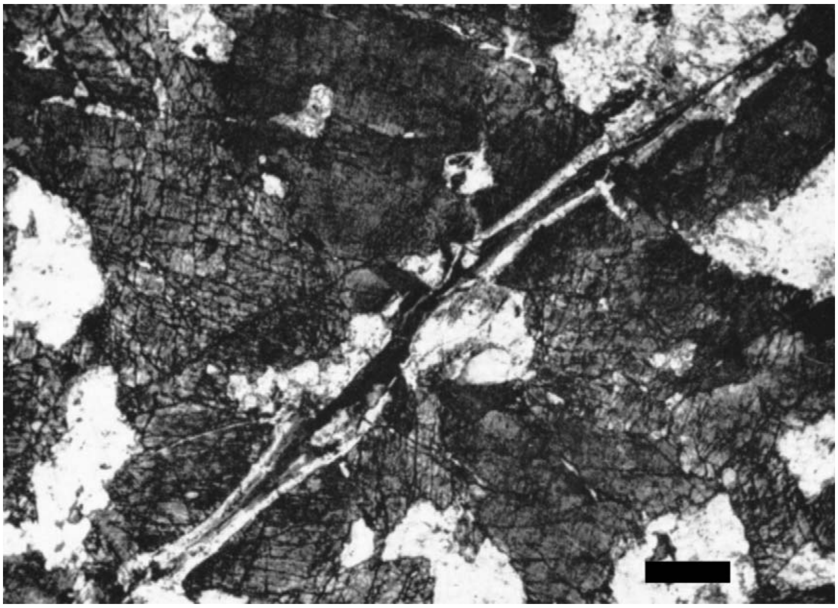

Fig. 1. Fine pseudotachylite vein in amphibolite clast in Bunte Breccia, north of Wemding, Ries impact structure. Note discoloration of hornblende along pseudotachylite vein. Scale is approximately 0.25 mm long (from Dressler and Graup, 1969).

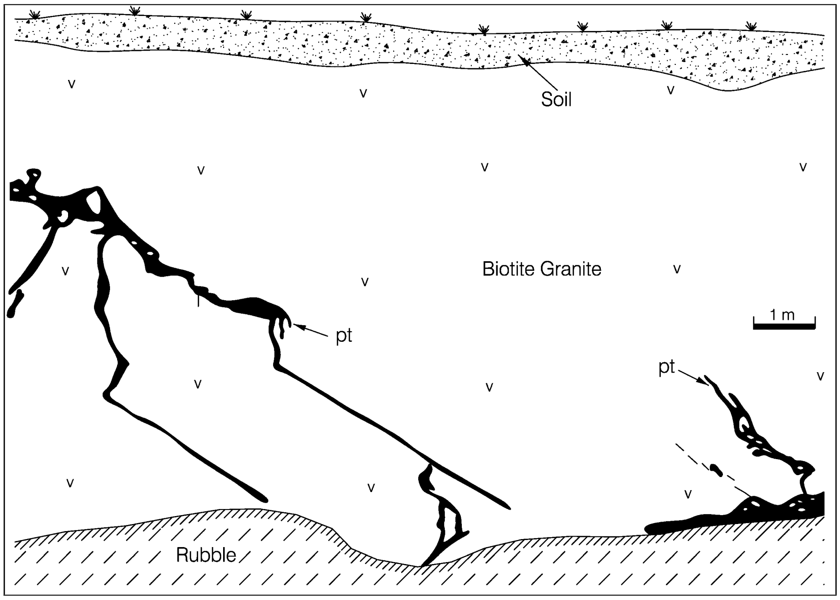

Fig. 2. Pseudotachylite in large ejected granite block. Vertical quarry wall. Near Sulzdorf, approximately 18 km southeast of center of Ries impact structure. "Explosionsbreccie" of Dressler et al. (1969).

(Stöffler, 1977; Stöffler et al., 1977). Clastic-matrix breccia dikes are exposed in crystalline rocks of the so-called "inner Ring".

The drill core did not reveal a presence of pseudotachylite veins in the basement rocks. The detailed drill log, however, shows dike-like breccias more or less down to the final depth of the hole. They are described as polymict, fine-grained, red-brown "Ries breccia" (Stöffler, 1977; Stöffler et al., 1977), which we would name polymict, clastic-matrix breccias. Pseudotachylites, however, have been observed in the Ries structure, but only in basement rock clasts ejected from the crater. For example, a fine, glassy pseudotachylite veinlet in an amphibolite clast (Fig. 1) in Bunte Breccie[1] was noted by Dressler and Graup (1969) and a large occurrence of pseudotachylite in a large, ejected granite block (Fig. 2) was documented by Dressler et al. (1969). For this pseudotachylite (Fig. 2), the term "Explosionsbreccie" was then used. It resembles pseudotachylite breccia bodies in other impact structures and consists of fragments derived from the immediate host rock and some scarce clasts of fine-grained mafic igneous rocks in a strongly altered, dark gray, aphanitic groundmass. The occurrence of pseudotachylites in clasts ejected from the crater is evidence that they were formed early in the impact process, i.e., during the contact and compression phase prior to the commencement of excavation.

3.3. Manicouagan Structure, Canada

The ~ 210-Ma-old Manicouagan Structure is approximately 100 km in diameter and located in central Quebec, Canada. Target rocks consist of anorthosite, gabbro, charnockite and various amphibolite facies gneisses of the Grenville structural province of the Canadian Shield. Ordovician limestone and minor siltstone and shale occur locally as well and have also been affected by the impact event (Murtaugh, 1975, 1976).

The central part of the structure defines a large island within the Manicouagan hydroelectric power reservoir and is densely vegetated by boreal forest.

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[1] An allogenic, polymict variegated ("bunt") breccia ejected from the crater. It consists of weakly shocked and unshocked target rocks fragments mainly derived from the upper target stratigraphy.

Outcrop is relatively scarce, with the exception of Mont de Babel—the central uplift of the structure—that consists of a strongly shock-metamorphosed anorthosite body of approximately 25-km diameter. It is in this central part of the structure, and particularly in the southern part of Mont de Babel, where pseudotachylites are relatively abundant (Fig. 3). However, nowhere in the structure are these rocks as abundant as in Sudbury and Vredefort, the two largest known terrestrial impact structures (compare below). The sizes of individual pseudotachylite bodies in the central part of the Manicouagan Structure are also considerably smaller than many of their counterparts in these two larger structures. Dikes are only up to about 20 cm wide and have exposed strike lengths of up to about 15 m. Irregularly shaped pseudotachylite "pods" of more than approximately 1 m in width have not been observed. Anastomosing networks of thin veins also occur (Fig. 4). Manicouagan pseudotachylites are red, pink, or black in color and regularly contain shock-metamorphosed mineral and lithic clasts derived from host rocks. Petrographic observations on thin sections show that the pseudotachylite groundmass apparently is glassy or devitrified and commonly exhibit textures suggestive of

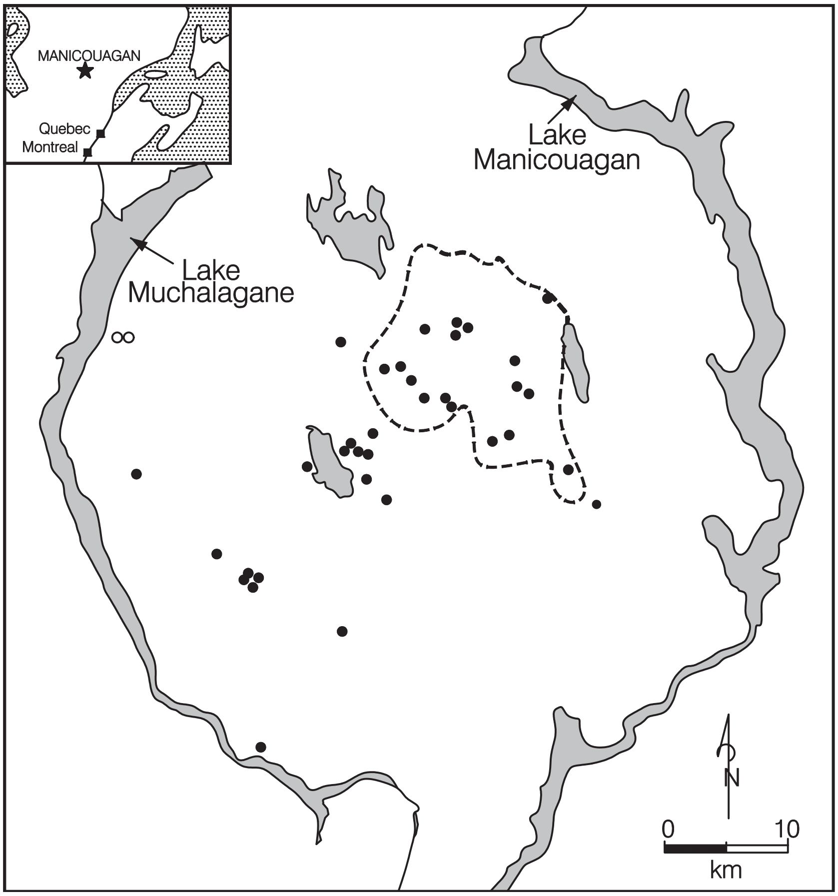

Fig. 3. Distribution of pseudotachylites in Manicouagan impact structure. Please note that the ∼ northeasterly distribution pattern is due to the fact that in other areas of the structure, the rocks of the crater floor are covered by the flat-lying Manicoaugan impact melt sheet. The lakes are shown as they were prior to the reservoir flooding. Occurrences of pseudotachylite (●). Occurrences of polymict and monomict clastic-matrix breccias (○). Stippled line marks approximate boundary of central uplift. Center of structure is located at ∼ 51°23′N and longitude 068°42′W (after Dressler, 1970).

Fig. 4. Network of (red) pseudotachylite veins in gneiss. Central Manicouagan Structure. Pencil for scale.

flow (Fig. 5). Its chemical composition is similar to that of the immediate host rock (Dressler, 1970; Murtaugh, 1975, 1976). The different colors relate to different degrees of alteration and/or composition.

The configuration of networks of anastomosing veins and veinlets, in general, is not suggestive of in situ pseudotachylite formation by faulting and shearing. However, displacement and friction along planes of displacement have locally played a role in pseudotachylite formation. These displacements of a few millimeters (Fig. 6) to possibly several tens of meters (Fig. 7) were not the last movements on these occurrences as pseudotachylite veins cut by later mylonite have been noted (Fig. 8) in a few places. It is not known when this later movement occurred, but it could have been related to the impact process, possibly crater modification. At one location of the central uplift, a pseudotachylite vein has been observed that is bounded by deformed anorthositic gneiss, which exhibits banding dragged by movement along the pseudotachylite. Similar observations concerning these enigmatic tachylite-like rocks have been documented at a few localities in the Vredefort Dome (see below).

3.4. Sudbury Structure, Canada

The Sudbury Structure in Ontario is 1.85 Ga in age (Krogh et al., 1984) and originally had a diameter of approximately 200–300 km (Peredery and Morrison, 1984; Dressler et al., 1987; Grieve et al., 1991). Deformation due to northwesterly directed thrusting during the Penokean Orogeny and kilometer-deep erosion does not allow a more precise estimate of the original size of the structure. Sudbury target rocks consist of Archean granite and gneisses, supracrustal rocks of the Proterozoic Huronian Supergroup, Proterozoic granites, and gabbroic rocks. The central part of the structure, the Sudbury Basin, consists of rocks of the Whitewater Group, which are from bottom to top, the impact melt breccias and suevitic breccias of the Onaping Formation, the mudstones of the Onwatin Formation, and the wackes of the Chelmsford Formation (Pye et al., 1984). The Sudbury Igneous Complex (SIC) beneath the breccias of the Onaping Formation has been interpreted as a large, differentiated impact melt sheet or as a combination of an upper melt sheet, the Granophyre, and a central and lower quartz–gabbro and norite unit. The lower unit could represent an impact-triggered intrusion or impact melt that originated beneath the transient crater

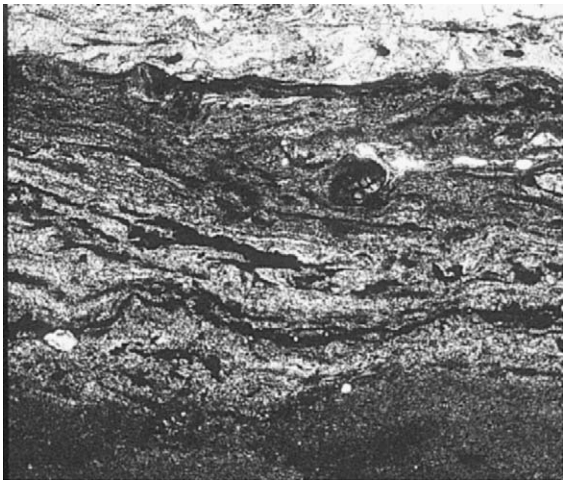

Fig. 5. Glassy, flow-textured pseudotachylite in anorthosite of central uplift, Manicouagan Structure. Mineral clast is garnet. Length of image is ~ 0.5 mm. Plane polarized light.

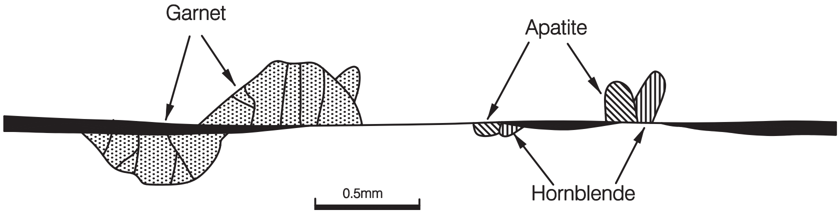

Fig. 6. Thin, glassy pseudotachylite vein in anorthosite of the central uplift, Manicouagan Structure. Vein is approximately perpendicular to thin section. Note the dextral displacement of minerals at vein.

and intruded beneath the granophyre impact melt proper. The "differentiated impact melt sheet" model is presently favored by many Sudbury researchers (Grieve et al., 1991; Deutsch, 1994; Deutsch et al., 1995; Ariskin et al., 1999; Dickin et al., 1999, and references in these publications), but not by all (Chai and Eckstrand, 1994; Cowan et al., 1999, and references in these publications). Proponents of a single, differentiated melt sheet base their interpretations mainly on geochemical considerations and impact cratering models. Those who have reservations with such geochemical arguments point also to geochemical data or base their objections on structural and intrusive relationships related to the various units of the SIC.

The crater floor of the central part of the Sudbury Structure beneath the rocks of the Whitewater Group is not accessible to direct observation. In comparison with what is known about the Vredefort Dome, the uplifted, central part of the Vredefort Structure (see below), and other large terrestrial impact structures, we assume that the Sudbury crater floor is shock-metamorphosed and that it contains large "pseudotachylyte" bodies similar to those first noted by Shand (1916) in the Vredefort Dome. In the basement rocks all around the SIC and up to a distance of about 80 km from the lower SIC contact, breccias known as Sudbury Breccias and resembling pseudotachylites are exposed in many places and have been and still are subject of intense investigation (Speers, 1957; Dressler, 1984a,b; Müller-Mohr, 1992a,b; Thompson and Spray, 1994, 1996; Spray and Thompson, 1995; Spray, 1997; Fedorowitch et al., 1999; and references in these publications).

The Sudbury Breccia bodies are most abundant and largest within a distance of 5–10 km from the SIC. Farther away, such bodies are generally less common and smaller in extent. Evidence, however, exists for the presence of specific zones of increased brecciation, as originally documented by Dressler (1984a) and Peredery and Morrison (1984). F. Hörz (NASA Johnson Space Center, Houston, TX), commenting on the Dressler (1984a) publication, interpreted these observations as being analogous to multiring systems around large impact craters where brecciation should be particularly intense (see Dressler, 1984a, p. 124). Spray and Thompson (1995) interpreted the Sudbury Breccia zones, continuous or not, to be related to a multiring Sudbury Structure. Randomly oriented and distributed Sudbury Breccia bodies are present also between these zones of apparently enhanced brecciation.

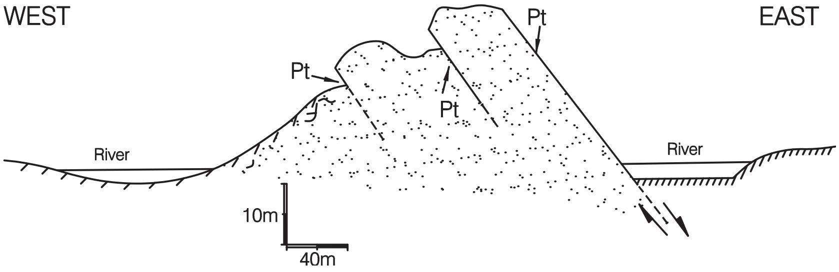

Fig. 7. Outcrop of pseudotachylite-bearing gneiss in Manicouagan Structure, south of central uplift. Relief of hill and location of pseudotachylites are suggestive of pseudotachylite formation along zones of movement. Pseudotachylite (Pt).

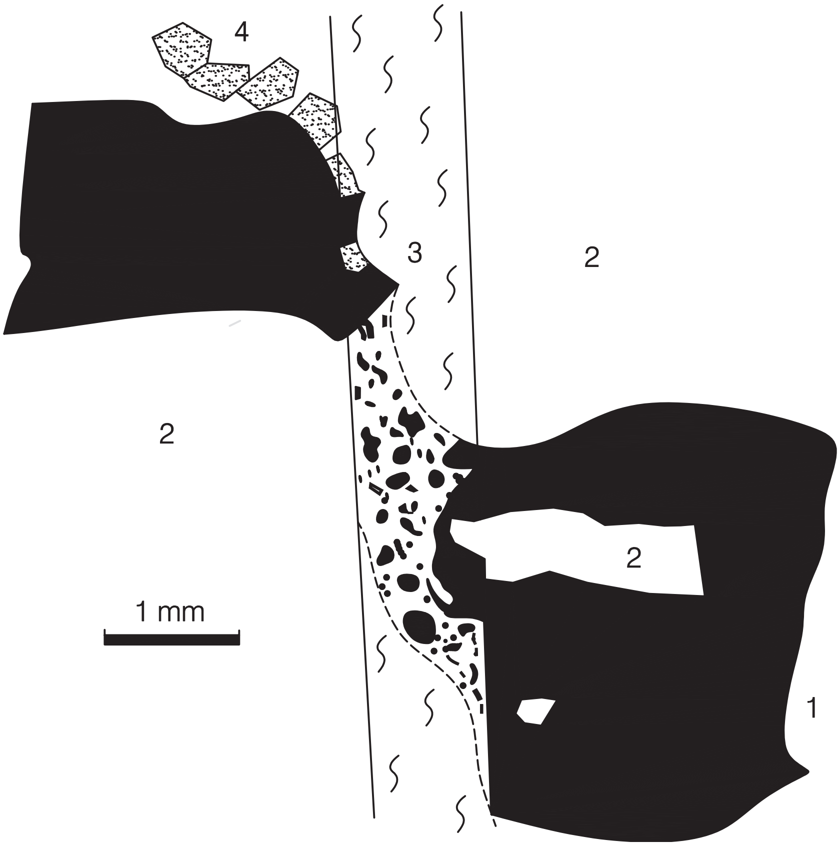

Fig. 8. Pseudotachylite vein (1) in anorthosite (2) of central uplift is cut by clastic-matrix breccia vein (3). Anorthosite contains garnet (4). Clastic-matrix breccia is probably related to crater modification. Manicouagan Structure.

South of the SIC, an extensive Sudbury Breccia zone—known as the Frood–Stobie zone—is well exposed over a distance of approximately 14 km in its eastern part but much less well exposed along its western extension. It is actually about 42 km long and up to several hundred meters wide (A. Bite, geologist, Wallbridge Mining, personal communication, 2002). The zone, from east to west, is depicted in Fig. 9. Spray (1997) used the term "superfault" for this feature and interpreted it as a terrace collapse feature related to the transient cavity collapse phase of the impact process. At the Frood–Stobie Mine and elsewhere, the Sudbury Breccia zone has been intruded by a quartz–dioritic "Offset" dike (see below) that is strongly mineralized. Mining of the Ni–Cu ores established that this breccia zone dips vertically to 75–85° towards the north.

The three-dimensional orientation of other Sudbury Breccia bodies, in general, is not well established around the SIC. The mapping efforts by Dressler (1984a,b) showed that a clear and convincing correlation of orientation maxima of small, rarely up to 30-m-long breccia dikes with the shape of the SIC is not obvious. Where this might be possible to some very limited extent, the orientations of small breccia dike may in reality reflect preimpact rock fabrics and not a distinct brecciation geometry (compare Figs. 6.2 and 6.7 of Dressler, 1984a) related to the spatial development of the impact structure.

Field and laboratory research on Sudbury Breccias have shown that they are, at least, to a large part, very similar to the pseudotachylites of the Vredefort Structure, the pseudotachylite type location. To illustrate this close similarity, we compare several impressions of such breccias from locations

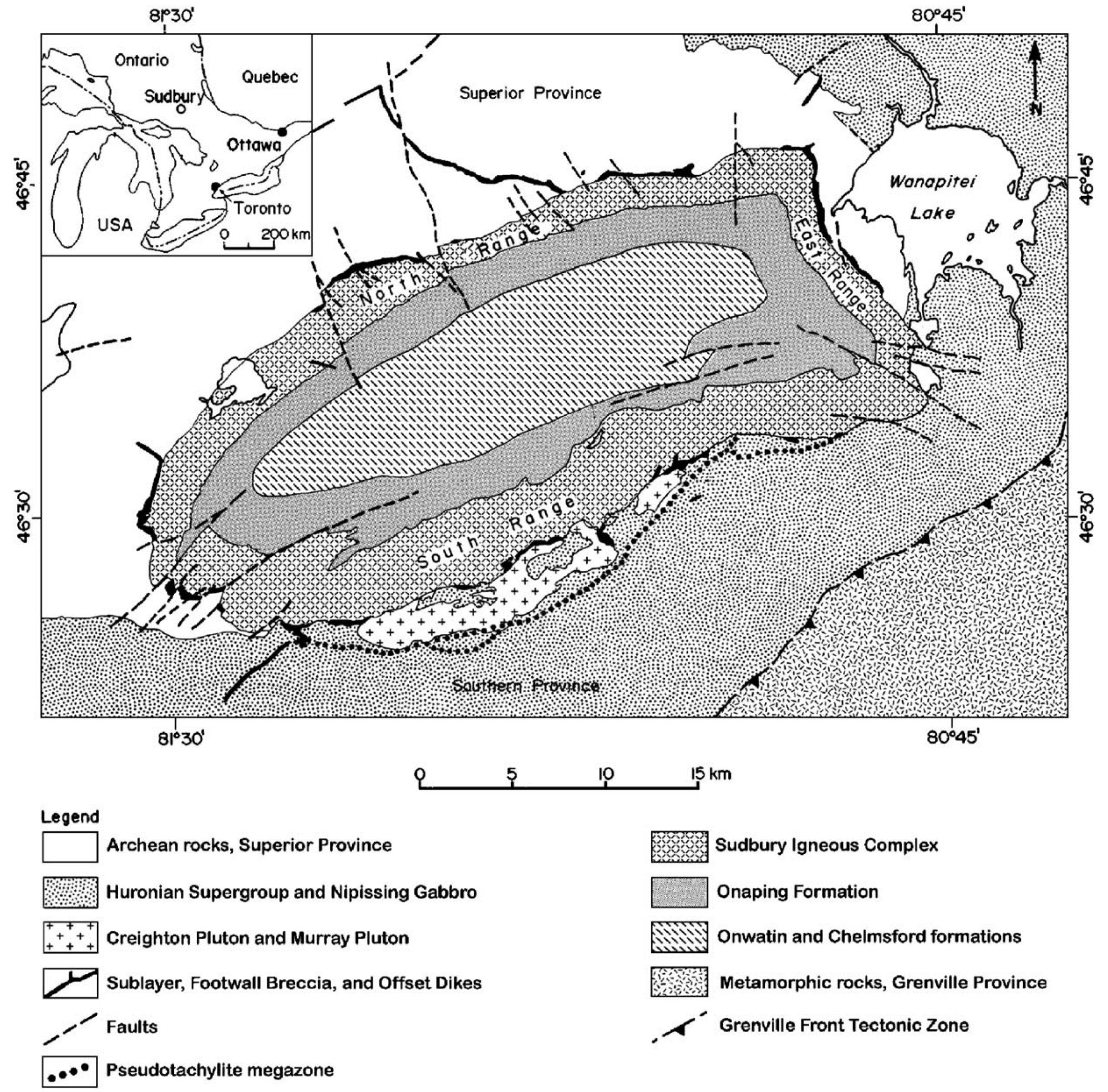

Fig. 9. Location of Frood–Stobie pseudotachylite megazone south of the Sudbury Igneous Complex (eastern 14 km by Dressler, 1984c; western 28 km courtesy of A. Bite, geologist, Wallbridge Mining, Sudbury) and distribution of Offset dikes. The Frood and Stobie mines are located close to the eastern end of the megazone.

in the two structures in Fig. 10. Thin section images are also very similar and chemical investigations have shown that the composition of the matrix of Sudbury and Vredefort breccias closely reflects the average composition of host rocks and clasts included in the respective breccias (e.g., Speers, 1957; Dressler, 1984a; Reimold, 1991; Müller-Mohr, 1992a).[2]

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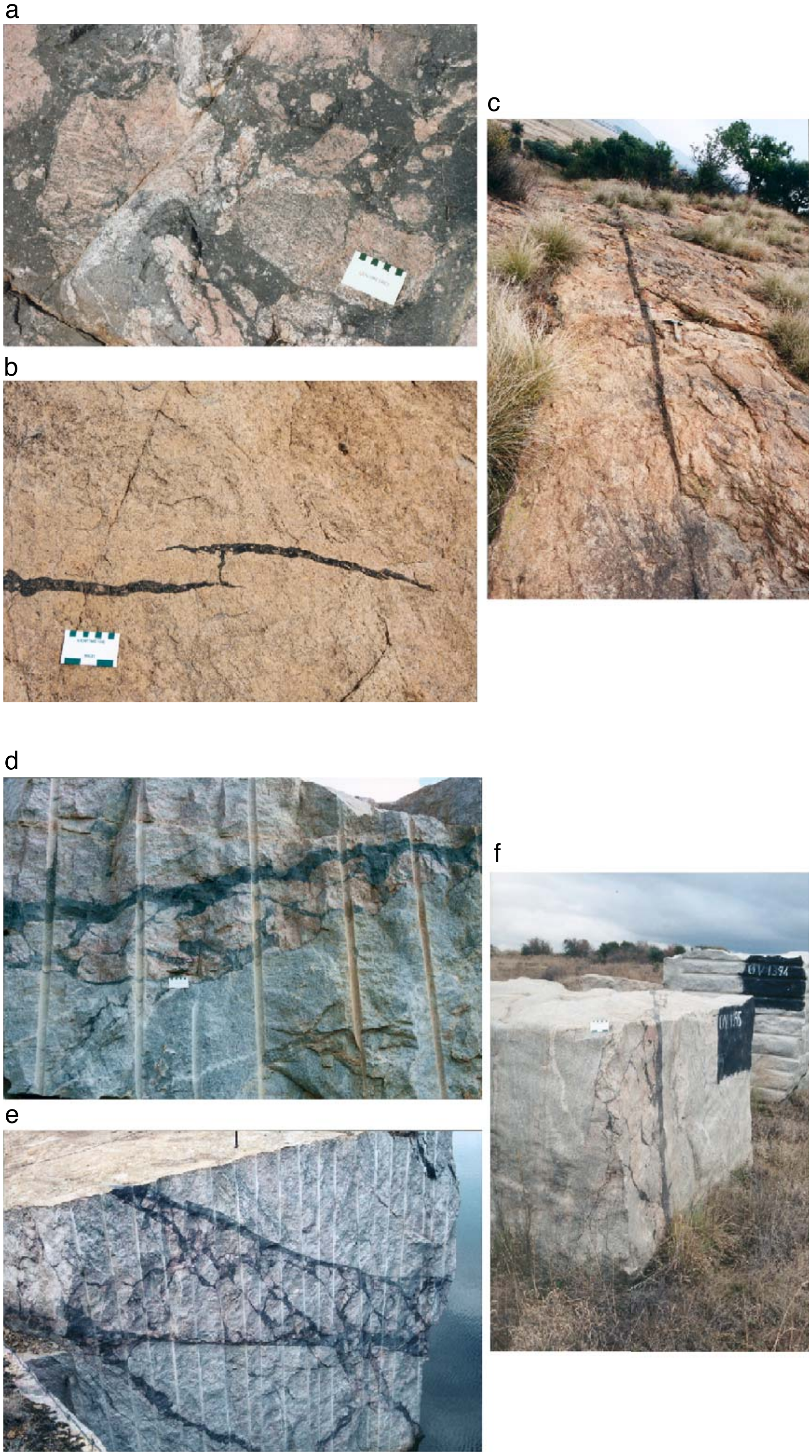
[2] In this context, the authors wish to note that the statement by Dressler (1984a, p. 119) that magnesium apparently does not follow this general trend, is wrong and based on a plotting error.


a
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c
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e
f

Several classifications of Sudbury Breccias have been proposed, all based on petrographic criteria. An early one was contributed by Peredery and Morrison (1984) who described "massive breccia", "flow-banded breccia", and "breccia with an igneous-looking matrix". Dressler (1984a) used similar petrographic criteria for classification purposes. Müller-Mohr (1992a,b) described four Sudbury Breccia types based on matrix characteristics and sequence of formation. These types are:

(1) early breccias with clastic/crystalline matrix,
(2) polymict breccia with clastic matrix,
(3) breccias with crystalline matrix, and
(4) late breccias with clastic matrix.

The classification is, in part, based on contact relationships between the different types. Type 1 is formed early during crater formation but possibly also later where pressure and temperatures were high enough for local melting. Inclusions of this breccia type are found in the polymict breccia, which according to Müller-Mohr (1992a) forms the most common Sudbury Breccia type. The breccias with crystalline matrix are relatively scarce and were never observed in contact with the other types. Type 4 breccias have inclusions of breccias with clastic/crystalline matrix. In comparison with the breccias in the Vredefort Dome, it must be emphasized that no clastic-matrix breccia type has ever been described from the currently exposed level of the central part of this impact structure in South Africa, but breccias with clastic matrices are noted from occurrences along bedding-parallel fault zones in the northern Witwatersrand basin, representing the ring basin around the central uplift structure. This all points toward different energy regimes and possibly also different pseudotachylite formation processes close to the center of impact structures compared with those at large distances away from their centers.

3.5. Vredefort Structure, South Africa

The Vredefort Structure is the type location of pseudotachylite (Fig. 11). This impact structure was formed at ~ 2.02 Ga (Kamo et al., 1996) and, despite deep erosion of at least 7–10 km, still has a diameter of >250 km. No near-surface allogenic impact breccias survived erosion of this structure (Gibson et al., 1998; Gibson and Reimold, 2000), but it is possible that such fallout breccias could still be part of the ring basin fill around the Vredefort Dome (Henkel and Reimold, 1998). Since the first treatise of the enigmatic pseudotachylites by Shand (1916), and first detailed field descriptions of these rocks in the Vredefort Dome by Hall and Molengraaff (1925), many a pen, typewriter, and computer-driven printer have been used to describe and interpret these tachylite-like rocks. It is beyond the scope of this paper to review the voluminous literature on Vredefort pseudotachylites. The reader is referred to the more recent reviews by Fletcher and Reimold (1989), Killick and Reimold (1990), Reimold and Colliston (1994) and Reimold (1995), as well as the recent bibliography by Reimold and Coney (2001), in which comprehensive reference lists are presented. Here we concentrate on the results of a field-based study on the Vredefort Dome conducted during the winter months of 2000 and 2002. Less emphasis was placed on pseudotachylite occurrences in the supracrustal rocks of the collar of the impact structure. Instead, we were mainly interested in the central part of the structure, which is commonly referred to as the core of the Vredefort Dome. We justify this emphasis by our desire to learn more about the deformation of central parts of the basement of impact structures, which are not exposed in other large terrestrial impact structures, such as Sudbury, and by the fact that, by far, the most extensive breccia occurrences are in the central Vredefort Dome. After presenting our new field observations on the Vredefort Dome, we briefly review what is known about pseu-

Fig. 10. Pseudotachylite occurrences of the Sudbury and Vredefort structures. Any of the images shown could be from either structure. (a) Massive, conglomerate-like breccia body. Near Hardy Mine, Sudbury. (b) En-echelon veins, Kafferkop Hill, near Parys, Vredefort. (c) Straight dike, Kafferkop Hill. (d) Dike with massive, inclusion-free upper part. Clasts nestle against lower dike boundary suggesting spallation from the host rock walls with minor or no transport of clasts. Clasts and hanging wall exhibit slight pink alteration. (e) Vertical wall of Salvamento Quarry, near Parys, Vredefort. Oval clasts in this breccia zone were not rotated. ~ 2-m-high vertical quarry wall, Rietpoort 518 Farm, north of Parys, Vredefort. (f) Straight, ~ 3-cm-wide vein with network of thin veinlets. Dimension stone block, Salvamento Quarry. Scales in centimeters or in centimeters and inches.

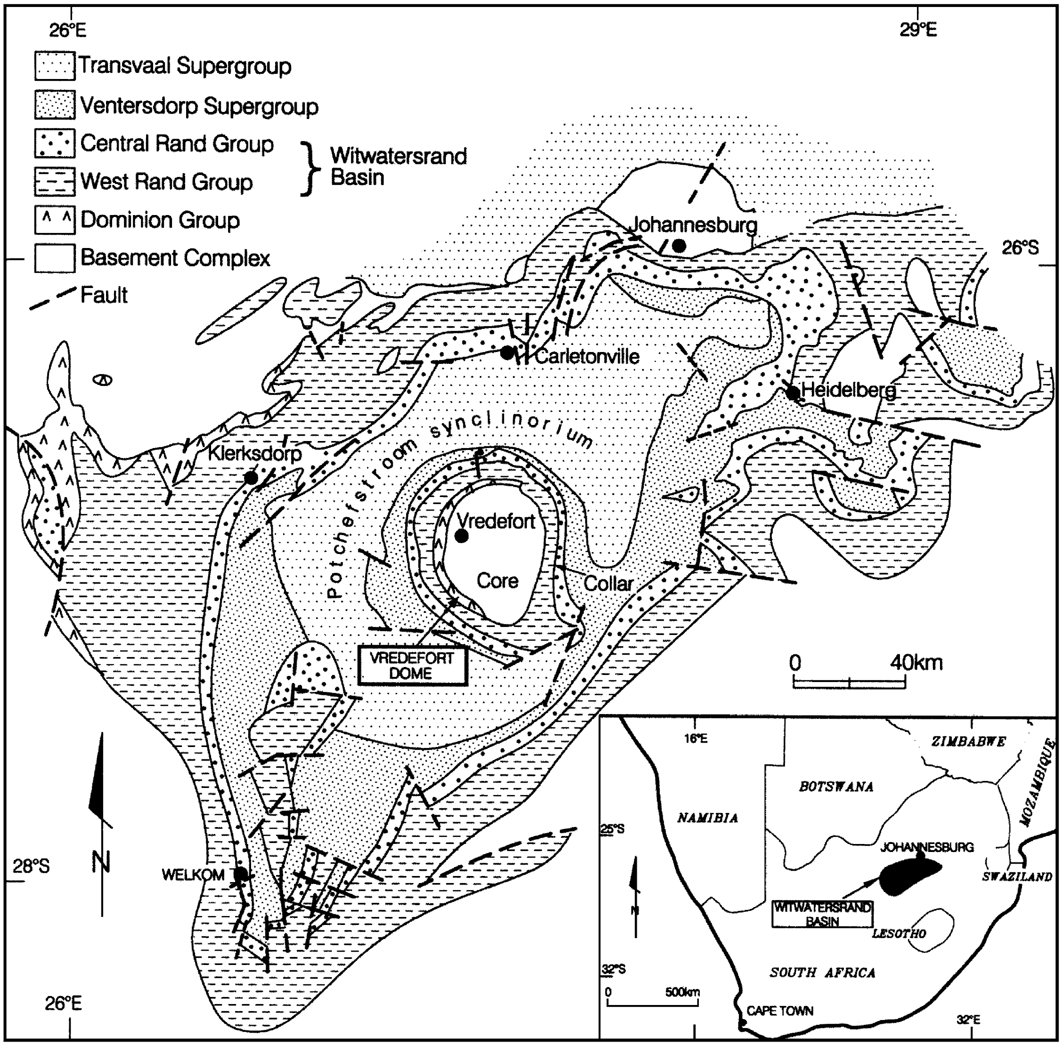

Fig. 11. The Vredefort Structure within the Witwatersrand Basin, South Africa.

dotachylites in the collar rocks of the structure. While in the field, we noticed various rock features that, to our knowledge, have not been reported previously and that may be relevant to explaining the origin of these enigmatic breccias.

3.5.1. Vredefort Dome

We have made a concerted effort to map and remap the distribution and orientation of large pseudotachylite occurrences in the central parts of the Vredefort Dome. This effort builds on an earlier study by Reimold and Colliston (1994). The basement exposed in this area consists mainly of granulite and amphibolite facies gneisses, magmatites and, less common, coarse-grained granitic rocks (Lana et al., 2004). Outcrop in the core of the Dome is scarce but where present, it is commonly large and devoid of vegetation, and in a number of places, it forms hills that reach up to 65 m above the generally only slightly undulating landscape of the core terrain. These hills and several quarries present excellent three-dimensional views of pseudotachylite dikes and zones. Massive pseudotachylites, in general, are more resistant to erosion than their host rocks. In several places, it is therefore possible to map the extent of breccia zones over considerable distances by following boulder trends; in a few places, from one outcrop to another. The longest zone so mapped is 2.6 km long and up to at least 120 m wide. It contains a central massive dike-like feature (“mother lode”) that ranges in width from about 6 to15 m (Fig. 12) and, in places, contains surprisingly few macroscopic host rock inclusions. Our attempt to trace breccia zones with a fluxgate magnetometer from exposed sections to unexposed parts was not successful. The magnetic properties of the dikes and their host rocks are too similar. At one location near Parys, a very strongly

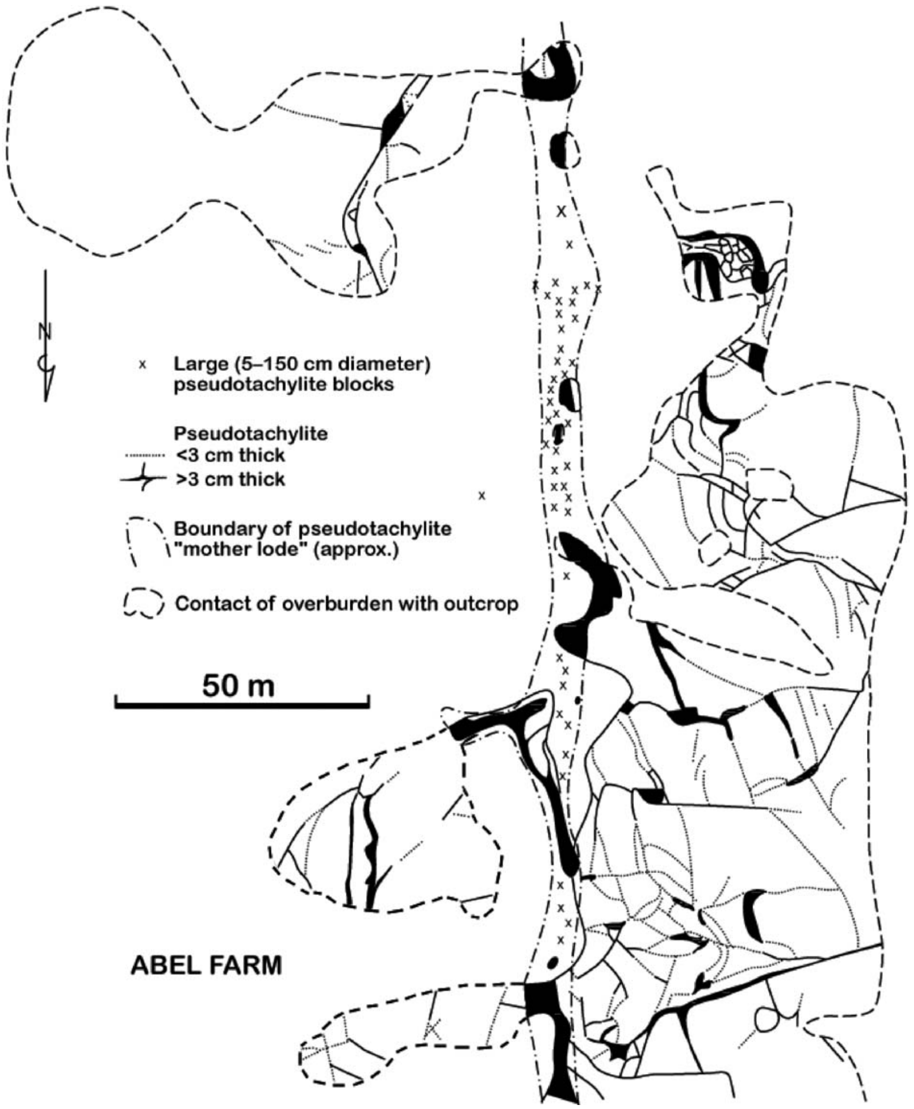

Fig. 12. The 210-m-long section of a pseudotachylite zone that has been mapped for a distance of approximately 2.6 km. The central “mother lode” dike is up to 15 m wide, massive and, in places, relatively clast poor. The “mother lode” is accompanied on both sides by a network of randomly trending pseudotachylite veins and dikes. Host rock is gneiss. Gneissosity trends E–W and dips about 40° North. Abel Farm, east of Parys, Vredefort Dome (for location, see Fig. 16a).

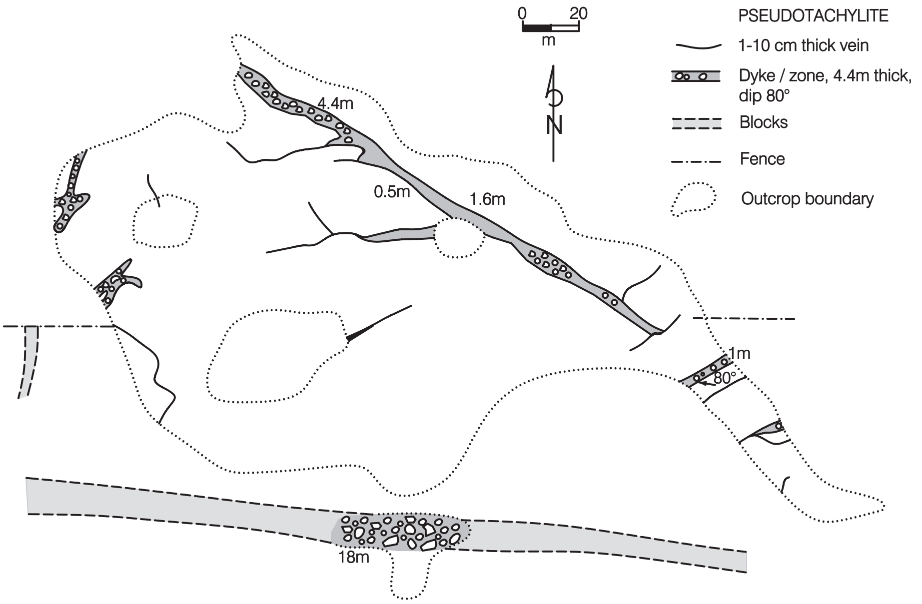

Fig. 13. Pseudotachylite dikes in northwestern Vredefort Dome, on farms Rooipoort 372 and Kronebloem 62 (for location, see Fig. 16a). The southern pseudotachylite zone is up to 18 m wide, well exposed over a distance of about 40 m, and can be traced in an east–west direction by boulder mapping for a total distance of about 260 m. There are several other pseudotachylite dikes exposed in a large outcrop adjacent to the north. Note random orientation of pseudotachylite dikes.

magnetic[3], 50–60-cm-wide pseudotachylite dike is exposed for about 10 m. Surprisingly, the gneissic host rock also has a strong susceptibility and we were thus not able to trace the dike with the magnetometer. The source of the magnetization is not known but has been debated as being largely the result of impact-related remanent magnetization (Henkel and Reimold, 2002). Pseudotachylite bodies have strike and dip directions that commonly change over relatively short distances. This is especially so where small veins and dikes branch off thick and long, massive, and more or less straight dikes, as observed at the 2.6-km-long Abel Farm occurrence (Fig. 12). The pattern of this zone is similar to branching lightning flashes in a dark thunderstorm cloud. It may very well be that also the central, massive, relatively straight "mother lode" dike changes its direction abruptly somewhere along strike. We attempted in vain to test this possibility, using a magnetometer to map the intermittent unexposed zone and its probable, unexposed extensions on Abel Farm. In another, well-exposed occurrence on farms Rooipoort 372 and Kronebloem 62, about 6–7 km west of the town of Vredefort, an 18-m-wide zone was mapped over a distance of approximately 260 m (Fig. 13). It trends more or less in easterly direction. Just to the north of this zone, and also shown in Fig. 13, is an outcrop with several pseudotachylite dikes, the largest of which trends northwesterly. At surface, it apparently does not connect with the 18-m-wide, east–west trending zone. One larger dike in this outcrop ends abruptly without becoming thinner at its termination. Note the obviously random orientation of the pseudotachylite dikes and dikelets.

On Farm Spitskop 1060, close to the collar of the Vredefort Dome, east of Parys, a thin pseudotachylite dike is exposed over a distance of ~ 250 m (Fig. 14). It has several branches and ends in a horsetail, similar to terminations of dikes of igneous rocks and kimberlites. It trends about easterly, parallel to another dike about 50–100 m to the north (not shown in Fig. 14). The trend of the dike is neither tangential nor radial with respect to the

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[3] The field compass at this location was strongly affected by this rock and a small horseshoe magnet attached itself strongly to the rock.

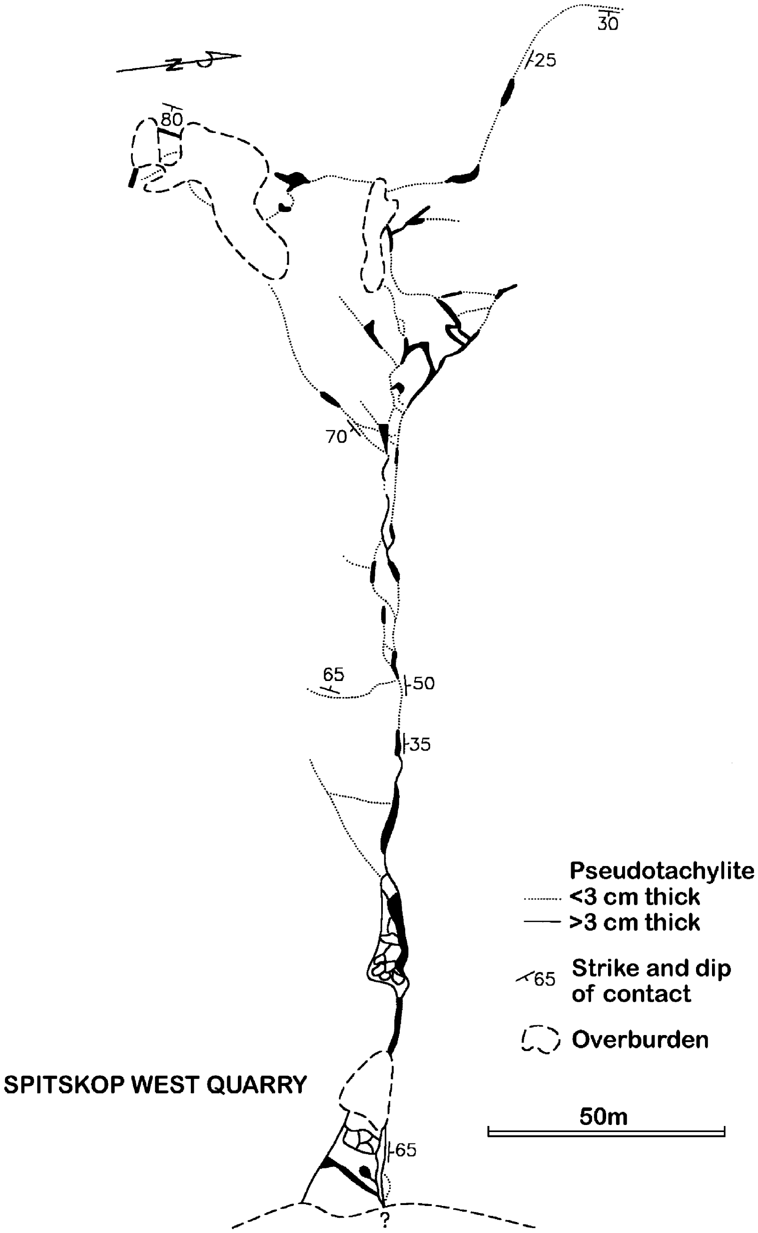


Fig. 14. Thin pseudotachylite dike trending east–west on Spitskop Farm 1060, 10 km west of Parys, Vredefort Dome (for location, see Fig. 16a). It is up to 40 cm wide, has several thin veins branching off it and ends in a "horsetail", similar to horsetails of dikes of igneous rocks. The configuration of this zone is suggestive of in situ, explosive melting (or melt injection) directed from east to west. Foliation in the coarse quartz diorite to granite host rock is vertical and trends NW–SE.

center of the impact structure. On Lesutoskraal 604 Farm, just north of the town of Vredefort, two thin, up to 60 cm wide, parallel, and near vertical pseudotachylite dikes trend northerly and are interconnected by a few thin straight veinlets. The orientation of these dikes and veins is independent of the strike and dip of the gneissosity of the host rock (Fig. 15a and b) and, again, the dikes are neither concentric nor radial with respect to the shape of the Vredefort Dome (Fig. 16).

In Fig. 16a–d, the location and orientation of approximately 100 pseudotachylite dikes and significant veins in the Vredefort Dome are shown. The three insert maps (Fig. 16 b–d) are of areas with many occurrences too small to show on the overview plan. The dikes on these four maps range from about 10 cm to 18 m in width and, in general, are more or less straight. Generally, only dikes of at least 50 m length have been included in this survey plot, with the exception of about 10–20 shorter

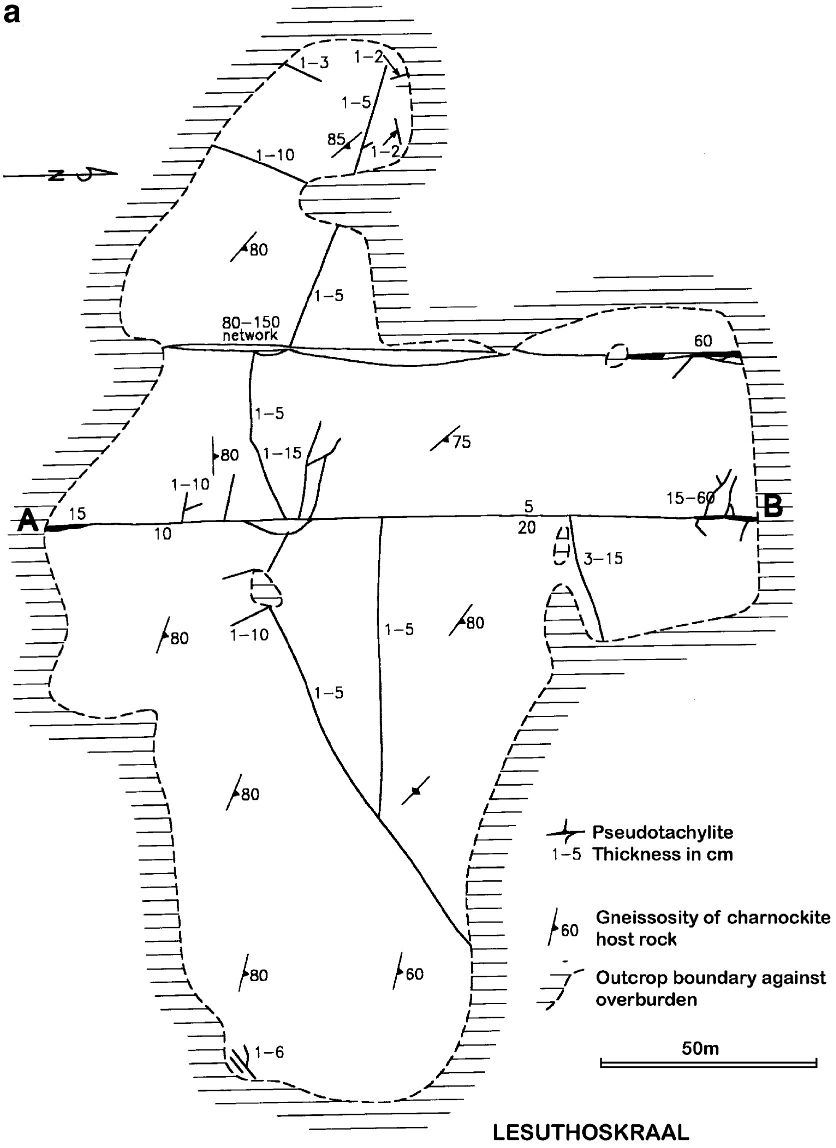


Fig. 15. (a) Two parallel, north-rending pseudotachylite dikes that are up to 60 cm wide and dip steeply to vertically. They are interconnected by a 1–15-cm-wide pseudotachylite vein and have several thin pseudotachylite branches. The orientation of dikes and veins branching off them is independent from the gneissosity of the target rock. Lesuthoskraal, just north of Vredefort, Vredefort Structure (for location, see Fig. 16a). The orientation of the long, parallel dikes is neither radial nor concentric with respect to the center of the impact structure. (b) Enlargement of dike AB.

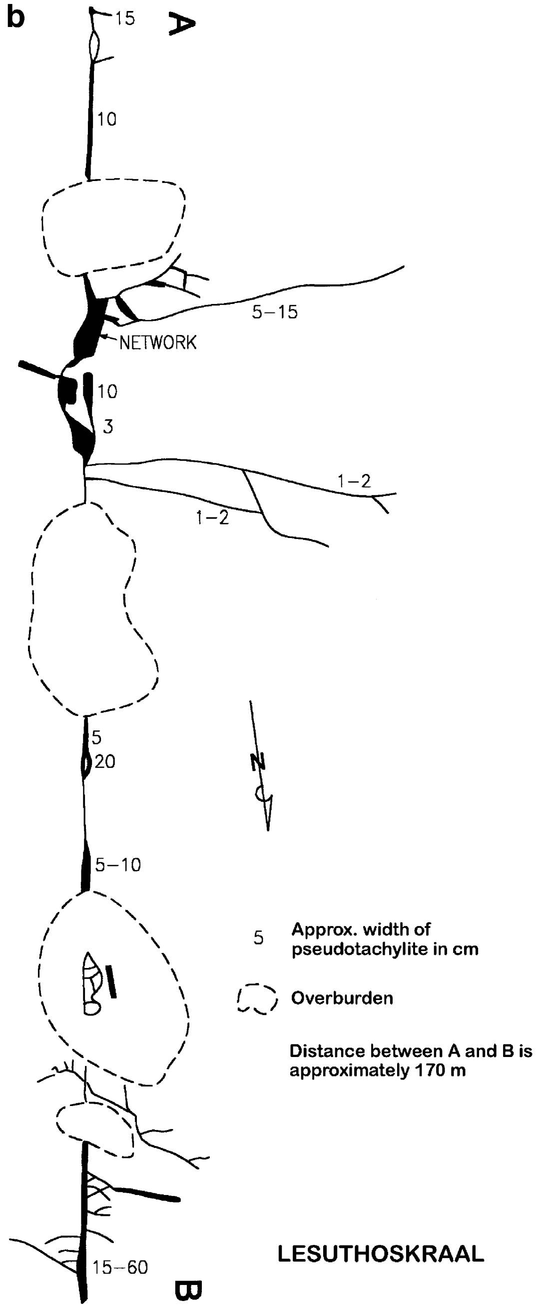


Fig. 15 (*continued*).

occurrences of straight dikes that are at least ~ 50 cm wide.

Several of the dikes close to the contact of the core with the collar rocks of the Vredefort Structure have a more or less concentric orientation in relation to the center and shape of the Dome. However, other dikes near the collar have radial or random orientations. The large occurrence on Leeukop Hill north of the town of Parys is oriented more or less concentrically (see Fig. 18), whereas the 2.6-km Abel Farm dike is neither concentric nor radial. In the area shown on insert map A (Fig. 16b) and at several other locations, dikes parallel to each other have been mapped that have random, radial, or concentric orientations with respect to the geometry of the Vredefort Dome. Apparently, the impact process did not result in a pseudotachylite orientation plan that can be readily related to the geometry of the Vredefort Dome. The enigmatic breccias, however, locally may have orientations that could reflect preexisting fabrics and structures in the target rocks such as foliations, faults, shear zones, and joints. For example, in a few places, pseudotachylite veins follow rock contacts and, in the collar of the Vredefort Dome, bedding planes (see below). Overall, however, the orientation of pseudotachylite dikes and veins in the central Vredefort Structure as shown in Fig. 16a and the insert maps of Fig. 16b–d is random.

It is essentially impossible, to differentiate between preimpact and postimpact faults and joints in the Archean granitic rocks and gneisses of the Vredefort Dome. Some shear zones could have formed as a consequence of the impact event. Rock foliations, however, are preimpact in age. Most macroscopic deformation features in the Archean basement are the result of several deformation phases that took place during the Archean, about 1 Ga prior to the Vredefort impact event (Lana et al., 2003, 2004). In Fig. 17, we compare the orientations of target rock gneissosity (courtesy of C. Lana, PhD candidate, University of the Witwatersrand, South Africa) with the orientations of pseudotachylite dikes and veins in two large outcrop areas, namely, the Leeukop Hill northwest of Parys and the hill traditionally known as Kafferkop located several kilometers southwest of this town to the east of the road between Vredefort and Parys (see Fig. 16a for locations). As can be seen on the stereograms of Fig. 17, there is apparently no correlation between the orientations of preimpact gneissosity on one hand, and of pseudotachylite veins and dikes on the other. Gneissosities have preferred trends whereas pseudotachylite veins have random orientations.

The Leeukop and Kafferkop hills and several other large hill outcrops and quarries provide good three-dimensional views not only of gneissosities and geometries of small pseudotachylite veins and dikes, but also of more extensive pseudotachylite bodies. One of those hills, the Leeukop hill north of Parys is about 65 m high. Several long dikes cut straight across it (Fig. 18). This is an indication that the dikes dip steeply or perhaps even vertically. At several spots, dips can be measured directly and in the main, east–west trending quarry near the highest elevation of the hill (1456 m), a 70–90° northward dipping dike is exposed in several quarry terraces. The large pseudotachylite zone trending along the southern flank of Leeukop Hill is well exposed at several locations, two of which allow dip measurements of 80° NW and 90°. The zone appears to end just northeast of the hill. Its southwestern extension could not be established because of lack of outcrop and boulder trends. The trend of the large pseudotachylite body is more or less concentric with

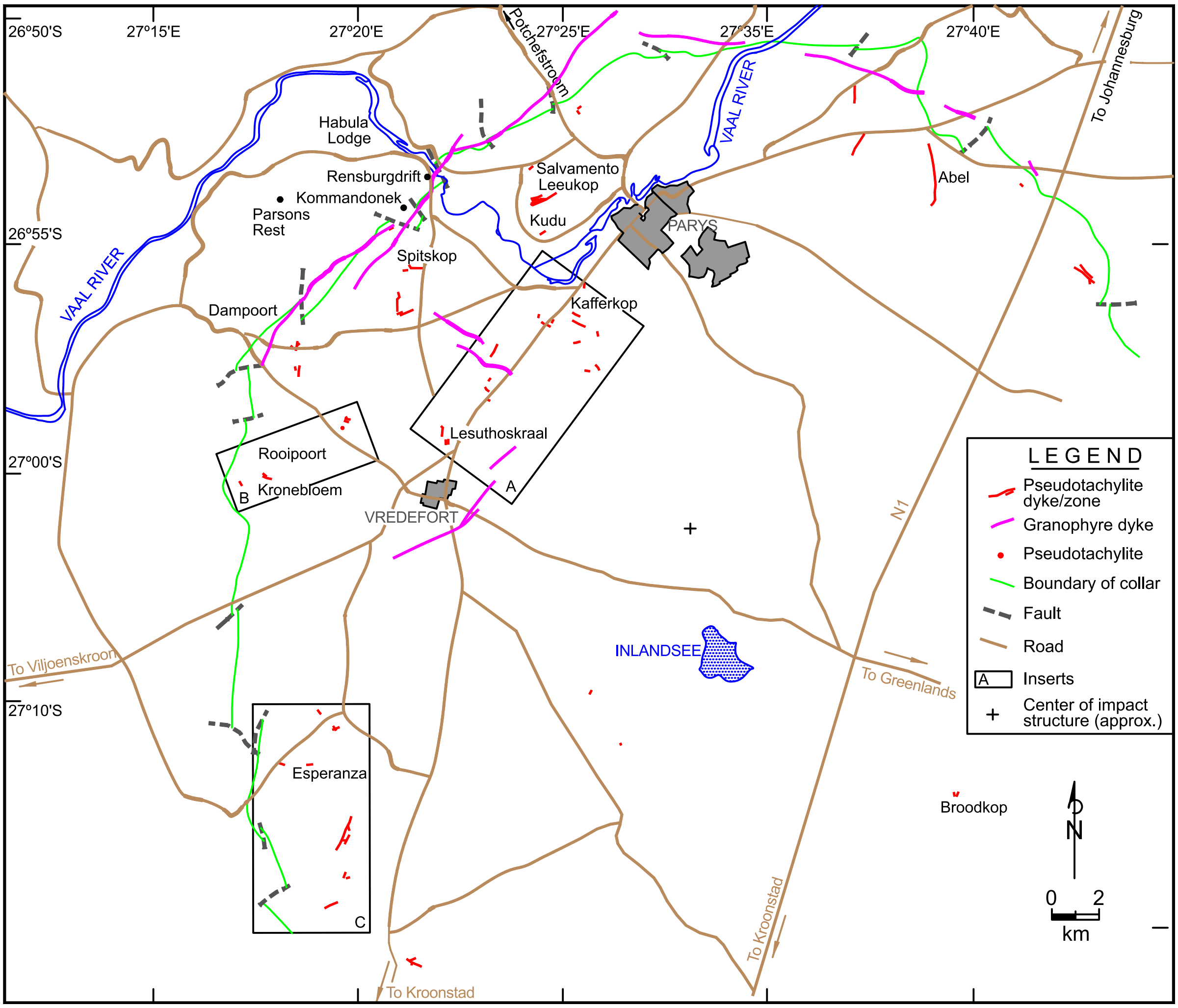


Fig. 16. Distribution and orientation of pseudotachylite dikes and zones and of Granophyre dikes in Vredefort Dome. (a) Largest occurrences. (b–d) Insert maps A, B, C (for location, see sketch in panel a).

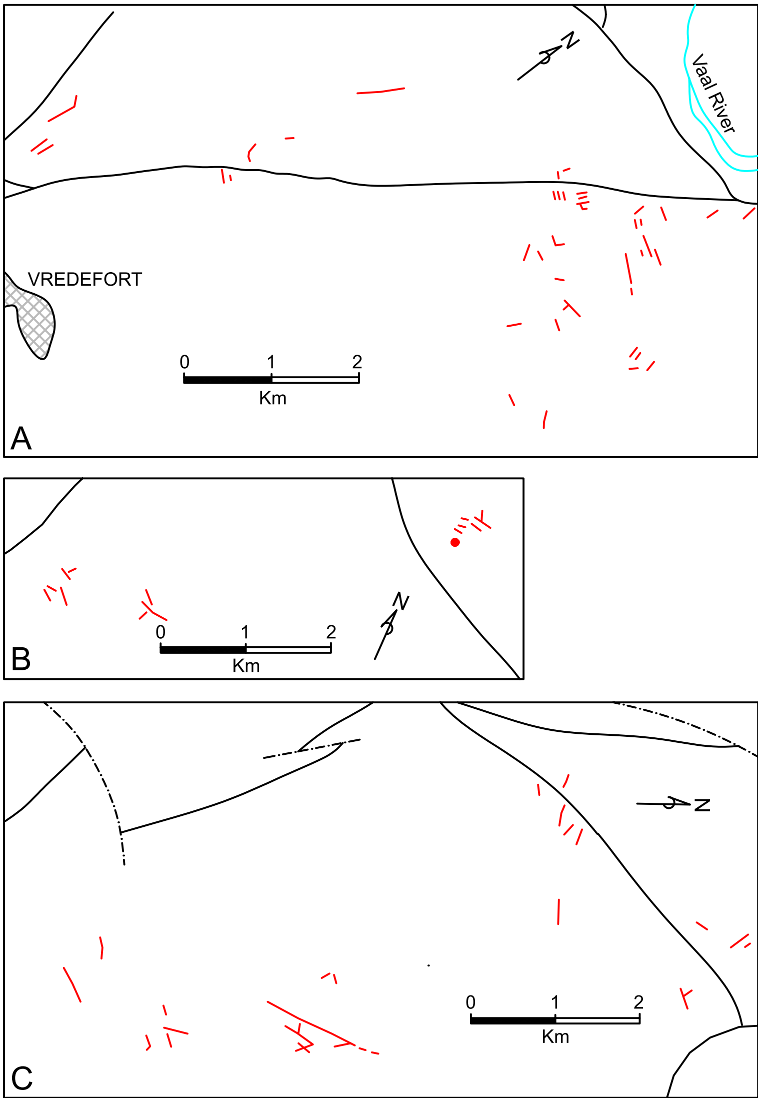
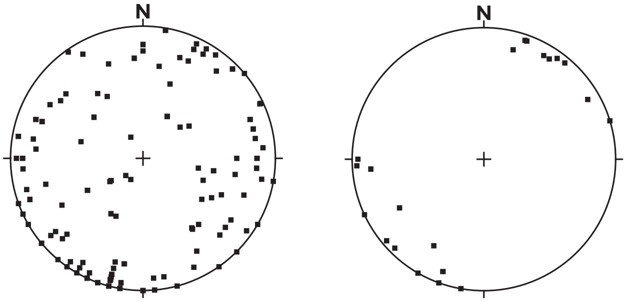


Fig. 16 (*continued*).

respect to the shape of the Vredefort Dome (compare with Fig. 16). Small dikes and veins trend randomly (Fig. 17).

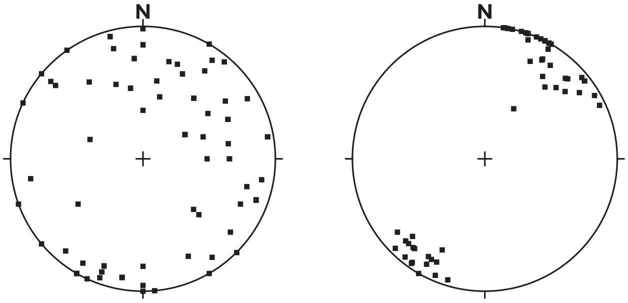
Just north of Leeukop Hill is the Salvamento Quarry. It provides an excellent three-dimensional view of a northeasterly trending pseudotachylite zone. Like the breccias on Leeukop, the Salvamento zone dips steep to vertical, as seen in the block diagram of Fig. 19. A plan view of a portion of the zone is shown in Fig. 20a, whereas Fig. 20b depicts a section of the vertical wall. At the Esperanza Quarry (Wittekopjes 169 Farm), in the southwestern sector of the core of the Vredefort Dome (Fig. 21), another steeply northward dipping breccia zone is exposed. It trends easterly on top of the horizontal level of the quarry parallel to the quarry wall. While the Salvamento occurrence has a dike-like configuration, the Esperanza pseudotachylite occurs as a very irregularly branching zone, despite forming a more or less straight, dike-like zone at the upper, horizontal quarry



Pseudotachylite veins and dikes
N=124

Gneissosity
N=21

Kafferkop Hill



Pseudotachylite veins and dikes
N=68

Gneissosity
N=52

Leeukop Hill

Fig. 17. Orientation of pseudotachylite veins and gneissosity of target rock. Kafferkop and Leeukop hills (for location, see Fig. 16a). There is no obvious relationship between preimpact gneissosity and the more or less random orientation of pseudotachylite veins. Equal area stereograms. (Gneissosity stereograms courtesy of C. Lana, PhD candidate, University of the Witwatersrand, South Africa).

surface (not visible in Fig. 21). It is not obvious how the various veins and dikes exposed on the vertical quarry walls connect with this 70-m-long, ~ straight dike at the top of the quarry. A limited, three-dimensional view, however, is provided on one section of the quarry wall (Fig. 21). It appears that the straight upper dike dips approximately north and forms an irregular, open, east–west trending and, in general, north-dipping network of dikes and veins beneath the upper, horizontal level of the quarry. These observations have to be kept in mind when mapping the distribution and orientation of pseudotachylite veins and dikes that are exposed only in a two-dimensional outcrop. Dikes that are straight and apparently dip in a certain direction in a more or less horizontal exposure may very well abruptly change orientation, sometimes only a few centimeters below the outcrop surface. The Esperanza pseudotachylite is a prime example for this behavior.

3.5.2. Vredefort collar

During the recent mapping phase, we did not investigate pseudotachylites in the supracrustal rocks of the collar of the Vredefort Structure in any great detail. The few occurrences studied here have all relatively thin veins. The widest vein ever observed by us in collar rocks measured only about 20 cm. However, most pseudotachylites veins observed in the collar strata are not wider than 5 cm, in fact mostly only 2 cm, or even less. Because of the rugged terrain and dense vegetation cover, we were not able to map any veins over long distances. The two best occurrences observed by us in this present investigation are in an area where the Vaal River transects the boundary of the relatively flat granitic terrain of the core with the upturned and overturned supracrustal rocks to the north: (1) a 30–50-cm-wide vein in an alkali granite close to the Habula Resort measured about 40 m in length; and (2) on farms

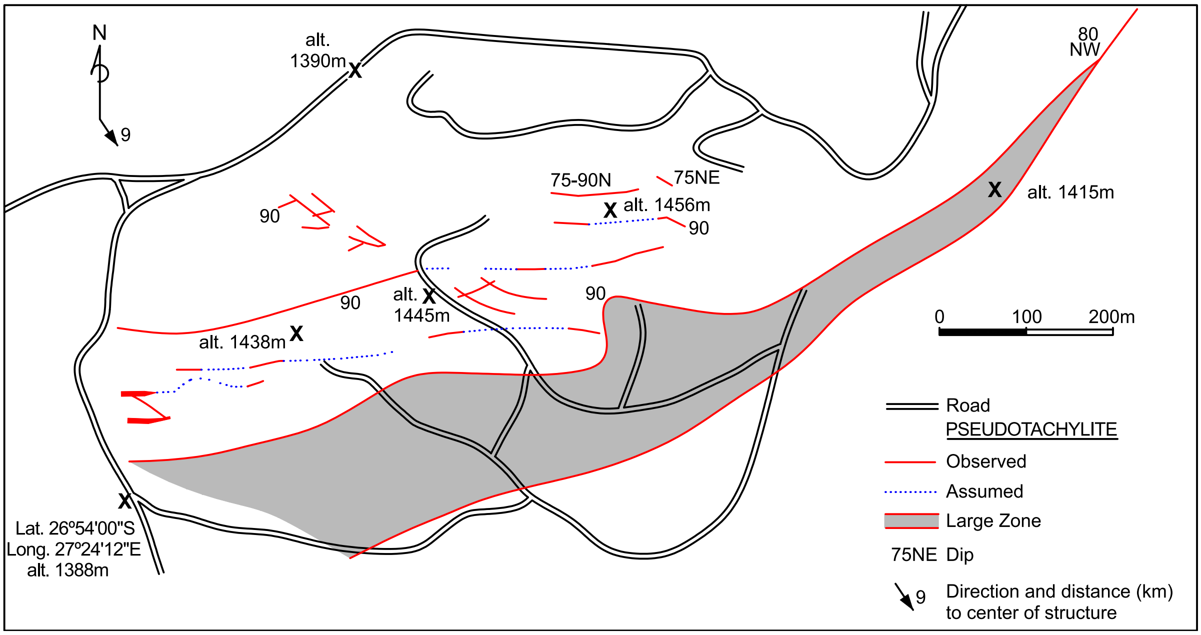


Fig. 18. Pseudotachylite occurrences of Leeukop Hill, north of Parys, Vredefort Dome (for location, see Fig. 16a). The northernmost dike is the one dipping steeply towards the north in the north-facing quarry wall. Most exposed Leeukop pseudotachylites dips are vertical to steep. Fig. 17 shows the orientation of pseudotachylite veins and compares it with that of the gneissosity. The mapping of the large, northeast-trending zone is based on a number of exposures and the tracing of large pseudotachylite boulders. The hill is about 65 m high and is more than 40% outcrop providing a good three-dimensional view of a number of pseudotachylite dikes.

Kommandonek and Rensburgdrift, in Hospital Hill quartz arenite, a thin (< 3 cm) pseudotachylite vein had previously been traced by W.U. Reimold and L.O. Nicolaysen along strike of the sharply upturned quartz arenite for some 500 m. The vein generally follows a bedding plane, but, in places, cuts across it. It also developed very narrow and generally up to several-decimeter-long offshoots of irregular shapes. Due to the terrain limitations, it cannot be stated with confidence that some of these offshoots could not actually be longer. On Farm Damport in the western collar, another bedding-parallel breccia vein of up to

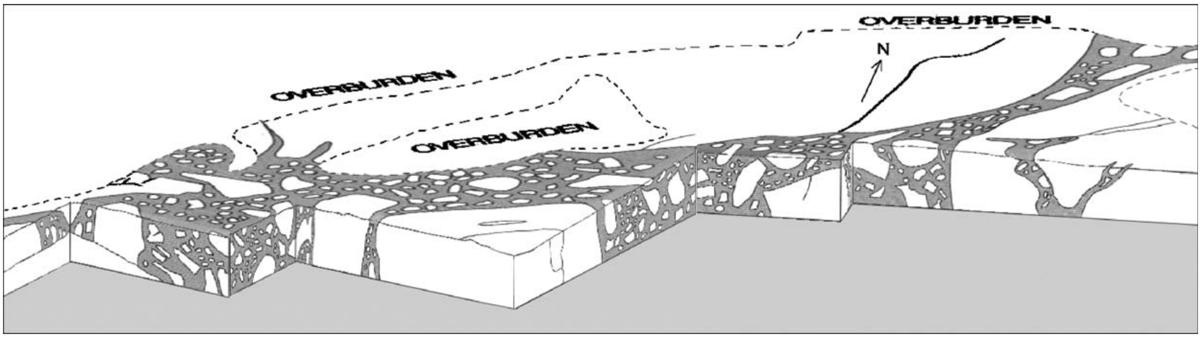


Fig. 19. Pseudotachylite zone at Salvamento Quarry, north of Parys, Vredefort Dome (for location, see Fig. 16a). The zone has a variable thickness and several offshoots branching off it. Overall, the zone trends approximately northeasterly, is more or less vertical, but assumes a steep southerly dip towards the west (not shown on this block diagram). Length of block diagram is approximately 50 m, height of quarry walls range from ∼ 2 m to just over 3 m.

Fig. 20. Pseudotachylite at Salvamento Quarry. (a) Part of horizontal upper level. (b) Part of a vertical wall.

5 cm width can also be traced along strike for several hundred meters and shows all the same geometries as the one previously described. In one location, where this vein can be studied in three dimensions due to a rockfall, the generally near-vertical narrow vein changes orientation into the subhorizontal, with actually two subhorizontal, subparallel offshoots developing.

In addition to bedding-parallel pseudotachylite veins, other geometries have also been observed in the collar: short, less than 1.5 m long, en-echelon sets of straight or sigmoidal veins indicative of extensional conditions; isolated pods, in places with short offshoots, in epidiorite, or at the contact between such mafic intrusive rocks and neighboring shale or quartz arenite; meter-scale network breccias with well-round-

Fig. 21. Pseudotachylite zone in Esperanza Quarry, Wittekoppies 169 Farm (western Vredefort Dome; latitude 27°06′26″S; longitude 027°18′52″E). On the upper, horizontal level of the quarry, the zone is straight and dike-like with branches towards the quarry wall. The dike trends more or less parallel to the quarry wall.

ed clasts in the decimeter to several decimeter size range formed in epidiorite host rock, and generally short (< 1.5 m) and thin (< 3 cm), commonly irregularly shaped veinlets in felsic and mafic igneous rocks.

In the northeastern sector of the collar, extensive alkali granite exposures can be studied. They also contain abundant veins and pods of pseudotachylite. It was noted previously (e.g., Colliston and Reimold, 1992) that the orientations of these pseudotachylites are generally irregular.

Pseudotachylite zones up to several tens of meters wide have been described from several fault zones in the northern and northwestern part of the Witwatersrand Basin (Fletcher and Reimold, 1989; Killick and Reimold, 1990), from underground mining operations, diamond drilling, and surface exposures. A major zone of brecciation trends tangential to the northern boundary of the Vredefort Dome as described by Fletcher and Reimold (1989) (cf. also Fletcher and Gay, 1971) from drilling and underground workings on the so-called Master Bedding Fault, a major bedding-parallel fault zone in the Witwatersrand Supergroup. Fletcher and Reimold (1989) identified another major, bedding-parallel fault zone with pseudotachylite at the base of the Transvaal Supergroup—the so-called Black Reef Décollement Zone. The contacts of the Ventersdorf Contact Reef at the base of the Ventersdorp Supergroup and at the contact with the Witwatersrand Supergroup may also be marked by fault breccia including some that resembles pseudotachylite (Killick et al., 1988; Fletcher and Reimold, 1989; Killick and Reimold, 1990; Berlenbach and Roering, 1992; Reimold et al., 1999a). In this setting, breccia may be developed at either the hanging-wall contact to mafic rocks of the Ventersdorp Supergroup or at the footwall contact between gold-bearing conglomerate (VCR Reef) and upper Witwatersrand quartz arenite. These breccias may be meters thick or just form centimeter-wide linings (Reimold et al., 1999a). In places, they abruptly crosscut from one lithological contact to the other, thereby commonly exploiting places where the width of the reef is suppressed. Pseudotachylite, ultramylonite and cataclasite have been observed at the VCR contacts. Those Witwatersrand breccia samples that have been dated with argon chronological methods yielded mostly 2000–2020 Ma ages (Trieloff et al., 1994), which is taken as evidence that most breccias in the wider Witwatersrand Basin were formed as a result of the 2.02-Ga Vredefort impact event. However, there are reports of preimpact brecciation in this region (Killick and Reimold, 1990; Reimold and Colliston, 1994). A recent argon chronological study of various breccia types from the southwestern part of the Witwatersrand Basin by Friese et al. (2003) yielded variable results, with some excellent Vredefort ages obtained, but other materials having given mixed ages between the age of the precursor sedimentary rock and the impact event, as well as extensive evidence for postimpact thermal and/or hydrothermal overprint.

A large, possibly several hundred meters long and tens of meters wide pseudotachylite breccia body occurs on farm Parson's Rest 465 (outside area covered by map of Fig. 16a) in the northwestern collar of the Dome in Hospital Hill quartzite that has been strongly folded, forming a several-hundred-meter-wide synform. Breccia occurs along the subhorizontal limb and in the hinge zone of this fold. Along the limb, most breccia observed does not occur parallel along the bedding-plane, but at low to steep angles to the plane or crosscuts it. Irregular, patch-like breccia bodies are associated with this large breccia occurrence. In the hinge zone, the quartz arenite is strongly deformed and, in places, shear laminated. Pseudotachylite is developed between slivers and fragments of the laminated arenite. Assuming that this extensive breccia zone is the result of the impact event, one possibly can conclude that the synform in which it occurs formed also during the impact. If this interpretation is correct, other (or even all) large-scale fold structures observed in many places around the collar of the Vredefort Dome could be related to the impact event (and not to some syndepositional or postdepositional, endogenic Witwatersrand deformation).

The bedding-parallel fault zones in the wider Witwatersrand Basin generally dip at low angles in the direction of the Vredefort Dome. There is field evidence supporting that these zones in the collar rocks are continuous over considerable distances, but, again, outcrop of these zones is scarce. And in the wider Witwatersrand, continuity of such bedding-parallel zones could not be well investigated due to generally only patchy exposure being available from mining operations. It has been noted that melting in the Witwatersrand breccia zones has occurred locally in pockets and schlieren within otherwise mainly clastic-matrix breccia (e.g., Reimold and Colliston, 1994). In this respect, these breccias could be analogous to the large pseudotachylite bodies of the Sudbury Structure away from the center of the impact structure, such as the Frood–Stobie zone, which has been variably described as a friction melt (Spray, 1997) and a clastic-matrix breccia (Müller-Mohr, 1992a). In addition to the more or less tangential pseudotachylite breccia zones to the north–northwest of the Vredefort Dome, pseudotachylites are also known from normal, north–south trending faults, such as the West Rand Fault and Bank Fault (Fletcher and Reimold, 1989). There are also occurrences, which have orientations that are more or less random. As stated above, radiometric age determination for a number of pseudotachylite specimens from the northern Witwatersrand basin (Trieloff et al., 1994) is similar to the age of the Vredefort impact event. Berlenbach and Roering (1992), however, state, that there are pseudotachylites in the Witwatersrand basin that are as old as 2.7 Ga, i.e., considerably older than the impact event.[4] Furthermore, multiple breccia generations have been noted in the collar rocks north of the Vredefort Dome, e.g., at the Elandrand Gold Mine (Killick and Reimold, 1990).

The Witwatersrand rocks of the collar of the Vredefort Dome have been mapped in good detail (Bisschoff, 1999 and personal communication 2002; Wieland, University of the Witwatersrand, personal communication, 2002). Therefore, it is unlikely that there is, anywhere in these rocks, a massive pseudotachylite zone as long and wide as the Frood–Stobie zone of the Sudbury Structure that has been interpreted to represent a terrace collapse superfault (Spray, 1997). The Witwatersrand faults are bedding-parallel faults that dip at 15–25° towards the Dome. Terrace collapse should result in steeply dipping, normal faults; however, it is not impossible that such faults when extending into the inner part of the impact structure change to listric geometries, flattening towards the interior of the crater. However, because of deep erosion and the scarcity of good outcrop in large areas *around* the Dome, it remains unknown if zones of enhanced brecciation relating to multiring features exist in the Vredefort impact structure.

3.6. Summary and origin of pseudotachylites

Almost a century of field and laboratory research on pseudotachylites, both from fault zones and impact structures (here called pseudotachylitic breccias by Reimold, 1998 and references therein) has resulted in a voluminous literature. Our new observations and those of other researchers provide some new data and interpretations.

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[4] In this context, we wish to caution the reader not to accept pseudotachylite ages as very accurate. Incomplete degassing, and the presence of target rock mineral and rock clasts in the analyzed matrix can result in age determinations that are not very meaningful.

3.6.1. Two- and three-dimensional orientation of pseudotachylite bodies

Based on 4 months of detailed outcrop mapping, we have shown that pseudotachylite zones and dikes apparently do not have any preferred orientation in the crater floor of the central Vredefort Structure. The results are depicted in Fig. 16a–d. Radially and concentrically oriented pseudotachylite bodies occur, but many others apparently are randomly oriented. Outcrop density in the Vredefort Dome is poor and it is commonly not possible to map pseudotachylite bodies over long distances. Prior to our detailed field investigations, we speculated that the long, linear bodies could have a zigzag configuration, more or less radiating from the center of the structure (Dressler et al., 2001). However, we now cannot substantiate this interpretation. Most, but not all large pseudotachylite bodies observed have steep to vertical dips. At Leeukop and Kafferkop locations we have shown that small pseudotachylite bodies also do not have any apparent preferred orientation with respect to the center of the impact structure and that, overall, their orientation is independent from the orientation of preimpact structures of the host rocks, such as gneissosity (Fig. 17). This is in contrast to earlier reports by Reimold and Colliston (1994).

This does, however, not mean that pseudotachylite formation under specific controls, such as at rock contacts and other disconformities have not been observed by us. Overall, however, these rock features apparently have no effect on the distribution and orientation of pseudotachylites in impact crater floors. From the recent experimental work by Kenkmann et al. (2000), it is clear that shock compression will preferentially exploit preshock structural defects, such as lithological boundaries, that then could act as shock pressure enhancements and lead to melting. Obviously, it is not easy to relate small-scale laboratory experiments to kilometer-scale observations. The very onset of melting may basically occur at structural defects also in an impact scenario. The subsequent explosive growth of the (shock compression stage) pseudotachylite bodies spreading from these structural defects apparently is mainly random, if not chaotic.

The central crater floor of the Sudbury Structure is not exposed as it underlies the Sudbury Igneous Complex (SIC). Large pseudotachylite zones in the country rocks around the SIC have been interpreted as the result of terrace collapse and multiring basin formation (Spray and Thompson, 1995; Spray, 1997). However, randomly distributed and oriented pseudotachylites are common between these assumed ring zones of enhanced brecciation. No large and continuous pseudotachylite bodies have been observed in the Manicouagan Structure, neither in the central uplift or the crater floor around it. They are known only from the Sudbury and Vredefort structures.

Both the Sudbury and Manicouagan structures, therefore, do not provide any additional insight—at this stage—relating to pseudotachylite orientation and distribution in the central parts of impact crater floors. However, it is worth noting that the relative scarcity of pseudotachylites in the central uplift of the Manicouagan Structure could be the result of the homogeneity of the anorthosite that forms the central uplift. This rock type is also distinguished from the granitic host rocks of the pseudotachylite at Vredefort by much higher melting temperatures.

3.6.2. Geochemistry of pseudotachylites in impact structures

Speers (1957), Dressler (1984a), Reimold (1991), Müller-Mohr (1992a) (and references in these publications) have shown that matrices to pseudotachylite breccias of impact structures have chemical compositions that are generally similar to the average composition of the respective host rocks and main inclusion types in the breccias. Reimold (1991) showed that systematic differences observed between matrix host rock pairs seemingly follow the same trends noted by other workers for tectonic pseudotachylites. All these observations point to a more or less in situ process of formation. Small veinlets branching off large pseudotachylite bodies such as the Abel Farm dike (Fig. 12) are commonly interpreted as apophyses injected into the host rock from the “mother lode” dike. Coney (2002) compared chemical composition of an approximately 10-cm-wide vein with the compositions of much thinner, only several-millimeter-wide “apophyses” exposed on a dimension stone block from the Vredefort Dome and observed that both the 10-cm-wide vein and the thinner veins had essentially the same composition. It could be included that even in very narrow veins homogenization of melt occurs. The gneiss—host for both the wide and very thin veins—however, has a more or less homogeneous composition. For this reason, Coney's results do not allow to differentiate between strictly in situ melting and an injection process for the very thin veins. However, one of us (WUR) carried out electron microprobe analysis along a millimeter-wide vein from Leeukop Hill (for location see Fig. 16a) and found that the glassy groundmass still mirrored the stoichiometric compositions of the locally existent minerals such as biotite, quartz and various feldspars. This is evidence for melt production by in situ fusion. There is also multiple evidence that at least some of the narrow veinlets branching off a thick "mother lode" dike are not apophyses sensu stricto, but formed strictly in situ. This process may be responsible for the formation of many, if not most, thin pseudotachylite bodies in the floors of central parts of impact craters.

The above interpretation is based on the following field observations and chemical considerations: We have noticed, in a few very thin, commonly < 1-cm-wide, clast-free or clast-poor pseudotachylite veins, an abrupt color change where they cut across different rock types. A thin vein, cutting across a gray gneiss, may be dark gray or black, but where it passes through an aplite vein, it may be very light colored. We have chemically analyzed three 1–5-cm-wide veins—that cut across two rock types—in both rock types and compared their compositions with those of the respective host rocks (Table 1). Within the gneiss, the thinnest vein (#3) has an overall composition that is similar to that of the gneiss, whereas in the aplite, its composition resembles the aplite composition. The results suggest a strictly in situ origin for this vein involving no injection of melt or shear friction. In this process, target rock is strictly replaced by melt. Here we coin the term "flash replacement melting" for this process. We suggest that melting in this process occurred due to explosive transfer of thermal shock energy from ground zero without material flow (i.e., injection) but through in situ transformation of wall rock into melt. We are, however, aware that material flow can occur in pseudotachylite bodies. Evidence for this is represented by the results from veins 2 and

Table 1
Composition of pseudotachylite veins cutting across more than one rock type compared with composition of host rocks

Sample	Rock type	SiO_2	TiO_2	Al_2O_3	Fe_2O_3 (total)	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	TOTAL
Pt Vein 1	**granite host rock**	77.41	0.21	14.56	1.49	0.00	0.27	0.74	nd	4.86	0.05	0.89	100.48
	pt in granite	66.03	1.05	14.23	7.77	0.10	2.16	3.64	nd	2.67	0.20	1.06	98.91
	epidiorite host rock	53.41	0.67	16.30	12.34	0.26	6.49	9.82	nd	0.44	0.10	0.40	100.23
	thin pt in epidiorite	52.80	1.71	14.60	15.17	0.26	5.57	8.78	nd	0.85	0.31	0.37	100.42
Pt Vein 2	**pt in mafic igneous rock**	57.07	1.82	14.06	13.59	0.22	3.61	7.00	nd	1.57	0.28	-0.31	98.91
	mafic igneous host rock	52.95	2.16	14.49	16.11	0.28	4.28	8.32	nd	1.06	0.33	0.04	100.02
	pt in granitic host rock	57.92	1.83	14.45	12.80	0.20	3.30	6.84	nd	1.77	0.31	0.35	99.77
	granitic host rock	74.31	0.42	15.31	3.34	0.03	0.78	2.24	nd	3.24	0.13	0.63	100.43
Pt Vein 3	**Aplite host for pt**	74.51	0.39	14.60	2.77	0.00	0.45	1.47	nd	4.17	0.08	0.70	99.14
	light colored pt in aplite	76.28	0.25	13.72	1.52	0.00	0.13	1.39	nd	4.55	0.06	0.68	98.58
	grey gneiss host rock	73.09	0.46	14.25	3.71	0.05	0.56	1.81	nd	3.87	0.11	0.50	98.41
	black pt in gneiss	72.34	0.40	15.26	4.90	0.01	0.61	1.98	nd	3.52	0.13	0.00	99.15

nd = not determined
pt = pseudotachylite
Interpretation of results:

host	**host**
pt in host 1	**pt in host rock 2**
rock 1	**rock 2**

Vein 1: Composition of pseudotachylite vein in epidiorite is very similar to the epidiorite host rock. Pseudotachylite in granite is less felsic than granite, but considerably more so than in epidiorite, suggesting some mixing. Results suggest minor mixing of melts and transport of melt from epidiorite to granite. Pseudotachylite vein is 2–3 cm thick.

Vein 2: Granitic host rock composition is dissimilar to compositions of pseudotachylite vein in both host rock types. Vein is 3–5 cm thick. Results suggest mixing of melts.

Vein 3: Results are suggestive of in situ melting without mixing. Pseudotachylite vein is only 0.5–1.0 cm thick. Aplite dike is only 30 cm thick. There is no evidence of host rock displacement along this vein (or veins 2 and 3).

3, also given in Table 1 (see explanatory legend in this table) and the presence of "exotic" fragments in some larger pseudotachylite bodies. Material flow is also suggested by flow lamination in some pseudotachylite veins, observed by others and ourselves in many places, in both the Sudbury and Vredefort structures (Fig. 22). It is, however, not known whether melt flow occurred during the melt formation process or during central uplift formation or postimpact readjustment of the floor of the impact structure.

It is difficult to chemically characterize very large breccia bodies, such as the Frood–Stobie zone of the Sudbury Structure (Müller-Mohr, 1992a). However, a small number of Sudbury Breccia occurrences of at least 200 m^2 in extent were sampled and analyzed in detail by Dressler (1984a). The results confirm the in situ origin also for these relatively large bodies. Reimold (1991) chemically investigated some large breccia occurrences, such as the Otavi Quarry (northeast core of the Vredefort Dome) and Leeukop Hill, and arrived at the same conclusion. However, "in situ" is a relative designation; the presence of "exotic" clasts in some large pseudotachylite bodies, such as the Frood–Stobie breccia zone in the Sudbury Structure, points to considerable movement of matter within the pseudotachylite, again during breccia formation or during postimpact tectonism. Reimold (1991) concluded that the composition of the Otavi breccia could be modeled by mixing of locally (i.e., within 20 m of the sampled breccia location) exposed lithologies. Some researchers may not wish to accept an in situ origin for such large bodies.

3.6.3. Timing of pseudotachylite formation

The contact and compression stage of the impact process lasts only a little longer than it takes for the impacting body to penetrate the target, by a distance corresponding to its diameter. During this very short time, the kinetic energy of the projectile is transferred to the target rocks causing vaporization and melting of the rocks near ground zero (Pierazzo et al., 1997). A supersonic shock wave expands from the zone of melting leading to the formation of shatter cones and microscopic shock features prior to the excavation stage of the impact process. That this stage seemingly also involves the formation of pseudotachylite breccia is evidenced by the observation of rock clasts with shatter cones and shock metamorphic features, as well as pseudotachylite fragments in allogenic impact breccias ejected from the crater. We have noted pseudotachylite-bearing fragments ranging in size from a few millimeters to about 15 m in size in the Bunte Breccia deposits of the Ries crater (Figs. 1 and 2) and in fragments incorporated in clastic-matrix

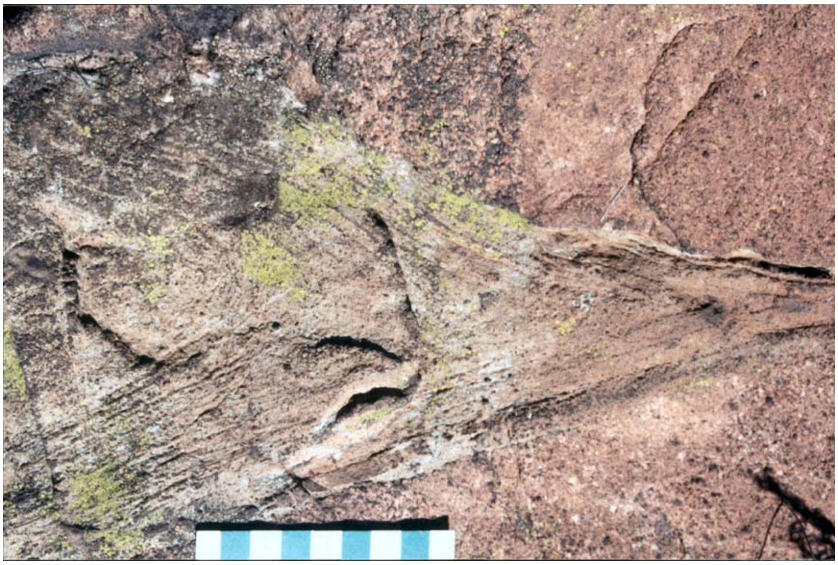


Fig. 22. Flow lamination of pseudotachylite vein in alkali granite. Near Habula Resort in Vredefort collar; west–northwest of Parys (for location, see Fig. 16a). Scale is in centimeters.

breccia dikes in Archean and Proterozoic basement rocks of the Slate Islands Structure (Dressler and Sharpton, 1997; Dressler et al., 1999). Evidence for the very early formation of pseudotachylites during terrestrial impact was also previously described from the Rochechouart Structure in France (Bischoff and Oskierski, 1987) and Vredefort (Martini, 1991). These early-formed, "first generation" pseudotachylites have been called type-A pseudotachylite (Martini, 1991) or S-type pseudotachylite (Spray, 1998). Lambert (1981) considers his A1-type breccias to be produced by the shock wave during compression. We believe that these pseudotachylites formed very early during the impact process (i.e., in our "flash replacement melting process) and are not the result of acoustic fluidization (Melosh, 1989), a process presumably following the passage of the shock wave through the target rock.

The extensive database collected in our recent field campaign seems to force the conclusion that much—if not all—of the larger pseudotachylite occurrences of the Vredefort Dome could also be derived from this early explosive compression stage of the impact process. This interpretation is based on the random distribution of pseudotachylites, the chaotic pattern of veins and dikes accompanying wide dikes (e.g., Fig. 12), and the locally derived melts indicated by the chemical database.

However, as suggested by a number of workers in the past (e.g., Müller-Mohr, 1992a; Spray, 1998), it cannot be excluded that pseudotachylite also forms at later stages, i.e., the crater modification stage during gravity-driven collapse of the transient crater cavity and central uplift and readjustment of large crustal blocks surrounding the central cavity. The existence of such late, modification-stage pseudotachylites had first been postulated in the Vredefort Structure where Martini (1991) named them "Type-B pseudotachylite". Dressler (1984a) made similar observation and stated that crustal readjustment after the impact leads "to more brecciation and milling of rocks in existing breccia bodies and along faults". Spray (1998) coined the term "E-type pseudotachylite" for these rocks (E for endogenic). However, criteria for the recognition of this "second generation" pseudotachylite type remain vague. Some of the largest pseudotachylite zones at and outside crater rims may have formed following the compression stage of the impact process, as a result of complete or partial frictional melting similar to the formation of tectonic pseudotachylites.

The breccias studied during our recent field investigations in the Vredefort Dome are believed by us to represent in their majority shock-produced pseudotachylites because of their central and near-central location in the impact structure. But there is no reason to assume that late-stage E-type pseudotachylites, formed in response to faulting and friction during block adjustment or after central uplift, should be completely absent from a large "collapsed" central uplift of an impact structure. There is, however, no known field evidence that the large dike-like pseudotachylite bodies, such as the Abel Farm breccia zone (Fig. 12), could be positively related to major faulting that might have formed in response to central uplift formation or collapse. At Vredefort, we have observed a number of veins of a few centimeters width that show evidence of displacement of up to about 1 m. Generally, however, displacements do not amount to more than 10–20 cm. There is no evidence that would allow us to relate these displacements to either an early or late stage of the impact process.

Nevertheless, we have made some observations that suggest that pseudotachylite formation in the Vredefort Dome was not an "instantaneous" process even in the center of the impact structure. For example, in the breccia zone in the Salvamento Quarry (Fig. 19), we have noted a large oval gneiss fragment (Fig. 23) with a smooth surface. This clast is cut by a thin pseudotachylite vein along which the banding of the gneiss has been offset (but not the surface of the clast). This observation suggests that the thin vein and the offset formed prior to the incorporation and rounding of the clast in the large breccia zone. We have also noted, in an area between the towns of Parys and Vredefort, a vertically dipping, 13–20-cm-wide pseudotachylite dike segment which lies between two parallel, 1-5-mm-wide, vertical breccia veins. The dike does not extend beyond the veins. At one of the veins, there is evidence of short-distance sinistral shear or faulting (Fig. 24a and b), which obviously is not sufficient to account for the configuration of the three pseudotachylite veins observed. Nevertheless, this may represent evidence that the dike has probably been formed shortly prior to the two parallel veins. However, the ticker dike may have been injected from a direction not exposed during tensile fracturing. It is

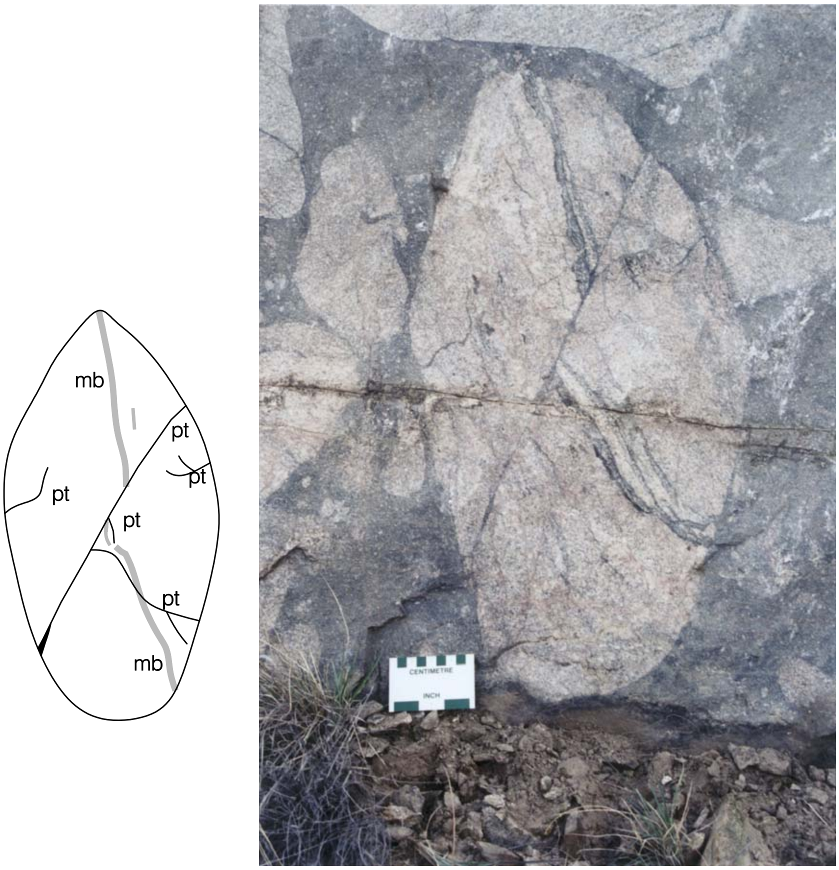
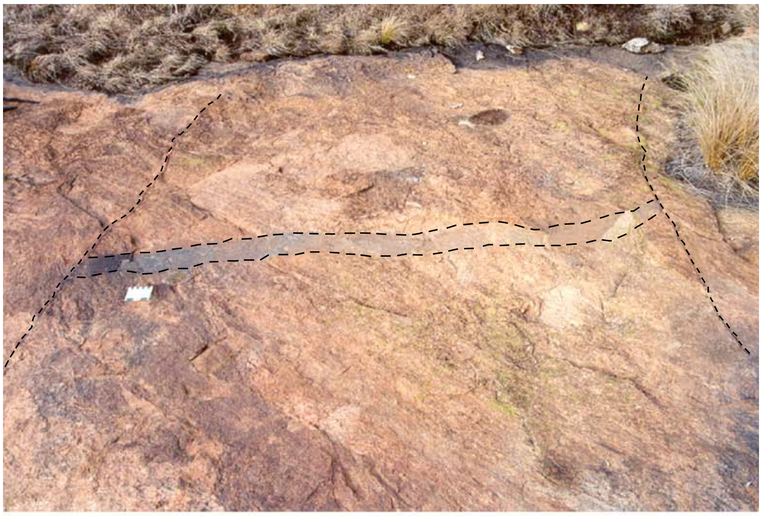


Fig. 23. Oval fragment in pseudotachylite of Salvamento Quarry. The fragment contains a pseudotachylite vein (pt) along which the banding (mb) of the gneiss is offset. Obviously, the vein was formed prior to the incorporation of the large fragment in the Salvamento pseudotachylite zone.

unlikely that the dike represents infillings from the thin veins or vice versa. Pseudotachylite breccias cutting across breccias of the same type have also been observed, both in the Vredefort (this work) and Sudbury structures (V. Müller-Mohr, personal communication, Univ. Münster, Germany, 1990). Colliston and Reimold (1992) and Reimold and Colliston (1994) also referred to two occurrences of pseudotachylite breccia veins on Farm Broodkop in the southeastern sector of the Vredefort Dome, where ovoid yet extended clasts of "older" breccia are included. At the Slate Islands impact structure, Dressler and Sharpton (1997) noted three pseudotachylite "phases" in a 1–2-cm-wide pseudotachylite vein. However, our observations cannot be taken as evidence for the formation of several pseudotachylite generations or for multistage pseudotachylite formation. There is also no reason to assume that veins branching off one pseudotachylite body cannot cut across veins that branched off another, or even the same, body—split seconds earlier but during the same compressional event. The entire process of shock deformation, especially during the early stages of the cratering event, is highly dynamic and characterized by unique strain rates, so that complicated, apparently multistage deformation could actually occur within an infinitesimally short time interval. We have shown that there is excellent evidence for the formation of pseudotachylites during the very early stages of the impact process. It is, however, less likely that the pseudotachylite breccias associated with bedding-parallel faults zones in the collar rocks of the Vredefort a



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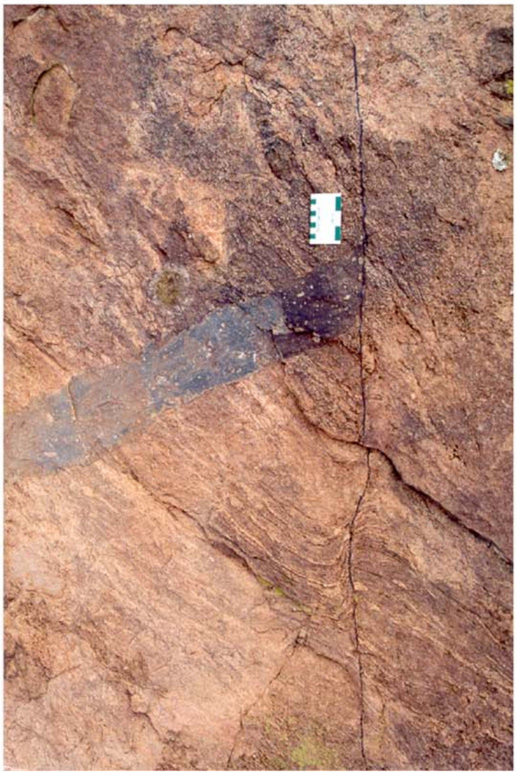

Fig. 24. (a) Approximately 10-cm-wide, vertical pseudotachylite dike section bordered by two very thin, vertical and parallel pseudotachylite veins. (b) Apparently minor, sinistral shear along left, very thin vein. Kafferkop area between towns of Parys and Vredefort (latitude 26°56′43″S; longitude 027°24′51″E). Scale in inches and centimeters.

Structure are the results of early, compression-phase shock deformation. It is likely that they formed during the collapse of the central uplift phase, when upturned sedimentary strata slid off bedding-plane or bedding-parallel discontinuities. The decameter-wide fault zones in the wider Witwatersrand Basin (e.g., the Master Bedding Fault, the Black Reef Décollement Zone, and the Ventersdorp Contact Reef Fault), all are located at distances from the center of the impact structure, where shock pressures likely did not exceed 5 GPa, too low a pressure for shock-induced melting. It should not be forgotten, that while most pseudotachylite formation in the Witwatersrand Basin is the result of the Vredefort impact event, it cannot be ruled out that some breccias predate the impact event (e.g., Berlenbach and Roering, 1992).

We have evidence (see above) for the formation of pseudotachylite bodies in the central parts of impact craters prior to excavation during the compression stage of the impact process. As stated above, however, we cannot rule out that they may also form during central uplift formation and collapse and later phases of the impact process. Farther away from ground zero, e.g., north of the Sudbury Igneous Complex and in the basin around the Vredefort Dome, pseudotachylite bodies may well have formed mainly in response to the development of important fracture and fault systems such as multiring structures. However, many relatively small pseudotachylite bodies also occur between these "zones of stronger brecciation" (Dressler, 1984a), interpreted by Spray and Thompson (1995) and others to be related to multiring formation. These small breccia bodies are up to ~ 20 m in size, have irregular shapes and orientations and actually have configurations similar to some Vredefort Dome breccias. They are probably not related to any large scale, directional deformational process such as multiring formation. Further work is required to investigate how and when these small breccia bodies formed and how far away from the point of impact they occur. In this aspect, it is noteworthy that Müller-Mohr (1992a) has shown that individual pseudotachylite bodies may show evidence of more than one pseudotachylite generation event. This is not surprising as this author's research was conducted on pseudotachylite occurrences around the Sudbury Igneous Complex where crater modification processes strongly affected the target. Further investigations around the central Vredefort Dome may very well lead to the discovery of large breccia zones similar to those around the Sudbury Igneous Complex. Very rough terrain around the central Vredefort Dome, however, hamper detailed mapping and observation.

3.6.4. Pseudotachylite matrix-clastic breccia, friction melt, or shock melt?

Fine comminution, friction melting and shock melting of target rocks, or a combination of these processes, are potentially responsible for the formation of the matrix of pseudotachylites in impact structures (e.g., Reimold, 1995, 1998). The very fine to submicroscopic grain sizes, the common distribution of fine grains of opaque minerals, the common abundance of tiny mineral and rock clasts, and especially postimpact alteration and metamorphism, regularly impede proper classification of the groundmass of pseudotachylites. Evidence for melting is the presence of glass—commonly with textures suggestive of flow—of fine-grained, igneous textures, vesicles or amygdules, sulfide and oxide blebs that appear as if they had separated from a melt, and possibly also of rounded mineral and rock fragments (Lin, 1999) that may exhibit signs of marginal melting (e.g., summaries in Magloughlin and Spray, 1992; Reimold and Colliston, 1994). These features have all been observed, e.g., in Sudbury Breccia (e.g., Dressler, 1984a; Peredery and Morrison, 1984). In addition, very fine-grained clastic matrices have been observed (Müller-Mohr, 1992a).[5] Communition is a forerunner to friction melting. Therefore, it is likely that clastic-matrix "pseudotachylites" with or without melt pockets also exist. Indeed, they have been described from the Witwatersrand occurrences (Killick and Reimold, 1990; Reimold et al., 1999a), in places in intimate spatial relationship with melt-bearing breccia or strongly flow-indicating breccia resembling ultramylonite or ultracataclasite.

Some observations point to very high temperature and pressure regimes for the generation of melt matrices of some pseudotachylites. The high-pressure modifications of SiO_2 coesite and stishovite have been described from thin Vredefort veinlets (Martini, 1978, 1991) providing evidence for the formation of these

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[5] In this case, the rock is not a pseudotachylite in the definition of most structural geologists.

Vredefort breccias under very high pressures. Shock veins in many ordinary chondrites are believed to have formed by shear melting under high shock pressures and very high temperatures (e.g., Langenhorst and Poirier, 2000). These authors investigated black melt veinlets in the Zagami meteorite and described various high-pressure minerals, like stishovite and silicate hollandite. The latter mineral, previously not known from terrestrial rocks, has recently been discovered by Langenhorst and Dressler (2003) in a shock vein from the anorthosite of the central uplift of the Manicouagan Structure in Quebec.

Our present study of impact pseudotachylites is mainly field based, but some new microscope and microprobe, and chemical results were also obtained that may provide some evidence against and in favor of specific modes of origin for pseudotachylites. Evidence for shear deformation leading to friction is scarce but has been observed in places. Very thin glassy veins, similar to those experimentally produced by, amongst others, Kenkmann et al. (2000) and Langenhorst et al. (2002) have been noted—even in the Vredefort case. Evidence of very limited shear along these veins has been observed in thin section but is not common (Fig. 6). In outcrop, displacement of host rocks at pseudotachylite veins and dikes is scarce and, in most places, the amount of displacement is minor. At only very few places did we observe obvious kinematic indicators within pseudotachylite bodies (Fig. 25). Nowhere in the Vredefort Dome did we note major displacement of country rocks at pseudotachylite zones that are wider than a meter or so. In this context, a proper structural analysis of the host rock of the Frood–Stobie breccia zone in the Sudbury Structure and their distribution is overdue.

Shearing and faulting, however, are not necessarily prerequisites for cataclasis and friction that may or may not lead to melting and the formation of pseudotachylites. Shock melting, as stated above, and not cataclasis and friction, may have been mainly responsible for the formation of pseudotachylites in the Vredefort Dome. This process is chaotic, leading to random distribution and orientation of pseudotachylite veins and dikes in the crater floor as has been observed in rocks of the core of the Vredefort Dome (see above). Major zones, such as the Abel Farm body, have a “mother lode” dike in its center that are accompanied at both sides by randomly trending veins branching off the mother lode. Commonly, these branches have been interpreted as injections from the main dike. However, these branching veins, at least in part, can be locally derived by our “flash

Fig. 25. Kinematic indicators in pseudotachylite veins suggestive of sinistral shear. Dimension stone block at Esperanza Quarry (Wittekopies 169 Farm, western Vredefort Dome; latitude 27°06′26″S; longitude 027°8′52″E).

replacement melting" process—as supported by textural and chemical results discussed above. In our opinion, the configuration of the small pseudotachylite veins accompanying "mother lode" dikes is not suggestive of their formation by friction and shearing. Long, straight, and relatively thin pseudotachylite dikes, with even thinner veins branching off them, also occur. One of these thin dikes has been observed on Spitskop Farm west of Parys (Fig. 14). It ends in a "horse tail", possibly supporting an origin other than by friction and cataclasis—namely, in situ flash-melting with or without injection. The long and tabular shape of "mother lode" dikes observed at several locations in the core of the Vredefort Dome, in our opinion, is not suggestive of pseudotachylite formation due to acoustic fluidization (Melosh, 1989).

We are aware that shock temperature and post-shock temperatures may not provide enough thermal energy for melting and the formation of all pseudotachylite veins, especially where pseudotachylites exist at considerable distances from ground zero (e.g., north of the Sudbury Igneous Complex). In addition, while the crustal level currently exposed in the Vredefort Dome was at amphibolite to granulite grade just prior to the impact event (Gibson and Reimold, 2001), which would have rendered the shocked rocks more susceptible to melting, the metamorphic grade of the basement rocks more than about 10 km from the Sudbury Igneous Complex where even more massive pseudotachylite breccias have been described, was only of greenschist to amphibolite grade at the time of impact impact. Part of the energy to render such vast rock volumes at great distances from the center of impact structures into brecciated and possibly completely molten state had to come from other sources, such as frictional heating.

Geochemical evidence has been forwarded in the past to support a more or less in situ origin for pseudotachylite matrices. As described above, the composition of the matrices is similar to that of the host rock or, where there are more than one host rock and type of inclusions, it is similar to the average composition of host rock and inclusions (Speers, 1957; Dressler, 1984a; Reimold, 1991, and references therein). Our new evidence (Table 1) supports a strictly in situ origin for at least some thin (centimeter scale or less) pseudotachylite veins.

Textures of pseudotachylite matrices are commonly not indicative of either in situ replacement shock melting or emplacement by injection from large pseudotachylite bodies. In both cases, similar or identical textures are expected. In large bodies, transport of material is indicated by the presence of "exotic" clasts derived from rocks not present in the immediate neighborhood. We have noted flow lines in the matrix of some veins and dikes of at least 3 cm width that also suggest some material transport. However, it is not known whether material transport occurred during the formation of the pseudotachylite or during later crater modification. In the case of Fig. 22, transport probably was over a short distance only.

3.6.5. Range of pseudotachylite formation in an impact structure

How far away from the center of an impact crater or from its rim do pseudotachylites form? Especially, what is the extent of pseudotachylite formation related to the crater modification stage of the impact process, and how does it depend on the lithology and stratigraphy of the target terrain? Knowing the answer to these questions would allow us to better estimate the dimensions of partially eroded impact structures. The information regarding these problematics may lie in the collar rocks of the Vredefort Structure that, to date, have not been sufficiently investigated, despite the detailed geological mapping compiled by Bisschoff (1999). Kenkmann et al. (2000) experimentally produced melt veins resembling pseudotachylites at shock pressures ranging from 6 to 34 GPa. No attempt was made to produce these veins at lower shock pressures (T. Kenkmann, personal communication, Humboldt Univ., Berlin; Germany, 2002); 6 GPa is, possibly, not the lower limit for the formation of such rocks. Knowing this lower limit would possibly allow us to use it as a shock barometer for the outer limit of shock-produced pseudotachylite veins.

In Sudbury, we do not know where the outer rim of the impact structure actually is. In this structure, however, Sudbury Breccia has been observed up to about 80 km north of the Sudbury Igneous Complex (SIC) that is at a minimum of 115 km from the center of the structure, making the perhaps simplistic, probably false assumption that the center of the Sudbury Basin is the center of the structure. However, it is unlikely that the Sudbury Breccias at this distance from the SIC have been produced by shock melting. Planar deformation features in quartz have been observed only up to a distance of 8 km north of the SIC (Dence, 1972; Dressler, 1984a) and shatter cones occur only for distances of about 17 km away from the SIC (Guy-Bray, 1966; Dressler, 1984a). Shatter cones form at minimum pressures of about 3 GPa and planar deformation features and fractures at shock pressures of at least 5 GPa, probably, 7 GPa (Stöffler and Langenhorst, 1994 and references therein). No shatter cones or planar deformation features are known to occur 80 km away from the SIC. However, it is still unlikely that the pseudotachylite occurrence farthest from the center of an impact structure represents its margin. It represents a minimum radial distance only.

4. Clastic-matrix breccias in target rocks

4.1. Introduction

In the following, we deal with three other breccia types, two of which appear to be more or less absent or not exposed at the two large Sudbury and Vredefort structures. We use the descriptive terms polymict and authigenic, monomict clastic-matrix breccias for them. A third breccia type has been termed "Footwall Breccia" in Sudbury. Although its matrix is strongly metamorphosed, it is interpreted as originally having been composed entirely of clastic material.

Our description of the clastic-matrix breccias is based on our field investigations in the Ries, Manicouagan, Slate Islands, and, to a minor degree, Haughton (Devon Island, Arctic archipelago, Canada) and Roter Kamm (Namibia) structures and on the results of scientific drilling in the Ries and Chicxulub (Yucatan) craters.

4.2. Polymict clastic-matrix breccias

4.2.1. Slate Islands Structure, Canada

Polymict, clastic-matrix breccias are superbly exposed on the Slate Islands archipelago in northern Lake Superior (Grieve and Robertson, 1976; Dressler and Sharpton, 1997; Dressler et al., 1999) (Figs. 26 and 27). The island group represents the central uplift of a 32-km complex impact crater. The breccias form veins and dikes ranging in width from a few centimeters to several meters, and irregularly shaped bodies that are commonly >10 m across. Dikes may be over 1000 m long. There is no apparent orientation of the dikes with respect to the center of the structure. Dips are mostly vertical or steep, but shallow dips were also observed.

Fig. 26. Polymict clastic-matrix breccia. Clasts are derived from Archean granitic and supracrustal rocks. The large, angular clast on top of outcrop is about 2 × 3 m in size. Slate Islands Structure, Lake Superior, Canada.

Fig. 27. Polymict clastic-matrix breccia dike containing relatively small clasts of Archean granitic and supracrustal rocks. Slate Islands Structure, Lake Superior, Canada.

Fragments in the polymict breccias are derived from various target rocks. Dressler and Sharpton (1997) observed up to seven different types of fragments in a single breccia occurrence. This is evidence for mixing of components over considerable distances of, at least, several hundred meters. Most of the rocks exposed at Slate Islands are Archean, igneous and metamorphic lithologies (Sage, 1991). Breccias hosted in these rocks may, in places, contain clasts derived from Proterozoic sedimentary rocks indicating downward movement of fragments from an originally stratigraphically higher level. Clasts are angular to rounded and the breccias may be either matrix- or clast-supported. In a few places, altered glass fragments and clasts of pseudotachylite have been noted in the breccias, but they are relatively scarce. More common are mineral and rock clasts exhibiting shock metamorphic features, also in dikes on outlying islands far away from the center of the structure, which cut across host rocks that are entirely devoid of these shock deformation features. This is further evidence of lateral movement and mixing of components over considerable distances.

4.2.2. The Ries Structure, Germany

The Nördlingen 1973 scientific drilling project (Bayerisches Geologisches Landesamt, 1977) encountered polymict clastic-matrix dike breccias in the rocks of the crystalline crater basement from about 602 m down to the final depths of the drill hole at 1206 m. The spacing of breccia dikes ranges from a few centimeters to approximately 50 m (Stöffler et al., 1977). Two fragment types have been identified by these authors: (1) parautochthonous fragments derived from the host rock to a given dike, and (2) allochthonous fragments of crystalline and sedimentary rocks that apparently had been transported over considerable distances. Sedimentary rock fragments are shales and limestones. Such clasts have been observed mainly in an upper zone of breccias above 1065 m that is characterized, besides the presence of sedimentary rock fragments, by quartz with planar deformation features. Beneath this upper zone, shock metamorphic quartz has not been observed. Most breccias in the drill hole display an excess of quartz in comparison with the amounts of basement rock and sedimentary rock fragments present. This observation was interpreted by Stöffler et al. (1977) as evidence for admixture of quartz mainly from Triassic quartz sandstones. The abundance of Jurassic limestone clasts decreases, whereas the content of quartz increases with increasing depth. If this interpretation is correct, the preimpact stratigraphy of the sedimentary target may be preserved in the breccia dikes occurring at different levels in the floor of an impact structure. Transport of clastic-matrix breccia components in the Ries crater floor occurred over distances of tens or even hundreds of meters. Polymict clastic-matrix breccias also occur in the uplifted, exposed crystalline basement rocks of the “inner Ring” of the Ries (Bayerisches Geologisches Landesamt, 1977).

4.2.3. Other impact structures

Polymict clastic-matric breccias have also been described from the Manicouagan Structure. The few dikes of such breccias observed there are oriented more or less vertical, brown-red in color and up to about 50 cm wide. They contain host rock and altered glass fragments and, therefore, have been termed ''red suevite dikes'' (Dressler, 1970; Murtaugh, 1975, 1976). They have been noted only close to the periphery of the central part of the structure, i.e., close to the shores of the Lake Muchalagane (Fig. 3) about 28 km from the center of the structure. Closer to the center, pseudotachylites formed at higher energy occur. This is substantiated by the observation of various shock metamorphic features, such as planar deformations in quartz and feldspar, in rocks hosting pseudotachylites and by the absence of these features from rocks hosting only clastic-matrix breccias.

A single, only approximately 3-m-wide occurrence of polymict clastic-matrix breccia has been observed, to date, in the Vredefort Dome (H. Sievers, University of Göttingen, personal communication). It is located in granotoid rocks of the center of the Dome on Farm Zandfontein northeast of the town of Parys. A purplish-reddish matrix contains rock and mineral clasts of various precursor lithologies. Detailed investigation of this occurrence is still awaited.

Polymict breccia dikes have also been found in the Yaxcopoil 1 drill hole in the Chicxulub Structure, but they are not very common there (Dressler, 2002; Dressler et al., 2003). They may contain altered glass fragments or are entirely devoid of glass components (Fig. 28). Both types form relatively thin, few-centimeters-wide veins in the Cretaceous target rock beneath 100 m of suevite and various melt rocks and melt breccias. The Cretaceous units of limestone, dolomite, and anhydrite encountered in the drill hole have been interpreted as megablocks and make up a total minimum thickness of approximately 600 m, ranging from about 900 m to the final depth of ~ 1511 m. There are possibly three megablocks, one on top of each other, as indicated by abruptly changing dips of bedding planes.

Fig. 28. Clastic-matrix breccias, Chicxulub Structure, Yaxcopoil 1 drill hole. Yucatan, Mexico. (A) Monomict breccia in dolomite (1318.95 m). (B) Polymict breccia vein (all of core section shown; 1341.75 m). (C) Polymict breccia vein (1316.0 m).

4.2.4. Summary and origin of polymict clastic-matrix breccias

The central part of the Sudbury Structure is not accessible to direct observation. Polymict breccias may or may not be present within the rocks of the crater floor. Hardly any polymict clastic-matrix breccias have been, to date, observed in the target rocks of the Vredefort Dome. Therefore, it is not impossible that such breccias could be absent also from the crater floor below the central part of the Sudbury Structure. Vice versa, where polymict clastic-matrix breccias are common, pseudotachylites may be scarce or absent, as observed at Slate Islands. The reason for this exclusiveness may be found in the character of the target rocks or the impact energy and distribution involved. At Slate Islands, the target consisted of a very wide variety of Archean and Proterozoic igneous and metamorphic rocks (Sage, 1991) forming an assemblage susceptible to cataclasis. The overall more homogeneous gneissic and igneous targets, coupled with the magnitude of the events, led to massive pseudotachylite formation at Sudbury and Vredefort. However, clastic-matrix breccias may be present at deeper, non-exposed levels at these structures. At the Slate Islands Structure, scarce pseudotachylite vein-bearing fragments occur in polymict clastic-matrix breccias. This is evidence for the formation of these breccias shortly after the contact and compression stage of the impact process (Dressler and Sharpton, 1997), i.e., during central uplift formation and collapse. Catalysis and milling of the target rocks during these impact phases may have occurred in a process for which Melosh (1989) coined the term "acoustic fluidization." Polymict breccia dikes at Slate Islands on islands at great distances from the center of the structure contain clasts and mineral fragments with shock metamorphic features—the host rocks are devoid of these features—and rock fragments that obviously traveled distances of several hundred meters. This requires a high-energy process and zones of weaknesses like joints and rock contacts, along which mineral and rock fragments could travel with high velocity, as we believe, during the crater growth, excavation, and central uplift phases of the impact process. At the Manicouagan Structure, the overall homogeneous anorthositic igneous body of the central uplift reacted as a large, cohesive body during the compression and central uplift formation and collapse phases, leading to little brecciation in the center of the structure.

4.3. Authigenic, monomict clastic-matrix breccias

In contrast to the commonly sharp contacts of polymict clastic-matrix breccia bodies with the country rocks, authigenic, commonly monomict varieties generally have gradational contacts with solid crater floor lithologies. Our observations are based mainly on our work in the Manicouagan and Slate Islands structures and on additional observations at the Haughton, Ries, and Chicxulub structures where monomict breccia dikes also occur, but, to date, were not widely observed.

4.3.1. Manicouagan Structure, Canada

In Manicouagan, authigenic, monomict breccias have been noted only at distances of about 28 km from the center of the crater, very close to the occurrence of the polymict breccia dikes described above (Fig. 3). They consist of angular fragments ranging in size from < 0.5 to >50 cm set into a matrix of finely crushed rock (Dressler, 1970). Contacts of the breccias with the host rocks are gradational. Clasts are devoid of shock metamorphic features. No authigenic, monomict, clastic-matrix breccias have been observed closer to the center of the crater.

4.3.2. Slate Islands Structure, Canada

Similar observation to those described for Manicouagan was also made by Dressler and Sharpton (1997) at the Slate Islands Structure. Monomict breccias have been observed only on the outlying islands of the archipelago away from the center of the structure, where, as in the Manicouagan Structure, polymict matrix-breccia dikes also occur. Again, the authigenic, monomict varieties have gradational contacts with the country rock and consist of angular, commonly rotated fragments in a fine rock flour. At one location, a polymict, clastic-matrix breccia dike has been affected by the brecciation that led to the formation of the monomict breccias; fragments of the polymict, clastic-matrix breccia dike have been observed within the otherwise monomict breccia body. The occurrence of mineral and rock fragments with planar deformation features and of exotic rock fragments in the polymict breccia dikes affected by the authigene brecciation is evidence for dike injection over considerable distances prior to the authigene brecciation process.

4.3.3. Other impact structures

At the Ries and Haughton impact craters, monomict, brecciated megablocks have been observed. The blocks at the Ries consist of limestone, have been ejected, and are locally known as Malmgriess (griess is coarse sand in German). At Haughton, limestone and dolomite megablocks within the suevitic breccia fill of the crater exhibit both thin monomict breccia dikes and zones of monomict breccia with transitional contacts with the host rock. At the 2.5-km-diameter, 3.4-Ma-old Roter Kamm impact crater in Namibia, extensive monomict clastic-matrix breccia zones of up to tens of meters width occur in the crater rim. These zones seem to have generally radial attitudes to the crater center (Reimold and Miller, 1989). They comprise fragments at the centimeter to half-meter size that commonly have been rotated. Such breccia has been observed outside the crater at distances of up to 500 m. In addition to these wide zones, narrow monomict clastic-matrix veins of 1–10 cm width have also been observed at the crater rim, although mostly at orientations that are more oblique than radial with respect to the center of the structure.

There is no reason to assume that significant amounts of monomict (and polymict) breccias were not associated with the two largest known terrestrial impact structures Sudbury and Vredefort, at least away from the more central regions of the structures. In the Canadian structure, monomict breccia has been observed in shatter-coned quartz–arenites a few kilometers northeast of the SIC, 4.5 km northwest of Lake Wanapitei (Dressler, 1982). A few exposures of clastic-matrix breccia are also known from the Witwatersrand Supergroup rocks of the collar of the Vredefort Structure (Fig. 29; F. Wieland, University of the Witwatersrand, personal communication 2002) and from the wider environs around the Dome, in Transvaal Supergroup strata. However, in both of these large structures, there is no direct evidence that this brecciation is related to the impact event or, instead, reflects some tectonic episode. For example, chert breccias are known to occur in the Transvaal Supergroup of South Africa, in the region around the Vredefort Dome, but also in parts of the Witwatersrand Basin at distances of hundreds of kilometers from the Dome. The breccia exposed northwest of Lake Wanapitei, in the wider environs of the Sudbury Structure, may even be associated with the 37.4 Ma Wanapitei impact. Clastic-matrix breccias are more susceptible to erosion than their host rocks. For this reason, outcrops of these rocks (if present) could be scarce in strongly eroded terrain, such as the Sudbury and Vredefort regions.

Our assumption that monomict breccia bodies would originally have been present at the Sudbury and Vredefort structures is substantiated by observations recently made at the Chicxulub Structure, the third largest impact crater known on Earth. At the Yaxcopoil 1 deep drilling site, about 60 km from the center of this structure in Yucatan, monomict clastic-matrix breccia bodies were encountered beneath a 100-m-thick sequence of suevitic rocks and impact melts (Dressler, 2002; Dressler et al., 2003). The drill penetrated five major monomict breccia zones, ranging in drill length from about 6 to 45 m. They occur in megablocks of Cretaceous target rocks. Monomict breccias have only been observed in dolomite and only at depths ranging from 1298 m to the final depth of 1511 m. They consist of angular

Fig. 29. Monomict, clastic-matrix breccia in quartz arenites of the Vredefort collar, roadside exposure near Venterskroon. Hammer for scale. (Latitude 26°52′39″S; longitude 027°15′07″E).

fragments ranging in size from <0.5 cm to several meters. The fragments are set in crushed dolomite (Fig. 28).

4.3.4. Summary and origin of authigenic, monomict clastic-matrix breccias

Authigenic, commonly monomict clastic-matrix breccias are the simplest type of breccias found in impact structures. They consist of clasts of the immediate host rock and the matrix in which the clasts are embedded is derived from the host rock. Tectonic breccias (cataclasites) exist that are very similar. Where associated with impact, they are commonly found in distal areas—away from the center of the structures. Closer to the center, the energy transferred to the target from the impacting body was high enough to lead to mixing of various breccia components over considerable distances to form polymict breccias. Monomict clastic-matrix impact breccias, therefore, are considered low-energy breccias. Polymict breccias, in places, have been affected by brecciation that led to the formation of monomict breccias, suggesting that at least some monomict breccias are formed late in the impact process. Authigenic, monomict brecciation also occurred in megablocks during their transport within the excavation cavity or their ejection out of the crater.

4.4. Footwall breccias

Bodies of so-called "Footwall Breccia" have only been described from the Sudbury Structure. Further research is needed to establish if somewhat similar rocks found in the center of the Vredefort Structure could represent similar or equivalent material.

4.4.1. Sudbury Structure, Canada

At the contact of the Sudbury Igneous Complex (SIC) with the footwall rocks of the North and East Ranges of the Sudbury Structure, a rock unit—known as Footwall Breccia (Langford, 1960)—has been identified that has been subject to several detailed investigations (Langford, 1960; Greenman, 1970; Pattison, 1979; Dressler, 1984a; Lakomy, 1989, 1990; Deutsch et al., 1989). In many aspects, the Footwall Breccia is very different from all other breccias found in the crater floor of impact structures. Pattison (1979) used the term "leucocratic breccia" for this type and included it with the Sublayer of the SIC, a classification that is no longer applied. The reason for Pattison's classification was the presence of substantial economic Ni/Cu deposits in both the Footwall Breccia and the Sublayer.

The breccia forms discontinuous, kilometer-long and up to about 200-m-thick units between the SIC

Fig. 30. Footwall Breccia. North Range of Sudbury Structure. Roadside exposure at Strathcona Mine. Scale in centimeters.

and the footwall rocks, as well as small offshoots or dikes up to 250 m away from main breccia bodies (Dressler, 1984b). Contacts of the large bodies along the SIC with the footwall rocks are transitional. Dikes have sharp contacts. The heterolithic breccia is characterized by angular to subrounded fragments of various sizes derived mainly from footwall rock types that are in direct contact with the breccia (Fig. 30). Exotic fragments also occur but are not common. For example, there are ironstone and anorthosite fragments in the Footwall Breccia of the East Range of the Sudbury Structure where these rocks are nowhere exposed in the direct vicinity. Pseudotachylite-bearing fragments, clasts of sulfides and, very rarely, of arenites of the Proterozoic Huronian Supergroup have also been noted.

Pattison (1979) described the texture of the matrix to this breccia as "mosaic-granoblastic, metamorphic". It has been interpreted as having a contact metamorphic origin (Dressler, 1984a; Avermann, 1988) caused by the emplacement of the SIC. The contact metamorphic zone around the SIC is about 1.2-km-wide and comprises a pyroxene subzone in contact with the SIC, and hornblende–plagioclase, and biotite–plagioclase subzones farther away. Despite the strong contact metamorphic overprint, some clasts in the breccia show relicts of planar deformation features in quartz. Close to the SIC, incipient, partial melting of Footwall Breccia matrix is indicated by granophyric intergrowth of quartz and feldspar, the presence of thin aplitic veins, and by flow textures. This partially molten Footwall Breccia intruded into the fractured country rock beneath the breccia bodies to form veins and dikes. Lakomy (1990) applied two-pyroxene thermometry and estimated an annealing temperature exceeding 1000 °C near the SIC. Prevec and Cawthorn (2002) modeled the thermal behavior of the footwall rocks (including the Footwall Breccia) over time and arrived at similar contact metamorphic temperatures immediately beneath the SIC. The original, premetamorphic nature of the breccia is not known; however, based on the presence of many small mineral and rock inclusions and the absence of an altered melt matrix or altered glass fragments, it originally probably was a purely clastic-matrix breccia.

4.4.2. Other impact structures

At the Manicouagan impact structure, clastic-matrix breccias occur beneath a ~ 200-m-thick impact melt sheet. They have not been studied in any great detail and have only vaguely been described as suevitic (Dressler, 1970; Murtaugh, 1975, 1976). They are not contact metamorphosed to the same extent as the Sudbury Footwall Breccia. Based on the limited

Fig. 31. Footwall Breccia (?) of Vredefort Dome. Approximately 50-cm-diameter block near Inlandsee Pan.

knowledge of these rocks, we dare not classify these occurrences at Manicouagan as ''Footwall Breccia''.

The Vredefort Structure experienced deeper erosion than the Sudbury Structure. Rocks comparable to the Sudbury Footwall Breccias are not known from outcrop. We have, however, found few, decimeter to meter-sized blocks near the Inlandsee pan, located about 4 km south of the geometric center of the impact structure, that macroscopically are somewhat similar to the Sudbury Footwall Breccia. They consist of clasts up to about 10 cm in size embedded in a leucocratic, fine- to medium-grained matrix (Fig. 31). Ongoing research will show whether these breccias are equivalents to the Sudbury Footwall Breccias or not.

4.4.3. Summary and origin of Footwall Breccias

The origin of the Footwall Breccia is enigmatic. In Sudbury, the rock occurs adjacent to the SIC of the North and East Ranges where a level of the Sudbury Structure is exposed that, before deformation and northward thrusting of the southern part of the Structure, lay probably at a 3–5-km higher elevation than the present South Range. The distribution of the Footwall Breccia and the clast population is evidence that the breccia was formed and deposited along the upper parts of the excavation cavity. The presence of exotic clasts, however, is suggestive that some clasts were transported some considerable distances before deposition. The breccia was obviously formed by crushing and displacement of rocks of the transient crater floor prior to the emplacement of the SIC but postdates (S-type) pseudotachylite formation as Sudbury Breccia clasts have been noted in Footwall Breccia.

5. Melt breccia dikes

5.1. Introduction

Pseudotachylite (or pseudotachylitic breccia, Reimold, 1998) in the floors of impact craters forms more or less in situ. Fragments in polymict clastic-matrix breccias commonly are derived from a wide range of lithologies suggesting transport, whereas authigenic breccias are monomict. Components of rock units mostly excavated during the impact process are very scarce in breccias of the crater floor but have been observed, e.g., Triassic quartz arenites in polymict breccias in the basement rocks of the Ries crater or Proterozoic rock clasts in breccias hosted by Archean target rocks of the Slate Islands Structure. Impact melt breccia dikes in the crater floors, however, are believed to represent downward injections from melt bodies that commonly form melt sheets within the excavation cavity of an impact structure. We are aware of four large terrestrial structures from which the presence of impact melt rock dikes has been reported. They are Manicouagan, Morokweng, Sudbury and Vredefort.

5.2. Manicouagan Structure, Canada

To our knowledge, no detailed investigation has ever been performed on melt breccia dikes of the Manicouagan Structure in Quebec, Canada. Murtaugh (1976) described dikes of spherulitic melt rock that he observed near the outer edge of the impact melt sheet. They are black, gray, or red, contain country rock inclusions with shock metamorphic features and, in places, have shapes indicative of partial melting and flow. A photomicrograph shown by Murtaugh (1976), represents a spherulitc rock consisting of plagioclase, pyroxene, and opaque minerals. The texture is that of a rapidly cooled melt rock and is strikingly similar to phases of the Vredefort Granophyre, described below. Murtaugh (1976) described these rocks as ''basalt or black suevite''. However, this classification as basaltic was not substantiated with a chemical analysis and the rock certainly does not resemble suevite. One of us (BOD) has seen some of the dikes and described them as ''brown, inclusion-bearing, and very fine grained to aphanitic'' (BOD, unpublished field notes, 1967). Their altitude is about vertical, and they are up to about 3 m wide and resemble the lower, very fine-grained to aphanitic unit of the Manicouagan melt sheet (Floran et al., 1978; Dressler and Reimold, 2001, and references therein). They occur in both the gneisses and the anorthosite of the crater floor.

5.3. Morokweng, South Africa

The size of the145-Ma Morokweng impact structure in the Northwest Province of South Africa has been subject of debate. Andreoli et al. (1995) and Corner et al. (1997) proposed a diameter in excess of 300 km. Reimold et al. (1999b) favored a diameter of approximately 200 km, but recently, Henkel et al. (2002) and Reimold et al. (2002) reported evidence suggesting a diameter of 70–80 km only.

The structure is not exposed, but has been explored by drilling. One of the three drill holes studied by Reimold et al. (1999b) penetrated a sheet of granophyric melt rock that is strongly weathered at its top. The preserved thickness of this sheet is approximately 145 m in one of these holes. The crater floor was reached in the deepest hole that penetrated granitoid rocks beneath the melt rock from 225 m depth to the final depth of 271 m. It is in these granitoid rocks where several breccia dikes occur. Andreoli et al. (1995) mentioned recrystallized pseudotachylite veins that are a few millimeters to ten centimeters wide. Hart et al. (1997) also described fine-grained recrystallized breccia veins that resemble pseudotachylite. Reimold et al. (1999b) tentatively identified some of these veins as melt breccia but also stated that it was not possible to say whether the melt represented an impact melt, which was intruded into the crater floor from the overlying melt sheet, an in situ shock-produced melt, or a friction-produced pseudotachylite. Further work is obviously needed to come to a better understanding of the origin of the breccia veins in the Morokweng crater floor rocks. However, based on observations made at the other structures described here, dikes and veins of impact melt rocks more than likely exist in the crater floor beneath the Morokweng melt sheet.

5.4. Sudbury Structure, Canada

Inclusion-bearing igneous dike rocks in the footwall rocks of the Sudbury Igneous Complex (SIC) are locally known as “Offset” dikes. They have been interpreted by several researchers to represent part of a Sudbury impact melt system (e.g., Grieve et al., 1991; Grieve, 1994; Ostermann et al., 1996, and references therein). Most of the dikes apparently connect with the Sublayer of the SIC and are radial or concentric with respect to the shape of the SIC or exhibit a more random orientation (Fig. 9). One dike in the southeast (not shown on Fig. 9), on surface, does not have a connection with the SIC. The longest dike, the Foy offset in the north, has been traced for a distance of about 30 km and is about 400 m wide near the SIC. It may be connected with the concentric Hess Offset in the north or may cut across it. In the south, the Copper Cliff Offset extends due south for approximately 19 km. It begins as a 1500-m-wide, funnel-shaped embayment of the Sublayer of the SIC with and has a gradational contact with the Sublayer (Grant and Bite, 1984). At the northeast corner of the SIC, near Whistle Mine, the Parkin Offset consists of a number of subparallel, anastomosing dikes ranging in thickness from <1 m to over 30 m (Lightfoot et al., 1997a,b). Several of the Offsets host significant Ni–Cu deposits, especially the Copper Cliff and Frood–Stobie Offsets south of the SIC. A few so-called internal Offset dikes also occur. They intrude into the lower units of the main mass of the SIC, are relatively scarce (Naldrett et al., 1984; Dressler, 1984b,c), and have been observed mainly in the South Range SIC near Creighton Mine. They have not been studied in any great detail and it remains to be shown if they are derived from the same source as the “external” Offsets.

The rocks making up the Offsets are generally referred to as quartz diorite or quartz diorite breccia. Grant and Bite (1984) recognized three types of quartz diorites, namely: (1) hypersthene–quartz diorite; (2) two-pyroxene quartz diorite; and (3) amphibole–biotite quartz diorite. The latter type is probably an altered version of the other two types (Grant and Bite, 1984). All three types contain inclusions of local footwall rocks, metavolcanic and metasedimentary rocks possibly derived from units of the Proterozoic Huronian Supergroup, and exotic mafic and ultramafic igneous inclusions. Massive and disseminated sulfides and inclusions of sulfides are common in some places. Near the contact with the SIC, in the Foy Offset, fragments of Footwall Breccia occur. All these characteristics are similar to those of the Sublayer, an inclusion-rich quartz diorite layer at the base of the SIC. For this reason, the Offset dikes were commonly linked to the Sublayer and interpreted as being intrusions of Sublayer material into the footwall rocks and, in places, the lower units of the SIC.

However, Lightfoot et al. (1997a,b) have challenged this interpretation. On the basis of ratios of incompatible trace elements, these authors claim that the quartz diorite of the Offset has greater compositional affinity to the main mass magma of the SIC than to the Sublayer magmas and were formed by the process responsible for the main mass rather than the one responsible for the formation of the Sublayer. Ostermann (1996), based on isotope characteristics and major and trace, including rare earth element investigations, concluded that the Offset dikes have a noritic composition. Therefore, they are products of differentiation and do not represent an undifferentiated impact melt injected during a very early phase of crater formation. Furthermore, the dikes are not the result of vertical, in situ differentiation, but intruded, as already differentiated SIC melt, at a later stage of crater formation.

Several authors, amongst them Grant and Bite (1984), Lafleur and Dressler (1985), and Lightfoot et al. (1997a,b), have shown that there are distinct differences between the chemical compositions of the Sublayer and Offset dikes in the North and South Ranges of the SIC, which in part are paralleled by differences between South Range and North Range units of the main mass of the SIC. These heterogeneities and the presence of sulfide ore bodies in some of the Offset dikes, coupled with a wealth of field observations, have to be taken into consideration when considering the origin of the Offset dikes (see below).

5.5. Vredefort Structure, South Africa

The Vredefort Structure hosts a number of dikes of a very fine-grained, granophyric rock commonly referred to as Vredefort Granophyre. Several possible processes for the formation of these rocks were proposed in the past. Hall and Molengraaff (1925) considered them to represent massive equivalents of pseudotachylite. Bisschoff (1972) advocated a magmatic origin and proposed that the Granophyre represented an original mafic igneous rock that was then strongly contaminated with crustal material. In the more recent and commonly accepted interpretation the Granophyre has been considered as impact melt breccia (French et al., 1989; French and Nielsen, 1990; Therriault et al., 1996; Grieve and Therriault, 2000). This was confirmed by the identification of traces of a meteoritic component in Vredefort Granophyre (Koeberl et al., 1996) and the observation of shock metamorphic features in clasts in Granophyre (Buchanan and Reimold, 2002).

The Granophyre dikes occur in the Vredefort Dome, either entirely in granitoids of the core or in the supracrustal rocks of the collar close to the boundary between the granitoid rocks of the core and the collar (Fig. 16a). Individual dikes straddling this boundary may enter the supracrustal terrain of the collar up to about 1.8 km from the contact. In the Dome, these dikes are oriented approximately radially or concentrically to the structure, and are up to about 20 m in width and up to about 5 km long. Straddling the central collar

Fig. 32. Granophyre of Vredefort Dome. Weakly flow-aligned inclusions of quartz arenite in very fine-grained igneous groundmass.

boundary, they are roughly concentric to the structure, up to 65 m wide, and up to 9 km long.

The Granophyre contains up to ~ 20 vol.% of rock and mineral clasts derived from all the major country rocks (Therriault et al., 1997), with granite, gneiss and quartz arenite the most abundant fragment types (Fig. 32). Clasts are commonly aligned parallel to the dike contacts. Larger clasts of up to 80-cm diameter, according to Therriault et al. (1997), are, in places, concentrated on one side of a dike. Under the microscope, fragments exhibit signs of intense recrystallization and assimilation by the melt. The dikes within the Vredefort Dome, in general, have spherulitic textures. The dikes near and in the collar rocks are generally of granular texture. Both varieties contain a significant component of granophyric intergrowth. The Granophyre bodies are generally not affected by any deformation related to the Vredefort impact.

The chemical compositions of both the granular and spherulitic granophyres are very similar: The composition is homogeneous between dikes and within individual dikes as shown by Therriault et al. (1997) substantiating earlier results (French et al., 1989; French and Nielsen, 1990; Reimold et al., 1990). Several authors attempted to model the Vredefort Granophyre composition by mixing various country rocks present in the Vredefort Structure (Bisschoff, 1972; French and Nielsen, 1990; Reimold et al., 1990). In the most recent attempt, Therriault et al. (1997) modeled the composition of the Granophyre by mixing ~ 40% Ventersdorp volcanic rocks, with ~ 30% Witwatersrand quartz arenite, ~ 25% Outer Granite Gneiss, and ~ 5% Witwatersrand shale and Transvaal carbonate. The resulting melt composition is close to the composition of the Granophyre.

5.6. Other impact structures

Most of the information on breccias in floors of impact structures comes from deeply eroded craters and from drilling. Impact melt breccia dikes in crater floors, therefore, are known only from a relatively small number of craters, such as the deeply eroded Sudbury and Vredefort structures and the Manicouagan structure where deep, selective erosion of the 200-m-thick melt sheet provides some access to the crater floor (see above). We know of two structures, besides Morokweng (see above) where drilling encountered melt rock dikes in crater floors, namely, the Chicxulub (Mexico) and Puchezh-Katunki (Russia) structures. A single, about 1-m-wide and >10-m-long outcrop of a dike or a pod of melt rock, near Trollberget close to the center of the ~ 65-km diameter Siljan impact structure in Sweden has been described in the past. This occurrence cuts across basement granite as well as a mafic dike. Bottomley et al. (1978) reported an ^{40}Ar–^{39}Ar age of 360 Ma for this rock, which to date is still the age quoted regularly for this impact structure.

In the recently completed Chicxulub Structure scientific drilling campaign at Yaxcopoil in Yucatan, a green, altered vein of melt rock was encountered at a depth of 1347 m in a large megablock of Cretaceous target rocks. The dike has an apparent width of 33 cm. In macroscopic appearance, the rock is similar to impact melt rocks encountered in the same drill hole at a depth of about 860–885 m, i.e., in a complex, 100-m-thick sequence of allogenic breccias and impact melts (Dressler, 2002; Dressler et al., 2003). Ongoing laboratory research will show whether this vein is also similar to melt rocks encountered at a depth of about 1260–1650 m in Y6, a deep petroleum exploration hole drilled in 1966 by the state-owned Mexican petroleum company in the Chicxulub Structure.

At the 80-km-diameter Puchezh-Katunki structure in the central part of the east European platform of Russia, several shallow and one deep hole were drilled. The deep Vorotilovskaya hole reached a depth of 5374 m and was drilled in the central uplift of the structure. Masaitis (1999) described thin veins of what he termed “tagamite” (a term widely used in the Russian literature for impact melt rock) crosscutting gneisses and amphibolites from this deep hole and from some shallow holes drilled near the central uplift.

5.7. Summary and origin of melt breccia dikes

There is general agreement that the melt breccia dikes in Manicouagan and Sudbury are related to thick and extensive impact melt sheets. At Vredefort, the corresponding impact melt sheet has been eroded. Disagreement, however, exists on how the dikes intruded and, at least in the case of the Sudbury Offset dikes, whether the dikes represent material from the primary undifferentiated impact melt or not. We believe that the final verdict on this question is outstanding, for the following reasons:

A homogeneous chemical composition has been a widely accepted characteristic of undifferentiated impact melt bodies (Grieve et al., 1977; Floran et al., 1978; Grieve and Floran, 1978; Dressler and Reimold, 2001). The Vredefort Granophyre dikes meet this characteristic, but the Sudbury Offset dikes do not. There appears to be a distinct difference between North Range and South Range Offset dike compositions, with the exception of one South Range dike (Manchester Offset) that chemically resembles North Range dikes. Lightfoot et al. (1997b) stated that the quartz diorite of the Offsets are dominantly derived from a main mass magma type and that it is possible "that it is representative of the bulk of the initial Sudbury Igneous Complex (SIC) although there are locally different spidergram patterns between the offset quartz diorite of the North Range and that of the South Range. These differences may reflect assimilation of compositionally different footwall rocks". (However, the difference could also be a result of incomplete mixing of the Sudbury impact melt before differentiation). In contrast, the Vredefort Granophyre dikes are very homogeneous irrespective of their host rocks and clast population.

An additional difficulty in interpreting the Offset dikes as representing the bulk impact melt is the presence of significant and, in places, economic Ni–Cu sulfide deposits in the dikes. It is generally accepted that the sulfides, having twice the density than their silicate magma host, sank as droplets to the bottom of the magma chamber or the impact melt sheet floor from where they were intruded as Sublayer at the base of the exposed SIC. The sulfide differentiation process probably took considerably more time than the injection of an initial impact melt as dikes into the crater floor would take. If we believe that the sulfide deposits in the Offset dikes are the result of a differentiation process that also gave rise to the formation of the various units of the main mass of impact melt, the Offset dikes cannot represent the original bulk composition of the Sudbury impact melt. The existence of so-called internal offsets, of more than one phase of Offset quartz diorite in one dike and inclusions in the Offset dikes derived from the main mass SIC (Grant and Bite, 1984), is further reason to question presently accepted models. Grant and Bite (1984) also stated that the composition of quartz diorite rules out in situ precipitation of the sulfide present. "This, along with the correlation of sulphides with high xenolith populations suggests that the quartz diorite (the Offset) was not the source of the sulphides, but merely the transport medium" (ibid.).

Tuchscherer (2002) and Tuchscherer and Spray (2002) proposed that the Offset dikes had been emplaced downward, from the main impact melt body, in one single pulse during rebound and uplift stage of the impact process. Tuchscherer (2002) also stated that the Foy offset (North Range) had a chemical composition close to that estimated for bulk SIC. He did, however, not address the fact that South Range dikes have a different composition but tried to explain the presence of sulfide deposits in the Offsets. "They must have settled out as immiscible liquids very early in the evolution of the impact melt body" (ibid), after dike emplacement. This interpretation is problematic for the reasons stated above. Even more problematic in this respect is the dike emplacement process advocated by Murphy and Spray (2002), who envisioned lateral injection upon excavation of the transient cavity. As stated above, we believe that sulfide differentiation is a process taking considerably more time than the injection of an undifferentiated bulk SIC melt during the very early stages of the impact process.

Presently, it is not possible to combine all observational, analytical, and theoretical data. A comprehensive interpretation of the origin of the melt breccia dikes in Sudbury is still outstanding. The timing of the various emplacement processes is not well understood. However, we very well understand the dilemma we are in by accepting Vredefort Granophyre dikes as undifferentiated impact melt and by contesting the same origin for similar dikes in Sudbury.

The melt breccia dikes intruded after the formation of at least some of the pseudotachylites. This has been shown by Bisschoff (1972, 1996), who noted a Vredefort Granophyre dike that cuts through a wide pseudotachylite body. In addition, Tuchscherer (2002) described pseudotachylite clasts in the Foy Offset dike north of the Sudbury Igneous Complex. We have also observed large inclusions of Footwall Breccia in the Foy Offset Dike near its contact with the Sublayer of the SIC. This puts some further constraint on the sequence of breccia formation during the impact process. In contrast, Reimold et al. (1990) reported two minor occurrences of possible pseudotachylite crosscutting Vredefort Granophyre. These breccias could, of course, also have been related to late crater modification or some postimpact tectonic event.

6. Conclusions

We have shown that pseudotachylites (or pseudotachylitic breccias; Reimold, 1998) in the central parts below impact craters (e.g., in the Vredefort Dome) have a random distribution and orientation plan and that they commonly have steep to vertical dips. Mother lode dikes are accompanied by an irregular network of smaller dikes branching off it, leading to a plan view that resembles lightning flashes. Away from the center of large impact craters (Sudbury Structure), pseudotachylite formation may follow a more regular pattern. This may lead to the formation of large continuous or discontinuous pseudotachylite bodies possibly reflecting multiring structures and structures that have been linked to terrace collapse features along the inside of the walls of the excavation cavity.

Substantiating research on these rocks by other researchers and by us, we have also shown that pseudotachylite formation essentially is an in situ process. Pseudotachylite apophyses of large dike-like bodies are not necessary apophyses in sensu stricto but may be formed by a process we call “flash replacement melting”, whereby melting occurs through an explosive transfer of thermal shock energy in a manner that is similar to melting that leads to the formation of fulgurites. It may be initiated at lithological contacts, fractures or other heterogeneities in the target rocks but apparently spreads from there in a chaotic, explosive fashion.

Based on our work and that of others, we suggest that shock compression-related pseudotachylites are the first breccias formed in crater floor rocks, followed later (a relative term in the short, high-energy impact process) by polymict and authigenic, monomict clastic-matrix and melt breccia formation. Apparently, pseudotachylites are most common in the floors of very large impact structures. In midsize craters, they do occur (e.g., Ries crater) but are not common. In these lower-energy craters, polymict clastic-matrix breccia dikes occur instead of abundant pseudotachylites. For example, in the Ries impact structure, pseudotachylites have been observed in components of ejecta deposits but not in the cores of a deep drill hole that penetrated about 600 m into the crystalline basement rocks of the crater floor. At Morokweng (70–80-km diameter), at best, a few-centimeter-wide pseudotachylite veins were confirmed in a drill core penetrating the crater floor. Polymict clastic-matrix breccias seem to be most common in heterogeneous target assemblages (e.g., Slate Islands Structure) where contacts and heterogeneous rock properties facilitate brecciation. The authigenic, monomict clastic-matrix breccias are here interpreted to represent the lowest-energy impact breccias. In large structures, they commonly occur radially farther from the point of impact than peudotachylites and polymict clastic-matrix breccias, but may also be present at depth beneath pseudotachylite- and/or polymict clastic-matrix breccia-bearing target rocks in the center of impact structures. In smaller impact craters (amongst others Steinheim, Germany; Wells Creek, TN, USA; and Crooked Creek, MO, USA) they occur in the center and form parts of the central uplift.

The formation of Footwall Breccia, known from the Sudbury Structure, is not very well understood. It contains pseudotachylite-bearing clasts and fragments that are derived mainly from rocks of the underlying crater rocks. Brecciation and minor transport along the crater floor seems to have occurred prior to the emplacement of the impact melt sheet.

We have very little information that would argue against the emplacement of the Vredefort Granophyre dikes immediately following pseudotachylite formation. We cannot and do not wish to rule out that these dikes represent undifferentiated Vredefort bulk impact melt, because of the high degree of chemical homogenization observed. This is, however, in conflict with the interpretation of the Sudbury Offset dikes as an initial, predifferentiation bulk Sudbury impact melt, but it must be observed that the settings of the Vredefort Granophyre in the central uplift and of the Offsets in the environs of the Sudbury impact structure are different. Therefore, melt breccia dike formation and the relationship of these dikes to the main melt pools in impact craters require additional research. The assumption, that the Sudbury Offset dikes represent undifferentiated impact melt is based on too little evidence. Some geochemical and structural/intrusive considerations remain in conflict with this interpretation.

Impact breccias in the floors of impact craters are the result of specific processes. While pseudotachylites and clastic-matrix breccias in the crater floors below central parts of large impact structures apparently have chaotic distribution plans, pseudotachylite distribution around the crater depression possibly reflects multiring structures and terrace collapse features. Based on our own observations, pseudotachylites in the target rocks between the zones of strong brecciation (Dressler, 1984a; Peredery and Morrison, 1984) or between the rings of multiring basins (Spray and Thompson, 1995) apparently have again a more chaotic plan of distribution and orientation. The distal pseudotachylite bodies of the Sudbury Structure are interpreted to have formed through cataclasis and friction leading to complete or partial melting of the breccia matrix. This is similar to the formation of tectonic pseudotachylites.

Based on currently available information, there is a distinct order in what time sequence breccias are formed or emplaced in crater floors: (S-type) pseudotachylites—polymict clastic-matrix breccias, authigenic, monomict clastic-matrix breccias, and footwall breccias—impact melt breccias. So far, only minimal pseudotachylite brecciation has been noted in Vredefort Granophyres (Reimold et al., 1990). It could be related to some minor postimpact crustal readjustment, after complete lithification of the Granophyre. No such brecciation has affected the Sudbury Offset dikes that could be related to the late crater modification stages of the impact process. Several Offset dikes, however, are faulted, especially at large distances from the Sudbury Igneous Complex (SIC). Faulting north of the SIC may have occurred as a result of late crater modification; in the south, it is probably the result of postimpact tectonism. However, nowhere north or south of the SIC have pseudotachylites or other impact breccias been observed that affected Offset dikes.

We have shown that there is a general order in which specific breccia types are formed during the impact process. There also appears to be some order to the spatial distribution of specific breccia types, which is mainly based on shock energy attenuation; (S-type) pseudotachylites and/or polymict clastic-matrix breccias occur closer to the center of impact structures than low-energy authigenic, monomict clastic-matrix breccias. Clastic-matrix breccia formation may, in part, be related to a brecciation process for which the term "acoustic fluidization" has been coined (Melosh, 1989). It is not very likely that acoustic fluidization was responsible for pseudotachylite formation in the central parts of impact structures (e.g., Vredefort Dome). Acoustic fluidization, as presently envisioned, follows the passage of the shock wave, and we interpret that central pseudotachylites formation is due to a very early process for which we coined the term "flash replacement melting", a process in which wall rock is transformed—strictly in situ—into melt, without involvement of cataclasis and friction. The orientation of specific breccia bodies within their range of occurrence in the central crater floors is random, if not to say chaotic. Our knowledge of breccia formation in the country rocks beyond central uplift and excavation cavity is very sketchy. There are breccia bodies that possibly are related to terrace collapse and multiring features. However, we do not know with any degree of confidence how far away beyond crater rims, target rocks are brecciated. Further field-based research is needed in these outlying areas, especially in the collar rocks of the Vredefort Dome and, in Sudbury, at distances of more than 10–20 km north of the SIC. Insight gained from these regions will eventually provide the tools that will allow the impact researcher to better estimate the crater dimensions of deeply eroded impact structures where only a few impact breccia bodies may be preserved.

We are aware that much research is still needed to come to a good understanding of the processes that lead to the formation of breccias in the floors of impact structures. The various interpretations forwarded in our review will be challenged in the future. The illustrations and descriptions provided, however, will hopefully be taken in consideration in future field and laboratory research.

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