Chapter 4

Pseudotachylitic breccias, other breccias and veins

4.1 Introduction

Pseudotachylitic breccias can be described as rare, clast-bearing melt rocks with a generally glassy or microcrystalline matrix, occurring in veins or irregular geometries, that contain angular to rounded clasts of wallrock lithologies (e.g., Stöffler and Grieve 1994). Pseudotachylites are most commonly found as millimetre- to centimetre-wide veinlets in normal tectonic settings, such as in shear zones or along faults (e.g., Maglaughlin and Spray 1992, and references therein). However, similar breccias are also present at some impact sites (e.g., Dressler and Reimold 2004) around the world where cumulative and individual breccia volumes may be exceptional (at Sudbury - Dressler 1984; Grieve et al. 1991 and at Vredefort - Reimold and Gibson 2005, 2006, and other references therein). Smaller occurrences of such breccias have been found at some smaller impact structures, such as Rochechouart in France (Reimold et al. 1987), the Nördlinger Ries in Germany (e.g., Dressler and Graup 1969), and the Manicouagan Structure in Canada (e.g., Dressler 1970). For a comprehensive review of such breccias in impact structures, refer to Dressler and Reimold (2004).

The Vredefort Dome became the type locality for pseudotachylite (original spelling "pseudotachylyte" - Shand 1916) long before it was recognised that the dome was formed as a consequence of impact. Shand (1916) noticed that the "dyke- and vein-like rocks" showed similarities to tachylite, a volcanic glass, and concluded that these melts did not form by shearing but by shock. Besides evidence of "pseudotachylites" in impact settings, pseudotachylites are also found in tectonic settings and have even been reported from landslides (Masch et al. 1985). Some workers (e.g., Philpotts 1964; Maglaughlin and Spray 1992 and references therein) argued for a formation by frictional fusion, while others (e.g., Wenk 1978; Maddock 1986; Swanson 1992) related the formation of pseudotachylites to cataclasis in the brittle upper crust at high strain rates during seismic slip events. Spray (1992, 1998) demonstrated in physical experiments that cataclasis and frictional sliding both contribute to the genesis of pseudotachylites. He also demonstrated that frictional melting depends on the shear strength and fracture toughness of rock-forming minerals in the host rocks. Melting is facilitated by the presence of hydrous mineral phases (Reimold 1991 and references therein). Despite this work and the evidence of formation of pseudotachylites by normal tectonic processes, some authors continue to suggest that pseudotachylites are diagnostic for an impact event (most recently, Bland 2003). In response to the contested nature of breccia genesis in impact settings, Reimold (1995, 1998) introduced the term *pseudotachylitic breccia* to describe those breccias for which no genetic information was available, but which could have been produced either during tectonic or impact processes, by friction or shock melting.

As part of this project, pseudotachylitic breccias were investigated in the collar of the Vredefort Dome, with particular emphasis on structural and geometric relationships to other structures in the collar rocks (such as folds, faults, fractures, see Chapter 2). Furthermore, in an attempt to contribute to the debate over whether pseudotachylitic breccias represent shock or frictionally generated melts, simple 1-dimensional cooling calculations were conducted in order to approximate if veins with different compositions and thicknesses that were formed in the early stages of the cratering process could have remained molten long enough to fill dilational sites created during central uplift formation.

4.2 Previous work

Shand (1916) defined *pseudotachylite* as a breccia with a black aphanitic groundmass, which he observed abundantly in the Archaean gneisses in the core of the Vredefort Dome. He speculated that the pseudotachylite had formed by melting of the surrounding granites, caused by shock or, as an alternative, by gas fluxing. Many workers have described specific breccias from the dome as having formed by shock processes (e.g., Bisschoff 1962; Wilshire 1971; Martini 1978, 1991; Schwarzman et al. 1983; Gibson et al. 2002; Dressler and Reimold 2004; Gibson and Reimold 2005). Others postulated a combination of friction and shock melting in general for pseudotachylites in impact structures (e.g., Kenkmann et al. 2000; Langenhorst and Poirier 2000; Dressler et al. 2001; Langenhorst et al. 2002). A detailed review of the controversy is given by Reimold (1995, 1998).

Pseudotachylitic breccias are the most ubiquitous outcrop-scale impact-related feature in the Vredefort Dome and have been described by many authors throughout the last century (e.g., Shand 1916; Hall and Molengraaff 1925; Nel

1927a-c; Willemse 1937; Bisschoff 1962; Fletcher and Reimold 1989; Killick and Reimold 1990; Reimold and Colliston 1994; Gibson et al. 1997; Dressler and Reimold 2004). Occurrences of pre-impact pseudotachylitic breccias in the Vredefort Dome and local evidence for the presence of more than one generation were reported by several authors (e.g., Killick and Reimold 1990; Killick 1993; Reimold and Colliston 1994). Reimold et al. (1990) also reported thin veinlets of pseudotachylitic breccia cross-cutting the Vredefort Granophyre (although this was disputed by Bisschoff 1996) and Reimold and Colliston (1994) discussed shatter cones superimposed on pseudotachylitic breccias (see section 3.2). These observations necessitate the conclusion that formation of these breccias occurred both before and after the Vredefort event. Given the variety of lineated fractures in the dome (for instance, curved pseudotachylitic breccia surfaces show, in places, slightly splayed striations), the features observed by these authors may not be true "shatter cones"; alternatively, it may imply that the pseudotachylitic breccia vein is shock-induced and that the shatter cones might be seconds younger (given a "late shock" origin for shatter cone formation, see sections 3.2 and 6.2.4). Although no such relationship was observed during this study, the possible implications of these observations are discussed in the following sections, in particular in the light of the cooling calculations for melts (see section 4.4).

Gibson and Wallmach (1995) and Gibson et al. (1997) showed that the pseudotachylitic breccias in the metapelites in the inner collar of the Vredefort Dome can be constrained to the impact event, based on an analysis of metamorphic mineral parageneses. These studies showed that the metapelites were metamorphosed to mid-amphibolite facies grade between 2.05 and 2.06 Ga, which corresponds to the Bushveld magmatic event. The breccias cut and include minerals formed during this event but they are, in turn, overprinted by a lower-grade paragenesis formed in response to shock heating (Gibson et al. 1997) that also caused annealing of shock microdeformation features. The model of Gibson et al. (1997) gives, thus, a narrow timeframe for the formation of the pseudotachylitic breccias in the Vredefort Dome. Argon-Argon ages of pseudotachylitic breccias in the wider Witwatersrand Basin (see summary in Reimold et al. 1995; Friese et al. 2003; Reimold and Gibson 2006 and references therein) are also consistent with a 2.02 Ga, syn-impact timing.

The specific parameters influencing the formation of the impact-related pseudotachylitic breccias (e.g., rock melting temperature, degree of superheating, etc.), which are discussed in detail in section 4.4, are largely influenced by the shock heating during the impact event. The current view suggests a normal thermal gradient in the crust prior to the impact (~18-20°C/km) in the central Kaapvaal Craton (Grieve et al. 1990; Martini 1992; Gibson and Jones 2002), indicating that the pre-impact temperature ranged from about 150°C in the Central Rand Group (at a depth of ~7-8 km) to ~300°C in the West Rand Group (at a depth of ~13-15 km). The pseudotachylitic breccias, however, must have formed during or after the input of the shock heat and the post-shock metamorphic temperatures are significantly higher than expected from the pre-impact crustal gradients (Gibson et al. 1998). Thus, based on the mineral assemblages in the metapelites in the dome (granulite facies in the centre and lower amphibolite to greenschist facies in the collar, Gibson et al. 1998), the impact-induced thermal overprint must have resulted in temperatures in the outer and inner collar rocks of ~300°C to 525°C, respectively (Gibson et al. 1998; Gibson and Jones 2002). Recent studies (e.g., Gibson 2002) also suggest that the elevated background temperatures in the rocks of the Vredefort Dome were largely derived from the geothermal gradient and the differential shock heating rather than by impact melt heating of the basement.

4.2.1 Classification of pseudotachylitic breccias in impact structures

Martini (1978, 1991) found coesite ± stishovite in pseudotachylitic breccias in Central Rand Group quartzites in the northeastern and northern parts of the collar. He postulated a shock origin for these veins, arguing that the localised high temperatures needed to induce melting were caused by a combination of shock-induced collapse of pre-existing joints and frictional heating achieved by differential acceleration of the wallrocks flanking these joints during the shock compression phase. He described this type of pseudotachylitic breccia as “A-type pseudotachylite”. However, he felt that the more voluminous (according to him, anything ≥1 mm width) pseudotachylitic breccias in the dome, which comprise the bulk of the occurrences and which appear to lack associated shock diagnostic features, were produced by post-shock (decompressional) melting along faults formed after the propagation of the shock wave through the target rocks or during the rise of the central uplift during the modification phase (so-called “B-type pseudotachylite”, Martini 1991). Reimold et al. (1992), however, raised doubts whether a subdivision into “A-type” (<1 mm) and “B-type” (>1 mm) pseudotachylites would be valid at all. Spray (1998) suggested that impact-related pseudotachylitic breccias could be divided into “endogenic (E)-type” and “shock (S)-type" pseudotachylites. According to him, S-type pseudotachylites were formed by friction and shock melting during the compression phase of the cratering process and the E-type breccias formed by friction during the modification phase in a way similar to the formation of pseudotachylites in normal tectonic settings, but possibly on a larger scale.

Spray (1997) suggested that the highly voluminous breccias found in the Sudbury and Vredefort structures, which are orders of magnitude larger than any tectonic breccias, were formed along so-called *superfaults* triggered by impacts. Proof of the presence of such faults and of a clear genetic relationship with the breccias remains elusive in the Vredefort Dome and at Sudbury (e.g., Lieger, D., MSc Thesis, 2005). Whilst small amounts of slip are commonplace on breccia-bearing fractures (Reimold and Colliston 1994; Gibson et al. 1997, 2002), no consistent relationship between volume of breccia and slip magnitude has been found (Reimold and Colliston 1994; Gibson et al. 1997; Dressler and Reimold 2004; this study). However, pseudotachylitic breccias up to metres thick are also observed in the goldfields of the Witwatersrand Basin around the Vredefort Dome (e.g., Killick and Reimold 1990; Killick 1993; Reimold et al. 1999) showing clear spatial and genetic relationships to large-scale faults that dip towards the centre of the Vredefort Dome. These are likely listric normal faults related to collapse of the crater rim and would correspond to Spray’s (1997) superfaults, but the breccia volumes are considerably smaller than those envisaged by him (see Reimold and Gibson 2006, for a full review and section 2.2).

4.2.2 Occurrence and timing of pseudotachylitic breccias in the Vredefort Dome

Pseudotachylitic breccias in the Vredefort Dome typically occur as millimetre- to metres-wide veins and pods and in the form of network breccias (e.g., Killick and Reimold 1990; Reimold and Colliston 1994; this work). The thin veinlets form pervasive vein-fracture networks in almost all rock types in both the core and the collar of the dome. In places in the core of the dome, the breccias occur in dykes of more than several hundred metres length and tens of metres width (Reimold and Colliston 1994; Dressler and Reimold 2004) (Figs. 4.1a and b). The largest dykes occur between 8 and 14 km from the centre of the dome, but volumetrically smaller pseudotachylitic breccias are also found in the central area of the dome (Gibson et al. 2002; Gibson and Reimold 2005). Gibson and Reimold (2005) speculated that this distribution may be linked to the progressive increase in shock pressures experienced by rocks towards the centre of the dome, with the proportion of shock-induced melting in discrete zones to generate pseudotachylitic breccias increasing radially inwards until the point where diaplectic glass formation from feldspars leads to dampening of extreme small-scale shock variation. According to them, this point is reached between 8 and 10 km from the centre of the dome.

Dressler and Reimold (2004) introduced the term “flash replacement melting” for the pseudotachyilitc breccia-forming process during which the wall rock is transformed into melt through “explosive transfer of thermal shock energy from ground zero without material flow (i.e., injection)”. Displacement along some pseudotachylitic breccia veins in the collar and core of the dome was reported by several authors but is generally less than 0.5 m and typically less than a few millimetres (e.g., Gibson et al. 1997; Dressler and Reimold 2004; Reimold and Gibson 2005, 2006).

In almost all cases where pseudotachylitic breccias are found, they contain clasts of variable sizes derived from the direct wallrock lithologies. Some authors (e.g., Bisschoff 1962; Reimold and Colliston 1994) observed exotic clasts in large pseudotachylitic breccia occurrences in the core of the dome, indicative of transport of these clasts over at least some tens of metres and, thus, at least similar amounts of movement of the melt away from its location of formation.

Recent field and petrographic studies (e.g., Gibson et al. 2002; Dressler and Reimold 2004; Gibson and Reimold 2005) suggest a correlation between overall breccia volumes and shock pressure in different parts of the dome and, thus, that most, if not all, of the pseudotachylitic breccias in the dome could have formed during the shock compression phase. However, in the light of the evidence of offset along the margins of breccia veins, and the *bona fide* friction melts that occur

Fig. 4.1: Typical appearance of massive pseudotachylitic breccia in Archaean gneisses of the core of the dome. (a) Leeukop Quarry, ca. 4 km northwest of Parys and (b) Salvamento Quarry, a few hundred metres to the north of (a). Length of hammer in (b), ca. 35 cm.

outside the zone of shock metamorphism in the goldfields along the outer limb of the rim syncline west of Johannesburg and in the Klerksdorp goldfield (Fletcher and Reimold 1989; Killick and Reimold 1990; Killick 1993; Reimold and Gibson 2006 and references therein), it is not possible to rule out the possibility of a friction melt origin for at least some of the pseudotachylitic breccias in the fault zones of the collar of the Vredefort Dome.

4.2.3 Geochemical and petrographic observations of pseudotachylitic breccias

Geochemical studies of the matrices of pseudotachylitic breccias found in impact structures indicate that their chemical compositions are similar to those of the surrounding rocks (e.g., Dressler 1984; Reimold 1991; Dressler and Reimold 2004). The vein fillings studied in these investigations consist of a microcrystalline groundmass and inclusions of host rock material that range from sub-millimetre to decimetre-size. In quartzite-hosted veins these clasts consist of strongly recrystallized quartz, in metapelite-hosted veins, part of the pre-impact mineral paragenesis of the metapelites is found in the veins as well (see Bisschoff 1982; Gibson and Wallmach 1995; Gibson et al. 1997). The quartz clasts do not seem to show any evidence of microdeformation, such as PDFs, as found in the wallrocks (e.g., Lilly 1981; Martini 1991; White 1993; Gibson et al. 1997). The latter authors suggested that the PDFs in these clasts, if they were present, might have been annealed during crystallization of the vein or, more likely, during the subsequent metamorphism. They also reported that, in many cases of metapelite-hosted pseudotachylitic breccias, the pseudotachylitic breccia matrix is entirely replaced by fine-grained cordierite-biotite, biotite-chlorite-muscovite or chlorite-muscovite parageneses, depending on the grade of post-shock metamorphism, which decreases with increasing radial distance from the centre of the dome.

Comparisons of matrices of veins up to 5mm and thin veinlets (~1 mm) led to the conclusion that the similarity in composition with the host rock is not dependent on the width of the pseudotachylitic breccia, suggesting an *in situ* formation of even the fillings of thicker veins (Dressler and Reimold 2004).

Offshoots of thin veinlets from thicker veins (so-called “mother lode” veins; Dressler and Reimold 2004) are common (e.g., Dressler 1984; Reimold 1991).

Fig. 4.2: Microphotographs of centimetre-wide pseudotachylitic breccia veins in metapelitic rocks of the northern part of the collar (on farm Donkervliet, location 432, see Appendix No. 6). (a) Flow folds in the matrix indicate migration of the melt. Note the generally sharp contact between host rock and pseucotachylitic breccia, represented by a layer of black melt (arrows). (b) Isoclinal fold within the matrix of the vein (vertical in centre of image), represented by intercalated layers of melt with possibly different compositions and clast content. The right limb of the fold is sheared out.

However, the usually homogeneous composition (Dressler and Reimold 2004) of these offshoots did not allow distinction to be made between an *in situ* formation or injection of these veinlets from the mother lode vein. Recent studies by Dressler and Reimold (2004) showed that the microcrystalline groundmass of these veins reflects the average mineral assemblage of the respective host rock, which was taken as further evidence for an *in situ* formation for these veins. This interpretation is supported by an observation by the same authors from the core of the Vredefort Dome, where a thin vein (~1 cm) cuts across different rock types. The colour of the vein changes abruptly when crossing from a grey gneiss into a white aplite vein, reflecting chemical compositional variation of the vein filling.

Evidence for melt and clast mobility in pseudotachylitic breccia veins was presented by many authors (e.g., Gibson et al. 1997; Dressler and Reimold 2004; this study). This evidence includes the presence of clasts that must derive from a certain distance (of up to several tens of metres, see Reimold and Colliston 1994) and of flow textures within the matrix of pseudotachylitic breccia veins (Gibson et al. 1997; Dressler and Reimold 2004). Although flow and mixing was observed

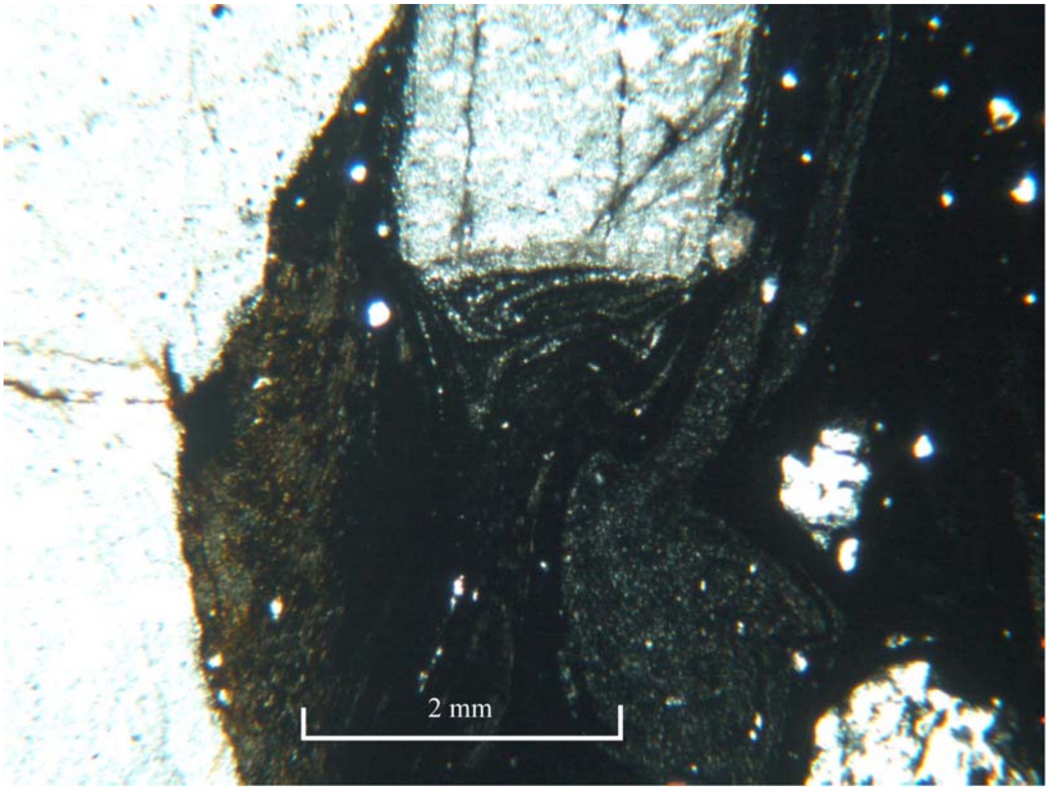

Fig. 4.3: Microphotograph of a cm-wide pseudotachylitic breccia vein in metapelitic rocks in the northern part of the collar (farm Donkervliet, location 432, see Appendix No. 6) showing flow folding around a polycrystalline quartz clast (bottom part of large fragment at top of photograph).

during this study at a millimetre-scale, as illustrated in Figures 4.2. and 4.3, the observation of cm- to dm-scale flow folds in previous studies (e.g., Gibson et al. 1997) suggests that migration of melt must have occurred on a much larger scale as well. Isoclinal folds are observed in the matrix of some veins (Fig. 4.2b) that consist of intercalated layers of different compositions and fine-grained host rock inclusions. One limb of the fold is sheared out (right limb in Fig. 4.2b).

4.3 Observations on pseudotachylitic breccias during this study

4.3.1 Distribution of pseudotachylitic breccias

Pseudotachylitic breccias are ubiquitous in the collar rocks in the Vredefort Dome, although they are not as voluminous and obtrusive as in the core of the dome. They are observed in the well-exposed quartzite and in the metapelite units of the Witwatersrand Supergroup, as well as in the alkali granite intrusions (see Figs. 1.11 and 1.12), and even in the Ventersdorp and Transvaal supergroups in the outer parts

Fig. 4.4: Example of cm-wide pseudotachylitic breccia veins from the northern part of the collar (location 341, see Appendix No. 6) in quartzite of the Turffontein Subgroup. At the top of the photograph the vein is bedding-parallel (bedding marked with arrows), but veins with oblique (left part of photograph) and perpendicular orientations (bottom part of photograph) are also present. For scale, length of pen ca. 10 cm.

of the dome (e.g., Fletcher and Reimold 1989; Reimold and Gibson 2006).

The overall volume of pseudotachylitic breccia and the size of individual occurrences decrease radially outwards through the Witwatersrand Supergroup rocks, but veins up to several centimetres thick are still found in the Ventersdorp Supergroup rocks and, more rarely, in the Transvaal Supergroup.

Localised and irregularly distributed veins were observed during this study in the rocks of both the Johannesburg and Turffontein subgroups. These veins seldom exceed a few metres in length and a few centimetres in width. They are commonly bedding-parallel, but show offshoots with variable orientations with regard to the bedding. The example in Fig. 4.4 shows that the pseudotachylitic breccias in the outer collar typically occur as veins up to a few centimetres wide (northern collar, location 341, see Appendix No. 6). The orientations of these veins with respect to the bedding range from parallel (upper part of image) to oblique (left part) and perpendicular (bottom part). All these veins are cut by the centimetre-spaced sets of parallel dilational fractures that are believed to have formed during the collapse of the central uplift (see section 2.7 and Chapter 6).

4.3.2 Morphology of pseudotachylitic breccias

In the vicinity of large-scale faults, pseudotachylitic breccias seem to be randomly oriented with regard to bedding. They typically do not exceed widths of a few centimetres but can, in places, reach widths of up to ~10 cm and can be traced locally over several tens of metres (e.g., observed at Smilin Thru in the northern collar, locations 28 to 30, see Appendix No. 6). These pseudotachylitic breccias occur as curved and anastomosing veins. More voluminous pseudotachylitic breccias are especially prominent in the hinge zones of large-scale folds (see section 2.5) where they occur as irregular, centimetre- or decimetre-thick veins and pods, commonly in a network pattern (e.g., Fig. 4.5). They typically do not show regular orientations with regard to the fold hinge, which is consistent with the irregular distribution of the extensional fractures within the hinge zone that they follow (Fig. 4.5). The extensional fractures that occur in the faulted and displaced fold hinges suggest that these veins may have intruded these dilational sites during the formation of these folds (see section 2.5). This pattern of prominent pseudotachylitic breccia occurrence

Fig. 4.5: Network-like pods and veins of pseudotachylitic breccia with irregular orientations with regard to bedding in a large-scale fold hinge (fold structure C, see section 2.4.2, locations 521-538, see Appendix No. 6) in the northwestern part of the collar. The veins appear to fill extensional sites within the fold hinge (for scale information, length of pen in (a) ca. 10 cm, of compass in (b) ca. 7 cm).

is strictly limited to a narrow zone in the fold hinge and is absent on the limbs of the fold structures, where only millimetre- to centimetre-wide, predominantly bedding-parallel veinlets are present. Figures 4.5a and b show features of the intensely fractured fold hinge of fold C (see section 2.5.3) in the northwestern part of the collar (locations 521-538, see Appendix No. 6).

Figure 4.6 shows the most commonly observed pattern of pseudotachylitic breccia occurrences, typically as millimetre- to centimetre-wide veinlets parallel to the bedding (location 817, see Appendix No. 6). Offshoots with variable orientations to the main vein occur as thin veins or small pods that seem to crosscut each other (Fig. 4.6). Apart from the irregularly oriented pseudotachylitic breccias in the vein networks in fold hinges, the dominant orientation of thin (mm) veins in the inner collar (West Rand Group) of the Vredefort Dome seems to be bedding-parallel and oblique to bedding. In the middle to outer collar (Central Rand Group, Ventersdorp Supergroup) the veins seem to be equally oriented parallel and oblique to bedding/layering. A definite change of the orientation pattern of pseudotachylitic

Fig. 4.6: Pseudotachylitic breccia veins close to a large-scale fault in the northern part of the collar on farm Donkervliet (location 817, see Appendix No. 6). Offshoots from the main, bedding-parallel vein (between arrow-points) show variable orientations with regard to the bedding and seem to crosscut each other (pocket knife for scale, ca. 7 cm long).

breccias from the inner to outer collar, however, cannot be confirmed, as the abundance of veins decreases with increasing distance from the dome centre, making it impossible to obtain a quantitative dataset.

The observation that large volumes and networks of pseudotachylitic breccia are less abundant in the strata in the outer parts of the collar may be explained by a decrease of shock pressure and temperature and/or by the fact that the slip magnitude along faults decreases with increasing distance from the center, consistent with the decreasing tangential shortening (see section 2.4.1).

4.3.2.1 Pseudotachylitic breccias in quartzite units

Away from the zones of structural complexity (such as fold hinges and fault zones), pseudotachylitic breccias generally occur in the collar rocks both parallel and oblique to bedding. Bedding-parallel veins are commonly only up to a few centimetres thick, but in several cases have been observed to be up to 20 cm wide (e.g., on farm Kommandonek in the northwestern part of the collar, locations 382-401, see Appendix No. 6). Individual veins can be traced for at least several metres, but sometimes for several hundreds of metres (up to 500 m, see Nicolaysen and Reimold 1999; this study – in Hospital Hill quartzite on farms Kommandonek and Donkervliet in the northwestern and northern collar, respectively). Such bedding-parallel veins commonly have orthogonal or oblique offshoots filling joints at a high angle to bedding (Fig. 4.7a). The orthogonal offshoots in Figure 4.7a observed on farm Mooihook in the northeastern collar have radial strike orientations with respect to the core of a gentle fold and away from it, consistent with intrusion of the pseudotachylitic breccia veins into extensional sites that opened up during the formation of this fold. These offshoots usually terminate after a few tens of centimetres.

Pseudotachylitic breccias with oblique orientations to bedding are not as common as bedding-parallel veins in the quartzite units in the Vredefort Dome, but can be observed locally, such as the vein in Figure 4.7b on farm Koedoesfontein in the northern part of the collar (location 294, see Appendix No. 6). These veins do not reach more than a few tens of centimetres in length and a few centimetres in width. They are not related to visible thicker veins, bedding- or fracture-parallel veins and/or offshoots, but seem to be single, localised features in the collar rocks. Discernable

Fig. 4.7: (a) Bedding-parallel pseudotachylitic breccia vein in folded quartzite in the northeastern part of the collar on farm Mooihook (location 723, see Appendix No. 6). This vein shows orthogonal and oblique offshoots, towards and away from the core of the fold. (b) Pseudotachylitic breccia vein perpendicular to undisrupted bedding surface in Hospital Hill quartzite in the northern part of the collar (location 294, see Appendix No. 6). Such veins are typically only a few centimetres in width and not longer than a few metres, and do not show any kinematic indicators. Plan view onto the bedding.

movement indicators that could be associated with these oblique veins (such as *en echelon* structures) are lacking.

4.3.2.2 Pseudotachylitic breccias in metapelite units

Pseudotachylitic breccias oriented perpendicular to the bedding are rare in the quartzites apart from fold hinges or vicinity of faults (see sections 2.5 and 2.6), but are more common in metapelitic units, where they occur as vein networks and are usually less than a few millimetres wide (Reimold and Colliston 1994; Gibson et al., 1997) (Fig. 4.8a and b). Some of these veins in the metapelites have offshoots that clearly intruded extensional fractures that opened up on either side of the vein (see also Gibson et al. 1997). They also occur in fractures that show millimetre- to centimetre-scale displacements consistent with either bedding-parallel extension or compression tangential to the dome (Fig. 4.8b). This pseudotachylitic breccia vein shown in Fig. 4.8b is associated with a kink band in the metapelite and follows the orientation of the kink band. Vein-fracture networks may display a fracture spacing of centimetres to a few tens of centimetres, approaching the intensity of a spaced cleavage (Gibson et al. 1997). Vein thicknesses increase, in places, up to 10-20 cm along the contacts between arenaceous and argillaceous sedimentary rocks and massive meta-diabase sills (so-called epidiorites), where metre-wide pods of network breccias are locally observed. The main veins usually strictly follow the contact, but offshoots from these pods can be found locally in both lithologies (e.g., Dressler and Reimold 2004 and references therein). In cases where these contact-parallel veins cross-cut mafic sills, they seem to be preferentially developed in the more mafic rocks (Reimold and Gibson 2006). Reimold (1991) suggested that the greater presence of hydrous ferromagnesian phases in the more mafic material is responsible for its preferred melting. Gibson et al. (1997) also reported that the pseudotachylitic breccias in the metapelitic units of the Hospital Hill and Government subgroups fill fractures that cut the porphyroblastic peak metamorphic assemblages. This indicates formation of fractures and pseudotachylitic breccias after the development of the peak metamorphic assemblage.

Pods of pseudotachylitic breccia ranging from a few millimetres to tens of centimetres in width are locally observed along fractures with orientations both parallel to bedding and at high angles to it (Fig. 4.9a,b).

Fig. 4.8: (a) Cm-wide pseudotachylitic breccia vein in a metapelite unit in the northern part of the collar (farm Donkervliet, location 17, see Appendix No. 6). The vein fills a fracture that cross-cuts the bedding over >1 m exposure. The pseudotachylitic breccia vein is associated with a brittle kink band in the metapelitic rock. (b) Close-up of the kink band in (a). The pseudotachylitic breccia vein seems to follow the orientation of the axial plane of this fold. Length of pen, ca. 10 cm. Both photographs courtesy of R.L. Gibson.

Fig. 4.9: (a) Small pod of pseudotachylitic breccia in Government Subgroup quartzite in the northern part of the collar (location 22, see Appendix No. 6) developed along a bedding-parallel fracture. Box marks the area shown in Fig. 4.10a. (b) Pod of pseudotachylitic breccia in Hospital Hill quartzite in the northwestern part of the collar (Kommandonek, location 384, see Appendix No. 6). View onto the bedding plane.

4.3.3 Structural relationships of pseudotachylitic breccias with other structures in the collar strata

Based on their work in the crystalline basement core of the dome, Reimold and Colliston (1994) concluded that, in many cases, pseudotachylitic breccia veins exploit pre-existing heterogeneities in the host rock, such as faults, foliations, lithological contacts and shear fractures. This observation is also valid for the collar rocks, where the veins, at least in the quartzite units, are observed predominantly parallel to bedding and where veinlets, as well as sizeable networks, are observed along fracture or bedding surfaces and lithological boundaries between, for example, epidiorite and shale, or quartzite, units. However, large pseudotachylitic breccias show a more complex outcrop-scale pattern (network breccias) within the hinge zones of large-scale folds and in the vicinity of large-scale faults that were formed during the impact (see also sections 2.5, 2.6, 4.3.2 and Fig. 4.4). Veins with oblique trends to the bedding have also been observed. These veins are typically parallel to obliquely trending (with regard to bedding) shear fractures (Gibson et al. 1997; this work). A consistent geometry for these shear fractures and, hence, the veins throughout the collar of the Vredefort Dome, however, could not be established.

These shear fractures commonly contain submillimetre-sized veinlets of pseudotachylitic breccia, especially in the metapelitic successions of the Witwatersrand Supergroup, where the occurrence of such fractures is very dense and reaches, in places, the intensity of a spaced cleavage (see section 2.7). Prime localities for the investigation of such breccia-filled fractures are found on farms Donkervliet (location 11, see Appendix No. 6) and Kommandonek (locations 396-401, see Appendix No. 6 and, e.g., Fig. 2.34) in the northwestern collar, respectively.

Evidence for movement (flow) of melt is present in thick pods and veins of pseudotachylitic breccia in the form of flow laminations and bands in the matrices of these veins (Figs 4.10a,b). Figure 4.10b shows a strongly weathered example of a decimetre-wide pseudotachylitic breccia vein in Government Subgroup quartzite in the northern part of the collar (location 277, see Appendix No. 6). Important to note in Figure 4.10b is the conjugate fracture set towards the right of the photograph that cross-cuts the vein, suggesting a formation of these fractures after melt formation (see section 2.7).

Fig. 4.10: Flow textures in pods and thick veins of pseudotachylitic breccias. (a) Close-up of the thin pod in Hospital Hill quartzite shown in Fig. 4.9a from the northern part of the collar (location 22, see Appendix No. 6). The pod shows a thin, dark-grey rim and light-grey and white laminations in the central part (for scale, length of pen ca. 2 cm). (b) Flow bands in a centimetre-wide pseudotachylitic breccia vein in weathered quartzite of the Government Subgroup (northern part of the collar, location 277, see Appendix No. 6). Note the conjugate fractures cross-cutting the vein towards the right of the photograph. Length of pen ca. 4 cm.

Although evidence of displacement along veins is generally rare in the quartzites, it is more common in the metapelites (Gibson et al. 1997). In a few cases the veins occur in *en echelon* tension gash arrays (Fig. 4.11) extending either parallel, or up to 60° oblique, to bedding. The pattern of tension gash arrays and the flow textures in bedding-parallel veins indicate movement parallel to bedding surfaces (in the case of Figure 4.11, the shear sense is sinistral). However, no consistent sense of movement along the bedding (sinistral or dextral) could be established throughout the collar, and vertical movement cannot be ruled out (see section 2.4). The example shown in Figure 4.11 was found within a few metres of a large-scale (hundreds of metres) left-lateral fault in the northern part of the collar on farm Donkervliet, indicating a possibly similar time of formation for the large-scale faults and the movements along these veins. Although these faults are not oriented parallel to bedding, well-developed examples of pseudotachylitic breccias occurring in an *en echelon* pattern close to large-scale faults can be found, e.g., on farm Smilin Thru in the northern part of the collar (locations 28 to 30, see Appendix No. 6, Fig. 4.12a). There, cm-thick veins are oriented with various orientations (parallel and oblique) to

Fig. 4.11: Plan view photograph of a ca. 1 cm thick bedding-parallel pseudotachylitic breccia vein in Hospital Hill quartzite from the northern part of the collar (on farm Donkervliet, location 817, see Appendix No. 6) showing *en echelon* tension gashes indicating a sinistral sense of movement. North is to the right. For scale, length of pocketknife ca. 7 cm.

Fig. 4.12: (a) Enlargement of 1: 25 000 aerial photograph (for flight details, see Appendix No. 1b) of a large-scale fault in the northern collar (locations 28, 35, 36, see Appendix No. 6). The fault produced a drag-fold in the quartzite strata indicating a right-lateral sense of movement. White box indicates the zone of pseudotachylitic breccia occurrence (oriented parallel and oblique to bedding). (b) and (c) Lower hemisphere equal area stereographic projections (Schmidt net) of bedding orientation to the east (b) and to the west (c) of the fault. Great circles indicate the average bedding orientation on the limbs.

bedding within a 200m zone ~100 m east of a large-scale radial right-lateral fault (Fig. 4.12a).

A homoclinal fold in the quartzites of the Hospital Hill Subgroup is disrupted and displaced by this fault in a right-lateral sense (Figs. 4.12a, b and c). Whether the formation of pseudotachylitic breccia veins in bedding-parallel *en echelon* tension gash arrays can be related to the movement along the fault or to the folding of strata, could not be conclusively established by field evidence. The temporal relationship between fold and fault indicates that folding probably slightly preceded faulting, as discussed in sections 2.2.6 and 6.2.1.

The thin pseudotachylitic breccia veinlets in the collar rocks are cut, but only rarely displaced, by subvertical, radial fractures. In particular, thin bedding-parallel veins of up to 1 cm width are regularly cut by these fractures. In a few cases the fractures show displacements of millimetres up to several centimetres, with either dextral or sinistral apparent dip-slip displacement (Fig. 4.13). These fractures are observed cross-cutting pseudotachylitic breccia veins in both quartzite and metapelitic units (see also Gibson et al. 1997) and are also visible microscopically (Fig. 4.14)

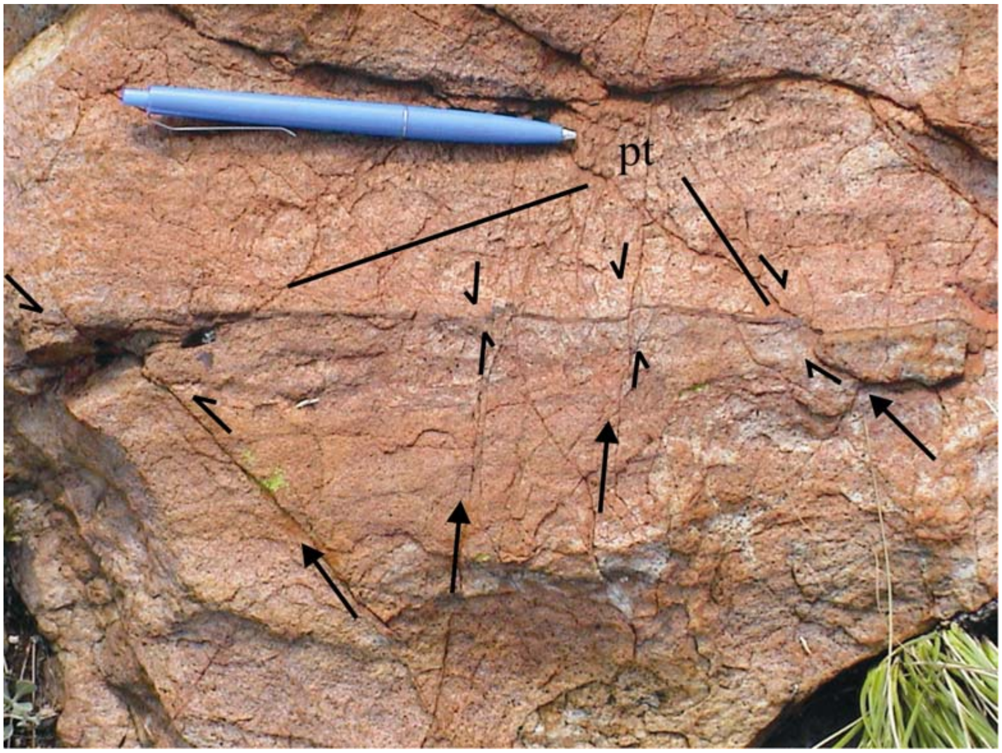

Fig. 4.13: Photograph of thin (< 1 cm) pseudotachylitic breccia veins in Hospital Hill quartzite cut and displaced by shear fractures (arrows). Plan view onto the bedding surface, northern part of the collar on farm Smilin' Thru (location 48, see Appendix No. 6), length of pen ~ 10 cm. North is towards the top of the photograph.

penetrating either the entire width of the vein (upper fracture in Fig. 4.14) or terminating, in places, against obstacles in the matrix, such as clasts (bottom fracture in Fig. 4.14).

Evidence for relationships between pseudotachylitic breccias and other structures in the collar rocks, such as folds ranging in size from a few metres to hundreds of metres and faults, was presented in the previous sections and chapters (see sections 2.5, 2.6 and 4.3.2). A genetic relationship between pseudotachylitic breccias and shatter cones was not found during this study (see Chapter 3). Pseudotachylitic breccias and shatter cones were found during this study commonly at the same location, but in no case was a shatter cone observed superimposed on a pseudotachylitic breccia vein, as the single case previously reported by Reimold and Colliston (1994) and the similar observation by Simpson (1981).

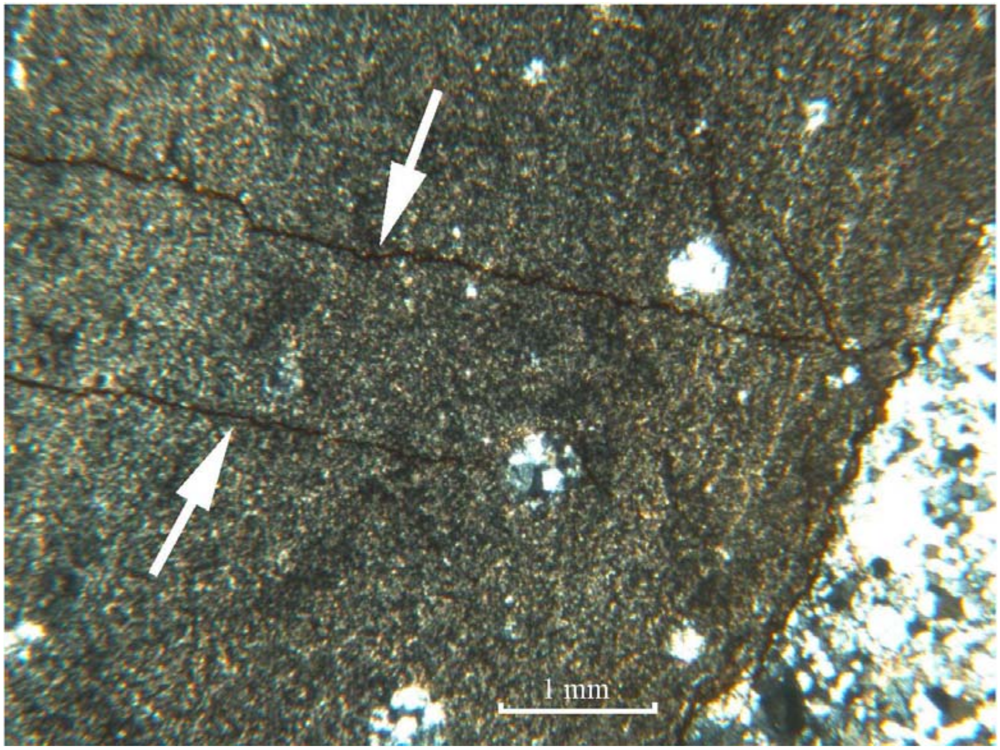

Fig. 4.14: Microphotograph of fractures (arrows) cutting through a cm-wide pseudotachylitic breccia vein in quartzite in the northern part of the collar (farm Donkervliet, location 817, see Appendix No. 6). Note also the fractures along the edge of the vein and transecting the vein in a NNW direction (at the top right of cross-cutting fracture).

4.4 Timing of breccia formation

The controversy about the timing of formation of pseudotachylitic breccias has been introduced above (section 4.2). Although 2.02 Ga ages for some of the pseudotachylitic breccias in the Vredefort Dome and the wider Witwatersrand Basin were determined by several authors (e.g., Trieloff et al. 1994; Spray et al. 1995; Kamo et al. 1996), some authors have previously postulated that some pseudotachylitic breccias in the Witwatersrand Basin, including in the Vredefort Dome, formed in pre-impact times before the deposition of the Black Reef Formation of the Transvaal Supergroup (e.g., Killick and Reimild 1990; Berlenbach and Roering 1992; Reimold and Colliston 1994). No evidence for post-impact formation of pseudotachylitic breccias has been confirmed (e.g., Gibson et al. 1997; Reimold and Gibson 2006; this work). Thus, the majority of the pseudotachylitic breccias observed in the collar rocks of the Vredefort Dome are believed to be impact-induced. This is supported by the observation that pseudotachylitic breccias show consistent relationships with impact-related structures in the Vredefort Dome, especially with large-scale folds and faults (see sections 2.5, 2.6 and 4.3).

If most of the pseudotachylitic breccias in the dome are impact-related the remaining question is whether they were formed in the very early stages of the impact (compression phase) by shock melting (with or without a frictional heating component), or solely by friction melting either in the early or later stages of the cratering process, or by a combination of both processes at various stages during cratering. Field observations in previous studies (e.g., Reimold and Colliston 1994) suggest that different generations of pseudotachylitic breccias may exist and they are well known from major fault zones in the Witwatersrand Basin. The problem of possible different generations of pseudotachylitic breccias is exemplified by Fig. 4.15 which shows cross-cutting pseudotachylitic breccias close to a large-scale fault in the northwestern part of the collar (on farm Mooihook, location 732, see Appendix No. 6). The bedding-parallel vein (vertical in Fig. 4.15) is cut by an obliquely dipping vein. This suggests that the thicker vein was solidified before the thinner vein intruded, which appears to be counter-intuitive if both veins formed at the same time during the impact event. If both veins formed coevally related to the faulting in the vicinity, this could have taken place possibly a few seconds apart, which might explain the cross-cutting relationship. Alternatively, the issue of multiple generations of pseudotachylitic breccias, possible compositional differences that result in some veins staying molten longer than others, and even the possible existence of non-impact-related pseudotachylitic breccias (e.g., Berlenbach and Roering 1992; Reimold and Colliston 1994) need to be considered. Unfortunately, this study did not extend to detailed petrographic and geochemical analysis of the breccias; however, these issues are addressed from a theoretical standpoint in the next section.

Evidence for melts formed by shock and by friction under shock conditions were reported from recent experiments (Fiske et al. 1995; Kenkmann et al. 2000; Langenhorst et al. 2002). While Fiske et al. (1995) and Kenkmann et al. (2000) suggested that they had produced melts by shock compression, the shock experiments by Langenhorst et al. (2002) on single olivine crystals suggested that the melts were formed by shear melting, and not by shock melting. The existence of friction-generated melts has long been known from normal tectonic processes; Sibson (1975, 1977) showed that melt formation depends on both the amount of displacement and the shear velocity. This is consistent with recent calculations (e.g., Melosh 2005) that propose that a displacement of as little as 1 mm is sufficient to produce melting. However, these studies also demonstrated that friction sliding is self-limiting and friction melting is restricted to a narrow zone (submillimetre to 1 mm in width). This is because, once melting occurs, the melt functions as a lubricant and, thus, reduces friction which terminates the production of friction heat and of further melt (Melosh 2005). If applied to the collar of the Vredefort Dome, these thin shear zones could

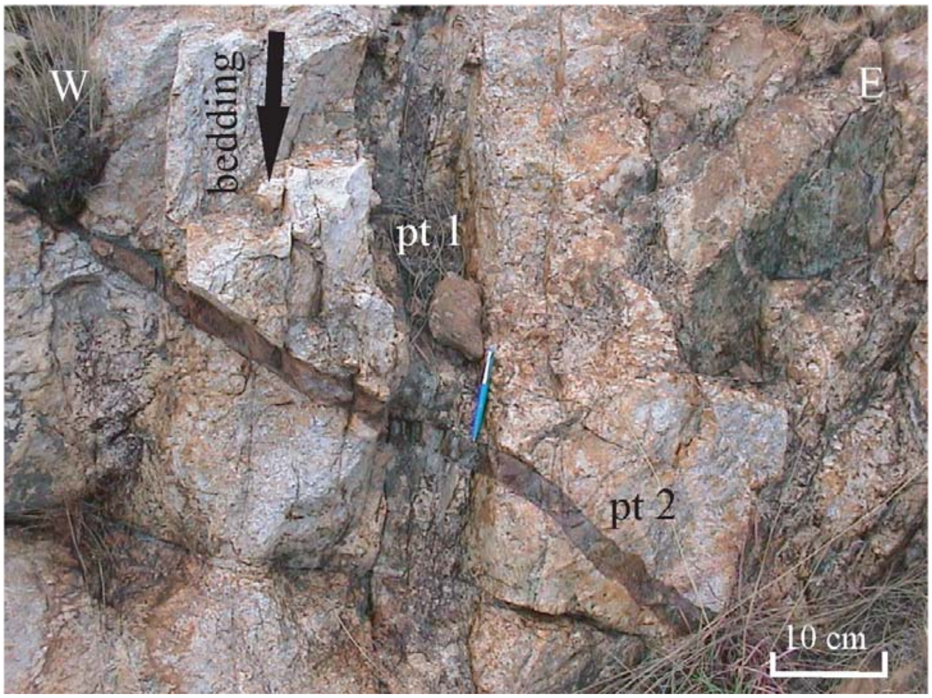

Fig. 4.15: Photograph of a thick, vertical bedding-parallel pseudotachylitic breccia vein showing a clear cross-cutting relationship with a younger, moderately-dipping vein (bedding marked by an arrow, length of pen, ca. 10 cm) from the northwestern part of the collar, location 732, see Appendix No. 6). No offset along the contacts could be observed, however.

correspond to the thin, up to 1 mm wide veinlets of pseudotachylitic breccia that are commonly observed in the metapelites and in quartzites. A friction origin for these veinlets might also be substantiated by the locally observed kinematic indicators (sinistral and dextral shear senses) along the veins (tension gash arrays, displacements along shear fractures that host the veins; see Figs. 4.10 and 4.11).

While this explanation may be valid for the thin veinlets in the Vredefort Dome, the origin of the more voluminous pseudotachylitic breccias requires additional consideration. The key question is how friction melting could drive voluminous melt accumulation given its self-limiting nature. Melosh (2005) suggested that if the core of the vein stayed molten long enough to escape into zones of lower or zero strain rate, melt might be able to accumulate and simultaneously continue to be generated along the shear surface. However, he pointed out that the melt must be squeezed out very rapidly, and this depends on the fault length (Melosh 2005) - the longer the fault, the more difficult it becomes for the melt to flow out of the shear zone. Consequently, faults that are hundreds of metres long with slip magnitudes of tens of metres (such as might be expected in impact craters) appear unlikely to be able to produce correspondingly large volumes of pseudotachylitic breccia (e.g., Martini 1991; Spray 1997; Melosh 2005). Faults with such slip magnitudes have also yet to be detected in the core of the Vredefort Dome where the most voluminous pseudotachylitic breccias occur. There are large syn-impact faults in the collar that contain metre-scale accumulations of pseudotachylitic breccia, but these are far smaller than the big dykes in the core (see sections 2.5, 2.6 and 5.4.3).

Evidence that voluminous friction melts may have been able to accumulate during impact-related faulting is documented in the goldfields of the Witwatersrand Basin, where pseudotachylitic breccia veins appear, in places, as wedge-shaped pockets up to metres wide along domeward-dipping normal faults (e.g., Killick and Reimold 1990). Again, however, they are dwarfed by the size of the dykes in the core of the Vredefort Dome.

In order to resolve this question, the key parameter concerning the melt precursors to the pseudotachylitic breccias is the degree of superheating (i.e., the difference between the actual melt temperature and the solidus for the melt). The longer the vein remains molten, the longer (and further) the melt can flow, which in turn would enhance accumulation of large volumes of melt in specific sites. The higher melt temperature would also reduce melt viscosity, similarly enhancing flow.

Melosh (2005) stated that a fault with a length of 100 m would require a melt viscosity equivalent to that of water, which would be difficult to achieve given the high viscosities of silica-rich melts (see Melosh 2005) such as those formed in granitic and quartzitic rocks in the Vredefort Dome, although Sibson (1975) suggested that it might be possible that melts may also escape at locations along the fault surface, and not only at its ends.

4.4.1 Cooling times for pseudotachylitic breccias

In an attempt to investigate how long pseudotachylitic breccia veins from the Vredefort Dome may remain molten (i.e., regardless of their origin), simplified 1-dimensional thermal modelling of pseudotachylitic breccia vein cooling using different vein thicknesses and different initial temperatures was carried out. The principal objective of these calculations was to investigate the conditions under which melts that could have formed during the shock stage of cratering could remain molten in order to intrude dilational sites in and close to large-scale structures (folds and faults) during the modification phase of cratering. This should not be interpreted as indicating preference for a particular mode or time of formation of the melts. Given the non-equilibrium nature of friction melting, there is, unfortunately, little conclusive data available concerning the temperatures of pseudotachylitic melts.

The simplified conductive cooling calculations applied are based on the heat flow equations from Jaeger (1959) and further developed by Spear (1993), who presented a time-dependent analytical solution to the one-dimensional heat flow equation for magmas:

$$\Delta T/\Delta t = K(\Delta^2 T/\Delta x^2)$$

with T (temperature, °C), t (time, sec), x (distance, in this case from the centre of the vein to the margin, cm) and K (thermal diffusity), where $K=k/pC_p$, with k being the conductivity (cal/cm s °C), p is the density (g/cm^3) and C_p is the constant pressure heat capacity (cal/°C g).

The calculations are based on a couple of assumptions and simplifications, as many of the involved parameters are still unknown. It is assumed that after melt formation there was no further conduction or heat contribution. This appears to be valid for the time scales of melt crystallization, even though thermal modelling by Ivanov and Deutsch (1999) and Ivanov (2005) indicates that slight prograde heating of crater basement is likely over a period of 1-2 million years after the impact as the post-impact isotherms relax. In the calculations, both types of veins (thick and thin) are assumed to have the same density, heat capacity, and thermal conductivity for veins with similar compositions. For simplicity, the veins are assumed to be only melt. The presence of clasts in the melt speeds up solidification due to heat exchange with the initially cooler clastic material. Studies of the thermal history of the impact melt sheet at Manicouagan (Onorato et al. 1978) indicate that clasts absorb heat from the melt relatively fast. It is not only the percentage of the clast content within a melt that is important; the composition and the surface area of these clasts also influences the cooling rate. For instance, a few big clasts would absorb less heat from the surrounding material than lots of small clasts (Onorato et al. 1978).

Absolute temperatures for the formation of the Vredefort pseudotachylitic breccias cannot be deduced from an existing dataset because of the non-equilibrium nature of both friction and shock melting. Furthermore, strong post-impact recrystallization of both the matrices and clasts has occurred, which has destroyed melt crystallization products that might help constrain crystallization temperatures. For this reason, the calculations below should be treated as only a first-order approximation that might guide future research. Previous and current studies of the pseudotachylitic breccias in the collar rocks of the dome indicate that quartzite has melted to produce some of the veins. In order to melt pure quartz, temperatures must exceed 1600 °C (e.g., Philpotts 1990; Bucher and Frey 1994). Whilst it is possible that melting also involved small amounts of muscovite and/or feldspar, which would reduce the solidus/liquidus temperatures to ~1050 °C (solidus) and to 1200-1300 °C (liquidus) for a feldspar content of only 20-30 vol% (e.g., Philpotts 1990), the proportion of these minerals in the annealed quartzite-derived pseudotachylitic breccias is insignificant. Given that the largest quartzite-hosted breccia extends for over 500 m (Nicolaysen and Reimold 1990), it is assumed that the melt must have been significantly superheated. An initial model melt temperature of 2000 °C has, thus, been chosen for the quartzite–derived veins.

In contrast to the quartzites, the other major rock type in the collar of the dome – metapelite – has a complex mineralogy and a much lower solidus and liquidus. The exact starting temperatures (solidus temperatures) for melting for such veins will vary based on a variety of factors in the vein (e.g., wet vs. dry, bulk composition). Also, the actual differences in the melt composition for veins with similar thicknesses result in different solidus/liquidus temperatures. Given the mineralogy of the pre-impact assemblages, which are largely muscovite-poor and H_2O-poor in the West Rand Group (Gibson and Wallmach 1995), it is assumed that biotite is the principal hydrous phase involved in melting, together with cordierite (see Gibson et al. 1997, 1998). Biotite melting is dependent on its composition, but typically occurs between 650-700 °C and 850-900 °C (e.g., Philpotts 1990; Bucher and Frey 1994). In the Central Rand Group biotite, chlorite and muscovite are all potential melting phases (Gibson et al. 1998), thus increasing the temperatures to 750-800°C (solidus) and to 950-1000°C (liquidus) (e.g., Philpotts 1990; Bucher and Frey 1994). It is, thus, reasonable to expect that melting in the metapelitic rocks occurred at significantly lower temperatures than in the quartzites. In this case, the degree of superheating may be even higher than for the quartzite melts. Because the length of time over which the melt remains molten for a given vein thickness is primarily a function of the degree of superheating, calculations involving similar amounts of superheating relative to the solidus or liquidus would not produce any major differences in the results presented below. Instead, given that these are first-order calculations, this study explores an alternative initial possibility, namely that the absolute temperature of all the pseudotachylitic breccia melts was similar. This creates the interesting possibility that the degree of superheating may have varied depending on the precursor rock type, with obvious consequences for the length of time the veins remained molten. In support of melt temperatures well in excess of 1000 °C even for the metapelite-derived veins, the following should be considered:

1. the amount of offset measured along shear fractures is very similar in all rock types in the dome – if the amount of slip drove melting, then similar amounts of energy for frictional heating were released in both quartzites and metapelites;
2. apart from the quartzites, the mafic and felsic (TTG) gneissic basement rocks in the core of the dome and the mafic sills in the collar all show evidence of plagioclase melting during pseudotachylitic breccia formation (e.g., Gibson et al., 2002). Intermediate to calcic plagioclase melts at temperatures of between ~1250 °C and ~1400 °C (e.g., Philpotts 1990; Bucher and Frey 1994). Significantly, Gibson et al. (2002) and Gibson and Reimold (2005) found no evidence to support melting of pyroxenes

in breccias from the central parts of the dome. This places an upper limit of ~1400 °C on these breccias. Consequently, a set of calculations assuming a 1400 °C melt temperature in the metapelitic rocks is also considered.

Petrographic studies of metapelites in the collar of the Vredefort Dome (e.g., Gibson et al. 1998; Gibson and Reimold 2000, 2005) indicate initial post-shock temperatures of up to 300°C in the Central Rand Group and outer collar, and 525°C for the inner collar. Recent numerical modelling studies have suggested even higher temperatures for the centre of the dome of >900°C (see Gibson 2002; Ivanov 2005). P. Ogilvie (pers. comm. 2006) has calculated temperatures of ≥700 °C for rocks 7-8 km from the centre of the dome. These temperatures influence cooling rates in the pseudotachylitic breccias. To assess their effect, calculations were done using 3 different host rock temperatures: for a background temperature of 300 °C in the outer collar, for 500 °C in the inner collar and for 700 °C as a representative temperature in the core.

The calculations were made for veins with a thickness of 1 mm, 1 cm and 10 cm, respectively, because this covers the typical range of widths of pseudotachylitic breccia veins observed in the collar rocks. Initial melt temperatures were set to 2000 °C, and, in order to investigate the effect of superheating, to 1400 °C and, to examine low degrees superheating, to 1000 °C. Although the latter two temperatures are below the liquidus temperature of quartzite melts and are only valid, *senso stricto,* for melts with a metapelitic composition, the level of superheating is almost directly compatible with quartzite melts with an initial melt temperature of 1750-1800 °C.

4.4.2 Results for melts with an initial temperature of 2000 °C

The results of the cooling calculations for all three vein thicknesses with an initial melt temperature of 2000 °C are presented in Figures 4.16a,b, 4.17a,b and 4.18a,b (and dataset in Appendix No. 4) for temperatures at the centre and at the margins of the melts, respectively. The initial melt temperatures of 2000 °C postulate ~400 °C of superheating for quartzite melts, but more than 1000 °C for metapelitic melts. This would ensure that metapelitic melts would stay molten over a longer period of time than quartzite melts. Although the cooling times for quartzite and metapelitic melts are consequently different, the results for 1 mm wide veins indicate

Fig. 4.16: Cooling temperatures for 1 mm wide veins with an initial melt temperature of 2000 °C for a background temperature of the host rocks at 700 °C in the core, at 500 °C at the core/collar contact and at 300 °C in the outer collar. (a) Temperature distribution in the centre of the vein and (b) at the margin. For detailed discussion see text and for data see Appendix No. 4.

Fig. 4.17: Cooling temperatures for 1 cm wide pseudotachylitic breccia veins with an initial melt temperature of 2000 °C. The background temperatures are set to 700 °C in the core, to 500 °C (core/collar contact) and to 300 °C (outer collar). (a) Temperature distribution in the centre of the vein and (b) at the margin. See text for further discussion and Appendix No. 4 for data.

Fig. 4.18: Cooling temperatures for 10 cm wide pseudotachylitic breccia veins with an initial melt temperature of 2000 °C. Background temperatures are set to 700 °C in the core, to 500 °C at the core/collar contact, and to 300 °C for the outer collar. (a) Temperature distribution in the centre of the vein and (b) at the margin. See text for further detail and Appendix No. 4 for data set.

that melts are quenched almost instantaneously regardless of their composition (Fig. 4.16). While quartzite melts reach the liquidus temperature in a fraction of a second, metapelitic melts crystallize after ~1 second (Fig. 4.16a). Subsolidus cooling takes place much more slowly until the melts reach the background temperature of about 300 °C after ca. one hour. These figures imply that 1 mm wide veins – if shock-induced – would not survive in a molten state into the modification phase, and, thus, that these type of veins were not able to flow substantial distances into dilational sites but must have remained largely *in situ*, even where extreme superheating could be achieved.

Similarly, 1 cm wide veins cool down to their respective liquidus temperatures before the onset of central uplift formation (which takes place after a few minutes, Melosh 1979; Henkel and Reimold 1998; see section 1.5). Quartzite melts reach the liquidus after ~10 seconds, while metapelitic melts stay molten up to 1 minute (Fig. 4.17). The background temperatures are reached after about 3 days. As a result, 1 cm wide veins that are found within structures such as fold hinges, fault traces and shear fractures that are related to central uplift formation (see sections 2.5, 2.6, 2.7, 6.2.1, 6.2.2, 6.2.3) can also not represent shock-induced melts that intruded these sites during the modification phase, unless they are offshoots of larger melt bodies (see below).

In contrast, the results for 10 cm wide veins show clearly that if 10 cm wide melts, regardless of their composition, could accumulate within a few seconds or even minutes, they may have stayed molten over the entire duration of the cratering process, which is in the order of ~15 minutes for the largest impact structures, such as Vredefort (Melosh 1989; Turtle et al. 2003). The crystallization times for both quartzite and metapelite compositions are in the order of tens of minutes (for quartzite melts after ~20 minutes and for metapelitic melts after ca. two and a half hours, Fig. 4.18). The background temperature for all three cases (i.e., for 300 °C, 500 °C and 700 °C background temperatures) is reached after ~12 years.

The cooling results in the host rock at the margin of melts described above show that the heat flow from the centre of the vein reaches the margins with a delay of several minutes to tens of minutes (Figs. 4.16b, 4.17b and 4.18b), before the temperature rises to a maximum that lies between 300 °C and 400 °C above the background temperature of the host rock. Subsequent cooling to the respective background temperatures is slow and is accomplished for all veins after a minimum of

1 year (Figs. 4.16b, 4.17b and 4.18b). The maximum temperatures that are achieved at the margins are not high enough to exceed the liquidus temperatures for melts with a quartzite or metapelite composition. Also, even if these temperatures were high enough for melting and to reduce the viscosity of the melt to stop friction along the margins, the temperature increase would take place long after the crater collapse, which is in the order of a few minutes (e.g., Melosh 1989; Turtle et al. 2003). Consequently, the temperatures along the margins of melts are not further considered in the following calculations.

These first calculations suggest that the difference in cooling rate for veins ranging from 1 mm to 10 cm in width may be several orders of magnitude (Fig. 4.16, 4.17 and 4.18).

The degree of superheating of such melts is a critical factor in influencing how long the melts could have stayed molten. If such high degrees of superheating were achieved and sufficiently voluminous melt pools or sheets were able to accumulate, it would have been possible for melts formed during the shock stage to survive to invade structural sites formed during the modification stage (for detailed discussion on this issue, see sections 4.4.5 and 6.2.6).

4.4.3 Results for melts with an initial temperature of 1400 °C

In order to better quantify the effects of superheating on longevity of melt in the pseudotachylitic breccias, further calculations were conducted with lower degrees of superheating involving metapelitic melts. Initial melt temperatures of 1400 °C would mean that there is between 500-600°C of superheating for metapelite melts.

In this scenario, the 1 mm wide melt veins reach their respective liquidus temperatures within a fraction of a second (Fig. 4.19). Depending on their background temperature, 1 cm wide veins crystallize after several tens of minutes to up to two hours (Fig. 4.20a) and reach their respective background temperatures after several years. The 10 cm wide veins require more than 24 hours in order to reach their liquidus temperature and hundreds of years to cool down to their respective background temperature (Fig. 4.20b). The cooling times for 1 cm and 10 cm wide veins suggest that these melts with 500-600 °C of superheating may also have survived almost the entire cratering process in a molten state.

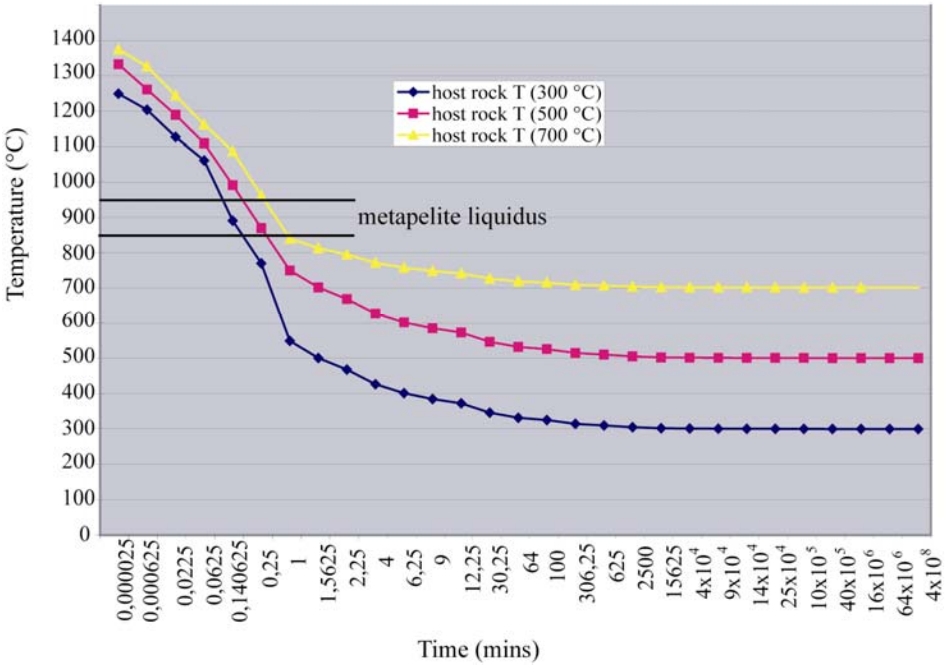

Fig. 4.19: Cooling calculations for 1 mm wide pseudotachylitic breccia melts with initial melt temperatures of 1400 °C. The background temperatures are set to 700 °C in the core and 300 °C in the outer collar. For further detail see text and for data Appendix No. 4.

4.4.4 Results for melts with an initial temperature of 1000 °C

A maximum melt temperature of 1000 °C corresponds to only 100-200 °C of superheating for metapelite-derived melts (depending on the composition of the metapelitic host rock as discussed in section 4.4.1). This temperature was chosen to test the effect of low degrees of superheating. Not unexpectedly, 1 mm wide veins crystallize almost instantaneously and would not be able to migrate from their location of formation (Fig. 4.21). The results for 1 cm veins are similar, with only veins in the core of the dome being capable of surviving for up to a minute (Fig. 4.22a). This would suggest that, if such low levels of superheating applied, 1 cm veins in structural sites related to central uplift formation could not have survived from the shock stage unless they were originally part of much larger melt pools. In contrast, the results for 10 cm veins (Fig. 4.22b) indicate that, at sufficient volume, even these marginally superheated melts are capable of surviving throughout the cratering process. Subsolidus cooling down to the background temperature is in the order of 3 days for 1 cm wide veins and of ~10 years for 10 cm wide veins. Given the time frame for central uplift formation in the cratering process and the duration of the

Fig. 4.20: Cooling calculations for veins with initial temperatures of 1400 °C (a) 1 cm wide veins and (b) for 10 cm wide veins. Background temperatures are set to 700 °C for melts in the core, 500 °C at the core/collar contact and 300 °C for melts in the outer collar. See text for detailed discussion and Appendix No. 4.

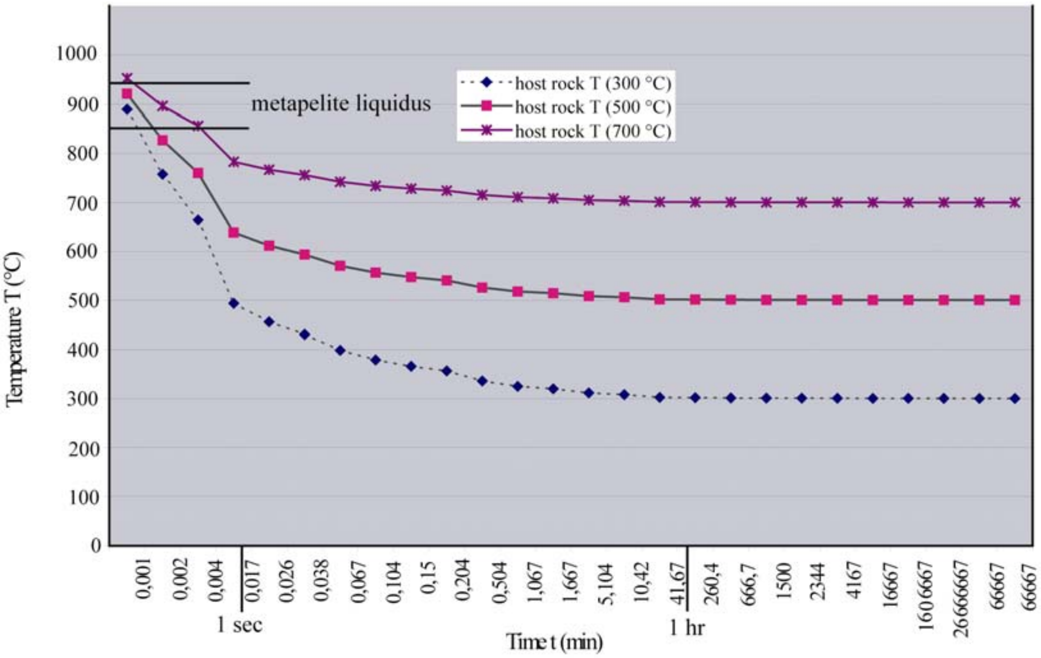

Fig. 4.21: Cooling temperatures for 1 mm wide pseudotachylitic breccia veins with an initial melt temperature of 1000 °C. The background temperatures are set to 700°C in the core, to 500 °C (core/collar contact) and to 300 °C (outer collar). See text for further discussion and Appendix No. 4 for data.

modification phase (e.g., Melosh 1979; Henkel and Reimold 1998; Turtle et al. 2003), it is unlikely that non-superheated melts or melts with very low superheating, regardless of their thickness, were fluid enough to migrate into sites of structural complexity (such as fold hinges and fault traces) during the modification phase. As mentioned above these calculations for low degrees of superheating can also be applied to melts with a quartzite composition but with an initial melt temperature of ~1750-1850 °C.

4.4.5 Synthesis of results

Calculations suggest that 1 mm veins are unlikely to survive as melts for more than 1 second, no matter what degree of superheating is invoked. Cooling is likely to be even faster given that pseudotachylitic breccias contain clasts. Clasts in a melt would also increase viscosity (and, thus, decrease mobility) of the melts. 1cm and 10 cm veins, however, can remain molten over the 10-15 minutes duration of the impact event, which potentially raises the possibility that melts formed during the shock stage could be emplaced within what are clearly late-stage structures like fold hinges and faults associated with the modification phase. This does not, however, preclude melts forming via friction-related processes during the modification phase. Nonetheless, it is worth considering the following:

1. shock-related features have been found associated with thin pseudotachylitic breccias (Martini 1978, 1991; Gibson 2002)
2. although there is evidence of slip, no evidence has been found that slip increases proportionately to the size of the pseudotachylitic breccias
3. evidence of movement of melts by tens of metres (Bisschoff 1962, 1996; Reimold and Colliston 1994) suggests low viscosity which is best achieved at large degrees of superheating. Melosh (2005) proposed that a temperature increase of ~100 °C is sufficient to decrease the viscosity of a melt by an order of magnitude
4. the presence of quartzite-derived pseudotachylitic breccias requires melt temperatures of >1600 °C – at least double those suggested for friction-generated melts. Whilst this might be possible through the extreme strain rates during impact, it may also point towards a shock origin.
5. Superheating is more likely to be achieved through shock processes than friction melting as the latter is likely to be self-limiting (once frictional sliding induces melt formation, the source of heat is reduced until the melt can be expelled from the slip surface. This raises the question of how friction melts could ever get sufficiently hot to flow significant distances, or to accumulate in sufficient volumes to create the big dykes in the dome);

Gibson (2002) speculated that melt may form by amplification of the shock wave when refracted and reflected shock fronts intersect. The source of this refraction and reflection is the heterogeneous nature of the target rocks. This has been demonstrated recently in shock experiments by Kenkmann et al. (2000) and Langenhorst et al. (2002), although other mechanisms such as void collapse and friction may have contributed to the melting.

What now needs to be done is a systematic analysis of the scales of melt migration and the reasons for cross-cutting relationships as seen in Fig. 4.15. Of key importance will be to check if melts migrate from narrow veins into larger ones, or vice versa. Complications may arise through intrusive relations (voluminous melts may have been injected into narrow veins prior to crystallization) and changing thicknesses caused by the severe structural adjustments during central uplift

Fig. 4.22: Cooling temperatures for 1 cm (a) and 10 cm wide pseudotachylitic breccia veins with initial temperatures of 1000 °C (b). The background temperatures are set to 700 °C in the core, to 500 °C (core/collar contact) and to 300 °C (outer collar). See text for further discussion and Appendix No. 4 for data.

formation. A key feature is further documentation of outcrop-scale structural relations with impact-related features. In Chapter 2 it was shown that shear fractures cut narrow veins but not thicker veins (compare Figs. 4.13 and 4.14). This relationship needs to be more systematically documented to corroborate timing of melt crystallization.

A problem with the shock model for pseudotachylitic breccias formation is that shock pressures in the collar have been estimated at <10 GPa (Gibson and Reimold 2005). Even with pre-shock temperatures of >200 °C, doubling of the shock pressure (by shock wave interference) does not appear to be able to raise the shock temperature to the point that melting would occur, let alone allow significant amounts of superheating.

The possibility that melt from superheated thick veins (1 cm, 10 cm) was injected into impact-related structural sites is substantiated by field observations during this study. Pseudotachylitic breccias of these widths occur predominantly in hinge zones of large-scale folds and in the vicinity of large-scale faults (section 4.3). The fact that these veins are commonly not truncated by late-stage or post-impact joints/shear fractures (see sections 2.7 and 4.3) can be reconciled with an annealing of these structures by the high temperatures that were present in these veins tens and hundreds of years after the impact or by the fact that these veins were still molten at the time of fracture formation. In contrast, the solidification of 1 mm veins indicates that almost no melt transport was possible. The regular cross-cutting relationship of the joints/shear fractures of likely impact origin (presented in section 2.7) with these thin veins confirms that the latter were already solid by the time of the formation of these fractures.

4.5 Occurrences of other veins and breccias

4.5.1 Quartz veins

Quartz veins are present throughout the collar of the dome. They are observed both in well-exposed sections in the collar, but also in areas where outcrop is poor. They commonly occur as up to 1 cm wide veins that, at most places, trend parallel to bedding. However, various other orientations are also observed, for example orientations perpendicular and oblique to bedding (Fig. 4.23), and, thus, no consistent orientation of these quartz veins with respect to bedding and the centre of the Vredefort Dome could be established (Fig. 4.24). No geometric or cross-cutting relationship with pseudotachylitic breccias in the collar rocks of the Vredefort Dome was found. Evidence for brittle or ductile deformation of these veins is absent; they are not folded, but are usually straight and only in rare cases do they exceed lengths of a few tens of centimetres. Most of the veins are cut and displaced by up to a few centimeters, in both dextral and sinistral senses, by subvertical, radial fractures (Figs.

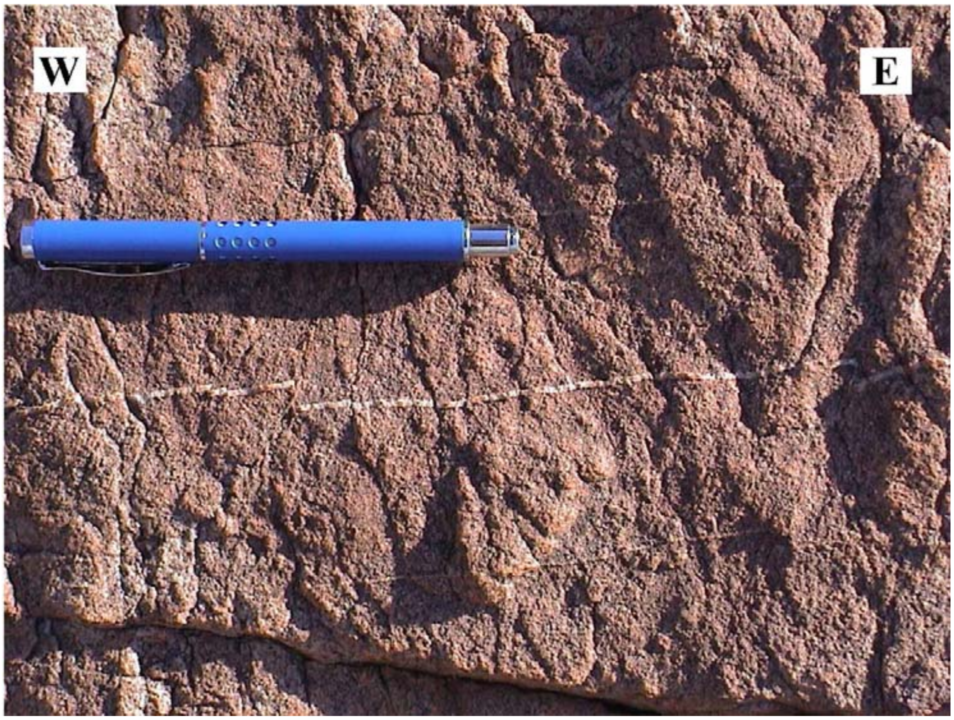

Fig. 4.23: Typical occurrence of millimetre-wide quartz veins in the collar of the Vredefort Dome with an orientation perpendicular to bedding (northern part of collar, location 336, see Appendix No. 6, plan view onto the overturned bedding surface, length of pen, ca. 10 cm). Note the relationship to shear fractures and the displacement along them, similar to those observed across pseudotachylitic breccias (e.g., Fig. 4.13).

4.23, 4.25), indicating a possible pre-fracture (and hence, possibly pre-impact) origin. No relationship was observed between these quartz veins and other large-scale structures, such as large-scale faults and folds. Given the pre-impact thermal history of these rocks, it is possible that the veins may be related to the ca 2.06 Ga metamorphism. Gibson et al. (1998) noted that much of the post-impact metamorphism is characterized by very little rehydration, suggesting little or no hydrothermal fluid circulation at such deep levels in the central uplift after the impact.

4.5.2 Other breccias in the Vredefort Dome

Within the context of the ultra-high strain rate deformation accompanying impacts, breccias in the crater basement are of particular importance. Besides pseudotachylitic breccias, other types of brecciation have been reported from other impact structures (e.g., Sierra Madera, Wilshire 1972; Gosses Bluff, Milton et al. 1996; Slate Islands, Dressler and Sharpton 1997). For instance, monomictic and polymictic fragmental breccias (also termed lithic breccias) were found in the central uplift of the Gosses Bluff structure (Milton et al. 1996). Milton et al. (1996) described both tangential, bedding-parallel and radial breccia occurrences in the outer parts of the central uplift of the Gosses Bluff structure. They attributed the radial breccias to "gaping" faults. The nature of these faults resembles the radial transtension troughs (RTT) of Kenkmann and von Dalwigk (2000) that have been related to tangential collapse of the central uplift during its final stages of formation. The origin of the tangential breccias was not discussed further by Milton et al. (1996).

Very little brecciation, besides the development of pseudotachylitic breccia or the Vredefort Granophyre, is observed in the Vredefort Dome. This may be partly due to the poor exposure of fault traces, or the greater erosion depth in the Vredefort Dome compared with other impact structures, such as Gosses Bluff (Milton et al. 1996), Sierra Madera (Wilshire et al. 1971) or Upheaval Dome (Kriens et al. 1999; Kenkmann et al. 2005). In the wider environs of the Vredefort Dome, evidence of cataclastic and other distinct brecciation is present (e.g., Fletcher and Reimold 1989; Reimold and Colliston 1994; Brink et al. 2000a). A distinct type of brecciation in rocks of the Pretoria Group, with what Brink et al. (1999, 2000a) termed "chocolate-tablet-type boudinage" was related by these authors to impact-related, outward-

Fig. 4.24: Schematic map of the exposed collar rocks (base map after Bisschoff 2000). The orientations of poles of observed quartz veins (crosses) and of bedding (filled circles) at the respective locations are given in lower hemisphere equal area projections (Schmidt net) for the (a) northeastern, (b) northern, (c) northwestern and (d) southeastern parts of the collar.

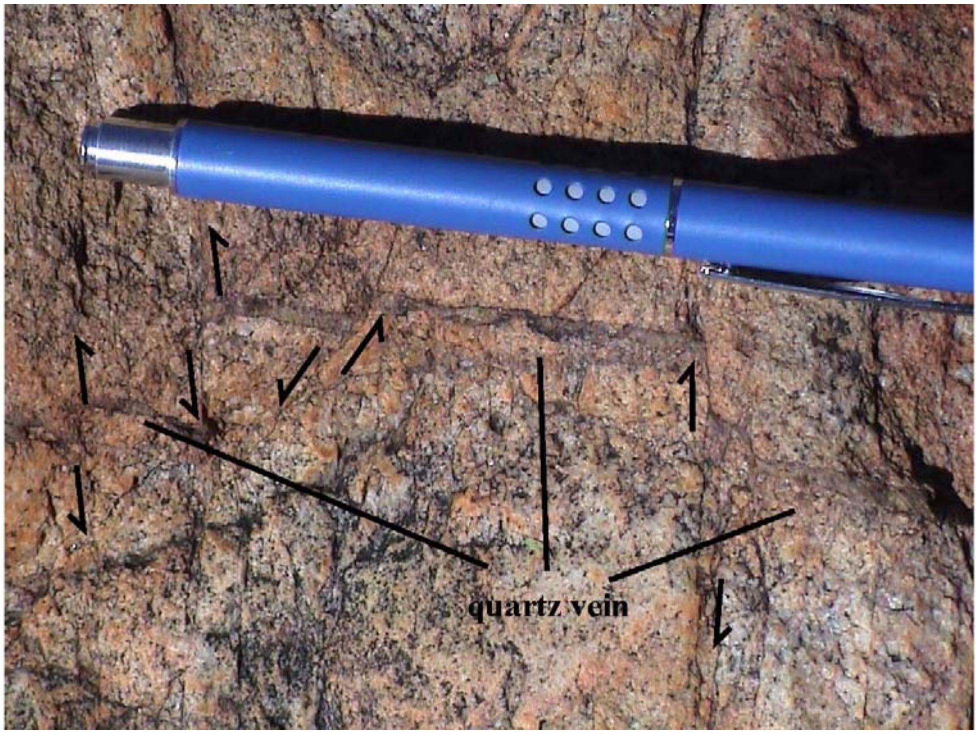

Fig. 4.25: Quartz vein (subhorizontal in photograph) that is cut and displaced by vertical, radial (with respect to the centre of the dome) fractures in both dextral and sinistral senses by up to 1 cm. Horizontal view, northern collar, location 282, see Appendix No. 6, length of pen ca. 10 cm.

directed thrust zones. This type of brecciation was first described by Fletcher and Reimold (1989). The presence of some of these brecciated chert horizons is confirmed by this study, and, because they are thought to be related to impact-related deformation by Brink et al. (1999, 2000a), a detailed description of this type of brecciation is given in section 5.4.2.

Distinctive breccias (Fig. 4.26) were found at three locations in the northeastern part of the collar (locations 188, 604, 735, see Appendix No. 6). The breccias are exposed as outcrops of 10 to 40 m length and 1 to 2 m width, and appear to be irregular with regard to bedding orientation; strike terminations of these occurrences are not exposed owing to the dense vegetation and soil cover at these sites. At two locations (188 and 604, see Appendix No. 6), these breccias seem to extend parallel to bedding, but no clear relationship to other structures, such as major faults or folds, was found. Only one location, in the northeastern part of the collar (location 735, see Appendix No. 6), exposes breccia parallel to and in the vicinity of a large-scale fault. These breccias consist of centimetre- to decimetre-sized, angular to subrounded clasts of medium- grained quartzites of the local Hospital Hill or Government Reef subgroups (Fig. 4.27). The clasts display intense fracture cleavage with various orientations (Fig. 4.27), implying that they were rotated after the formation of the fracture cleavage. Considering that only one set per clast could be

Fig. 4.26: Quartz-hosted breccia that is found at three locations in the northeastern part of the collar (locations 188, 604, 735, see Appendix No. 6). For further detail see text. Length of pen ca. 10 cm.

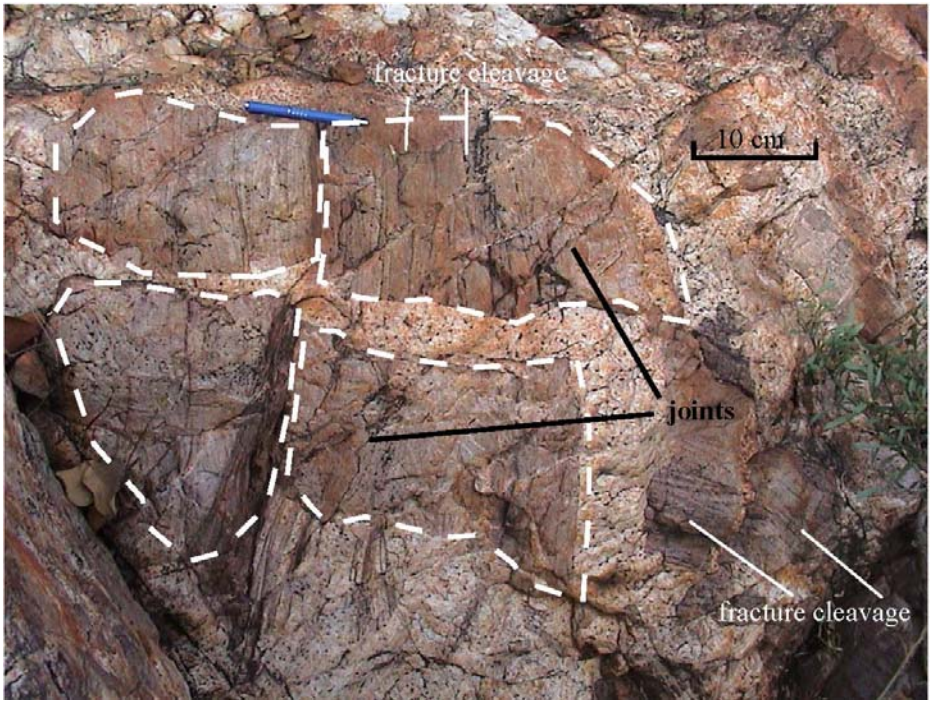

Fig. 4.27: Quartz clasts and matrix of fine-grained recrystallized quartz in breccia are cut by late-stage shear fractures (diagonal from upper right to lower left). In places, the clasts show a parallel fracture cleavage with various orientations, suggesting rotation of the clasts after cleavage formation. For further detail see text.

observed, this feature may also represent bedding laminations or cross-bedding. The matrix comprises massive white recrystallized vein quartz with local vugs containing euhedral quartz crystals up to 10 cm in length (Fig. 4.28). No shatter cones or pseudotachylitic breccia veins have been found in the breccia matrix, but it is cut by the major fracture sets that are observed in the collar rocks (see section 2.7).

4.5.3 Synthesis of data

The question of timing for the formation of these veins and breccias is important with regard to impact-related deformation in the collar rocks of the Vredefort Dome. As stated above, impact-related breccias are known from other impact structures (Sierra Madera, Wilshire et al. 1972; Gosses Bluff, Milton et al. 1996; Upheaval Dome, Kenkmann et al. 2005), but are not as prominent in the Vredefort Dome. While this may reflect the deeper levels of erosion in the Vredefort Dome, a non- impact-related formation of the quartz-matrix breccias may also be possible. This is substantiated by the fact that impact-related structures

Fig. 4.28: Euhedral quartz crystals in the matrix of an observed quartz breccia in the northeastern collar (location 188, see Appendix No. 6). In places, these crystals can reach lengths of up to 10 cm. Length of pen for scale, ca. 10 cm.

(oblique fractures) cut the matrix and clasts of the breccia, suggesting a formation of the breccia before these structures and, thus, a possible pre-impact origin. A pre-impact origin of this breccia would also mean that the fracture cleavage resembles more likely bedding laminations or cross-bedding, as the best cause for formation of this cleavage would have been the impact event, thus making the breccia a post-impact feature. However, the limited observations on these breccias does not allow a conclusive assessment of the time of their formation.

The origin of the quartz veins remains uncertain. If the quartz veins are from post-impact hydrothermal activity, this would mean that the cross-cutting shear fractures were also formed in post-impact times (see section 2.7). This scenario is possible, considering that the formation of these shear fractures cannot unequivocally be linked to either syn- or post-impact times, owing to the uncertainty of the duration of the modification phase, as discussed in detail in Chapter 6. Alternatively, the quartz veins could be related to the formation of pre-impact faults, the existence of which in the collar of the Vredefort Dome was established in section 2.2. Some of these bedding-parallel faults may have been annealed by the pre-impact metamorphism.

The latter scenario, however, is not supported by the orientation pattern of quartz veins observed in the collar rocks of the Vredefort Dome. Quartz veins were found predominantly in the quartzite units in the northeastern, northern, northwestern and southeastern parts of the collar (Fig. 4.24). Although the data from the northwestern and northern sectors demonstrate that many quartz veins are oriented parallel and perpendicular to bedding, which could fit the abovementioned scenario, the overall pattern seen on all stereonets suggests a rather random orientation of the quartz veins with respect to bedding and the centre of the dome (Fig. 4.24).