A geochemical contribution to the discussion about the genesis of impact-related pseudotachylitic breccias: Studies of PTB in the Otavi and Kudu Quarries of the Vredefort Dome support the *"In Situ Formation"* hypothesis

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Abstract

This work is aimed at contributing to the understanding of the formation of massive pseudotachylitic breccias (PTB) in impact structures. In the past this has been debated as being due to either melting of locally available country rocks or a combination of injection of impact melt from a higher level of the impact structure plus assimilation of other, including locally derived, material. Two occurrences of massive PTB in the Otavi and Kudu quarries of the outer crystalline core of the Vredefort Dome (South Africa) have been investigated petrographically and chemically. As shown in many previous studies of PTB, lithic and mineral clast populations only support derivation of PTB from local precursor material (granitic gneiss and amphibolite in the case of Kudu Quarry and various granitoids and a dolerite/amphibolite component in Otavi Quarry). The new major and trace element chemical systematics of melt rock and possible local precursors are fully consistent with this petrographic finding: in both cases PTB chemistry is readily explained by derivation from directly adjacent country rock, or mixtures of locally occurring granitoids and amphibolite. Harmonic least-squares mixing (HMX) calculations also do not indicate that additional components, such as a Vredefort Granophyre-like impact melt intrusive phase, contributed to the formation of these PTB. Absence of evidence (such as significant displacements along PTB developments) for the origin of PTB by friction melting along significant faults/shear zones is also recorded. As melting immediately after shock wave propagation (end of early compression stage of cratering), which is widely considered as the genetic process for shock vein formation in impact-affected rocks, including meteorites, does not apply to formation of such voluminous PTB, only local melting due to rapid decompression upon central uplift formation, followed by melt pooling in dilation sites, can be called upon to satisfactorily address PTB formation.

Introduction

Over 50 years of dedicated field, laboratory and numerical modeling investigations have greatly advanced the understanding of, in the planetary sense, fundamental impact cratering process and the geology of impact structures. Currently, about 189 confirmed impact structures are recognized on Earth (Earth Impact Database, 2016). The oldest and largest of these is the Vredefort impact structure in the region of the Witwatersrand Basin of South Africa (Gibson and Reimold, 2008; Reimold and Koeberl, 2014). The Vredefort impact event took place at 2.02 Ga ago (e.g., Kamo et al., 1996) and lead to the formation of a 250 to 300 km wide impact structure that is widely regarded as the remnant of an original multi-ring impact basin (e.g., Grieve et al., 2008). The Vredefort Dome (Figure 1), a ca. 90 km wide crustal uplift structure centered some 120 km southwest of the city of Johannesburg, represents the deeply eroded remnant of the central uplift of this impact structure (Gibson and Reimold, 2008). The dome is the type locality for a lithology originally termed "pseudotachylyte" by Shand (1916; modern spelling: pseudotachylite) that has in recent years become somewhat notorious in terms of nomenclature and genetic debate. Several hypotheses (see below) for the formation of such melt breccia have been widely debated. The Vredefort Dome features some of the world's best exposures of this lithology and much of what is known about its genesis has been gleaned from this locality (e.g., see the recent review by Reimold and Koeberl, 2014).

Pseudotachylyte (pseudotachylite - modern spelling) is the well-known and universally accepted synonym for friction melt generated on faults and shear zones (e.g., Sibson, 1975; review by Spray, 2010; discussion in Mohr-Westheide and Reimold, 2011, and references therein). Unfortunately, the type locality for this material, the Vredefort Dome, is located within a large impact structure. This causes a serious complication, because the impact cratering community has been applying the term pseudotachylite indiscriminately to a range of materials of generally similar appearance but potentially widely different origins, including tectonic pseudotachylite *sensu strictu*. This has included, as reviewed and discussed repeatedly (e.g., Reimold, 1995, 1998; Mohr-Westheide and Reimold, 2011; Reimold and Koeberl, 2014): shock compression melt - also known as shock veins when occurring in meteorites and widely studied for inherent high-pressure polymorphs of silicates and oxides generated during shock compression and/or by crystallization from impact generated melt at high pressure; melt produced upon rapid decompression caused by the formation of central uplifts in large impact structures; friction melt; melt formed by combination of these various processes; and finally intrusion of impact melt from a coherent melt sheet. Some, e.g., Spray (2010), have considered essentially all so-called "pseudotachylite" in impact structures the product of friction melting on slip zones - on microscopic to "superfault" scales (ibid). In view of this confusion, Reimold has since 1998 promoted the application of the term pseudotachylitic breccia (PTB) for these impact-related melt rock occurrences in a purely descriptive sense until such time that the true genesis of any given occurrence has been resolved.

At Vredefort, at least 3 types of PTB occur. Reimold and Colliston (1994) documented evidence for (Type 1) pre-impact, tectonically deformed bona fide pseudotachylite veins occurring on the Vredefort Dome, and Berlenbach and Roering (1992) showed that pseudotachylite veins of pre-Vredefort impact age occur in the wider Witwatersrand Basin. Type 2 comprises impact-generated melt veinlets containing coesite and stishovite that occur at a number of sites in the outer Vredefort Dome (Martini, 1978, 1991). These PTB have been related to shock compression melting – i.e., actually melting upon release from peak shock pressure, in the compression stage early in the cratering event. Finally (Type 3), there are numerous, in part massive occurrences of melt rock, some of which can attain lengths of up to a kilometer and widths of tens of meters – as highlighted, for example, in the study by Dressler and Reimold (2004). The latter study also highlights that similar melt rock, locally even more massive than at Vredefort, occurs in the Sudbury impact structure (known there as Sudbury Breccia). In recent years some authors (e.g., Mohr-Westheide and Reimold, 2011; review by Reimold and Koeberl, 2014) have related these voluminous melt occurrences to local decompression melting in the course of central uplift formation. Others (Lieger, 2011; Lieger et al., 2011; Riller et al., 2010) advanced the hypothesis that such massive melt occurrences represented mixtures of allogenic impact melt that had intruded from a coherent melt body at the uppermost level of the impact structure, thereby assimilating country rock material.

In a renewed effort to contribute to the understanding of formation of PTB from the Vredefort Dome and to specifically address the controversial genesis of relatively massive melt occurrences in large impact structures, we comprehensively sampled the melt rocks and host lithologies (for field photographs, see Figures 2 to 5) at Otavi Quarry in the northeastern outer sector of the crystalline core of the Vredefort Dome and in the Kudu Quarry of the northern core (Figure 1).

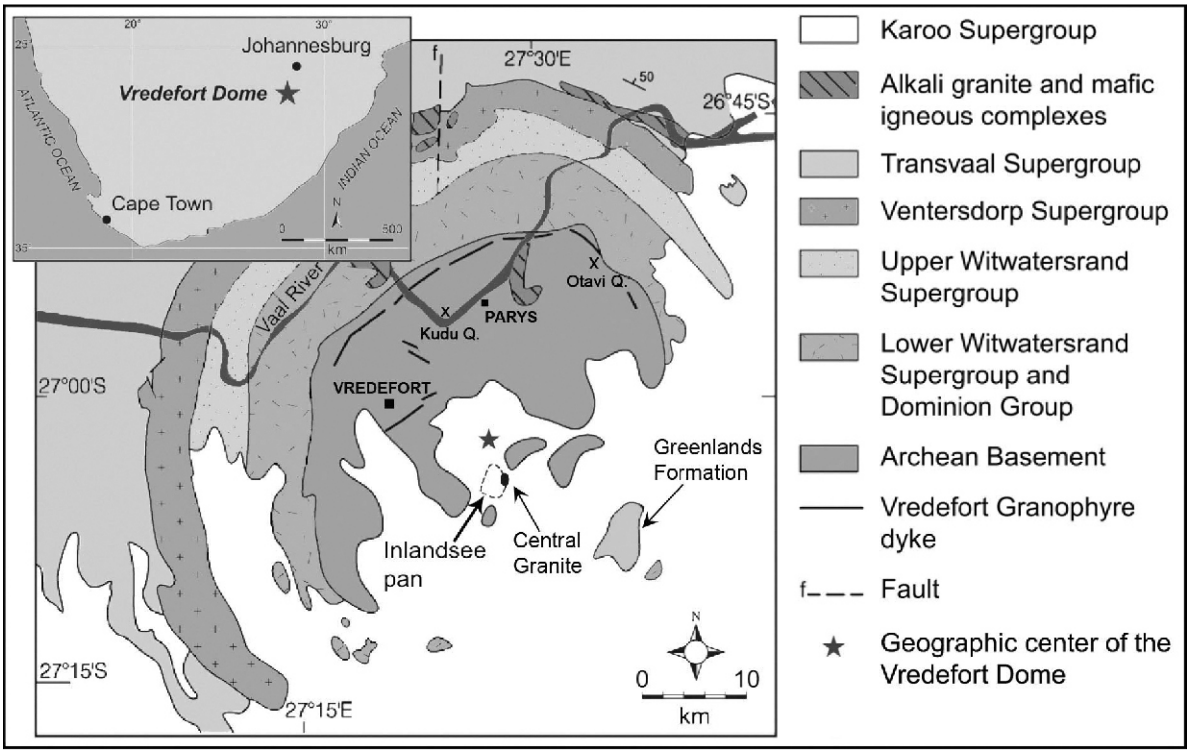

Figure 1. *Schematic map of the geology of the Vredefort Dome (inset showing the location of the dome to the southwest of the city of Johannesburg in the northeastern part of the southern African subcontinent). Locations of Otavi and Kudu quarries are indicated in the geological map.*

We present detailed petrographic and chemical observations that further support the hypothesis that such melts are derived from locally existent precursor lithologies, and that they were, thus, formed *in situ*, and do not require an external impact melt component.

Methodology

The large (in terms of volume) PTB occurrences in the Otavi and Kudu quarries were studied on the ground and sampled for host rock types and PTB. Samples from melt breccia and host rock were taken as closely to the lithological interface as possible. Sampling at Kudu took place where the PTB was sandwiched directly between granite gneiss and amphibolite. PTB samples were prepared by excluding all visible (i.e., roughly >0.7 mm) clasts before further sample preparation for XRF analysis.

All analytical work was performed at the Museum für Naturkunde Berlin. Polished thin sections from all samples of this investigation were studied with a standard polarizing microscope in transmitted and reflected light. X-ray fluorescence spectrometry (XRF) was carried out with a Bruker ASX S8 TIGER instrument. Major elements were determined on fused glass discs, whereas trace elements were measured on powder pellets. More detailed information about the procedure and its aspects such as sample preparation, reference materials and analytical programs, as well as assessment of the statistical quality of data, can be found in Raschke et al. (2013).

Electron microprobe analysis was done with a field-emission cathode JEOL JSM-6610LV (type 8500F) instrument equipped with 5 wavelength-dispersive and one energy-dispersive X-ray detector. Measurements of PTB matrix were done at 15 kV and 15 to 20 mA with a beam diameter of 10 µm to reduce nugget effects. The following international mineral standards (from Smithsonian and Astimex reference materials) were used for peak searching and subsequent correction of elemental data: plagioclase (for Al_2O_3 and CaO), sanidine (K_2O), albite (SiO_2, Na_2O), magnetite (FeO), Cr-augite (MgO, Cr_2O_3), ilmenite (TiO_2), and bustamite (MnO). To provide reliable data, reference materials were measured several times before and after sample data acquisition. Additionally, matrix effects were minimized by automatic processing using the conventional ZAF routine provided as part of the JEOL operating program.

Finally, the HMX harmonic least-squares mixing calculation program after Stöckelmann and Reimold (1989; but updated to a Windows version in the working-group of C. Koeberl, University of Vienna) was employed. This program includes different components (lithologies) with their respective parameters (major elements or trace elements), also considering the respective statistical errors, to calculate the composition of a given mixture (e.g., PTB). The results are given in percent component contribution and are evaluated via a “discrepancy factor” (DF), which is a relative indicator for the accordance of measured and calculated parameters (i.e., the sum of differences between observed and calculated parameter values for the mixture), whereby a DF of <1 would reflect an extremely good agreement and <3 a very good agreement.

Geological setting and some background on PTB

The original diameter of the 2020 ± 5 Ma old (Kamo et al., 1996; Gibson et al., 1997; Spray et al., 1995) Vredefort impact structure has been estimated at 250 km (e.g., Henkel and Reimold, 1998; Grieve et al., 2008). After extensive erosion by 7 to 10 km (Gibson et al., 1998) it still covers the entire extent of the Witwatersrand Basin between Johannesburg in the northeast and the Welkom gold field in the southwest. This deep exhumation has removed the bulk of the impactite formations that existed in the crater structure, but it has also provided a unique view into the deep parts (root zone) of such a large, complex impact structure. The Vredefort Dome, a ca. 90 km wide domal structure, with a ca. 45 km wide central core of crystalline rocks surrounded by a 20 to 25 km wide collar of supracrustals, has long been interpreted as the eroded remnant of the central uplift. It is estimated that rocks exposed in the central-most part of the dome have been structurally uplifted by as much as 20 km or more (e.g., Ivanov, 2005; references in Gibson and Reimold, 2008). Figure 1 provides a schematic geological overview of the Vredefort Dome.

The 40 km wide core comprises a >3.1 to 3.2 Ga (Armstrong et al., 2006) tonalite-trondhjemite-granodiorite gneiss terrane (Lana et al., 2004) with two small greenstone inliers of possibly up to 3.4 Ga age and strong lithological affinity to the greenstones of the Barberton Mountain Land (Minnitt et al., 1994; Minnitt and Reimold, 2000). This core is surrounded by the Vredefort Mountain Land, a 20 to 25 km wide collar of upturned (in the inner collar) to overturned (in the outer part) supracrustals with ages of 3.07 to 2.1 Ga. Stratigraphically these collar rocks belong to the Dominion Group, and the Witwatersrand, Ventersdorp and Transvaal supergroups (e.g., Marsh 2006; McCarthy, 2006; van der Westhuizen et al., 2006; Eriksson et al., 2006; for a stratigraphic column, refer to Gibson and Reimold, 2008). Still further out the core grades into the wider Witwatersrand Basin, specifically what is known as the Potchefstroom Syncline. This annular region represents the impact ring basin developed around the central uplift structure.

The core of the Vredefort Dome comprises migmatitic gneisses and syn-metamorphic granitic-granodioritic bodies (Lana et al., 2004). They range in pre-impact metamorphic grade from granulite facies in the central part of the core to upper amphibolite grade along the core-collar interface, and greenschist facies in the upper Witwatersrand strata of the mid-collar (e.g., Gibson and Wallmach, 1995; Gibson et al., 1998; Gibson, 2002). The impact event imparted a strong shock-metamorphic overprint (both in respect of shock pressure and temperature) onto the rocks of the core and inner collar. Gibson and Reimold (2005) determined that along a radial traverse, shock pressure ranged from >30 GPa in the rocks now exposed in the innermost terrane to 10 GPa in the inner collar. Post-shock temperatures contributed significantly in the rocks of the central-most part of the dome, where the gneisses are affected by extensive annealing. This lead to post-impact thermal metamorphism involving temperatures of 800 to >1000°C in the rocks of the inner-most part of the dome to about 300°C in the collar rocks some 25 km further out.

PTB and Vredefort Granophyre

Two types of impact-generated melt rock occur in the Vredefort Dome: pseudotachylitic breccia (PTB) as well as *bona fide* impact melt rock, the Vredefort Granophyre (e.g., reviews by Reimold and Gibson, 2006; Gibson and Reimold, 2008; Reimold and Koeberl, 2014). The Granophyre occurs in the form of meter- to decameter-wide and up to several-kilometer-long dykes within the core and along the core-collar boundary (see Figure 1). The PTB, the topic of the present contribution, represents the most prominent impact-generated deformation phenomenon on the dome with numerous excellent two- and three-dimensional exposures (e.g., Reimold and Colliston, 1994; Dressler and Reimold, 2004). Especially a number of currently no longer worked dimension-stone quarries provide excellent perspectives on massive occurrences of these breccias, with most of these sites being located some 10 to 15 km from the center of the dome (Fletcher and Reimold, 1989; Dressler and Reimold, 2004). In this zone shock pressures as estimated by Gibson and Reimold (2005) would have been of the order of 10 to 20 GPa (corresponding to 1 to 2 sets of planar deformation features [PDFs] in quartz).

PTB occurs as large breccia zones up to tens of meters wide and hundreds of meters long, or ubiquitously in form of millimeter to decimeter wide veinlets and veins (Dressler and Reimold, 2004). Millimeter-wide veinlets in collar rocks have been shown to occasionally carry coesite and/or stishovite, which has been taken as evidence for the origin of these veins directly after shock compression ceased (akin to the formation of shock veins in meteorites – e.g., Stöffler and Grieve, 2007). PTB occurrences are rare in the innermost part of the core, but in this zone outcrop is comparatively scarce and the extensive post-impact thermal overprint has further obscured original fabrics and structures. Displacements along PTB veins are rarely observed and generally short (rarely achieving 1 m, for instance, for 50 cm wide dyke occurrences); major faults or shear zones for generation of friction melt are completely absent on the dome (Gibson and Reimold, 2008, and references therein) but have been discussed further out in the ring syncline (Fletcher and Reimold, 1989).

The Otavi and Kudu quarries were dimension stone operations that were worked in the 1950s to 1960s, and up to about 2000, respectively. The main PTB occurrences at these sites are described in the following section.

Results

Geological setting of PTB

Otavi quarry

The Otavi Quarry is situated south of road R59 leading into the Vredefort Dome from the N1 freeway to the east-northeast, at longitude 26°52'41.10'' / latitude 27°32'19.46''. The prominent outcrops found here (first described by Bisschoff, 1962) are a nicely exposed quarry floor of mostly pseudotachylitic breccia, also including up to several meter sized granitic and gneissic country rock clasts (blocks), as well as an up to 10 m high wall along the eastern and southern sides of the quarry (Figure 2).

Figure 2. *Panoramic view of the central part of Otavi Quarry. The main pseudotachylitic breccia feature is a shallowly northward (left) dipping vein (marked 1) of up to 20 cm width, from which a series of moderately to steeply southward dipping veins (marked 2) seemingly are branching off. Further significant exposures of network-type PTB (Colliston and Reimold, 1994) are found in the flat quarry floor of the foreground to this image. Width of field of view is ca. 45 meters. Note the dichotomy of light pinkish, K-feldspar rich granite and light greyish, comparatively plagioclase enriched granite to granodiorite (e.g., in foreground on the right).*

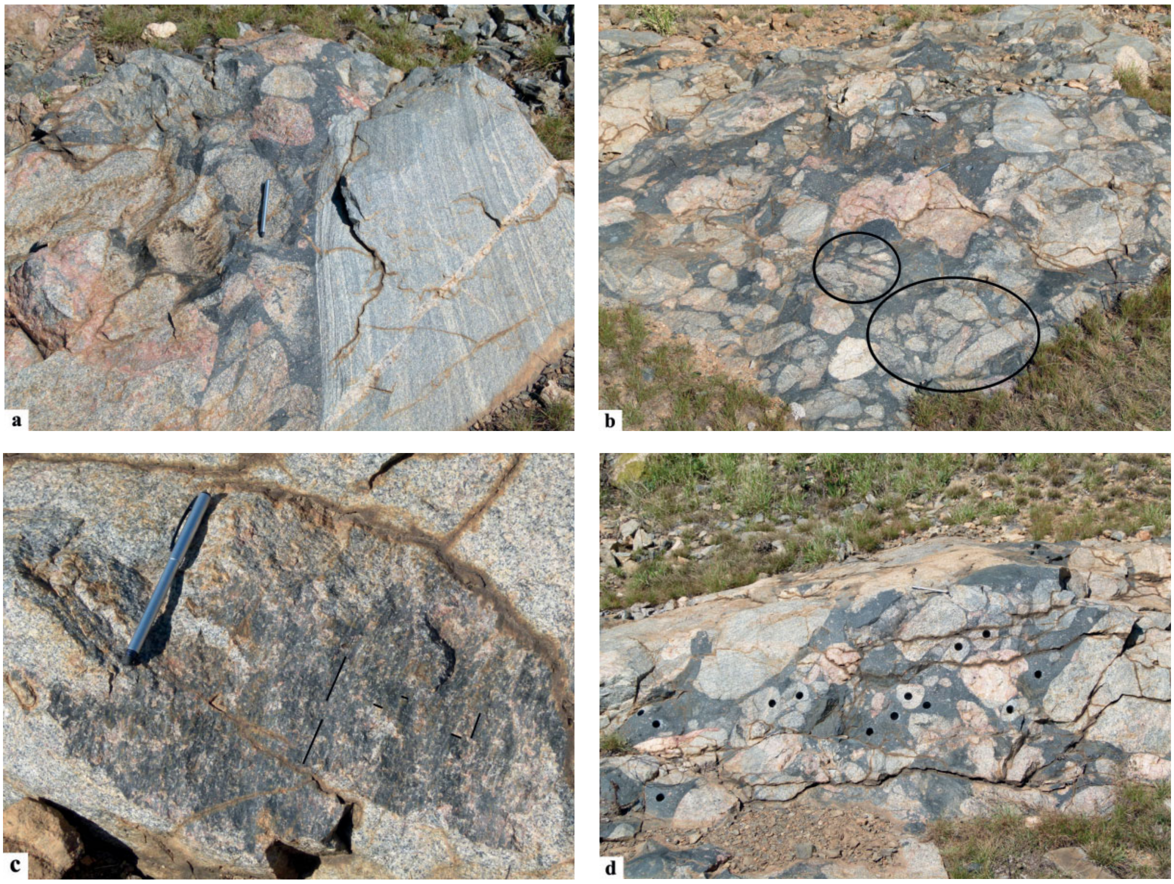

Figure 3. *(a) to (d) Some field photographs of exposures in Otavi Quarry. (**a**) Straight contact between well-banded granitic gneiss (right) and a network-style pseudotachylitic breccia occurrence on the floor to the quarry. Apparently, the PTB was formed at the contact between a K-feldspar-rich granite gneiss (left) and the grey tonalitic gneiss (right). (**b**) Typical network breccia exposure of the flat quarry floor. Note the variety of grey and pinkish clasts, the rounded nature of many clasts that is likely due to thermal abrasion by superheated melt, as well as an observation that the clasts in the lower center (within circle) form what one could call "pieces of a jigsaw puzzle". This indicates local disruption and breccia formation. (**c**) Melt-coated slickenside (harnisch) development on a joint in granite gneiss. It must be assumed that this melt development relates to friction melting. (**d**) A nice network PTB development of the quarry floor that has been abused by alleged 'geoscientific' core drilling. A typical example of geovandalism that unfortunately is ripe on the Vredefort Dome – even in the area protected under World Heritage statute.*

The main lithology of the quarry is a light-grey, in parts brownish weathered granite to granodiorite. The wall, as well as most of the clasts in the pseudotachylitic breccia of the floor rocks, is made up of this material. Locally granite clasts with correspondingly higher amounts of alkali feldspar, as well as granitoid clasts with strong gneissic layering, are found. The wall (Figure 2) exhibits mostly grey granodiorite and displays several 20 to 30 cm wide straight veins of pseudotachylitic breccia that occur sub-parallel to each other and dip with an angle of circa 50° to the southwest. These veins are connected to a more shallowly northward-dipping breccia vein that in the past has been repeatedly referred to as a generation vein having fed pseudotachylitic melt into steeper-inclined injection veins. No PTB occurs above this "feeder zone", where the lithology is a 3 m thick package of grey, strongly weathered granite mainly containing quartz, plagioclase and biotite.

PTB are mostly made up of very fine-grained, dark blue-grey to black PTB matrix encompassing millimeter- to decimeter, occasionally larger, clasts in what is generally considered a network fashion (e.g., Reimold and Colliston, 1994). The pseudotachylitic breccia contains many sub-rounded granite or granodiorite clasts of different sizes ranging from <1 cm to 2 m. For some impressions of larger PTB developments in the floor of the quarry, see Figure 3. Note that in Figure 3d groups of clasts can be seen that seemingly have been parts of a larger individual and have been separated due to dilation. Similar dilation effects are found abundantly across the Vredefort Dome, for example at Salvamento Quarry north of the town of Parys. Many of the grey granodiorite clasts display pegmatoidal veins or zones, and some clasts are entirely pegmatoid derived. The contacts of PTB to clasts and surrounding granodiorite are sharp; locally, small offshoots and PTB veinlets can be observed away from meter-scale developments into the wall rock as well as extending into larger clasts.

As shown in Figure 3c, slickensides are locally developed on granite-granodiorite, attesting to intense faulting/shearing in post-impact times. In addition, two types of radiating fracturing phenomena occur in granite of the Otavi Quarry (Figure 4). First, shatter cones (Figures 4a, b) are abundantly developed in medium-grained granite. It has, however, not been possible to decide whether shatter cone formation pre-dates PTB formation, or not. Second, in Figure 4c a typical blasting-induced radial set of vertical fractures is shown, normal to the surface of the quarry and arranged radially around the base of the original drill-hole that had been filled with explosive. A number of these anthropogenic features are in evidence throughout the quarry.

About 50 m towards the southwest of the quarry is a several meter wide outcrop of amphibolite. Contacts with the adjacent (presumably) granitic rocks are obscured by scree. In the direct vicinity of the amphibolite exposure, PTB also occurs, but the direct contact with the amphibolite is not exposed. PTB could be sampled though less than 30 cm from the presumed location of this contact. The eastern section of the quarry floor network also carries decimeter sized, rounded clasts of dolerite as a further potential precursor component to the melt rock (previously analysed by Reimold, 1991). A source body has so far not been identified.

Figure 4. *Some field photographs of striated fracture phenomena in Otavi Quarry. (a) and (b) Divergent striations on several fracture surfaces of the lower quarry floor and western foreground. These occurrences are reminiscent of shatter cones, with the somewhat cruder appearance likely related to the coarse-grained nature of the local lithology. As demonstrated in image (**b**), pseudotachylitic breccia cross-cuts a conical striated feature. (**c**) In contrast to the likely shatter cones shown in images (**a**) and (**b**), this radial arrangement of fractures represents a blast location related to the quarrying operation. Fractures are mainly arranged strictly radial and spaced at <1 cm to a decimeter. The fractures are sharp and while striations seem to occur on the upper surface perpendicular to the radial fractures, these are readily revealed as traces of such radial fractures.*

Kudu Quarry

This quarry is located at longitude 26°53'58.11" / latitude 27°25'57.25 on the Kopjeskraal road just north of the Vaal River, to the northwest of the town of Parys. The main lithology that was quarried here is a more or less intensely pink granite, of medium to coarse grain size, with locally even pegmatoidal bands. Locally, greyish granite gneiss varieties alternate with this main lithology. In some places the greyish gneiss and the pinkish granite seem to be interbanded, and pegmatoidal, restitic veins can be observed that cut through both granite and gneiss. Often the rocks are heavily deformed and sheared so that the gneissic banding appears folded. On some walls shear zones can be observed, where dark, mafic, rounded enclaves of up to 40 cm size are entrained in the granite gneiss.

In the inner part of the quarry a long (>50 m) dyke of pseudotachylitic breccia of variably decimeter to several-centimeter width occurs. It strikes northwest-southeast and along most sections is sandwiched between an up to 50 cm wide amphibolitic gneiss band in the granitic gneiss and granite (see Figure 5). However, there are some intervals where the PTB transects the amphibolite only. The PTB is a very fine crystalline to aphanitic, dark green to black rock that contains small (<2 mm) rounded clasts of quartz and feldspar. Contacts of PTB with either host rock are relatively sharp but locally embayments and mostly short (several decimeter maximum length) PTB injection veins occur. One injection vein of several meter length but <2 cm width was seen to run towards the northwest. The PTB contains predominantly granite-derived clasts (Figures 5a and b). However, as is evident in Figure 5b, PTB may occur in amphibolite only and can locally encompass cm to dm clasts of this lithology entirely. Especially in the wider sections of the PTB granite clasts can be up to 15 cm in size. As documented in Figure 5a, angular granite clasts are ripped off the contact face, and their angular shapes are largely the result of shearing and faulting with up to centimeter displacements.

Petrography of the samples from Otavi Quarry
Pseudotachylitic breccia

The pseudotachylitic breccias of the Otavi Quarry are composed of 50 to 60 vol% aphanitic to finest-grained crystalline matrix, with the remainder comprising mineral and lithic clasts. The groundmass is somewhat altered but the general

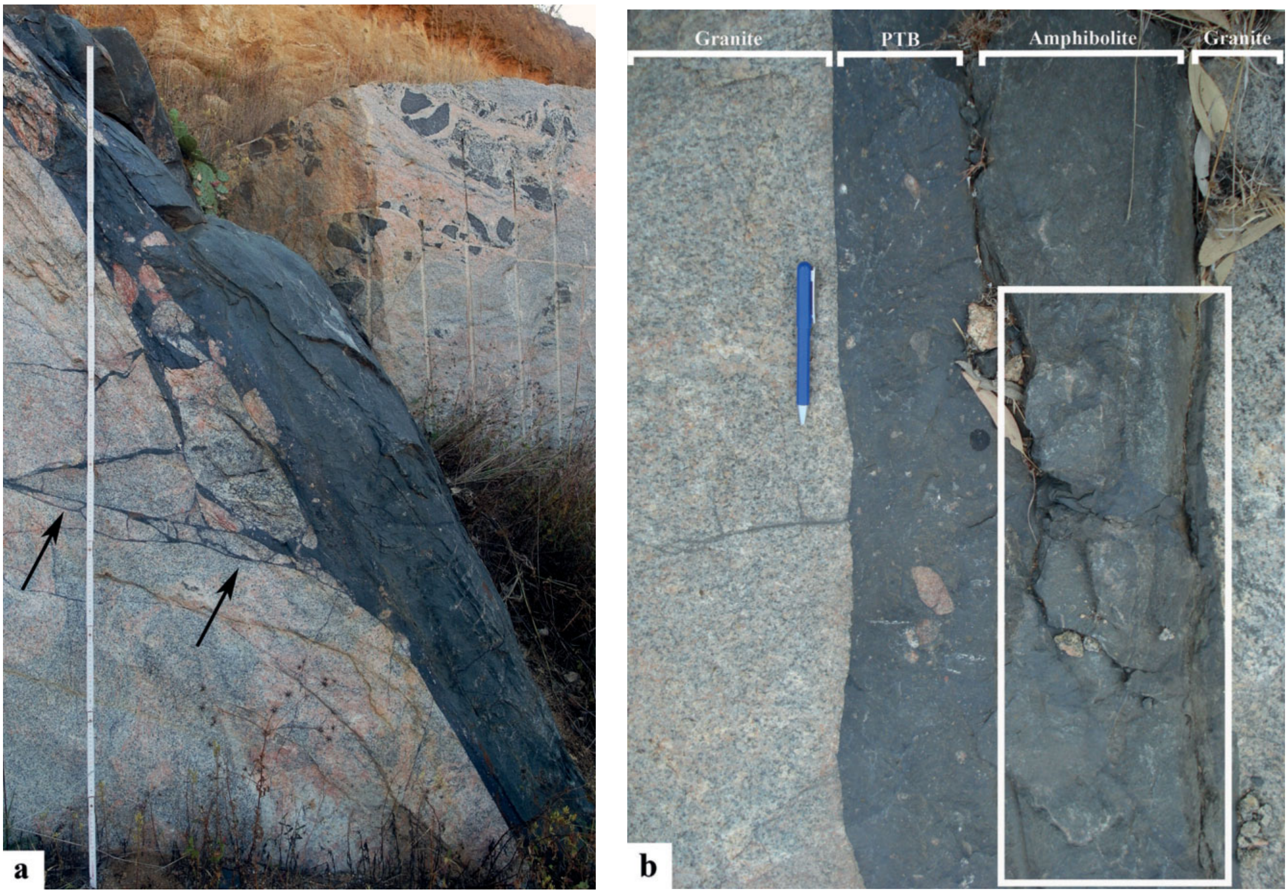

Figure 5. *Field photographs of the PTB dyke in Kudu Quarry between amphibolite (right) and granite gneiss (left). **(a)** A relatively wide portion of the dyke, with PTB carrying granitic clasts sandwiched between granitic and amphibolite hosts, whereas in **(b)** the same lithological situation is shown for a portion of dyke that is not wider than about 10 cm. Note the sharp contacts between dyke and host rocks, as well as the rip-off clasts of granite gneiss in the PTB. In (a) a thin PTB offshoot (marked by arrows) into a shear fracture in granite gneiss is noted. And in (b), the amphibolite is strongly invaded by PTB (in the framed area), and PTB also occurs in the form of a narrow band parallel to the right margin of the amphibolite dyke. Note that granite-gneiss clasts are also an important component in this PTB. Pen for scale measures 13 cm in length.*

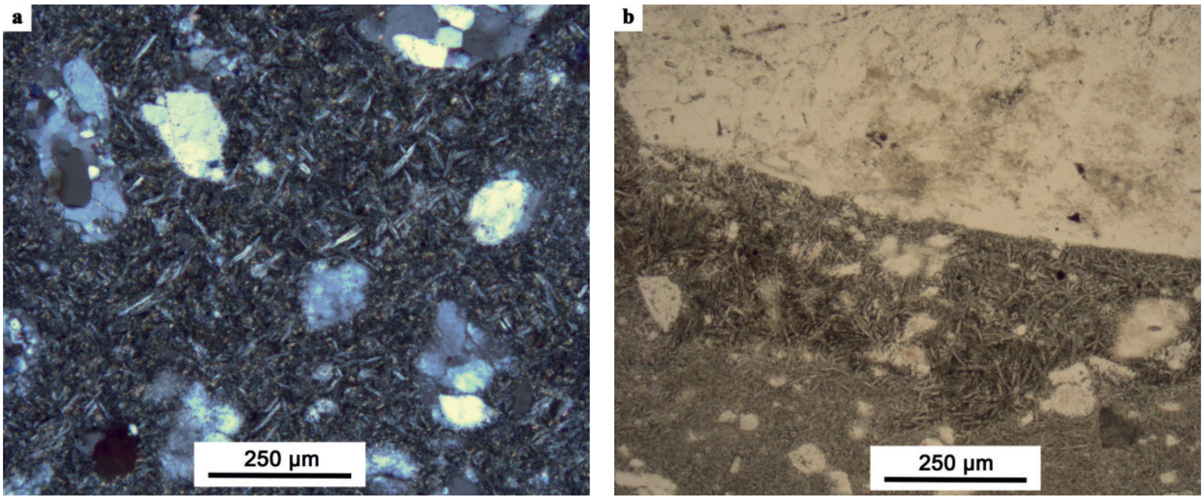

Figure 6. *Very fine-grained crystallization products in matrices of pseudotachylithic breccia in granitic host rock of the Otavi Quarry. (**a**) Feldspar and pyroxene microlites and partially recrystallized quartz and feldspar (center) clasts. (**b**) Cryptocrystalline matrix (bottom) with slightly larger microlites in the contact zone to a fine- to medium-grained granitic clast.*

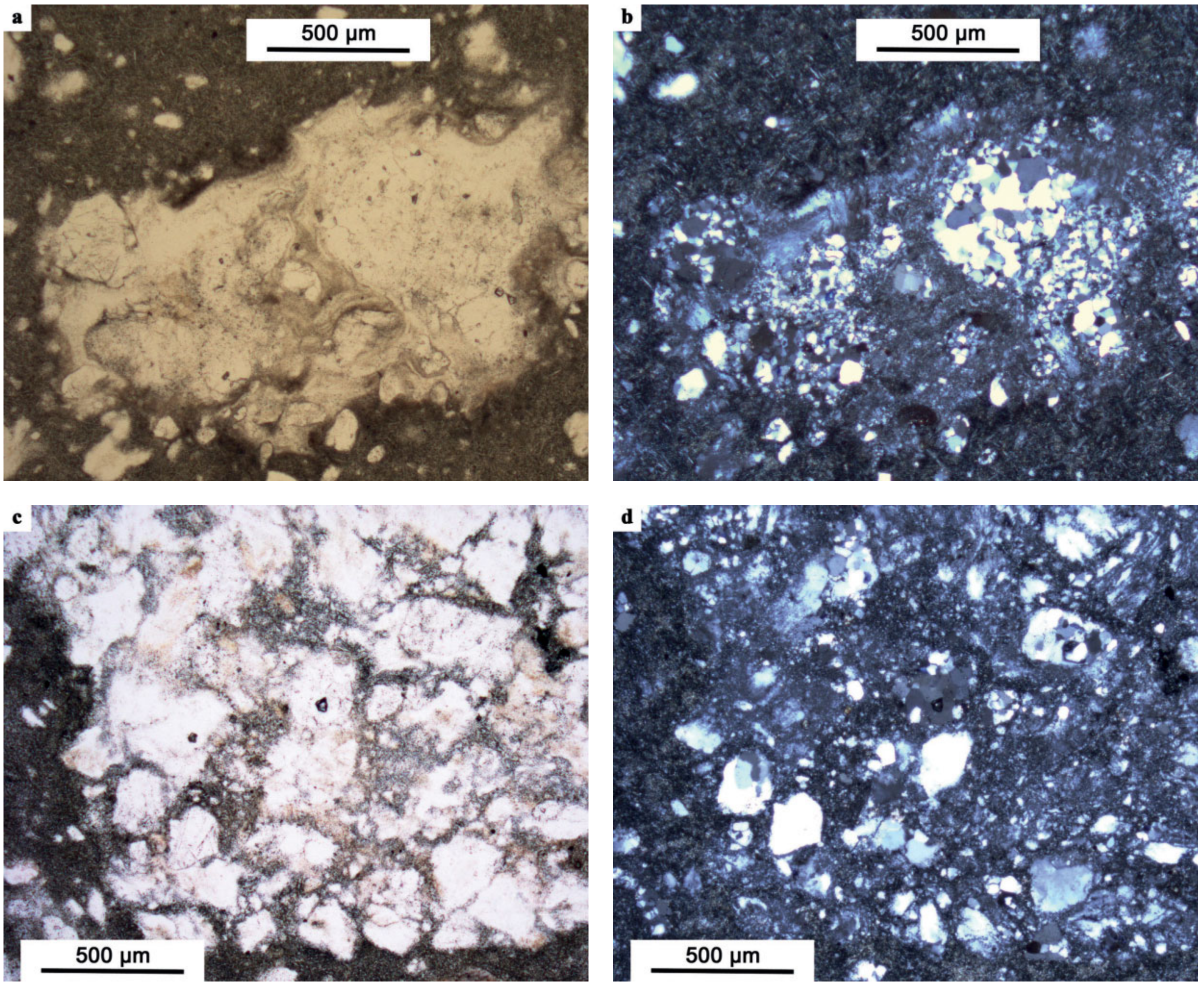

Figure 7. *Two typical, partially molten granitic clasts in pseudotachylitic breccia from Otavi Quarry (a and c in plane polarized light; b and d with crossed polarizers). The first grain in (**a**) and (**b**) shows distinct areas of melt development (flow structures in (a) and near isotropism in (b)) encompassing crystalline remnants of mostly quartz-precursor that are now completely recrystallized to very fine-grained aggregates of mosaic quartz. The second grain (**c**) and (**d**) comprises angular and only partially recrystallized "blocks" of quartz and feldspar (e.g., upper right remnant of twinned plagioclase) within a network of very narrow veins of melt.*

composition of mesostasis, as well as microlites (Figure 6) of mostly prismatic feldspar, amphibole, and smaller amounts of magnetite and pyrite, can be easily distinguished. The feldspar needles are mostly 20 to 60 µm long (Figure 6a). In narrow zones surrounding relatively large clasts, the needles can be up to 100 µm in length (Figure 6b). Notably, such clasts show extensive evidence of resorption (assimilation of marginal material into the groundmass – e.g., the embayements all around the clast shown in Figures 7a, b). Another intriguing clast type is shown in Figures 7c and d. This clast displays a texture that is best explained by cataclastic deformation (disruption into small subgrains) followed by local melting of already comminuted material.

Clasts are poorly sorted and occur in thin section at sizes from 20 µm to 6 mm. The main mineral clasts are quartz (60 to 65 vol%), alkali feldspar (30 vol%), and minor amounts of plagioclase (ca. 5 vol%). Lithic clasts are composed of the same minerals. Amphibole, chlorite, and pyrite occur as accessory micro-clasts. Nearly all the clasts show annealing and well rounded edges, and partial melting is frequently observed. Quartz and alkali feldspar grains commonly display features of high-temperature overprinting, such as extensive recrystallization (annealing) in 60 to 80% of quartz grains, or reduced birefringence in many alkali feldspar grains. Some of the feldspar grains are entirely isotropic (diaplectic feldspar glass). The plagioclase grains often display selective annealing of twin lamellae. Shock deformation in the form of planar deformation features (PDF) in quartz is rare and when present, only single sets of PDFs were noted. In most cases, PDFs sets are more or less annealed. Frequently, however, remnants of PDFs can still be discerned between annealed PDFs that consist now of small, mosaic neocrysts. Overall, micro-clasts are in their vast majority granitoid derived. Rarely, micro-clasts derived from mafic lithology can be observed in thin section. These micro-clasts are generally strongly altered and/or oxidized - possibly related to the thermal overprint from the hot melt matrix. This makes it impossible to judge the exact composition of their precursor rock. However, based on field observations, it is probable that these clasts are derived from amphibolite and/or dolerite precursors.

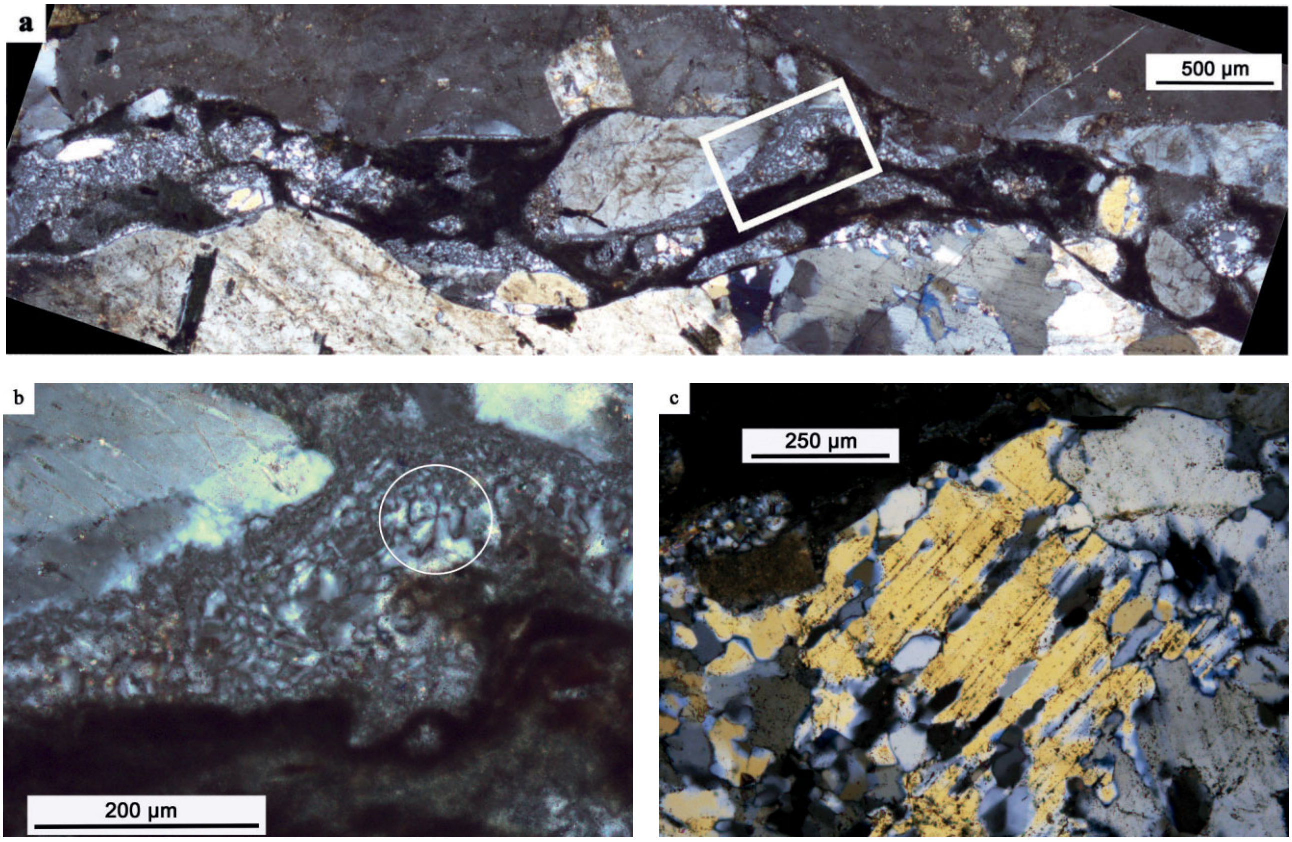

Figure 8. *A millimeter wide veinlet of pseudotachylitic breccia cutting across a granite-gneiss specimen from Otavi Quarry. **(a)** A "panorama" of several microphotographs showing a typical section of this altogether two centimeter long section of the veinlet. The vein interior comprises a dark, mafic melt formed from mafic precursors in the granite gneiss (probably biotite) alternating with devitrified melt derived from feldspar and locally also quartz (the latter at extreme right side of this image). Note that both quartz and feldspar relicts are significantly rounded due to marginal "thermal abrasion". Rectangle marks the area magnified in (b). **(b)** Host rock alkali-feldspar (upper left) grading into devitrified feldspar melt (the circle marks a rosette of fibrous crystals identified by electron microprobe analysis as orthoclase). This felsic melt intermingles with the dark, almost opaque melt phase in this vein. **(c)** Quartz grain in host rock to (a) and (b), showing remnants of a prominent set of planar deformation features (PDFs). The PDFs were the loci for partial annealing at post-impact time, resulting in replacement of PDF sections by strings of extremely fine-grained mosaic quartz.*

Granitoids

The granitoids in the Otavi Quarry range from tonalitic to granodioritic in composition. The rocks are mainly equigranular and medium- to coarse-grained, with hypidiomorphic grains of <3, and up to 15 mm size. Main minerals are plagioclase, alkali feldspar and quartz. In many samples, plagioclase is the dominant phase, with up to 65 vol%, and quartz contributes at 30 vol%, but there are also thin sections in which alkali feldspar is abundant (up to 25 vol%). Biotite and chlorite can occur in minor amounts, and titanite, apatite, zircon and amphibole are accessories. The quartz grains are often slightly recrystallized (annealed) but not as strongly as quartz in clasts within PTB. There are certain narrow zones in some thin sections, where an increase of recrystallization can be observed. In some such cases very small, extremely fine-grained bands appear in these zones and likely represent micro-shear bands or very thin, annealed PTB veinlets (Figures 8a, b). Fibrous, sometimes radiating crystallization signifies that a melt phase then has been present (Figure 8b).

A lot of quartz crystals exhibit PDFs. These are mostly decorated and occur in up to about 30% of the quartz grains (Figures 8c and 9a, b). Note that the relatively broad and seemingly not quite planar fluid inclusion trails in Figure 9b do indeed represent PDFss that are, however, cut at a relatively low angle by the thin section plane. No evidence for an increase of shock deformation towards the contacts with PTB veinlets could be detected.

Amphibolite

Amphibolite samples derived from the aforementioned exposure to the southwest of the main quarry and also from decimeter sized amphibolite clasts in PTB are characterized by a predominantly equigranular, hypidiomorphic texture. They are relatively fine-grained with grain sizes mostly ranging from 0.5 to

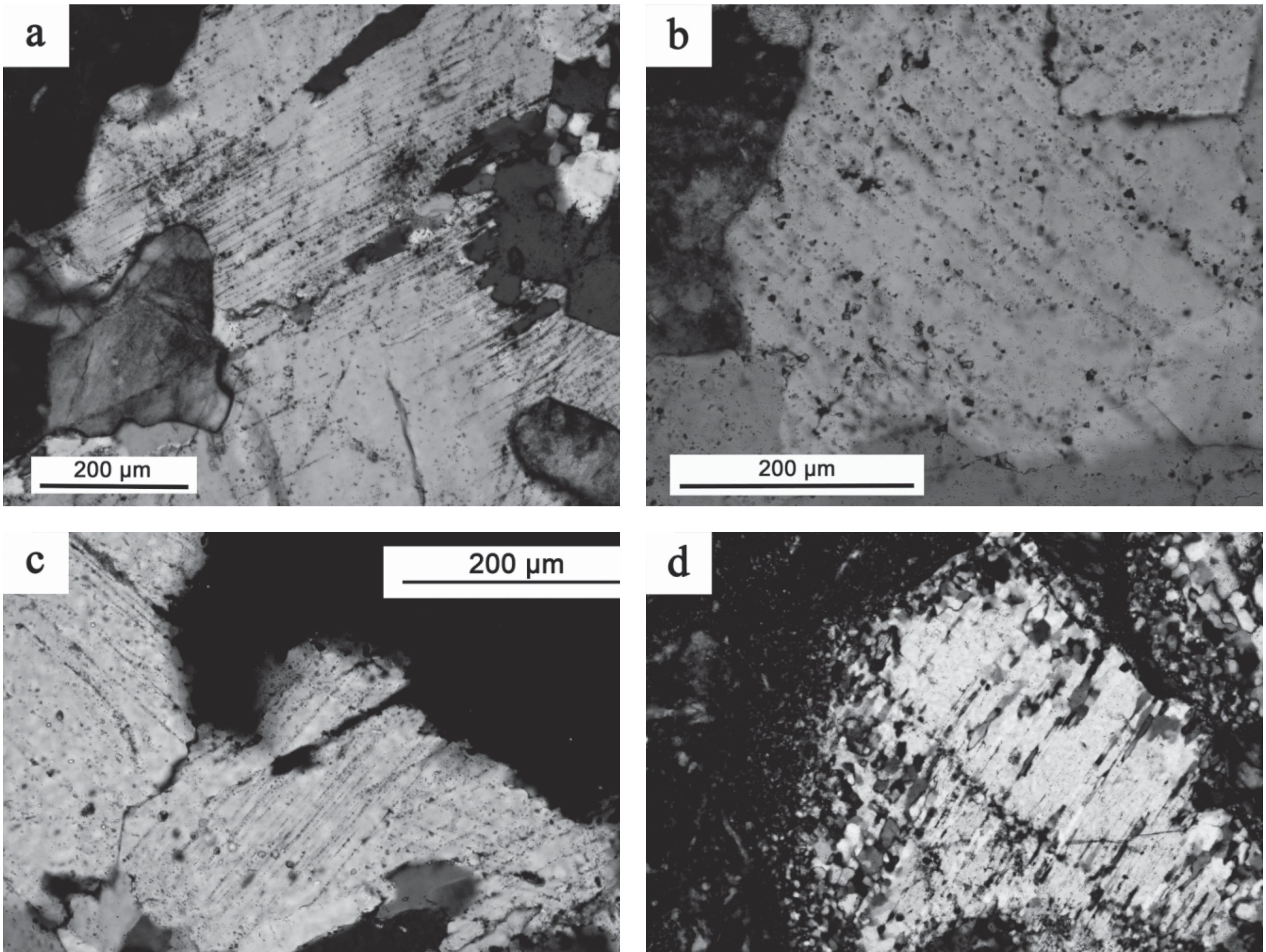

Figure 9 . *Planar deformation features in Otavi (a) and (b) and Kudu (c) and (d) specimens. **(a)** and **(b)** Quartz in granitic gneiss from Otavi displaying single sets of decorated PDFs in basal orientation (0001). **(c)** Granitic host rock to PTB (Kudu) with quartz grain (center) showing two sets of PDFs in northeast-southwest and northwest-southeast orientation. **(d)** A set of planar fractures (northwest-southeast) and PDFs (northeast-southwest), along which partial recrystallization with fine -grained mosaics has taken place - quartz clast in pseudotachylitic breccia from Kudu*

1 mm. Mineral composition includes 20 vol% amphibole, 20 to 30 vol% biotite, 30 vol% feldspar (alkali feldspar and plagioclase in approx. equal amounts), and about 15 vol% quartz. The rocks are foliated and show a strong, preferred orientation of biotite and some of the amphibole. Titanite is a minor component, and apatite and zircon are accessories. In some sections amphibole crystals display a very pronounced cleavage that may have been enhanced by impact deformation. Biotite shows extensive kink banding. Some of the zircon grains exhibit grape-like aggregation and magnetite-emphasized margins. It is not impossible that at least some of the former is related to impact-caused granularization. Besides these features, there is no further evidence of shock metamorphism, such as PDFs or PFs in quartz or feldspar. This reduced degree of shock metamorphism, when compared to the shock deformation of the granitoids, must be related to the finer grain size and the impedance contrast between biotite and amphibole, whereby the latter mineral is anyway less prone to display characteristic shock effects.

Otavi geochemistry

The new X-ray fluorescence spectrometric analyses for major and selected trace elements in Otavi samples are compiled in Table 1. The MgO versus SiO_2 data are shown in Figure 10 and all the data in the profile plots of Figure 11a (major elements) and b (trace elements). Figure 10 illustrates a clear bi-component mixing trend – emphasized by the regression line and its inherent correlation coefficient. Even taking both amphibolite end-members into consideration, the Vredefort Granophyre (impact melt rock) does not feature in this mixing situation.

From Figures 11 it is immediately obvious that sample pairs of PTB and immediate host rock have strongly comparable chemical compositions. For example, for nearly all PTB and host rock suites (as separated by vertical lines in Figure 11) the mafic PTB has chemical compositions that are very similar to those of adjacent amphibolite or that represent obvious mixtures between amphibolite and a granitic lithology sampled on the other side of the PTB occurrence. PTB sampled in granite gneiss has similar compositions to those tonalitic or trondhjemitic country rocks as well. Only the K_2O profile in Figure 11a shows some irregular behavior, which in part may be related to alteration or, perhaps, to contribution from mixed granitic phases rather than only the directly exposed, adjacent granitic component.

This general trend of more mafic composition of PTB where amphibolite occurs close-by is also displayed by many trace elements, as exemplified by V and Sr (Figure 11b). Some less obvious trends may be related to nugget effects for specific elements relatively enriched in the melt rock, or to alteration.

Table 1. Major and trace element compositions determined by XRF for Otavi samples. All data in wt%, total Fe as Fe_2O_3.

Sample ID	VPU 32	VPU 33A	VPU 33B	VPU 34	VPU 35	VPU 36	VPU 37	VPU 38	VPU 39	VPU 40	VPU 41	VPU 42	VPU 43
Lithology	Amph.c.	PTB	PTB	Ton.	Ton.	PTB	PTB	Tr.	Tr.	PTB	Tr.	Amph.	PTB/Amph. c.
Major elements [wt%]													
SiO_2	52.2	53.0	65.2	70.2	69.4	70.2	70.6	74.7	74.1	69.6	73.7	51.4	63.6
TiO_2	1.05	1.06	0.64	0.37	0.33	0.41	0.37	0.07	0.19	0.48	0.05	0.99	0.79
Al_2O_3	18.2	18.2	14.5	15.8	15.8	15.2	15.4	13.7	13.8	14.9	14.2	16.6	14.8
Fe_2O_3	9.30	9.04	4.47	2.30	2.14	2.57	2.28	0.54	1.38	3.01	0.30	10.3	5.73
MnO	0.12	0.12	0.06	0.03	0.03	0.04	0.03	<0.01	0.01	0.04	<0.01	0.16	0.07
MgO	3.60	3.51	1.71	0.66	0.58	0.81	0.71	0.07	0.20	0.94	0.07	5.08	2.28
CaO	6.29	6.37	3.17	2.12	1.95	2.15	2.18	0.97	0.78	2.31	0.26	7.37	3.76
Na_2O	5.11	5.16	4.22	4.74	4.77	4.55	4.62	3.43	3.21	4.45	2.85	4.29	4.10
K_2O	2.04	1.97	2.77	2.60	3.17	3.04	3.09	5.10	5.80	3.18	7.62	1.90	2.86
P_2O_5	0.65	0.64	0.19	0.10	0.08	0.11	0.10	0.01	0.01	0.13	<0.01	0.61	0.24
LOI	1.2	1.0	3.0	0.6	0.8	0.5	0.6	0.6	0.4	0.8	0.5	1.3	1.1
Sum	99.76	100.07	99.93	99.52	99.05	99.58	99.98	99.19	99.88	99.84	99.55	100.01	99.33
Trace elements [ppm]													
V	151	143	72	20	13	28	19	<5	12	35	<5	182	98
Ni	34	34	25	7	7	9	9	<5	<5	13	<5	54	33
Zn	100	97	61	49	49	50	48	<15	23	54	<15	110	68
Ga	21	21	18	20	18	18	18	<15	<15	17	<15	21	18
Rb	97	89	101	89	117	110	106	120	149	104	199	75	95
Sr	686	709	310	310	284	300	303	301	210	298	170	507	344
Y	39	36	18	13	20	17	15	<10	<10	15	<10	40	20
Zr	166	159	188	217	186	199	213	34	93	237	13	190	189
Nb	13	13	14	15	13	14	12	<10	<10	13	<10	14	13
Ba	391	474	518	430	512	494	468	813	608	531	515	299	528
La	50	51	50	57	59	60	59	<10	71	72	<10	47	55
Ce	106	94	100	106	104	108	109	21	121	145	<10	118	100

Amph. = Amphibolite; Amph. c. = Amphibolite at contact to PTB; PTB = Pseudotachylitic breccia; Ton. = Tonalite; Tr. = Trondhjemite.

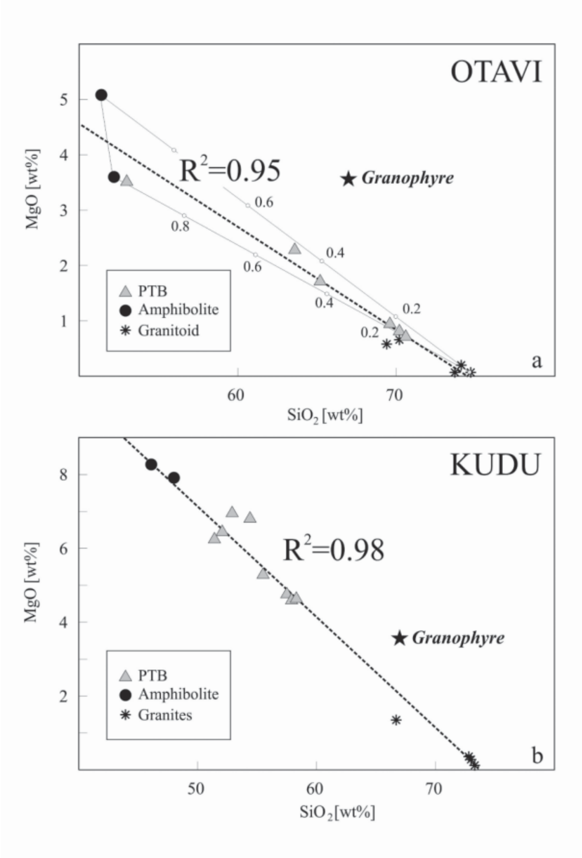

Figure 10. *SiO_2 vs. MgO diagrams for the samples from Otavi (a) and Kudu (b) quarries. For comparison, the data point for the average Granophyre composition (compare Table 4) is also shown. In (**a**), a very well constrained regression through all Otavi data is shown, as well as mixing trends between the obvious end-members (two different amphibolite varieties and the granitoid data cluster). In (**b**), the regression line through all data minus the Granophyre also has a very good correlation coefficient. In both diagrams, the Granophyre component is not required to generate the PTB mixtures.*

Petrography of the samples from Kudu Quarry
Granite

The granite in Kudu Quarry is a medium- to coarse-grained rock with similar amounts of plagioclase and alkali feldspar (orthoclase as well as microcline, 40 vol% each), and about 15 vol% quartz. In addition, there are minor amounts of amphibole, biotite and calcite (primary and secondary), and traces of magnetite. The quartz grains are often partially recrystallized, frequently along former linear features (presumably originally PDFs). Only rare grains now still show one or two sets of PDFs. They appear as decorated PDFs (Figure 9c) or are variably annealed (Figure 9d). The feldspar grains are all altered to varied degrees and display abundant sericitization. Some of the feldspar grains also show recrystallization.

Amphibolite

The amphibolite is composed of 50 vol% amphibole, about 30 vol% quartz, and equal amounts of alkali feldspar and plagioclase (10 to 15 vol% each). Additionally, there is some biotite that often occurs in zones enriched in this mineral and that alternate with more amphibole-rich bands. Accessory minerals are magnetite and secondary calcite. The rock is strongly foliated, fine- to medium-grained, and relatively equigranular. The grains are mostly hypidiomorphic. Biotite often exhibits strong kink banding, and, locally, amphibole grains display microfracturing. Cleavage in amphibole is very pronounced. Where the amphibolite is in contact with the pseudotachylitic breccia the amount of biotite increases against the PTB. This may well indicate that biotite rich zones of the amphibolite were loci of preferred melting because of the enhanced presence of volatiles.

Pseudotachylitic breccia

The PTB sampled in Kudu Quarry has a very fine-grained, dark matrix similar to the one from Otavi Quarry. The matrix makes up about 60 to 70 vol% of the PTB and encompasses many poorly sorted and subrounded clasts. Felsic clasts are dominant and often exhibit evidence for local melting, recrystallization, and annealing of twin lamellae in plagioclase or PDFs in quartz. Single sets of PDFs in quartz are prevalent, and only rarely are as many as two per host grain observed. Rarely larger than 2 cm sized clasts of amphibolite can be observed in the PTB. They are clearly thermally altered, and most of the amphibole grains no longer exhibit their characteristic features. They are mostly dark brown to black and isotropic, and the normally pronounced cleavage is hardly observable and only preserved in very small crystals. The foliation of the amphibolite is still mirrored by biotite bands within clasts. Additional accessory minerals are chlorite, and calcite that likely formed due to secondary alteration of the feldspar component. The PTB shows small offshoots into the neighbouring lithologies that sometimes grade into zones of fine recrystallized quartz.

In both amphibolite and granite thin veins of pseudotachylitic breccia (about 0.5 to 1.5 mm wide) occur that may or may not be directly linked to the main PTB dyke. These veins have been formed along orientations that are slightly oblique to the foliation, as documented by one offshoot vein from the main PTB dyke in Figure 5. Close to such veinlets quartz and plagioclase annealing is comparatively enhanced. Clasts inside the PTB are derived from the felsic minerals of the granite as well as the mafic minerals of the amphibolite, with felsic clast material somewhat more abundant than amphibolite debris.

An electron microprobe investigation of a PTB veinlet

The section of a ca. 1 mm wide PTB veinlet shown in Figure 12 was analyzed by EMPA using a 10 µm wide, defocussed electron beam. This vein was sampled as an offshoot from the main PTB dyke. The purpose of this study was to investigate whether different host rocks (amphibolite or granite) can be related to different compositions in the vein. The three areas marked on the figure represent a section of vein only occurring within granite (Area 1), one straddling the slightly (by about 1.2 mm) displaced contact zone between amphibolite and granite (Area 2), and one

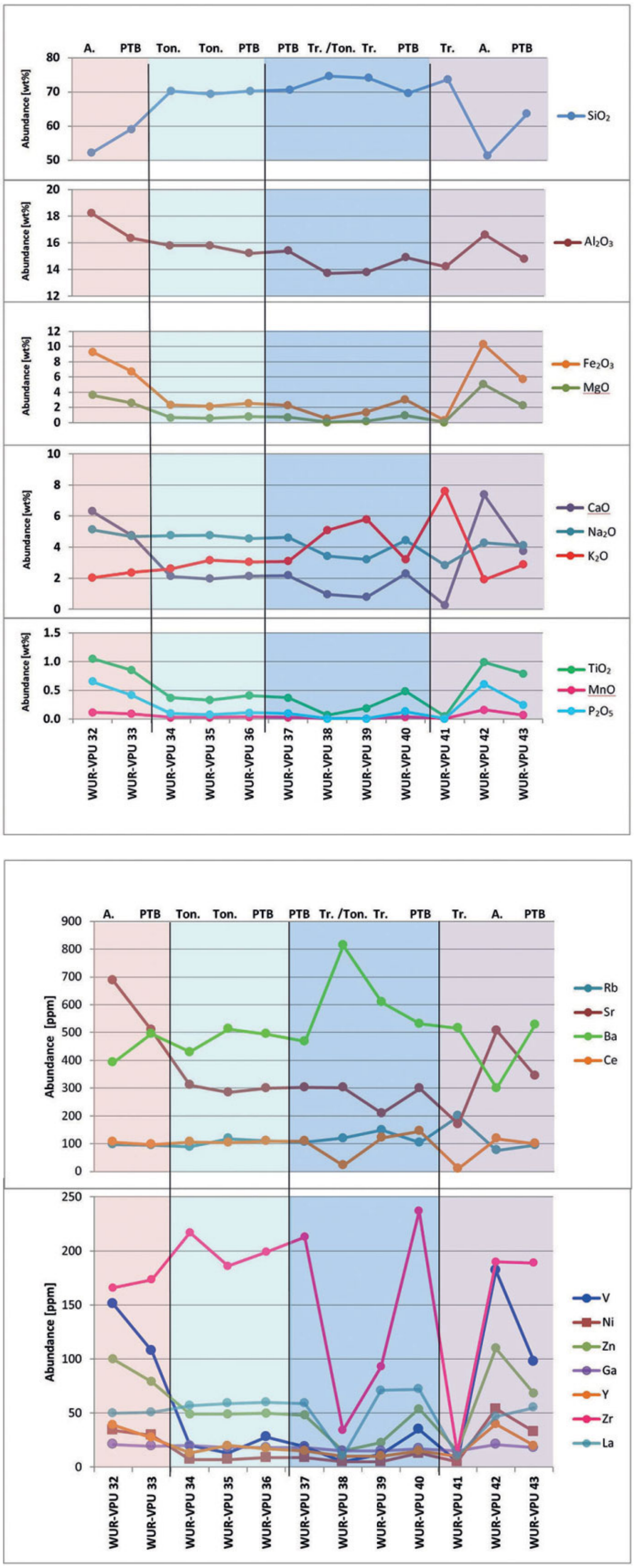

Figure 11. *Chemical systematics for the suite of Otavi pseudotachylitic breccia and respective host rock samples (compare Table 2).* ***(a)*** *Major element oxide abundances given in wt%;* ***(b)*** *trace element data in ppm. Vertical lines separate individual groups of samples that were obtained in close proximity of each other. A. – amphibolite; PTB – pseudotachylitic breccia; To. – tonalite; Tr. – trondhjemite.*

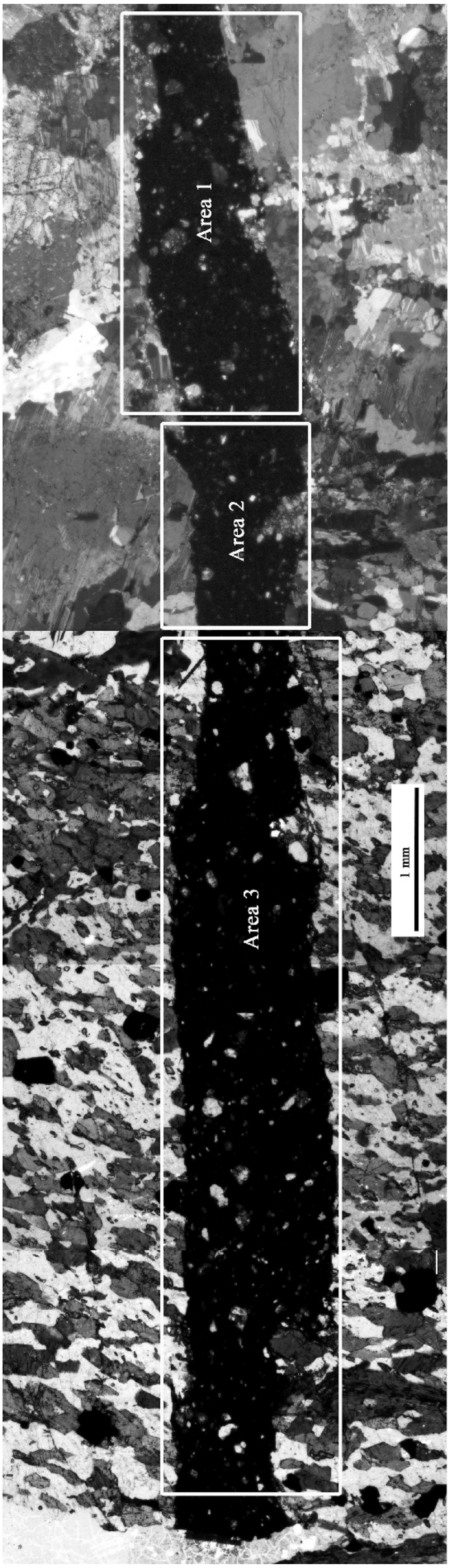

Figure 12. *A 1 mm wide PTB offshoot from the main dyke in Kudu quarry showing short displacement at the contact between granitic gneiss and amphibolite country rocks. Rectangles (marked* ***1*** *to* ***3****) indicate areas along this veinlet where matrices were analyzed by EMPA to check for possible variation in groundmass composition (compare Table 2). The image is a composite of two photographs taken with plane polarized light (left) and cross polarized light (right) to enhance respective distributions of different minerals in contact with the PTB veinlet.*

Table 2. Average composition of matrices along PTB veinlet from Kudu Quarry (compare Figure 12). (**a**) shows results where only measurements with a total of >97 wt% where taken into account, whereas (**b**) shows results when all measurements were taken into account. All data in wt%.

(**a**)

	Area 1 (n=9)		Area 2 (n=3)		Area 3 (n=8)	
Oxide	**Mean**	**Std. dev**	**Mean**	**Std. dev**	**Mean**	**Std. dev**
SiO_2	50.55	2.08	48.69	2.57	50.02	2.27
TiO_2	3.20	2.91	5.68*	6.01	2.44	3.38
Al_2O_3	9.53	1.79	10.07	2.23	8.45	1.64
FeO	11.27	1.05	10.84	2.85	12.42	2.64
MnO	0.22	0.05	0.18	0.05	0.21	0.06
MgO	8.45	1.47	6.53	2.11	9.09	1.93
CaO	9.64	2.35	10.21	4.55	10.95	2.69
Na_2O	3.15	0.80	3.75	0.29	2.86	0.82
K_2O	1.57	0.60	1.44	1.14	1.30	0.54
Sum	97.60	0.44	97.42	0.35	97.79	0.64

* Nugget effect: apparently an ilmenite grain is involved in one of these analyses.

(**b**)

	Area 1 (n=19)		Area 2 (n=9)		Area 3 (n=25)	
Oxide	**Mean**	**Std. dev**	**Mean**	**Std. dev**	**Mean**	**Std. dev**
SiO_2	48.76	2.74	47.71	4.00	46.89	3.37
TiO_2	3.72	3.50	4.38	5.44	2.52	3.16
Al_2O_3	10.12	1.93	10.21	1.98	10.25	2.23
FeO	11.18	2.69	11.84	4.12	13.96	2.95
MnO	0.20	0.06	0.17	0.04	0.18	0.05
MgO	8.43	2.12	8.00	2.42	9.38	1.66
CaO	8.84	2.75	8.68	4.48	7.73	3.78
Na_2O	2.95	0.88	3.24	0.53	2.70	0.78
K_2O	1.69	0.71	1.64	1.01	1.67	0.88
Sum	95.92		95.90		95.31	

that is fully enclosed by amphibolite host rock (Area 3). The analytical data are compiled in Table 2a, as average vein compositions calculated from those analyses only that gave >97 wt% totals. Table 2b relates average area compositions based on all available compositions.

Comparing the average area compositions given in Tables 2a and 2b, they are quite similar within error limits. TiO_2 values are partially quite high and it is assumed that this is based on a nugget effect involving small ilmenite crystals. It is also obvious from these data that there is no distinct compositional trend from PTB in granite only to PTB in amphibolite (Area 1 → Area 3). Instead, all areas display an amphibolitic composition similar to the bulk chemical composition of the Kudu Quarry amphibolite as given in Tables 3 and 4. Interestingly, when corrected for the anomalously high TiO_2 content, the thin veinlet becomes even more mafic than the PTB of the main dyke.

Kudu geochemistry

As only few samples from this location had been analyzed previously (Mohr-Westheide, 2011; Lieger, 2012), a suite of more representative samples from all three lithologies at Kudu Quarry was collected for chemical analysis. The XRF results are compiled in Table 3. Two amphibolite analyses are quite similar. Amongst 4 analyses of granitic country rock from the quarry, one analysis clearly represents a K-feldspar rich variety. It is reasonable to assume that the available analyses constitute a good representation of the granitic host rock to PTB at Kudu Quarry.

The new analyses of samples of PTB illustrate the relatively homogeneous composition of the dyke. The composition itself is intermediate between those of amphibolite and granite, not only for the major elements but also for many trace elements (V, Cr, Co, Ni, Cu, Zn, Zr, Ba). For several other trace elements, the variability between individual samples of a rock type is too strong to allow investigation of this trend (e.g., Sr or Ba). Overall, affinity of the PTB is much closer to amphibolite than to granitic host rock.

Mixing calculations

From the data for samples collected in Otavi Quarry, average mixture (PTB) and component (country rock types) compositions were calculated (Table 4a) as input for mixing calculations with the harmonic least-squares HMX routine of Stöckelmann and Reimold (1989). The data base for the calculation of the mafic component also contains two analyses of mafic clasts in PTB from the quarry floor. These analyses were originally published by Reimold (1991). HMX calculations were performed with the element oxide parameters SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, and K_2O. Two calculation modes were chosen: (a) only admitting the country rock lithologies listed in Table 4a, and (b) allowing for contribution from an additional impact melt component akin to the average composition of Vredefort Granophyre. For this, an average Granophyre component calculated from data in Wannek (2015) was taken (see Table 4a). Both calculations yielded the same results (compare Table 4c): the PTB in Otavi Quarry can be generated from mixing of ca. 70 ± 3% granite-gneiss and 30 ± 3% amphibolite/dolerite. The Discrepancy Factors for both calculations were 2.6, indicating a very good match. A Granophyre contribution to the PTB is clearly not required by these findings.

A HMX calculation was also performed with granite and amphibolite components for PTB from the Kudu Quarry, with the average compositions listed in Table 4b. The parameter selection was the same as given above for the Otavi calculations. The result (Table 4c) is straightforward: PTB can be generated with high confidence (Discrepancy Factor: 0.2) with 74 ± 1% amphibolite and 26 ± 1% granite, again without a Granophyre contribution being required. The HMX results for both localities are listed in Table 4c.

For both these case studies, chemical and mixing calculation results are consistent with the petrographic findings, whereby only clasts derived from accessible country rock types were observed in the respective PTB. No quartzite or shale clasts, as they are characteristic for the Vredefort Granophyre and testify to a contribution from the Witwatersrand Supergroup to Vredefort impact melt, were noted in the PTB investigated from these two

Table 3. Major and trace element compositions by XRF for Kudu samples. All data in wt%, total Fe as Fe_2O_3.

Sample ID	TMV-19	V1	PZ-Tm3	Kudu A1*	Kudu A2*	KU 3a	KU 3b	KU 3c	KU 4	V3	Kudu A3*	VPU-20	KU 1	KU 2
Lithology	Amphibolite	Amphibolite	PTB	PTB	PTB	PTB	PTB	PTB	PTB	PTB	Granite	Granite	Granite	Granite
Major elements [wt%]														
SiO_2	46.10	48.00	55.5	52.07	51.41	57.5	57.9	58.3	52.9	54.4	72.99	72.8	66.7	73.3
TiO_2	2.33	2.26	1.60	1.92	2.20	1.47	1.41	1.42	2.01	1.95	0.16	0.22	0.46	0.14
Al_2O_3	10.60	10.20	12.0	11.52	9.90	12.5	12.8	12.6	10.7	10.5	13.97	14.4	17.0	14.3
Fe_2O_3	15.60	15.30	11.0	12.94	13.98	9.50	9.32	9.44	13.9	12.9	1.49	1.42	2.99	1.35
MnO	0.23	0.23	0.15	0.20	0.19	0.16	0.14	0.15	0.20	0.19	0.02	0.02	0.04	0.01
MgO	8.27	7.91	5.28	6.44	6.24	4.75	4.59	4.63	6.95	6.80	0.28	0.36	1.35	0.12
CaO	9.43	9.19	6.51	8.06	7.74	6.00	5.80	5.70	7.76	7.63	1.35	1.75	2.24	0.45
Na_2O	3.03	3.15	4.03	4.41	4.64	4.44	4.14	4.30	3.89	3.80	8.23	4.34	3.56	3.82
K_2O	1.49	1.52	2.33	2.02	0.46	2.25	2.33	2.39	0.67	1.00	0.80	3.21	4.56	5.82
P_2O_5	0.47	0.48	0.31	0.42	0.44	0.29	0.29	0.28	0.38	0.37	0.02	0.04	0.09	0.01
LOI	1.70	1.80	1.1	0.88	1.23	0.9	0.9	0.9	0.8	0.6	0.99	1.2	0.8	0.4
Sum	99.25	100.04	99.81	100.88	98.43	99.76	99.62	100.11	100.16	100.14	100.3	99.76	99.74	99.72
Trace elements [ppm]														
Sc	21	18	15	n.d.	n.d.	14	14	15	17	18	n.d.	<5	<5	<5
V	368	346	229	257	286	202	193	199	310	268	<12	11	53	5
Cr	228	226	122	192	182	110	108	110	196	171	186	<5	21	<5
Co	51	48	31	45	49	27	27	28	41	39	7	<5	7	<5
Ni	141	133	86	88	87	77	72	73	122	110	11	<5	21	<5
Cu	414	383	271	301	313	253	228	224	145	208	24	<15	74	<15
Zn	139	136	92	118	130	84	88	79	118	112	23	29	32	25
Ga	18	18	17	n.d.	n.d.	17	17	17	17	16	n.d.	16	16	21
Rb	23	28	39	41	11	46	48	48	12	19	23	63	75	156
Sr	323	260	431	476	253	447	432	433	196	219	664	507	504	50
Y	12	14	13	15	15	12	11	12	15	11	4	<10	<10	13
Zr	75	79	97	128	94	112	111	112	84	84	185	112	106	124
Nb	21	21	19	20	21	18	16	16	19	18	<3	<10	<10	43
Mo	<10	<10	<10	n.d	n.d	<10	<10	<10	<10	<10	n.d	<10	<10	<10
Ba	411	444	547	584	174	616	588	807	596	227	675	1032	1875	158
La	23	20	28	n.d.	n.d.	38	31	33	17	17	n.d.	30	<10	18
Ce	26	18	48	n.d.	n.d.	55	51	56	24	27	n.d.	60	<10	32

n.d. = not determined; < xx = below detection limit; * from Lieger (2011).

quarries (or, indeed, have ever been reported previously from any of the numerous samples of PTB studied from the Vredefort Dome – unless a quartzite/quartz pod or vein occurs in the immediate vicinity of the PTB occurrence and was a likely litho-component that contributed to the locally formed PTB).

Discussion

Origin of the PTB at Otavi Quarry

Otavi Quarry is a 3-dimensional exposure of voluminous ("massive") pseudotachylitic breccia that can be regarded as a window into a much larger, kilometer-long PTB dyke extending onto the farm Abel to the southeast of Otavi (Dressler and Reimold, 2004) and perhaps further towards the northwest across the R59 road. Within the quarry the PTB is observed to carry clasts of only locally occurring country rock types - mainly granitoids but also minor amphibolite and dolerite, consistent with the clast population in PTB thin sections. The dolerite was not observed in outcrop, but the fact that such inclusions are only detected in the northwestern part of the quarry floor must be interpreted to indicate close vicinity of the exposed PTB to the parent intrusion. It was concluded that – in all likelihood – the lithologies that contributed to PTB have been identified in the field and analysed in the available samples. Shock deformation levels gauged from microdeformation in micro-clasts are consistent with the assessment by Gibson and Reimold (2005) that shock grade attained in the rocks now exposed in the outer crystalline core of the Vredefort Dome is <20 GPa. This is supported by the fact that mostly single sets of PDFs are found in quartz grains, which suggests shock pressures lower than 15 GPa (Stöffler and Langenhorst, 1994; Huffman and Reimold, 1996).

Reimold (1991) concluded from first analyses of granitic and amphibolitic country rocks and a single PTB sample from Otavi that the PTB had likely been formed locally from the analyzed lithologies. Our new chemical analyses for basement lithologies in close contact with a number of PTB emphasize a close chemical resemblance of adjacent pairs of PTB and country rock(s), and that PTB represents a mixture of two different country rock types (Figure 10). The mixing situation illustrated for MgO versus SiO_2 in Figure 10 and the chemical profiling (Figure 11) demonstrate that for both major and trace elements no additional lithological components are required to make up a PTB composition. This result is further supported by the HMX mixing calculations that rule out the need to resort to an addition

Table 4a. Input parameters for Otavi HMX mixing calculations based on data from Reimold (1991) and this work. Data in wt%; 1σ standard deviations.

Lithology	PTB	Std. dev.	Ton/ Tr.	Std. dev.	Amph. + MC*	Std. dev.	Granoph.	Std. dev.
[wt%]								
SiO_2	65.41	5.30	72.71	1.91	49.56	2.96	66.99	0.60
TiO_2	0.65	0.22	0.22	0.17	1.27	0.53	0.50	0.07
Al_2O_3	15.40	1.10	14.82	0.95	14.76	3.21	12.7	0.01
Fe_2O_3	4.57	2.03	1.45	0.90	12.50	2.59	7.30	0.25
MnO	0.07	0.03	0.03	0.01	0.18	0.03	0.14	0.02
MgO	1.69	0.87	0.37	0.32	6.30	2.84	3.56	0.22
CaO	3.33	1.29	1.29	0.83	7.93	1.03	3.98	0.22
Na_2O	4.54	0.30	3.31	0.82	3.98	0.65	2.86	0.33
K_2O	2.83	0.35	4.80	2.01	1.61	0.42	2.25	0.12
P_2O_5	0.23	0.16	0.07	0.06	0.53	0.22	0.10	0.01
LOI	1.20	0.74	0.62	0.16	1.34	0.52	0.08	0.10
Sum	99.93		99.69		99.95		100.37	

*MC = mafic clast, analysed by Reimold (1991); Granophyre - average of analyses listed in Wannek (2015); PTB – pseudotachylitic breccia; Ton./Tr. – both tonalite and trondhjemite compositions were averaged; Amph. - amphibolite.

Table 4b. Input parameters for Kudu HMX mixing calculations*. Data in wt%; 1σ standard deviations.

Lithology	Amphibolite	Std. dev.	PTB	Std. dev.	Gran.	Std. dev.
[wt%]						
SiO_2	47.05	0.95	55.00	2.55	71.44	2.77
TiO_2	2.3	0.035	1.7	0.29	0.2	0.13
Al_2O_3	10.40	0.2	11.57	1.02	14.9	1.21
Fe_2O_3	15.45	0.15	11.62	1.91	1.81	0.68
MnO	0.23	0	0.17	0.02	0.02	0.01
MgO	8.09	0.18	5.71	0.94	0.53	0.48
CaO	9.31	0.12	6.90	0.93	1.45	0.66
Na_2O	3.09	0.06	4.21	0.27	4.99	1.89
K_2O	1.51	0.015	1.68	0.77	3.60	1.86
P_2O_5	0.5	0.005	0.3	0.06	0.0	0.03
LOI	1.75	0.05	0.91	0.18	0.85	0.29
Sum	99.65		99.86		99.88	

*includes chemical data from Mohr-Westheide (2011) and D. Lieger (2011); Amph. - amphibolite.

Table 4c. Results of HMX mixing calculations for Otavi and Kudu PTB. Data in %. DF = Discrepancy Factor

Locality	Mixing components						
	Granite	Std. dev	Amphibolite	Std. dev.	Granophyre	Std. dev.	DF
Otavi (a)	69.6	3.2	30.4	3.0			2.6
Otavi (b)	69.6	2.9	30.4	2.8	0.00	1.20	2.6
Kudu	25.9	0.9	74.1	1.0			0.2

of a Granophyre-like impact melt component to contribute to the PTB. The PTB from Otavi Quarry are heterogeneous in composition, which is consistent with their indicated local derivation from several different precursor rocks (Figure 10a) or precursor rock pairs, such as the two amphibolites (VPU42 and VPU32), dolerite, and granitic/granitic gneiss components.

Origin of the PTB in Kudu Quarry

The samples from Kudu Quarry were collected from a prominent PTB dyke sandwiched between granite and amphibolite. No additional lithologies were observed in the vicinity and wider environs of this dyke. Samples of PTB analysed to date cover an at least 50 m long section of this dyke. Clast populations of PTB observed in the field as well as in thin section are dominated by granitic clasts with subordinate abundances of amphibolite-derived material. The shock level of the clasts is similar to that of clasts in PTB at Otavi, with a dominance of single sets of PDFs in quartz suggesting shock pressure of <15 GPa.

The bulk chemical analysis of PTB and country rocks, as well as a subsequent HMX mixing calculation, confirm that the two observed and analysed country rock components are sufficient to generate a melt rock with the composition of the analysed PTB. As is the case with PTB from the Otavi Quarry, PTB along the dyke in Kudu Quarry is heterogeneous, indicating different proportions of granitic and amphibolitic precursors were involved at different places.

A thin PTB veinlet extending from the main dyke into neighbouring rock across a microfaulted contact between granite and amphibolite was investigated by defocussed beam electron microprobe analysis. The material forming the veinlet consistently yielded amphibolite-like mafic compositions, irrespective of whether it was analysed on the amphibolite or granite host rock side of this specimen (compare Figure 12). This can be interpreted as indicating that the melt was generated in amphibolite and that very little granitic material, less than 5%, was incorporated during intrusion into the fracture. Thus, both the melt of the main dyke and of the thin veinlet were formed predominantly from an amphibolite precursor.

Reimold (1991) concluded on the basis of a large number of analyses of both Vredefort PTB and host rock that the PTB, in each case, had been formed from the local host rock(s), and that preferential melting of hydrous ferromagnesian material had consistently caused formation of slightly more mafic melt, in comparison to the host rock composition. The new geochemical data for samples from the Otavi and Kudu quarries presented here provide strong additional support for this interpretation. An extraneous component, such as a Granophyre-like felsic – or even more mafic - impact melt rock, as postulated by Riller et al. (2011) and Lieger et al. (2012), is not supported by the chemical data base now available for the PTB and their host rocks from the Vredefort Dome. This is also well demonstrated in Lieger's 2011 PhD thesis that contains a summary of all previously published data on PTB and host rock compositions. Entirely independent of the more felsic or more mafic character of the respective host rock, the unique Granophyre composition with elevated Fe, Mg, and Ca, and tightly constrained Si and Al contents provides a test for whether a Granophyre contribution to host rock material is needed to explain the increases or decreases in the abundances of these elements. When carefully comparing the cited chemical analyses for PTB and host rock pairs, it is obvious that this is not the case (with only a few ambiguous instances when granitic host rock of a composition similar to that of the Granophyre obscures clear distinction of the effect of admixture of Granophyre).

Neither a felsic nor a more mafic impact melt component are required by the petrographic or chemical data at hand, and as recently presented by Reimold et al. (2015b), radiometric isotopic systematics do not support such an addition to Vredefort PTB genesis either. To the contrary, these data illustrate that PTB from 3 different quarries were each characterized by distinct isotopic ratios similar to values for the respective country rocks at these different sites. Lafrance et al. (2010) concluded from isotopic and chemical data for PTB from the Sudbury impact structure, the so-called Sudbury Breccia, that their PTB was formed from the locally occurring lithologies.

Contribution of recent PTB investigations to understanding the main process(es) of PTB formation

Drill core of pseudotachylitic breccia (PTB) from the central uplift of the 380 Ma Siljan impact structure in Sweden was recently analysed by Reimold et al. (2015a). In drill core Hättberg BH-5 numerous veins and pods of melt-bearing PTB were identified over a 600 m core interval, including two major zones of 60 m combined width that contain extensive PTB network breccias (30% actual melt breccia component), with individual melt breccia occurrences up to >1 m in length. The authors concluded that (1) the impact event caused low to moderate (<20 GPa) shock deformation in the host rock and in clasts of PTB. (2) No evidence for shock melting (i.e., compression/decompression melting early in the cratering process) could be observed. (3) Chemically PTB and alkali granite host rock are essentially comparable. (4) A frictional heating component upon melt generation could not be entirely excluded, as many PTB samples contain clasts of a mafic (gabbroic) component, although only in one place along the entire core, a 1.2 cm wide section through such material in direct contact to host rock was observed. Consequently, it was suggested that upon uplift in the central part of the impact structure considerable melt volumes were generated locally, especially in areas that had been affected by extensive cataclasis and where grain size comminution favoured melt formation. Rapid decompression related to central uplift formation was the preferred process for the generation of these PTB melt breccias.

Both in the case of Vredefort and Siljan the respective geological settings do not favour significant impact shock-related melting, e.g., the observed shock levels of between 15 and 20 GPa. Other evidence that might support shock compression melting, in the form of high-pressure polymorphs of rock-forming minerals, is in the Vredefort case only known from millimeter to sub-millimeter wide PTB veinlets in the outer collar of the dome (see review by Reimold and Koeberl, 2014). Finally, local enhancement of shock levels would be expected to occur along shock veins – shock compression melts – and this is also completely absent from any PTB developments in the outer core of the Vredefort Dome. On the other hand, it should be noted that a handful of thin (millimeter-scale) PTB veinlets from the core of the Vredefort Dome and from the Siljan drill core were analysed by Reimold (1991), Mohr-Westheide et al. (2010), and Reimold et al. (2015a), and it was found that melt compositions vary at the grain size scale of the adjacent host rock. This suggests that in situ melt formation took place, possibly as a consequence of shock melting – akin to the process assumed (with or without assistance from friction melting) for the formation of millimeter- to centimeter-wide shock veins in meteorites. But this process cannot be related to the formation of the voluminous melt breccias investigated here.

Evidence for frictional melting has not been forthcoming from the Vredefort Dome, as the large fault/shear zones required by, e.g., Spray (2010), to allow formation of significant pseudotachylite (*sensu stricto*) (see Melosh, 2005) are simply not present. Evidence for slip in the form of sizable displacements on centimeter- to meter-wide PTB developments on the Vredefort Dome is restricted to rare, at maximum up to 1 meter wide displacements of vein walls. The proposal that the massive occurrences of PTB on the Vredefort Dome are products of frictional melting on alleged superfaults (Spray, 1997) has, to date, not been supported by field evidence.

The fact that the bulk of melted material was derived locally and that the range of shock deformation in clasts was similar to that of the host rocks mitigates against formation/emplacement of PTB by injection of impact melt. In such cases, one would also expect to find the complete range of shock effects from planar fracturing to mineral and bulk melting represented in the clast content. This is not the case for either the Vredefort or Siljan PTBs (Reimold 1991; Mohr-Westheide et al. 2010; Mohr-Westheide and Reimold 2011; Lieger 2011; Lieger et al. 2011 and Reimold et al. 2015a). The chemical systematics as compiled by these earlier workers and from the present work do not support contribution from an external litho-component at all.

Reimold et al. (2015a) concluded for the Siljan PTB that exclusion of the previous processes implies the generation of considerable volume of melt during rapid decompression from the shock compression stage to equilibrated pressure/temperature conditions as a consequence of central uplift formation upon the modification stage of cratering (i.e., collapse of the transient cavity and concomitant uplift in the central crater). This process was previously promoted by Mohr-Westheide and Reimold (2011) for the formation and emplacement of voluminous (massive) Vredefort pseudotachylitic breccias. Melt forms by decompression of an extended volume of rock and then, upon collapse of the central uplift, moves into dilational sites, thereby picking up local material. In the case of the Otavi melt breccias this process would allow incorporation of some lithic clast material not in direct evidence at PTB sampling sites but coming from decameter wide environs.

Conclusions

This study was undertaken to contribute to the understanding of the formation of voluminous occurrences of pseudotachylitic breccias (PTB) in impact structures. The two processes favored for this were (1) melting of locally available country rocks and (2) a combination of injection of impact melt from a higher level of the impact structure plus assimilation of other, including locally derived, material. This study showed that lithic and mineral clast populations only support derivation of PTB from local precursor material. Major and trace element chemical systematics of melt rock and possible local precursors are fully consistent with this petrographic finding. HMX mixing calculations do not indicate that additional components, such as a Vredefort Granophyre-like impact melt intrusive phase, ought to have contributed to formation of these PTB.

These results clearly support process 1 (melting of locally available country rocks), with to date no evidence to support process 2 (injection of impact melt plus assimilation of local material) ever having been presented from geological, petrographic, chemical – or any other - findings from this group or other workers. Any process proposed for the formation and emplacement of voluminous PTB melt breccias in impact structures has to contend against all available evidence. The impact melt intrusion plus assimilation idea has so far remained speculative and unsupported by evidence.

In the absence of evidence for shock compression melting related to the formation of voluminous PTB, and for friction melting along significant faults/shear zones, only local melting due to rapid decompression upon central uplift formation can satisfactorily explain formation of such impact-generated PTB.

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