PSEUDOTACHYLITIC BRECCIA DEVELOPMENT IN IMPACT STRUCTURES – STATUS OF RESEARCH IN THE VREDEFORT DOME (SOUTH AFRICA) AND BASIS FOR PROCESS MODELING.

W.U. Reimold[1] and R.L. Gibson[2], [1]Museum for Natural History, Humboldt University Berlin, Invalidenstr. 43, 10115 Berlin, Germany (uwe.reimold@museum.hu-berlin.de), [2]Impact Cratering Research Group, School of Geosciences, University of the Witwatersrand, Private Bag 3, P.O. Wits 2050, Johannesburg, South Africa (roger.gibson@wits.ac.za).

Introduction: "Pseudotachylite" is a volumetrically minor but relatively widespread clast-laden melt rock that most commonly occurs in cm-wide and dm-long veins in fault and shear zones. Its presence in these environments is attributed to cataclasis and frictional melting during high strain rate ($>10^{-1}s^{-1}$) coseismic slip. Together with the Sudbury area in Canada, the Vredefort region of South Africa is one of only two great "pseudotachylitic breccia" provinces in the world. It lies in the central parts of the geological Witwatersrand Basin, centered on the Vredefort Dome. Both the Sudbury and Vredefort-Witwatersrand breccia occurrences dwarf the individual and total volumes of melt breccia found at all occurrences of pseudotachylite around the world. This, and geological and geochronological evidence that, in both cases, links the formation of these breccias to major impact events, and the clear absence of any spatial links to faults and shear zones capable of generating such large melt volumes, has raised questions about the processes by which these breccias were formed. The Vredefort Dome itself was declared the type locality for *pseudotachylite* (i.e., friction melt *only*)[1]. These authors have challenged such a simplistic definition for the Vredefort breccias, pointing out that several different types of breccias can form during impact or be part of the target (impact melt, friction melt, cataclasite, ultramylonite). Consequently, they favor the non-genetic term *pseudotachylitic breccia*.

Witwatersrand pseudotachylitic breccias: Breccias exposed in the goldfields around the NW and W margin of the Witwatersrand basin range from decimeters to meters in thickness and are associated with wide cataclastic zones that display a more or less bedding-parallel orientation dipping towards the Vredefort Dome at shallow angles, or that are associated with subvertical faults generally radial to the dome. Although some evidence exists for the presence of some pre-impact pseudotachylite [2], the bulk of the breccias appear to be associated with the Vredefort impact event [3]. The inward-dipping faults appear to have been generated during normal dip-slip movement, and their scale and geometry are consistent with faults having formed during collapse of the transient crater by inward slumping of blocks off the crater wall. The radial faults appear to be, at least in part, older structures that were reactivated by impact-related block movement. In both cases, slip magnitude of hundreds of meters to perhaps as much as several kilometers, over at most a few minutes, provide the reasonable mechanism for the generation of such large breccia volumes by cataclasis and local friction melting. This far from the center of the impact structure no shock deformation effects have been observed and shock melting for the breccias can be precluded.

Melt breccias in the Vredefort Dome: Whilst the breccias in the Witwatersrand goldfields dwarf all known fault-related pseudotachylite occurrences in the world, they are, in turn, dwarfed both in terms of volume and abundance by the melt breccias in the Vredefort Dome. Within a 25 km radius of the center of the 90 km wide dome, few rocks are found that do not contain at least a small breccia vein, and veins remain common into the Ventersdorp Supergroup at 30-35 km from the center of the dome. Veins and lenses in the submillimeter to centimeter width range are associated with extensive, outcrop-scale fracture networks that sometimes display offsets (mostly mm to perhaps a few cm). Distinct relationships to fault or shear zones could only be rarely established. Relatively voluminous network breccias are found in a small number of roughly radial faults in the dome; however, similar "network breccia" outcrops are also observed entirely dissociated from faults. In addition, relatively voluminous breccia occurrences are found in the hinge zones of large radial folds. It is, thus, necessary to consider the possibility that the breccias in radial faults and folds were derived elsewhere and could have ponded in dilational sites. Wieland [4] speculated that, given the right degrees of superheating and shock-enhanced wallrock temperatures, mm- and cm-thick veinlets formed in either quartzite or shale host rock could have remained fluid for minutes, whereas thicker melt veins could have remained above their solidus T for up to several hours.

In the Archean gneiss core of the dome, several breccias reach widths of tens of meters and lengths of many hundreds of meters, and show no obvious links to shear zones commensurate with their size [5]. Petrographic analysis of thin veins in these rocks has shown that, whilst some evidence exists for cataclasis and displacement of mineral grains, the grains in the immediate walls of the veins are commonly marked by textures that are consistent with elevated shock pressures relative to the rest of the sample. Although recrystallization is strong owing to post-impact heating effects, the textures indicate transient fluidization of grains, either through the formation of mineral glasses or melts. We have shown that the rocks of the dome experienced background shock pressures between <10 GPa at r > 20 km to >30 GPa at r < 5 km, consistent with their proximity to the original point of impact. The textures along breccia veins are also clear evidence for the extreme heterogeneity of shock pressure at a local scale, and even at a scale of single grain diameters.

A similar scenario was proposed by Martini [6] who observed coesite and stishovite within and adjacent to thin melt veinlets in Witwatersrand quartzite in the outer dome. He speculated that thin melt breccia veins in the dome could be shock-induced melts resulting from explosive collapse of pre-impact joints during passage of the shock wave, or due to their activation as slip surfaces under shock compression owing to differential acceleration of their wall rocks. However, the existence of an intense joint set in all rock types of the dome, including those buried at mid-crustal depths prior to impact, appears unlikely.

Discussion: Several recent experimental and numerical modeling studies [7-9] of shock wave passage through heterogeneous materials have emphasized the heterogeneous nature of the shock wave, with large fluctuations of shock pressure caused by refraction- and reflection-induced interference. Kenkmann et al. [7] noted enhanced melt volumes along lithological interfaces, even where these were orthogonal to the shock propagation direction. Heider & Kenkmann [9] predicted that *in situ* veins would also form oblique to a plane of heterogeneity due to refraction of shock waves. Whilst slip is also possible as a result of differential acceleration of the wallrocks on either side of the plane of heterogeneity, an alternative explanation for at least some of the slip observed along Vredefort vein-fracture networks is that the fractures related to shock melting acted as slip surfaces for the brief period before crystallization or quenching of the melt. We believe that (many of) the most voluminous veins and dikes in the Vredefort dome could represent melts ponded in dilational sites that opened as the result of the structural disturbance accompanying central uplift formation immediately after passage of the shock wave and, more specifically, the late-stage collapse of the central uplift. Generation of the melts could involve either (or both of) decompression melting upon uplift or shock melting immediately after shock passage. Naturally, the rapid acceleration of large rock volumes does allow for the formation of a friction melt component, too, although the absence of suitably large faults in the dome remains problematic for such a mechanism..

Our model of shock melting with or without a friction melting component not only removes one of the biggest problems of pseudotachylitic breccia formation in an impact structure setting, namely how a slip zone can continue to generate melt once the first melt has formed and lubricates the slip surface. It also explains the staggering volume of melt found in the Vredefort Dome rocks in the absence of evidence for large-slip magnitude structures in the central uplift. The current studies of Lieger et al. and Mohr et al. [both this volume] attempt to further improve the meso-scale to microscopic data base on volumetry and geometry of pseudotachylitic breccias in different lithologies and their relationship to other parameters, including lithological contrasts (shock impedance), fracture density, relative timing of fracturing and breccia formations related to the impact.

Conclusion: With the detailed field and petrographic analysis of recent years and the current reinvestigations by Lieger et al. and Mohr et al. a basis will soon be available for comprehensive numerical modeling of the formation of pseudotachylitic breccias under shock compression and/or as a result of shock and friction melting. Once the likely processes upon breccia formation are fully understood, the cooling behavior of such impact-generated melts can also be refined through consideration of additional parameters such as clast content in different ambient environments (greenschist and amphibolite facies).

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