Pressure-temperature-time paths for shock vein formation in the Vredefort Impact Structure.

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Introduction: The extreme physical conditions imposed by shock waves resulting from impact events on planetary bodies generate unique effects on the target material through which they pass. These changes can be both macroscopic (e.g., shatter cones) or microscopic (e.g., planar deformation features), and can be used to interpret thermobarometric conditions realized by the target rock during the impact event. Shock veins, or S-type pseudotachylites [1], are unique among shock modification effects because they provide insight into timing relationships of pressure-temperature paths realized by target rocks during the shock wave passage.

Shock veins are thin (<2 mm width) anastomosing melt veins that appear as dark veins under plane polarized optical microscopy. Under a scanning electron microscope the matrix of shock veins commonly display a texture ranging from fluidal-glassy to microcrystalline with the presence of host-rock clasts suspended in the melt. Shock veins have the same chemical composition as the parent rock in which they formed, leading to the belief that they form in situ [2].

Shock veins have been found in many meteoritic materials but have only been identified in situ within the central uplift structures of three terrestrial craters: Manicouagan, Canada [2], Steen River, Canada [3], and Vredefort, South Africa [4].

High-pressure/temperature polymorphs are commonly found within or adjacent to shock veins which has led them to be associated with strong shock wave interactions, or localized pressure excursions. Both of these interpretations are the subject of some debate due to kinetic barriers of high pressure/temperature polymorph formation [5].

Here, we use thermal modelling to determine the pressure-temperature-time history of coesite and stishovite-bearing shock veins from the Vredefort Impact Structure, South Africa. The shock wave generated during the impact event is also evaluated to provide insight into the relationship between shock duration and shock vein formation. This study can be considered complementary to that of [4] such that we look to add to the shock vein formation model at Vredefort.

Geologic Setting: The Vredefort dome is located 120 km south-southwest of Johannesburg, South Africa. The structure's core is ~80 km wide and has been identified as the root of a central uplift structure of an ancient impact structure (2.02 Ga); with an apparent rim-to-rim diameter of ~180 km [6]. The Vredefort dome is perhaps the best exposure to the root of a central uplift structure on the planet.

The structure sits within the Witwatersrand Basin, comprising a 40-50 km diameter central core, of Archean basement gneisses surrounded by a collar of subvertical to overturned Late Archean to Early Proterozoic sedimentary and volcanic strata including the Dominion Group, Witwatersrand Supergroup, and Ventersdrop Supergroup [6]. Although the original structural form cannot be identified, geophysical investigation of the region has determined that the center of the structure has undergone the most relative uplift [7].

The extent of erosion, apparent transient cavity diameter, and approximate amount of uplift were used to place the samples original depth at approximately 12 km. Pre-shock metamorphism at Vredefort suggests a geothermal gradient of 25°C km^{-1} at the time of the impact event [6]. This corresponds to a pre-impact temperature of 300°C prior to the impact event at the sample location.

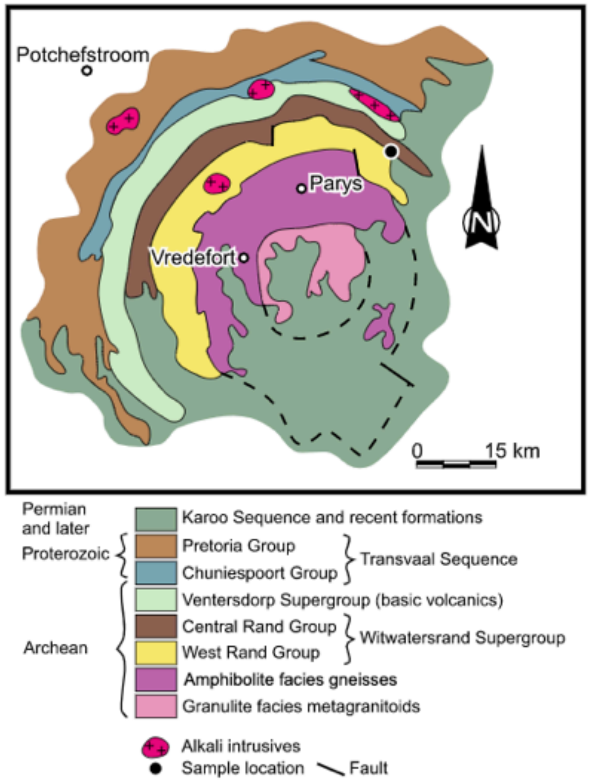

Figure 1: Simplified geology of the Vredefort Dome with the location of the studied sample within the Witwatersrand Supergroup. [4]

Sample Description: The sample was obtained from the Witwatersrand Supergroup in the central area of the collar structure (Figure 1). The mineralogy of the sample consists of 96% quartz, 3% muscovite-phengite, and trace amounts of alkali feldspar, apatite, zircon, rutile, and opaques. The shock veins are typically <2 mm (Figure 2a) in width and can be traced for at least 1 m in length, depending on outcrop exposure, forming anastomosing systems [4].

The shock veins display a microcrystalline matrix texture comprised of quartz, coesite, kyanite, biotite, rutile, and possible alkali feldspar and stishovite. Clasts are commonly suspended in thicker sections of the veins (>1 mm) (Figure 2b). Coesite is developed within the clasts displaying a tile-like texture of sub-rounded rectangles surrounded by microcrystalline quartz. Stishovite is also present in the veins but is much less common than coesite. Stishovite occurs in clusters of needles at clast/vein or host/vein interfaces growing into the clasts and host rock.

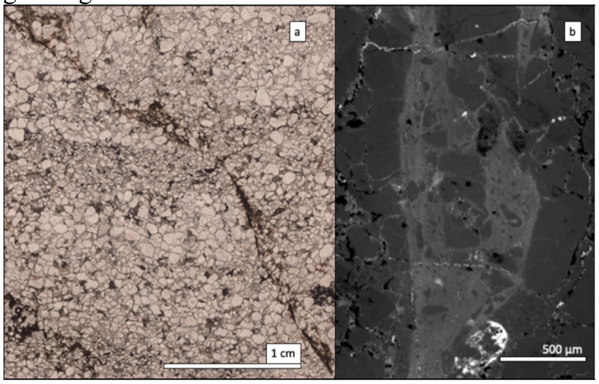

Figure 2: (a) Plane polarized light image of Vredefort quartzite displaying anastomosing pattern of shock veins (dark brown) (b) Scanning electron microscope image of shock vein with multiple suspended quartz clasts. These clasts are composed of α-quartz cores with coesite rims and localized areas of stishovite at melt/clast interfaces (See [4] for further details on polymorphs).

Conditions of shock vein formation: An attempt to determine the conditions experienced during shock vein formation was made by solving the shock wave that formed the Vredefort impact structure, coupled with thermal modelling of the shock veins immediately following their formation.

Shock waves form when a material is stressed by a pressure wave beyond its elastic limit. When this happens a shock front forms at the leading edge of the wave. Shock fronts can be treated as a mathematical discontinuity such that the material "jumps" from the unshocked to shocked conditions nearly instantaneously. The shock front is characterized by five variables: shock wave velocity U, particle velocity u, specific volume v, pressure P, and internal energy E. By using the Hugonoit jump equations (conservation of mass, momentum, and energy across the shock front) as well as the U-u and P-v Hugonoit equations, the conditions of shock wave passage can be estimated [8][9].

The shock veins were then thermally modelled using KWare Heat3D thermal modelling software. High pressure/temperature polymorph-bearing locations within the shock veins were prioritized as these locations provide a pressure constraint to determine the P-T-t conditions of shock vein formation (Figure 2b). The shock veins were determined to reach transient temperatures of >3500°C, which is consistent with complete melting of the quartz under high pressure conditions (≥12 GPa) [10].

As a result of this investigation, it was determined that the shock veins cool to the solidus before the complete passage of the shock wave. This finding indicates that the coesite and stishovite within the clasts and matrix of the shock veins formed during shock loading, eliminating the need of shock collisions or localized pressure excursions to explain the high pressures needed for high pressure polymorph formation within the shock veins at Vredefort.

References: Use the brief numbered style common in many abstracts, e.g., [1], [2], etc. References should then appear in numerical order in the reference list, and should use the following abbreviated style:

[1] Spray J. G. (1998) *Meteorites: Flux with Time and Impact Effects*, *140*, 195-204. [2] Biren M. B. and Spray J. G. (2011) *Earth and Planetary Science Letters*, *303*, 310-322. [3] Walton E. L. et al. (2016) *Geochimia et Cosmochimica Acta*, *180*, 256-270. [4] Spray J. G. and Boonsue S. (2018) *Meteoritics and Planetary Science*, *53*, 93-109. [5] Sharp T. G. and DeCarli P. S. (2006) *Meteorites and the early solar system*. *804*. 653-677. [6] Gibson R. L. et al. (1998) *Geology*, *26.9*, 787-790. [7] Henkel H. and Reimold W. U. (1998) *Tectonophysics*, *287*, 1-20. [8] Melosh J. H. (1989) *Impact Cratering: A Geologic Process*. [9] Cooper P. W. (2018) *Explosives Engineering*. [10] Duffy T. et al. (2015) *Treatise on Geophysics*, *2*, 149-178.