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Frictional melting processes and the generation of shock veins in terrestrial impact structures: Evidence from the Steen River impact structure, Alberta, Canada

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Abstract

Shock-produced melt within crystalline basement rocks of the Steen River impact structure (SRIS) are observed as thin (1–510 μm wide), interlocking networks of dark veins which cut across and displace host rock minerals. Solid-state phase transformations, such as ferro-pargasite to an almandine–andradite–majorite garnet and amorphization of quartz and feldspar, are observed in zones adjacent to comparatively wider (50–500 μm) sections of the shock veins. Shock pressure estimates based on the coupled substitution of Na^+, Ti^{4+} and Si^{4+} for divalent cations, Al^{3+} and Cr^{3+} in garnet (14–19 GPa) and the pressure required for plagioclase ($Ab_{62–83}$) amorphization at elevated temperature (14–20 GPa) are not appreciably different from those recorded by deformation effects observed in non-veined regions of the bulk rock (14–20 GPa). This spatial distribution is the result of an elevated temperature gradient experienced by host rock minerals in contact with larger volumes of impact-generated melt and large deviatoric stresses experienced by minerals along vein margins.

Micrometer-size equant crystals of almandine–pyrope–majorite garnet define the shock vein matrix, consistent with rapid quench (100–200 ms) at 7.5–10 GPa. Crystallization of the vein occurred during a 0.1–0.15 s shock pressure pulse. Majoritic garnet, formed during shock compression by solid state transformation of pargasite along shock vein margins, is observed in TEM bright field images as nanometer-size gouge particles produced at strain rates in the supersonic field (10^6–10^8). These crystals are embedded in vesiculated glass, and this texture is interpreted as continued movement and heating along slip planes during pressure release. The deformation of high-pressure minerals formed during shock compression may be the first evidence of oscillatory slip in natural shock veins, which accounts for the production of friction melt via shear when little or no appreciable displacement is observed. Our observations of the mineralogy, chemistry and microtextures of shock veins within crystalline rocks of the SRIS allow us to propose a model for shock vein formation by shear-induced friction melting during shock compression.

1. INTRODUCTION

Shock veins in meteorites have received much attention owing to their association with minerals stable at high pressure and high temperature (e.g., Sharp and DeCarli, 2006; Gillet et al., 2007). Notably, shocked meteorites provide nearly all natural examples of deep Earth minerals, including the first reported natural occurrence of $MgSiO_3$ bridgmanite, the most abundant mineral in Earth, documented from shock veins in the Tenham L6 chondrite (Tomioka and Fujino, 1997; Tschauner et al., 2014). These high-pressure minerals, formed by crystallization from

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impact-induced melt or solid-state transformation of igneous precursors, constrain the *P-T-t* conditions experienced by the rocks during shock metamorphism, provide insight into the mineralogy of planetary interiors, and shed light on mechanisms of phase transformation. Similar features explicitly linked to shock have been documented from a few terrestrial impact structures including Manicouagan (Biren and Spray, 2011), Ries (Dressler and Graup, 1969; Stähle et al., 2011), and Vredefort (Martini, 1978, 1991). Micro-pseudotachylites, the so-called S-type pseudotachylites of Spray (1998) and the A-type pseudotachylite of Martini (1991), or pseudotachylitic breccias formed as a result of shock compression (Reimold, 1998), are widely accepted as analogous to shock veins in meteorites, and for both shock-induced melt veins the term "shock veins" will be used (Stöffler and Grieve, 2007).

In this study a network of shock veins from the Steen River impact structure of Alberta, Canada is described. The mineralogy, composition and micro-textures of impact-induced phase transformations associated with shock veins constrain the *P-T-t* conditions during shock metamorphism and provide insight into the mechanisms involved in the formation of shock veins in crystalline rocks during a hypervelocity impact event. In addition to constraining the shock conditions, studies of shock veins in terrestrial impact structures also relate to meteoritics because they preserve the geological content of the rock within the crater structure, which is lacking in studies of these same features in meteorites. Here, high-resolution transmission electron microscopy has been applied for the first time to a novel shock-induced amphibole transformation, which has been documented previously from a single terrestrial impact structure (Stähle et al., 2011). This is the first reported occurrence of high-pressure minerals in the Steen River impact structure.

2. GEOLOGIC SETTING OF THE STEEN RIVER IMPACT STRUCTURE

The Steen River impact structure (SRIS; 59° 31′ N, 117° 39′ W) is a buried complex crater in NW Alberta, Canada (Grieve, 2006) (Fig. 1), ascribed to hypervelocity impact based on the presence of shock deformation and transformation features in quartz and feldspar (Carrigy and Short, 1968; Winzer, 1972). The target rocks include 70 m of Mississippian calcareous shale underlain by ~1530 m of Devonian marine sedimentary rocks including evaporites, carbonates and shales. This ~1.6 km thick package of sedimentary rock overlies Lower Proterozoic crystalline rocks of the Hottah Terrane and Great Bear Magmatic Arc, thought to be joined along a faulted contact (Burwash et al., 1994). With a roughly elliptical shape and ~25 km diameter length, the SRIS is the largest known impact structure in the Western Canada Sedimentary Basin. This structure is of economic interest because it is an oil and gas producer, and reservoir host (Grieve, 2006). A central uplift measuring 4 km at its top and 8 km at its base raises fractured basement 800–1100 m above regional levels (Winzer, 1972). The impact crater age, reported as 95 ± 7 Ma, is based on a single K–Ar whole rock age obtained from a 'pyroclastic vesicular rock' (Carrigy and Short, 1968). This rock represents an impact-melt bearing polymict breccia sampled in the allochthonous impactites of core IOE Steen 12-19-121-21 near the center of the structure. Although this age, recalculated using more recent decay constants of Steiger and Jager (1977) to be 91 ± 7 Ma, is roughly consistent with stratigraphic constraints, the SRIS remains a candidate for further isotopic analysis to better constrain this estimate on impact timing.

3. MATERIALS AND ANALYTICAL METHODS

In early 2000, New Claymore Resources Ltd drilled three continuous but shallow diamond drill holes into the crater fill deposits of the SRIS (ST001, ST002, ST003). These cores are currently housed at the Mineral Core Research Facility in Edmonton (Molak et al., 2002). One hole, ST003, encountered ~154 m of melt-bearing polymict impact breccia (Walton et al., 2015). The lower 16 m sampled granitic basement; either the hole penetrated parautochthonous rocks of the central uplift or a large block in a basal breccia lying between polymict breccia and more massive rocks of the parautochthone or autochthone proper. Unfortunately this can only be resolved by deeper drilling. Three polished thin sections of shock-vein bearing rock were prepared from the ST003 core sampled at a depth of 378 m (within crystalline rocks at the bottom of ST003). These thin sections were examined by transmitted and reflected light microscopy, and via back-scattered electron (BSE) mode imagery with a Zeiss EVO MA 15 scanning electron microscope (SEM) with a LaB_6 filament at the University of Alberta. BSE images were acquired with a Si diode detector using a 20 kV accelerating voltage and a 7.5 mm working distance. This SEM is fitted with a Bruker silicon drift detector for energy dispersive spectrometry (EDS) analysis with a peak resolution of 125 eV. Commercial image analysis software, the freeware program ImageJ, was used to accurately measure apparent vein width and grain size on BSE images, and on photomicrographs acquired with the petrographic microscope. Major and minor elemental abundances of minerals were measured using a JEOL 8900 electron microprobe (EMP) at the University of Alberta, equipped with five wavelength dispersive spectrometers using an accelerating potential of 15 kV and a beam current of 10 nA. Most minerals were analyzed using a focused beam (1 μm) with the exception of beam-sensitive feldspars. To minimize alkali element migration in this beam-sensitive material a defocused (10 μm) beam was employed. Natural minerals were used as standards and raw data were corrected by the ZAF procedure. X-ray elemental maps were obtained on select areas of the thin section using the JEOL 8900 EM with an accelerating voltage of 20 kV and a beam current of 20 nA. The excel spreadsheets of Locock (2008, 2014) and Grew et al. (2013) were used to recast chemical analysis of garnets and amphiboles following IMA recommendations. Micro-Raman spectra of various phases were obtained using a Bruker SENTERRA instrument at MacEwan University, operating with an Ar+ laser of 532 nm wavelength. The focal spot size was ~1 μm. Two areas of interest were exca-