The high-pressure mineral inventory of shock veins from the Steen River impact structure. Walton E.L.,
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Introduction: The Steen River impact struc-
ture (SRIS; $59^o31'$N, $117^o39'$W) is a buried complex
crater with an apparent diameter of ~25 km [1]. The
SRIS is the largest known impact structure in the
Western Canada Sedimentary Basin and is a producer
and host of oil and gas reservoirs [1]. The target rocks
comprise a 70 m layer of Missippian calcareous shale
underlain by a thick (1530 m) sequence of Devonian
marine sedimentary rocks including carbonates and
evaporates. This ~1.6 km thick sedimentary cover
overlies Precambrian basement rocks (primarily gran-
ite / gneiss / granodiorite). A variety of shock meta-
morphic effects have been observed at the SRIS, in-
cluding kink banding in biotite, planar fractures and
planar deformation features in quartz and feldspar,
ballen quartz, lechatelierite and diaplectic glasses of
feldspar and quartz [2, 3, 4], which helped to ascribe a
hypervelocity impact origin to this structure. Despite
the documentation of diagnostic shock effects in min-
erals, mostly quartz and feldspar, uncertainty as to the
origin of the SRIS structure by volcanic or meteoritic
origin remains, primarily within the industrial sector
(e.g., [5]), with terms such as "pitchstone" and "tuff"
used to describe the SRIS impactites. A portion of this
uncertainty lies in the inability of previous studies to
isolate high-pressure, high-temperature minerals such
as the SiO_2 polymorphs coesite and stishovite in SRIS
deposits. This may also reflect the lack of recognition
of impact cratering as a ubiquitous geologic process
outside the planetary science community.

Here, the results of a combined SEM, EMPA, Ra-
man and TEM study of shock veins in the central uplift
of the SRIS are reported. These shock veins exhibit a
unique assemblage of high-pressure, high-temperature
minerals within and around shock veins. This study
clarifies the impact origin of the SRIS, helps to eluci-
date the location and distribution of high-pressure
minerals in impact structures, and constrains the P-T
conditions experienced by rocks in the central uplift of
a moderate-size complex impact structure.

Anaytical Methods: A total of 44 polished thin
sections were prepared from core offcuts for petro-
graphic analysis (optical microscopy). From these,
several thin section were selected for detailed investi-
gation using a Zeiss EVO MA LaB6 filament SEM in
BSE imaging mode, focusing on the minerals associat-
ed with the shock veins. Major and minor element
abundances were analyzed with a JEOL 8900 EMPA

equipped with five WDS spectrometers. Raw data
were corrected using the ZAF procedure. The excel
spreadsheets of [6,7] where used to recast chemical
analyses of amphiboles and garnets following the IMA
reccomentations. Micro-Raman spectra of various
phases were obtained with point measurements, using
a Bruker SENTERRA instrument. The 100X objective
of a petrographic microscope was used to focus the
excitation laser beam (532 nm line of Ar+ laser) to a
focal spot size of ~1 µm. TEM sections will be pre-
pared using an FEI Nova200 NanoFab dual-beam FIB,
focusing on the shock vein and associated transformed
minerals. Analytical TEM will be done using an FEI
CM200 FEG. High-pressure minerals will be indenti-
fied using a combination of electron diffraction, EDX
and imaging. Transformation microstructures will also
be investigated to illucidate the mechanisms of horn-
blende and biotite transformation.

Sample Selection: In early 2000, New Claymore
Resources Ltd drilled three continuous drill holes into
the allochthonous proximal deposits of the SRIS. One
(ST003) penetrated the central uplift. This core, previ-
ously logged in detail by [4], has been re-visited in this
study (see Walton et al. LPSC companion abstract for
a description of ST003 impactites). Sample names in
the following description refer to depth (in meters).
The lower 10 m of the hole (between 352–377.4 m)
comprises granitic to gneissic rocks of the Precambrian
basement. Fabrics in these rocks are cut across by
thicker mm-size veins of finely-comminuted melt-
bearing material and thin, opaque veins. These micro-
pseudotachylites are similar to shock veins in meteor-
ites, and the general term for all these shock-induced
melt veinlets will be referred to as "shock veins" fol-
lowing [8]. These shock vein-bearing rocks represent
either meter-size megablocks within the allochthonous
impactites or more likely the hole penetrated the cen-
tral uplift. An anastomosing network of thin shock
veins (<1 µm up to 0.5 mm apparent diameter) in a
plagioclase-amphibole-biotite-quartz gneiss was sam-
pled at a depth of 374 m. Apatite, zircon, ilmenite,
titanite and chloritized biotite occur as accessory phas-
es.

Results: Quartz and plagioclase in the granitic
gneiss, far away from the shock vein, exhibit planar
deformation features (up to three distinct orientations
in quartz) with weak to moderate mosaicism. Plagio-
clase, in a zone ~0.5 mm surrounding the shock vein,

has transformed to maskelynite, a diaplectic glass of feldspar composition. Quartz near the shock vein possesses an unusual texture of thin veins or elongated aggregates surrounded by smooth silica glass. Raman spectra contain peaks at 464 cm^{-1} and 520 cm^{-1}, indicating an intimate mixture of α-quartz and coesite.

Amphibole in the host rock is pleochroic in shades of green, yellow-green and brown. EMPA analyses show that it is ferro-pargasite with general formula $(Na_{0.41}K_{0.27})(Ca_{1.82}Na_{0.10}Mn_{0.08})(Fe^{2+}_{3.04}Mg_{1.33}Al_{0.29}Ti_{0.19}Fe^{3+}_{0.14})(Si_{6.60}Al_{0.40})O_{22}(OH)_2$. Within a zone ~100–300 μm along the shock vein margin and clasts entrained within the shock vein matrix, ferro-pargasite has undergone a nearly isochemical phase transformation to garnet. This is observed under plane polarized light as a striking transition from green amphibole to a bright orange garnet. The garnet is weakly anisotropic. The shock-transformed pargasite is almandine, $(Fe_{1.37}Ca_{0.97}Mg_{0.42}Na_{0.2}Mn_{0.05})(Al_{0.92}Si_{0.36}Fe_{0.35}Mg_{0.22}Ti_{0.10})Si_3O_{12}$, with a 36% majorite component (based on 0.36 pfu of Si in the octahedral site). The pargasite-almandine phase transformation was nearly isochemical, with the exception of the most volatile species (Na, K and Cl). Raman spectra collected on ferro-pargasite show sharp peaks at 150, 533, 660-667 and 734 cm^{-1}, characteristic of well-crystallized amphibole. Spectra collected on almandine garnets show peaks near 360 and 910 cm^{-1}. Biotite in direct contact with the shock vein has also undergone a phase transformation. This biotite breakdown material is opaque in transmitted light and appears to be Raman inactive, although one spectrum obtained on this material showed a single peak at 667 cm^{-1} (12 additional spectra were collected, none of which yielded a useful spectra). BSE images show a brighter greyscale of this phase compared to adjacent non-transformed biotite. EMPA analyses show enrichment in Al, Fe and Mg, and depletion in Ti, K, Na and Cl compared to biotite. Totals for wt% oxides close to 100 for this phase indicate that it is anhydrous.

The matrix of the shock vein is opaque in plane light, ranging from black, reddish-brown to grey. BSE imaging show the texture to be fine-grained (≤2 μm) and granular. The largest micron-size crystals were analyzed with Raman and EMPA, and found to be almandine garnet with general formula $(Fe_{1.54}Mg_{1.31}Ca_{0.05}Na_{0.04}Mn_{0.03})(Al_{1.81}Si_{0.11}Mg_{0.04}Ti_{0.03})Si_3O_{12}$. These garnets also have a majorite component, but in this case only 11% compared to shock-transformed garnets within the host rock which have a higher (36%) majorite component. Raman spectra collected on the vein matrix show peaks at ~360 cm^{-1} and 910 cm^{-1}, consistent with garnet as the main mineral; however, peak positions near 660 cm^{-1} and 1113 cm^{-1}, suggest that pyroxene may also have crystallized from the shock melt. One spectra from the vein matrix was consistent with the presence of shishovite with a sharp peak at 750 cm^{-1}. TEM work is needed to confirm this.

Discussion: The majorite component in the shock-produced garnets at the SRIS is a strong indicator of high pressure. This is consistent with the presence of coesite and stishovite, as well as the transformation of plagioclase to maskelynite, only in those grains within or surrounding the shock vein. Although both garnets are shock-produced, their distinct texture and composition implies a different formation mechanism (solid state transformation of amphibole vs. crystallization from impact melt). A shock pressure estimates of 15–17 GPa for similar amphibole-garnet transformations described by [9] from shock veins in clasts within suevite of the ~25 km diameter Ries impact structure, also apply to the same phase transformation described here for the SRIS. The coexistence of crystalline plagioclase and maskelynite suggests a moderate shock pressure of 16–23 GPa [10], and is constitent with, but slightly higher than, the 15–17 GPa required to produce the majorite-bearing garnets.

Conclusions: In meteorites, the association between minerals stable at high pressures and temperatures and shock veins is well-documented [e.g., 10]. However, the high-pressure mineral inventory of shock veins from terrestrial impact structures has been described in detail by relatively few researchers. Previous studies of impactites at the SRIS failed to identify high-pressure mineral polymorphs largely because they were looking in the wrong place, i.e., small clasts in clast-rich impactites which remain hot after shock pressure release. In these rocks high pressure minerals are less likely to be preserved because they will rapidly back-transform to their lower pressure compositional equivalents. The high pressure mineral inventory documented in this study formed at ~15–23 GPa, and are preferentially associated with thin shock veins in large meter-size blocks of crystalline basement where post-shock temperatures were low enough to preserve these minerals.

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