EVIDENCE FOR MELTING AND DECOMPOSITION OF SEDIMENTARY TARGET ROCKS FROM THE STEEN RIVER IMPACT STRUCTURE, ALBERTA, CANADA.

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Introduction: To date, there are 190 confirmed terrestrial impact craters [1]. Among this inventory, sedimentary rocks are present in the target materials of ~70%. Compared to crystalline rocks, the impact behavior of sedimentary rocks may be drastically different due to the effects of porosity, grain size, and volatile content [2]. Whether carbonate and evaporite rocks melt, or decompose (e.g., $CaCO_{3(s)} \rightarrow CaO_{(s)} + CO_{2(g)}$), remains contentious [3, 4], but has important implications for post-impact environmental effects [5]. Study of impactites formed in sedimentary target rocks has the potential to yield insight into this debated topic, and provide data that may be used to provide ground truth for numerical and computer-based models.

Here, we report the first evidence for impact melting of carbonates and evaporites, and post-impact carbonate decomposition at the Steen River impact structure (SRIS), Alberta, Canada (D = 25 km). At the time of impact the sedimentary target stratigraphy comprised ~1.2 km of Devonian shales, carbonates, and evaporites overlying Precambrian crystalline (granitic) basement rocks of the Canadian Shield. Samples were acquired from a thick, exceptionally well preserved sequence of impact melt-bearing polymict breccias, derived from both Devonian and Precambrian strata.

Samples and Methods: Polished thin sections of breccia were prepared from three diamond drill core (ST001, ST002, and ST003), which penetrated allochthonous crater-fill deposits. These thin sections were investigated using optical microscopy and a ZEISS Sigma 300 FE-SEM in BSE imaging mode at the University of Alberta (UAb). The FE-SEM is equipped with an EDS system used to identify minerals based on major element composition. Major and minor elemental abundances were quantified using a Cameca SX100 electron microprobe at UAb, equipped with five wavelength dispersive spectrometers. Reidite was identified by a Bruker micro-Raman spectrometer at MacEwan University. The 532 nm Ar+ laser was focused to a 1 µm spot size. Orientation mapping of reidite was conducted via EBSD at Curtin University using a Tescan MIRA3 FE-SEM. Sample numbers indicate the specific core and depth in meters (e.g., S3-209.85 = ST003 core sampled at a depth of 209.85 m).

Results: In hand specimen, the breccias between ~200–242 m are composed of a grey-brown groundmass, supporting shocked mineral and lithic fragments, and pale grey- to white-colored masses of generally contorted material. The texture and composition of these latter clasts, and the contact between the breccia groundmass and lithic limestone clasts, are the main foci of this study. The groundmass has a clastic texture composed of fragments derived from crystalline basement rocks (quartz, feldspars, biotite, titanite, zircon and apatite), and calcite rhombs and pyrite cubes embedded in a matrix of platy clay minerals. In addition to limestone, lithic clasts of fine-grained siliciclastics and granitic rocks, in order of decreasing volume% abundance, are present.

Melting of carbonate and evaporite target rocks: The white masses of impact melt are defined by calcite with ocellar or fluidal textures. Four ocellar-textured varieties are observed: (1) calcite globules in pure silica glass (lechatelierite), (2) calcite globules in silicate glass (SiO_2-, Al_2O_3-, NaO-, K_2O-rich), (3) globules of lechatelierite in carbonates, and (4) globules of barite and calcite in silicate glass. Fluidal calcite is intermingled with lechatelierite or is found as schlieren in silica and silicate glass. These schlieren exhibit vesicles (gas bubbles), now filled by clay minerals. Sharply curved boundaries reminiscent of menisci between calcite and lechatelierite, as well as budding between lechatelierite and carbonates are documented. At the contact with calcite, the silicate glass composition is enriched in CaO (wt% oxides). Examples of flow-textured, vesiculated barite are found as clasts in all three core, but are particularly abundant in S1-280.7. Fluidal barite is associated with calcite, and, in some samples, contains tiny plagioclase microlites.

Shock provenance from reidite: Two individual carbonate clasts with fluidal textures from S3-209.85 and S3-214.27 each contain zircon. In BSE images, the zircon grains exhibit thin (≤1 µm wide) lamellae crosscutting primary zoning patterns. Laser Raman spot analyses shows a mixture of reidite and zircon. CL-imaging and EBSD mapping conducted on S3-209.85 confirm the presence of reidite with the following zircon-reidite orientation relationships: $\{110\}_{\text{reidite}} = \{001\}_{\text{zircon}}$ and $\{110\}_{\text{reidite}} = \{110\}_{\text{zircon}}$. However, despite the presence of several sets of bright lamellae, only two tiny patches index as reidite.

Carbonate Decomposition: Carbonate-bearing lithic clasts can be divided into larger clasts (cm-size) with visible sedimentary structures and smaller (mm-size) recrystallized limestone. The latter appears as small, grey-colored clasts (≤500 μm size) in thin section. Internal textures are defined by roughly equigranular, interlocking calcite crystals with straight crystal boundaries and 120^{o} triple junctions. The contacts between cm-size limestone lithic clasts and the breccia groundmass was sampled in all core. In thin section, these clasts are pale grey with visible fossils, possessing a distinctly darkened 0.5–1 mm wide rim, defined by calcite rhombs with interstitial smectite group clay minerals. Calcite at the outermost portion of the rim in S3-214.27 and S3-221.89 has a highly vesicular or frothy texture. In contrast, an assemblage of calcite + andradite-grossular garnet ± clinopyroxene is found at the rim of cm-size carbonate clasts in S1-291.50, S2-252.07 and S3-239.57. Garnet also decorates the rim of submillimeter-size, recrystallized carbonate clasts in the breccia.

Discussion: Ocellar textures, spherules and coalescing globules, fluidal textures, vesiculated schlieren and inclusions of plagioclase microlites are consistent with melting of carbonate- and sulphate-bearing Devonian target rocks at the Steen River impact structure (SRIS). These impact melts are found exclusively as clasts within impact breccias and are documented in the uppermost breccia units in contact with overlying shale (~200 m), to a maximum depth of 280.7 meters in ST001. The distribution of carbonate melts as clasts in a breccia unit that is, at present erosional levels, ~40–80 meters thick and laterally continuous for 14 km, therefore supports widespread melting of sedimentary target rocks at the SRIS.

Further evidence for the strong shock provenance of carbonate melt-bearing clasts comes from the preservation of reidite lamellae in enclosed grains of zircon. This makes Steen River the seventh impact crater globally to preserve this rare $ZrSiO_4$-polymorph. Shock recovery experiments show the conversion of zircon to reidite begins >20 GPa, and is complete by 52 GPa [6]. The orientation relationship between reidite and zircon at the SRIS is the same as reported by [7] for grains in clasts of crystalline basement in Ries suevite shocked to stages II and III. According to the classification of [8], the Ries reidite-bearing clasts experienced a shock pressure of 35 GPa to ≤65 GPa, suggesting a similar pressure history for the carbonate clasts in this study, at least above the threshold for reidite shock lamellae (taken here as 20 GPa).

Carbonate decomposition occurs below pressures of 0.003 GPa, within the temperature interval 1500–1200 K [9]. Decomposition is therefore predominantly a post-shock phenomenon in response to adiabatic shock-release heating following a hypervelocity impact event. Evidence of degassing and dissociation of sedimentary clasts has been reported from only a handful of terrestrial impact structures; in our study of SRIS breccias, we document decomposition occuring when lithic clasts are mixed in hot breccias. This mechanism of CO_2 release was very minor at Ries, affecting 3–10% of limestone clasts [10]. In contrast, decomposition is much more prevalent at the SRIS, with 70–100% of limestone clasts exhibiting evidence for decomposition in all three core [this study, 11]. Decomposition is marked by vesicular or frothy calcite, and andradite-grossular and clinopyroxene formed at the margins of carbonate lithic clasts. These minerals (Ca-garnet / clinopyroxene) are well known from limestone-replacing skarn deposits and have been produced experimentally [12].

While their work on Chicxulub (D = 180 km) drill core provides similar evidence for melting and decomposition of carbonate clasts mixed into a hot impact melt layer [13], our study demonstrates that this process is not restricted to large impact structures, but also operates in mid-size craters (e.g., Steen River D = 25 km), which occur more frequently in the rock record. When combined, these findings suggest that this mechanism for volatile loss (CO_2) is likely equally as important as gas-release in response to extreme shock pressures (~100 GPa) near the point of impact, although in the latter case gases are released by vaporization of target rocks (solid to gaseous state).

Conclusions: In this study we report evidence for impact melting of carbonate target rocks at the Steen River Impact Structure (SRIS) and the first description of naturally shocked barite. Our results support the evolving view among researchers studying the products of impact cratering – that melting of sedimentary target rocks is more typical than previously recognized [e.g., 3, 10]. We have also identified a novel process for post-impact decomposition of carbonates, mixed as clasts in hot impact breccias. Zircon grains with lamellar reidite have been documented from carbonate-melt bearing breccias, attesting to their strong shock provenance. When coupled, these findings significantly advance our understanding of how sedimentary rocks respond to hypervelocity impact.

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