

**HYPERVELOCITY IMPACT INTO CARBONATE-BEARING TARGETS: PROCESSES AND PRODUCTS.** G. R. Osinski<sup>1,2</sup>, <sup>1</sup>Dept. of Earth Sciences/Centre for Planetary Science and Exploration, University of Western Ontario, London, ON, Canada, <sup>2</sup>Dept. of Physics and Astronomy, University of Western Ontario, London, ON, Canada ([gosinski@uwo.ca](mailto:gosinski@uwo.ca))

**Introduction:** The products of meteorite impacts into dense non-porous rocks, as exemplified by the numerous craters in the Canadian and Fennoscandian Shields, are relatively well understood. Solid-state deformation of the target rocks and whole-rock melting resulting in impact melt rocks and classes with typical igneous textures are the norm [1, 2]. In contrast, the response of porous and volatile-rich sedimentary rocks to impact remains debated, in particular carbonates. Historically, it was thought that limestone (major mineral  $\text{CaCO}_3$  [calcite]) and dolomite (major mineral  $\text{CaMg}(\text{CO}_3)_2$  [dolomite]) decompose during impact to produce large amounts of climatically active  $\text{CO}_2$  [3]. In the late 1990s and 2000s, it became apparent that melting of carbonates is also an important process (see review in [4]). Here, the processes and products of hypervelocity impact into carbonates are reviewed and discussed.

**Theory:** Consideration of the phase diagram for  $\text{CaCO}_3$  suggest that calcite shocked to a pressure of  $>10$  GPa first enters the liquid field, with decomposition only possible after pressure has dropped to  $<0.003$  GPa (30 bar) at temperatures of  $\sim 1500$  K [5]. Decomposition is terminated at temperatures of  $<1200$  K at atmospheric pressure. Thus, the phase relations of  $\text{CaCO}_3$  suggest that the expected result of hypervelocity impact into calcite is melting, with decomposition only occurring during post-shock cooling.

**Experiments:** Shock experiments provide incredibly contrasting and ambiguous results regarding the fate of carbonates during impact events. Early studies suggested that calcite undergoes significant decomposition ( $>10$ – $50\%$ ) at pressures as low as 10–20 GPa [6]. Subsequently, other experiments suggest that decomposition of calcite and dolomite only occurs at pressures  $>65$  GPa and  $>70$  GPa, respectively [7, 8]; and instead that complete shock melting of calcite at pressures of  $\sim 25$  GPa and temperatures of  $\sim 2700$  K occurs [8]. Most recently, it has been suggested that calcite remains stable with no major decomposition or melting up to up to 60 GPa [9]. Thus, unfortunately, at present it is difficult to know which shock experiments are providing realistic results. The vast range of results may be due to a number of factors, including differences between experimental techniques (e.g., single shock versus reverberation), and/or properties of the sample material (e.g., porosity), and/or the duration of the shock state.

**Observations:** At the time of writing the 2008 review [4], evidence for the melting of carbonates had been provided for Chicxulub [10–12], Haughton [13, 14], Meteor Crater [15], Ries [16, 17], and Tenoumer [18]. Since then, Steinheim has also been added to the list [19]. This evidence comes from crater-fill deposits and proximal and distal ejecta, which suggests that carbonate melts can be preserved in a variety of different settings within and around impact craters.

It remains clear, however, that the identification of carbonate melts remains a challenge as both calcite and dolomite can also represent pre-impact target rocks and post-impact products of low- or high-temperature alteration. Thus, detailed micro-analytical investigation of samples is required – *neither* field observations *nor* optical microscopy provide adequate unequivocal evidence. A case study from the Ries impact structure highlighting these challenges is provided below.

*Case study: The Ries impact structure, Germany.* Despite the earlier evidence for carbonate melting, first published by Graup [16], in a recent review, Stöffler et al. [20] dismiss this large body of previous peer-reviewed literature and, based on no provided data, suggest that the volume of carbonate melt “is subordinate and cannot be derived from shock-molten Malmian limestone”. In response to this, we are carrying out a new micro-analytical study of the fate of carbonates at the Ries structure [21]. It is clear from this study that carbonates of hydrothermal origin and clasts of pre-impact Malm limestones do occur within the impact melt-bearing breccias of the Ries structure; however, it is possible with consideration of textures and chemistry to distinguish these carbonates from those that are clearly of an impact melt origin based on the following properties:

*Liquid immiscible textures:* Textural evidence immiscible textures between calcite and silicate phases (e.g., ocellar or emulsion textures of globules of carbonate in silicate glass, sharp menisci and budding between silicate and carbonate glasses, and deformable and coalescing carbonate spheres within silicate glass) are widespread at the Ries. Such textures provide unequivocal evidence for carbonates and silicate glasses being in the liquid state at the same time.

*Carbonate spherules and globules:* Individual calcite spherules and more irregularly-shaped globules are common at the Ries structure.

*Vesicular carbonates:* In the Ries impact melt-bearing breccias, there are unique angular fragments of

calcite that contain vesicles. The simplest explanation for these textures is that they represent rapidly quenched particles of carbonate melt which, if the melt was silicate, would be a vesicular glass.

**Carbonate chemistry:** Analyses of the above carbonates possessing textural evidence of a melt origin show a distinctly different composition to vuggy calcite of obvious secondary origin. In general, the hydrothermal vuggy calcite is more-or-less pure  $\text{CaCO}_3$  with only trace (<1 wt%)  $\text{MgO}$ ; whereas the calcite with textural evidence for a melt origin typically contains >1 wt%  $\text{MnO}$  and  $\text{FeO}$ . This distinction in composition is consistent with, and supportive of, the melting of carbonates at the Ries.

In summary, consensus in the literature over the past 15 years is that the dominant response of carbonates to hypervelocity impact is melting. This is not to say that decomposition does not occur, just that it is minor in nature.

**The dolomite question:** The majority of the theoretical and experimental studies to date have dealt with calcite. However, dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ) is an important component of the target stratigraphy of many terrestrial impact sites, such as Haughton. If dolomite decomposes during impact event, it should produce  $\text{MgO}$  – which unlike  $\text{CaO}$  that may rapidly react and disappear from the rock record – is stable in the form of periclase. Periclase has only been documented at two impact craters on Earth, West Clearwater [22] and Manicouagan [23] where it was formed during contact metamorphism of carbonates, present either as clasts within a silicate impact melt layer – i.e., this is a post-impact contact metamorphic product.

Consideration of experiments on analogous systems  $\text{CaO-MgO-CO}_2\text{-H}_2\text{O}$  [24] and  $\text{CaO-MgO-SiO}_2\text{-CO}_2\text{-H}_2\text{O}$  [25], suggests that calcite is the liquidus phase for a wide range of compositions and pressure-temperature conditions. This is consistent with observations from the Haughton structure in which the groundmass of crater-fill impact melt breccias comprises calcite and  $\text{MgO}$ -rich glasses [13]. Thus, for impacts into dolomite-rich target rocks, it is suggested a  $\text{CaO-MgO}$ -rich melt will be generated and calcite will typically be the first phase to crystallize out of the melt, with dolomite only forming at lower temperatures upon slow cooling.

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