SHOCK-METAMORPHOSED AND SHOCK-MELTED $CaCO_3$-BEARING SANDSTONES FROM THE HAUGHTON IMPACT STRUCTURE, CANADA: MELTING OF CALCITE AT ~10–20 GPa. G. R. Osinski, Canadian Space Agency, 6767 Route de l'Aeroport, Saint-Hubert, Quebec, J3Y 8Y9 (gordon.osinski@space.gc.ca).

Introduction: Sedimentary rocks are present in the target sequence of ~70% of the world's known impact structures. In the past it has been widely held that carbonates and evaporites decompose after pressure release due to high residual temperatures [e.g., 1]. However, recent work suggests that carbonates [e.g., 2–4] and evaporites [5] can also undergo shock melting.

Current classifications of shock metamorphic stages are based almost entirely on features developed in dense, non-porous crystalline rocks [e.g., 6]. The only available shock classification scheme for sedimentary rocks is for Coconino sandstones from Meteor Crater, Arizona [7,8] These studies revealed the dramatic effects of porosity, grain characteristics, and volatiles on the response of quartz to impact in sedimentary targets. For example, in crystalline rocks, quartz will typically be transformed to diaplectic glass at >32.5<50 GPa, with melting at >50–60 GPa [9]. At Meteor Crater, however, diaplectic glass is present in rocks shocked to pressures as low as ~5.5 GPa, with whole rock melting occurring at >30–35 GPa [8].

In contrast to sandstones, very little is known about shock metamorphic effects in carbonates. This prompted the present study of calcite-bearing sandstones from the Haughton impact structure. By comparing the shock effects in calcite with known, calibrated effects in quartz, a better understanding of the response of calcite to impact has been made possible. In addition, a shock classification scheme for quartz in the Haughton sandstones has been compiled.

Haughton impact structure: Haughton is a well preserved 23 km diameter, 39 Myr. old complex impact structure situated on Devon Island in the Canadian Arctic Archipelago (75^o 22' N, 89^o 41' W). The target sequence comprises a ~1880 m thick series of Lower Paleozoic sedimentary rocks, predominantly carbonates, overlying Precambrian metamorphic basement of the Canadian Shield. Allochthonous crater-fill impact melt breccias form a virtually continuous ~54 km^2 unit in the central area of the structure [4,5]. These pale gray impactites comprise variably shocked mineral and lithic clasts set within a groundmass of calcite + silicate glass ± anhydrite [4,5]. The lithic clasts are typically angular and are predominantly limestone and dolomite, with subordinate lithologies from the Paleozoic cover sequence and the crystalline basement.

Samples and analytical techniques: Centimeter-size clasts of sandstones were investigated during a study of over 350 samples of crater-fill impact breccias. In addition, ~30 hand specimen-size clasts were studied. Polished thin sections were prepared and investigated using a JEOL 6400 digital scanning electron microscope (SEM) equipped with a Link Analytical eXL energy dispersive spectrometer (EDS) and Si(Li) LZ-4 Pentafet detector. X-ray diffraction (XRD) was performed on powdered samples using a Philips 1710 diffractometer and generator, with operating conditions of 40 kV and 20 mA.

Results and interpretations: $CaCO_3$-bearing sandstones from Haughton have been divided into five classes following the shock classification scheme developed by Kieffer [7] and Kieffer et al. [8].

Class 0 (<1 GPa). Unshocked sandstones are typically mature, fine-grained quartz arenites, comprising well-rounded quartz grains, with a cement of quartz and/or calcite (sparite). Rare grains of calcite and variable amounts of K-feldspar are also present. Porosity ranges from ~5 up to ~25 vol%.

Class 1 (<5.5. GPa). Class 1a rocks show no recognizable signs of shock in hand specimen or with optical and SEM microscopy. The presence of shatter coned surfaces coincides with a gradual reduction and eventual destruction of original porosity, corresponding to class 1b of Kieffer [1]. Calcite in class 1 rocks shows a progressive decrease in grain size and an increase in the density of microtwins.

Class 2 (>5.5<10 GPa). The majority of class 2 sandstones display the classic "jigsaw" texture described by Kieffer [7]. This texture is produced by rotation and shear at quartz grain boundaries, leaving the interiors of grains relatively undamaged [7]. In contrast, the calcite has been reduced to fine-grained polycrystalline "microbreccia".

Class 3 (>10<20–25 GPa). XRD analysis reveals the presence of substantial amounts of coesite in class 3 rocks, although in lower amounts than in the Coconino sandstones [7]. The lower amounts of coesite in the Haughton samples are compensated by an increased development of diaplectic glass. Class 3 rocks show the widespread development of "symplectic regions" which represent microscopic intergrowths of quartz, coesite and diaplectic glass (Fig. 1) [cf., 7]. Sandstones from Haughton with coesite and diaplectic glass were also recognized by Redeker and Stöffler [10].

Calcite in class 3 rocks is fundamentally different from that in class 1 and 2 samples. It is always coarser grained, lacks pervasive microtwinning, and is present as rounded globules and/or irregularly shaped bodies in silicate glasses, or as crystals with well-formed euhedral faces. Figure 1 shows small (<15 μm diameter), euhedral crystals of calcite embedded in hydrous SiO_2-

rich glass. These textures are not compatible with a hydrothermal origin for the calcite as vesicles in the glasses remain devoid of calcite, and the glasses are pristine and unaltered. The silicate glasses and calcite, must, therefore, represent impact melt phases.

In other class 3 rocks, calcite is seen to infiltrate shocked quartz grains (Fig. 2). Importantly, a layer of SiO_2 glass occurs at the contact between symplectic quartz and calcite. The following textures have been observed: (1) sharp and curved menisci between SiO_2 glass and calcite; (2) irregularly-shaped globules of SiO_2 glass with cores of symplectic quartz, within the calcite. EDS analyses reveal that this calcite contains up to ~4 wt% SiO_2. These observations indicate that calcite is an impact melt phase and is in the process of melting and assimilating the quartz, which requires post-shock temperatures of >1713 ^{o}C.

Class 4 (>25 GPa). Class 4 rocks have lost all original textures and grain relationships. Calcite is seen to intermingle with K-feldspar glasses and SiO_2 glasses indicating that all these phases were in the liquid state at the same time.

Class 5 (>30–35 GPa). The most highly shocked sandstones at Haughton comprise vesiculated SiO_2 glass or lechatelierite that is unequivocally shock melted. Unshocked, microcrystalline calcite is present as globules within these glasses. The calcite globules are interpreted as melt droplets that were trapped in the vesiculating SiO_2 melt [cf., 11].

Discussion: It is well known that the response of quartz to shock compression in porous sedimentary targets is fundamentally different from that in non-porous crystalline targets [7,8]. The present study has shown that the detailed classification scheme developed for sandstones from Meteor Crater is broadly applicable for the Haughton samples. The major differences between the Haughton and Meteor Crater samples are in the moderately shocked rocks (class 3 and 4). Diaplectic glass is more abundant at Haughton in class 3 and 4 rocks; whereas coesite is less well developed. The reasons for this are not clear, but may be due to the different porosities and/or presence of calcite and K-feldspar in the Haughton samples.

The results of this study provide further unequivocal evidence for the melting of carbonates during impact events. Based on the textural and chemical data provided by this study, it is appears that calcite underwent melting at >10 to <20 GPa in porous sandstones at Haughton, corresponding to shock temperatures of >1000 ^{o}C [7]. These findings are broadly consistent with the phase relations of $CaCO_3$, which predict that calcite shocked to >0.1 GPa *and* temperatures >1200–1300 ^{o}C, should undergo impact melting [12]. Thus, temperature is obviously the limiting factor and explains why melting did not occur in the Haughton sandstones at pressures <10 GPa (i.e., the corresponding shock temperatures were not high enough). This work, together with previous studies [4,5], has shown that a large part of the sedimentary target sequence underwent shock melting during the Haughton impact event.

References: [1] Agrinier P. et al. (2001) *Geochim. Cosmochim. Acta, 65,* 2615–2632. [2] Graup G. (1999) *Meteor. Planet. Sci., 34,* 425–438. [3] Jones A. et al. (2000) *Lecture notes in Earth Sciences, 91,* 343–361. [4] Osinski G. R. and Spray J. G. (2001) *Earth Planet. Sci. Lett., 194,* 17–29. [5] Osinski G. R. and Spray J. G. (2003) *Earth Planet. Sci. Lett., 215,* 357–370. [6] Stöffler D. (1971) *J. Geophys. Res*., 76, 5541–5551. [7] Kieffer S. W. (1971) *Rev. Geophys. Space Phys.*, 18, 143–181. [8] Kieffer S. W. et al. (1976) *Contrib. Min. Pet*., 59, 41–93. [9] Grieve R. A. F. et al. (1996) *Meteor. Planet. Sci., 31,* 6–35. [10] Redeker H. J. and Stöffler D. (1988) *Meteoritics, 23,* 185–196. [11] Osinski G. R. and Spray J. G. (2001) *LPS XXXII,* Abstract #1908. [12] Ivanov B. A. and Deutsch A. (2002) *Phys. Earth Planet. Int., 129,* 131–143.

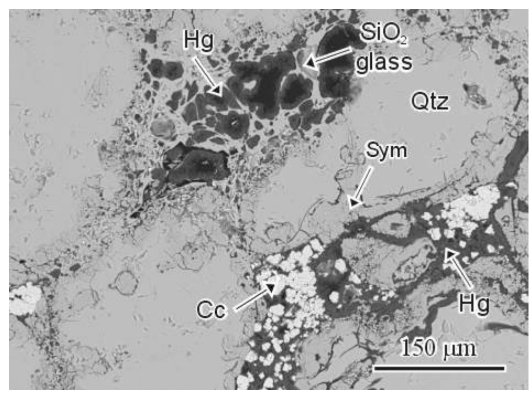

Fig. 1. BSE image showing euhedral crystals of calcite (Cc) embedded in hydrous SiO_2 glass (Hg). Qtz = quartz; Sym = symplectic quartz.

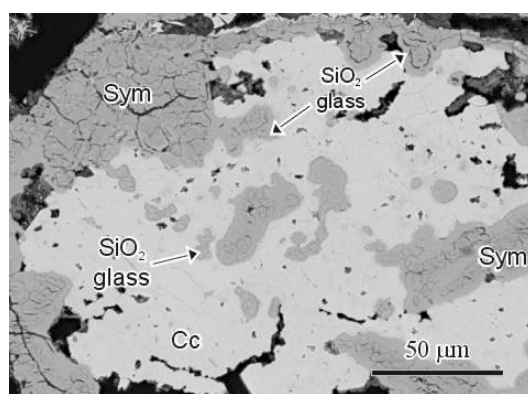

Fig. 2. BSE image showing symplectic quartz (Sym) in the process of being melted and assimilated in calcite (Cc).