

CARBONATES, NEW TOOLS TO INVESTIGATE SHOCK METAMORPHIC EFFECTS IN CHONDRITES. E. Dobrica¹, K. A. McCain², K. D. McKeegan², and A. J. Brearley³, ¹Hawai'i Institute of Geophysics and Planetology, School of Ocean, Earth Science, and Technology, University of Hawai'i at Mānoa, Honolulu, HI (dobrica@hawaii.edu), ²Dept. of Earth, Planetary, and Space Sciences, UCLA, Los Angeles, CA, ³Department of Earth and Planetary Sciences, MSC03-2040, 1University of New Mexico, Albuquerque, NM.

Introduction: Recently it has been proposed that some of the clasts that make up the Boriskino meteorite were subjected to high-intensity impact(s) between 10 to 30 GPa [1]. Several lines of evidence for shock features include (i) a strong 2D petrofabric in different lithologies, (ii) flattened chondrules, (iii) calcite veins and fractures subparallel to the petrofabric, (iv) squeezed chondrules, and (v) millimeter clasts with variable petrographic characteristics in direct contact with each other [1]. Since shock events could potentially disturb or completely reset the isotope chronometers measured in carbonate minerals [e.g., 2], it is important to characterize and understand the shock metamorphic effects before interpreting the isotopic measurements related to age dating, as discussed by [3]. Considering that carbonates are susceptible to shock metamorphism because the bonding between Ca cations and CO₃ groups is relatively weak [4-5], they could be used as recorders of the shock metamorphic environment and help interpret metamorphic conditions on asteroids.

In this study, we examine carbonate microstructures from two CM2s with two different shock metamorphic stages (Boriskino – ~S3-S4 according to the pressure values from [1] and Murchison – S1-S2 [6]). Our detailed TEM observations will help assess if impact events are recorded in these minerals. As a consequence, a new shock metamorphism classification scheme based on carbonates instead of silicates could be considered in future studies, especially for chondrites that lack the shock indicator minerals typically used in the shock classification scheme of meteorites (olivine, pyroxenes, and feldspars, [6-8]).

Methods: Two polished sections of Boriskino and Murchison (on loan from the Field Museum of Natural History and the UH meteorite collection, respectively) were first characterized by scanning electron microscopy (SEM) using backscattered electron imaging on a Helios 660 dual-beam focused ion beam SEM (FIB-SEM) instrument at the Advanced Electron Microscopy Center (AEMC) at the University of Hawai'i at Mānoa. Six electron transparent sections of carbonates and the surrounding fine-grained matrix were prepared by the conventional *in situ* FIB technique (five FIB sections in Boriskino and one in Murchison).

Each FIB section was studied using a variety of TEM techniques, including scanning transmission electron microscopy (STEM) imaging, nanodiffraction,

and energy-dispersive X-ray spectroscopy (EDS). The images and analysis were carried out at 200 kV and 300 kV using the Titan G2 analytical (S)TEM at AEMC, TitanX at the Molecular Foundry, Lawrence Berkeley National Laboratory, and the JEOL NEOARM aberration-corrected STEM/TEM instrument at the Center for Micro-Engineered Materials, at UNM. Nanodiffraction was carried out using a camera length of 190 mm, and a convergence angle of 0.3 mrad.

Results: In this study, we analyzed four Ca carbonate and two dolomite crystals from Boriskino, and one Ca carbonate from Murchison. Based on the mineralogical classification of CM Ca carbonates [1, 9-10], they can be classified into two types: (i) Type 1a grains, which are surrounded by a serpentine/tochilinite rim, and (ii) Type 2a grains, which have replaced primary minerals [1]. These represent two petrographic and isotopic distinct generations of Ca carbonates [9, 11-12]. We analyzed both Type 1a (one from Murchison) and Type 2 (two from Boriskino) Ca carbonates in this study. Two additional Ca carbonates from Boriskino were selected in this study. Their unique petrologic textures and isotopic compositions are inconsistent with the mineralogical classification of CM Ca carbonates [13]. The carbonates analyzed mainly occur in the form of subhedral or anhedral single or polycrystalline grains with typical sizes in the range from a few tens to hundreds of micrometers.

TEM observations show the occurrence of complex microstructures in the carbonates from Boriskino (Fig. 1). The most pervasive microstructural features are dislocations (screw Fig. 1b-c, and loop dislocations Fig. 1c, and parallel strain Fig. 1d) that appear in all investigated carbonates (Ca carbonate, and dolomite). These dislocations are accompanied by twinning (Fig. 1b) in three out of the four Ca carbonates analyzed from Boriskino. Most of these microstructural features are visible only in the STEM micrographs taken using a convergent beam (0.3 mrad) that provides better contrast, especially in deformed crystals. Additionally, we identified a large number of anhedral pores with sizes up to ~400 nm in one of the dolomite crystals from Boriskino. Multiple Mg-, Fe-rich silicate inclusions (~20 nm in diameter) and Ni-rich sulfides were observed in a Ca carbonate from Boriskino (Fig. 1e); however, the exact mineralogy of these inclusions was

not yet obtained due to the large thickness of the FIB section.

Furthermore, we analyzed one Ca carbonate (~20 x 25 μm) crystal from Murchison (Fig. 1a). Twinning is the dominant microstructural feature identified in this mineral. However, Ca carbonates from CM chondrites are often twinned and may show zoning in cathodoluminescence (CL) [14]. No other deformation features such as dislocations are present to any significant degree.

Discussion: Previous studies show similar microstructural features identified in experimentally deformed carbonate crystals at a constant confining pressure of 700 MPa and variable temperatures of 20 to 800°C [15-16]. Therefore, we argue that the extensively strained carbonates from Boriskino record evidence of shock. Additionally, the presence of shock features in different generations of carbonates indicates that shock deformation event(s) occurred after the precipitation of all the carbonates.

Conclusion: We have shown that the microstructures of carbonates in Boriskino (~S3-S4) record very distinct microstructures from Murchison, which we interpret as being the result of shock metamorphism. Furthermore, we suggest that carbonates should be considered as important candidates in the shock metamorphism classification scheme. Future studies will assess if carbonates show similar increasing microstructural changes as the shock pressure increases. The effects of shock events on the isotopic systematics of carbonates (e.g., Mn-Cr) remain to be determined.

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References: [1] Vacher L. G. et al. (2018) *Geochim. Cosmochim. Acta* **239**, 213–234. [2] Dobrica E. et al. (2022) *Geochim. Cosmochim. Acta* **317**, 286–305. [3] Fritz J. et al. (2017) *Meteorit. Planet. Sci.* **52**, 1216–1232. [4] Nicolas A. and Poirier J. P. (1976) Wiley, New York, p. 444. [4] Langenhorst F. (2002) *Bull. Czech Geol. Survey* **77**, 265–282. [6] Scott E. R. D. et al. (1992) *Geochim. Cosmochim. Acta* **56**, 4281–4293. [7] Stöffler D. et al. (1991) *Geochim. Cosmochim. Acta* **55**, 3845–3867. [8] Rubin A. E. et al. (1997) *Geochim. Cosmochim. Acta* **61**, 847–858. [9] Tyra M. A. et al. (2012) *Geochim. Cosmochim. Acta* **77**, 383–395. [10] Lee M. R. et al. (2014) *Geochim. Cosmochim. Acta* **144**, 126–156. [11] Lee M. R. et al. (2013) *Geochim. Cosmochim. Acta* **121**, 452–466. [12] Telus M. et al. (2019) *Geochim. Cosmochim. Acta* **260**, 276–291. [13]

McCain et al. (2021) 84th Annual Meeting of The Meteoritical Society, #6263. [14] Brearley A. J. et al. (1999) *LPSC XXX*, #1301. [15] Barber D. J. et al. (1981) *Phys. Chem. Min.* **7**, 271–286. [16] Barber D. J. and Wenk H. R. (1979) *Tectonophysics* **54**, 45–60.

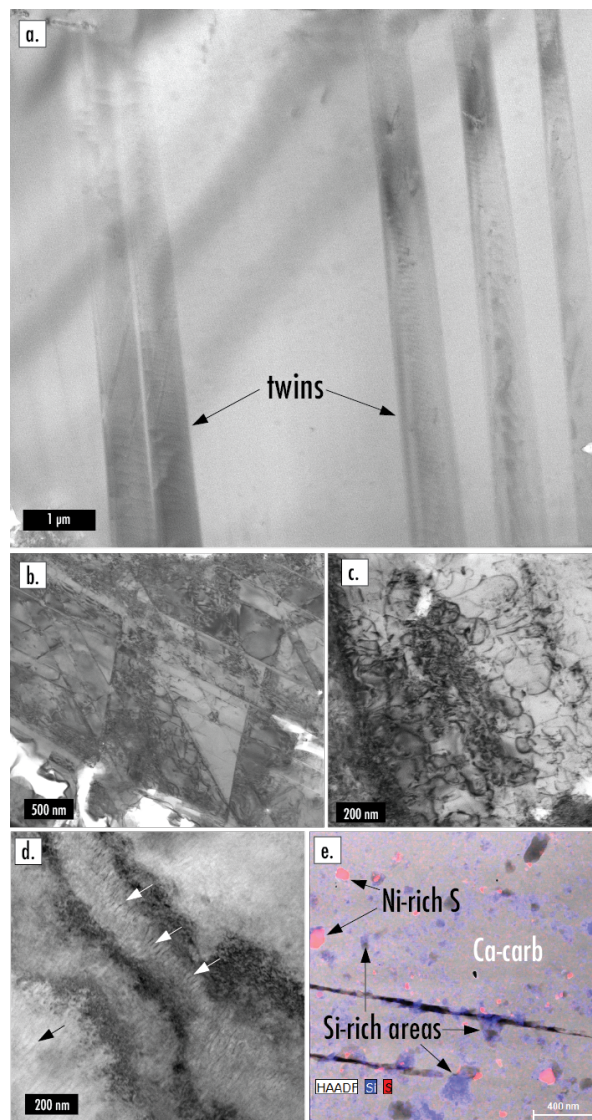


Figure 1. Bright-field (BF) STEM micrographs of the Ca carbonate (Ca-carb) analyzed from Murchison (a) showing simple twinning and a low dislocation density compared with Ca-carbonate (b-c) and dolomite (d) from Boriskino, displaying the occurrence of complex microstructural features, such as twins (b), high-density of dislocation loops (c), and parallel strain (d, see arrows). All STEM images were obtained using a camera length of 190 mm, and a convergence angle of 0.3 mrad. e) EDS maps and a high-angle annular dark-field (HAADF) micrograph showing the distribution of Si (blue) and S (red) inside a Ca carbonate (Type 2) from Boriskino.