SHOCK EFFECTS IN NWA 8159: EVIDENCE FOR A MODEST SHOCK PRESSURE AND A LARGE IMPACTING BODY. T. G. Sharp[1], E. L. Walton[2,3] and J. Hu[1] [1]School of Earth and Space Exploration, 550 East Tyler Mall, PSF 86, Tempe, AZ 85287-1404 (tom.sharp@asu.edu and jinpingh@asu.edu) [2]MacEwan University, Department of Physical Sciences, 10700 104 Ave, Edmonton, AB, T5J 2S2, Canada (waltone5@macewan.ca / ewalton@ualberta.ca), [3]University of Alberta, Department of Earth & Atmospheric Sciences, Edmonton, AB, T6G 2E3, Canada.

Introduction: Martian meteorites have experienced a range of shock effects, ranging from nearly unshocked (S1) to very highly shocked (S6). NWA 8159 is an augite-plagioclase basalt that is distinct from other SNCs [1]. The sample consists of augite, plagioclase (An_{50-65}), olivine (Fa_{61-76}), magnetite and minor orthopyroxene [1]. This meteorite represents a distinct sample of the Martian crust [1]. NWA 8159 has several mm-thick shock-melt veins that contain a fine-grained granular mixture of silicate and sulfide with a texture unlike that seen in other shocked meteorites [2]. The purpose of this study is to determine the high-pressure phases in and associated with the shock veins. These minerals can be used to estimate the shock pressure and the duration of the shock pulse to better understand the impact processes experienced by this sample.

Methods: Samples were characterized using optical petrography, scanning electron microscopy (SEM) electron probe micro-analysis (EPMA). Backscatter-electron (BSE) images were obtaind using the Zeiss EVO MA scanning electon microscope at the University of Alberta (UA). Emphasis was given to minerals associated with the shock veins. Major and minor element abundances of minerals were measured by EPMA with a JEOL 8900 electron microprobe at the UA. High-pressure minerals were identified by Raman spectroscopy usng a Bruker SENTERRA micro-Raman instrument at MacEwen University. The 100X objective of a petrographic microscope was used to focus the excitation laser beam (532 nm laser) to a focal spot size of ~1 µm. A sequence of two 10 s exposures, acquired using a laser power of 10 mW, and then summed to achieve the final spectrum. Regions of interest in SEM images were selected for focused-ion-beam (FIB) sectioning for TEM analysis. FIB lift-out was performed using a FEI Nova NanoFab200 in the LeRoy-Eyring Center for Solid Sate Science (LE-CSSS) at Arizona State University (ASU). Analytical TEM was performed on the FIB sections using a FEI CM200-FEG and an FEI Techni 200-FEG in the LE-CSSS at ASU. EDX analyses were performed with a EMiSpec analytical system on the CM200. Nanometer scale mineralogy was determined using a combination of imaging, electron diffraction and EDX analysis.

Results: *Petrography, SEM and Raman.* Our sample thin sections have several shock veins that range up to 1-mm in width. Although the shock effects in this sample are similar to those of other Martian meteorites, the plagioclase remains predominantly anisotropic (crystalline) with polysynthetic twinning and fractures visible throughout much of the sample. However, in the vicinity of shock veins, the plagioclase is isotropic and stoichiometric with undisturbed grain boundaries and no fractures. Some plagioclase in contact with shock melt has transformed to tissintite, a non-stoichiometric Ca-jadeite-like pyroxene [3]. In contact with shock melt, fayalitic olivine is partially transformed to ahrensite (Fe_2SiO_4-rich ringwoodite [3]). As in several other shocked Martian meteorites, such as Tissint [4], olivine is also transformed into a nanometer-scale mixture of oxide and silicate. Raman spectra from these areas in NWA 8159 are consistent with the presence of magnetite, rather than magnesiowüstite, as seen in Tisint. Minor silica grains have radiating fractures through the surrounding minerals, indicating expansion during partial back transformation from a high-density phase. Raman spectra from the silica indicate the presence of stishovite and coesite.

BSE images of the shock veins in NWA 8159 show a unique texture, unlike that seen in chondrites or SNCs. The veins are fine grained at their margins, with increasing crystal size toward the vein centers. The dominant phase forms large poikiolitic grains in the vein centers. Raman spectra from the veins suggest that Ca-rich garnets are the predominant silicate in the shock veins, but the textures of the poikiolitic crystals is distinctly different from those of majorite-pyrope solid solutions in shock veins of L chondrites. BSE images of shock veins also show the presence of blocky silicate crystals and sulfides in addition to the garnets.

FIB-TEM. TEM analyses of a fine-grained vein-edge assemblage indicate a mixture of majoritic garnet and stishovite (Fig. 1). The garnets range from 200-nm equant crystals to 1-µm poikiolitic crystals. The average chemical formula for these majoritic garnets is $(Na_{0.34}Ca_{0.83}Mn_{0.04}Fe_{1.64}Mg_{0.15})(Mg_{0.27}Al_{1.31}Si_{0.38}Ti_{0.04})Si_3O_{12}$ They are Na-rich almandine-grossular garnets with ~38% majorite component. The stishovite occurs as tetragonal prisms around smaller garnets and enclosed within poikiolitic garnets. The average formula for the stishovite is $Fe_{0.01}Al_{0.04}Si_{0.96}O_2$.

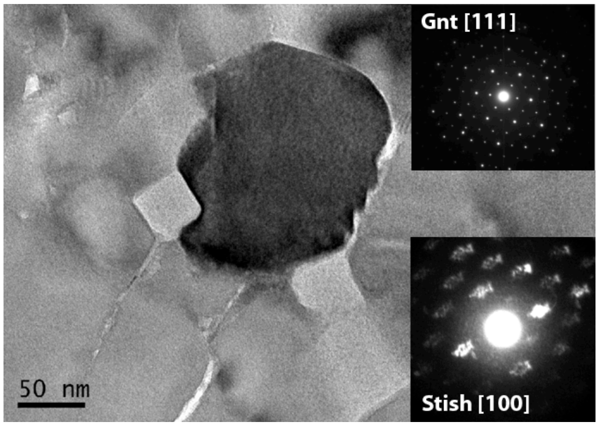

Figure 1. TEM image of the shock-vein edge assemblage of majoritic garnet (Gnt) and stishovite. The stishovite tetragonal prisms appear as light-gray square crystals. Phases were identified by SAED (Gnt) and CBED (stish) diffraction patterns.

The central region of a 1-mm thick shock vein has a different assemblage that consists of majoritic garnet, sodic-calcic clinopyroxene, stishovite and glass, along with Fe-sulfide. The garnets are poikiolitic with abundant melt inclusions as well as stishovite inclusions. The garnets are Na-rich almandine-grossular solid solutions with a majorite component of ~36%: $(Na_{0.36}Ca_{0.90}Mn_{0.04}Fe_{1.54}Mg_{0.26})(Mg_{0.36}Al_{1.30}Si_{0.36})Si_3O_{12}$. The clinopyroxene is a solid solution between jadeite and Fe-rich augite with an average chemical formula: $(Na_{0.43}Ca_{0.32}Fe_{0.25})(Fe_{0.51}Mg_{0.16}Al_{0.33})Si_{2.03}O_6$. The glass is rich in SiO_2 and Fe.

TEM analysis of the oxide plus silicate mixtures intransformed olivines within shock veins confirms the presence of magnetite and identifies the silicate as clinoenstatite ($En_{55}Fs_{43}Wo_2$). This assemblage is the same as the larger-scale magnetite plus pyroxene rims that occur around olivine grains outside of shock veins.

Interpretation: *Shock conditions.* The transformation of fayalitic olivine (Fa_{75}) to ahrensite does not provide tight constrains on the shock pressure because the the transformation can occur under any conditions where anhensite has a lower free energy than Fa_{75}-olivine. Based on the phase diagram for 1600°C [5], the sample experienced a minimum shock pressure of 8 GPa. The coexistence of crystalline plagioclase and maskelynite suggests a moderate shock pressure of 16 – 23 GPa [6]. However, the association of maskelynite with shock veins indicates that high temperatures were required to transform the plagioclase. The shock-vein assemblages also provide constraints on the shock pressure. The shock-vein margins have an assemblage of majoritic-garnet plus stishovite whereas the the vein centers have an assemblage of majoritic-garnet plus clinocpyroxene plus stishovite. Based on the phase relations for MORB [7] (Fig. 2), these two assemblages coexist at approximately 16 GPa and 2300 K. One explanation is that the more rapidly quenched shock-vein edge crystallized above 16 GPa and the more slowly quenched central-vein assemblage crystallized below about 16 GPa as a result of decreasing pressure during quench. Although we have not yet modeled the cooling of she shock veins, the presence of a majoritic garnet in 1-mm wide shock veins suggest a relatively long shock-pulse duration.

Contraints on impact conditions. The constraints on shock pressure and duration, given above, will be compared to those of other martian meteorites and used to constrain impact conditions for this sample.

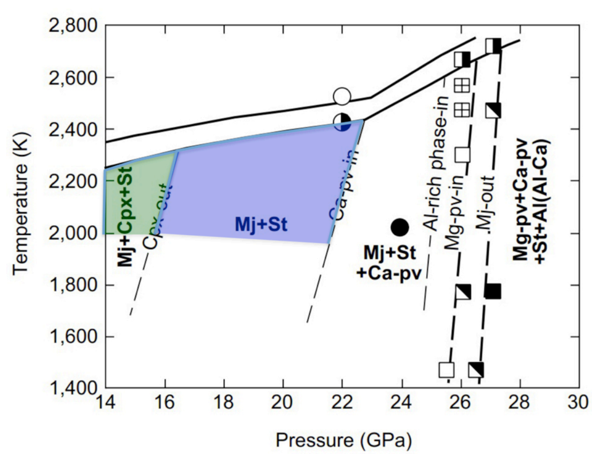

Figure 2. Liquidus phase diagram for MORB [7] showing the stability fields for majorite plus stishovite (Mj+St) in blue and majorite, clinopyroxene and stishovite (Mj+Cpx+St) in green.

References: [1] Agee C. B. et al. (2014) *AGU Fall Meeting* Abstract #P54B-02. [2] Sharp T. G. et al. (2014) *AGU Fall Meeting* Abstract #P54B-01. [3] Ma C. et al. (2014) *77th Annual MetSoc Meeting* Abstract #5166. [4] Walton et al. (2014) *Geochimica et Cosmochimica Acta 140*, 334–348. [5] Fei Y. and Bertka C. M. (1999) *Geochemical Society Spaecial Paper 6,* 189-207. [6] Kubo et al. (2010) *Nature Geoscience 3*, 41-45. [7] Hirosi et al, (1999) *Nature 377*, 53-56.

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