Shock effects in new martian olivine basalt Northwest Africa 10416: Distinct from shergottites but akin Northwest Africa 8159.

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Introduction: Martian meteorites record a range of shock effects associated with hypervelocity impact events on their parent body. These range from nearly unshocked (S1) to very highly shocked (S6) [1]. Studies of shock effects in meteorites place constraints upon the size of the crater from which they were ejected. Relating martian meteorites back to their source crater remains a major scientific priority. Recently, the first basaltic meteorite from Mars to preserve igneous crystalline feldspar, Northwest Africa (NWA) 8159, was reported [4]. In 2015, NWA 10416 was purchased as a 964 g stone. NWA 10416 is a martian olivine basalt, with strongly altered olivine macrocrysts set in a finer-grained groundmass of clinopyroxene and crystalline plagioclase with accessory ilmenite, spinel, chromite and pyrrhotite [Herd et al. *LPS XLVII* companion abstract]. NWA 10416 is therefore the second martian basalt recovered which preserves igneous feldspar and therefore records shock conditions distinct from those of other basalts (shergottites) within which original plagioclase has been amorphized or melted [1]. The purpose of this study is to characterize shock deformation and transformation effects within and adjacent to shock veins in NWA 10416 and in non-veined regions of the host rock. New phases produced by shock, through crystallization or solid-state transfromation, 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.

Samples and Methods: Two polished thin sections were initially characterized using an optical microscope. Backscatter-electron (BSE) images were acquired using the Zeiss EVO MA scanning electon microscope (SEM) at the University of Alberta (UA). Major and minor element abundances of minerals and glasses were measured with a JEOL 8900 electron microprobe (EMP) at UA. For analysis of beam-sensitive glasses a defocused electron beam (10 µm) was employed, under conditions of 10 nA and 15 kV. For crystalline minerals operating conditions of 20 kV, 10 nA and a fully focused beam (1 µm) were employed.. High-pressure minerals were identified by Raman spectroscopy usng a Bruker SENTERRA micro-Raman instrument at MacEwan University. The 100X objective of a petrographic microscope was used to focus the excitation laser beam (532 nm) to a focal spot size of ~1 µm. A sequence of two-10 s exposures, acquired using a laser power of 10 mW or 2 mW, were then summed to achieve the final spectrum. Regions of interest were selected for further characterization using micro-X-ray Diffraction (XRD). Diffraction data were collected at beamline 13-IDD (GSECARS) at the Advanced Photon Source, ANL, Chicago with a primary beam energy of 25 keV. The beam was focused to 2×3 µm² onto the sample surface. Diffraction data were collected in transmission geometry and by grid scans over regions of interest.

Results: The thin sections contain several veins of shock melt cutting across and displacing igneous minerals. The apparent thickness of these veins ranges from several micrometers up to 1.1 mm. Plagiclase in the host rock remains predominantly anisotropic (crystalline) with polysynthetic twinning. Fractures in this mineral range from irregular networks to planar deformation features (PDFs) with up to three sets of closely-spaced PDFs with distinct crystallographic orientation observed in a single grain. Patchy amorphization is observed in host rock plagiclase, with ~4–8% transformed based on visual estimates. The degree of plagioclase amorphization increases with proximity to shock veins, with complete amorphization observed in those grains immediately adjacent to the veins. Although what was originally plagioclase glass has been extensively altered (Herd et al. *LPS XLVII* companion abstract), cores of coarser grains (150–350 µm) remain intact (unaltered). These cores are fracture-free glasses, yielding good totals (99.5–100.2 wt % oxides) with 4.7438 to 4.9926 cations calculated based on 8 oxygens. Raman spectra from these glasses contain a broad hump centered over 518 cm^{-1}. Plagioclase in direct contact with now quench-crystallized shock melt along vein margins and clasts entrained within veins, has been converted to tissintite, a non-stoichiometric vacancy-rich Ca-jadeite-like pyroxene with plagioclase composition [3]. Raman spectra from this mineral contain sharp peaks at 692, 998 and 1107 cm^{-1}.Tissintite in NWA 10416 has a representative formula of $(Ca_{0.45}Na_{0.29}\square_{0.26})(Al_{0.98}Fe_{0.01}Mg_{0.01})(Si_{1.80}Al_{0.20})O_6$.

Olivine in the host rock exhibits pervasive fracturing, both irregular and planar. Spacing between planar fractures (2 to 20 µm) and degree of development varies between olivine grains. Under crossed polars olivine exhibits moderate mosaicism. Olivine along the shock vein margin has not been transformed to its high pressure compositional equivalent, although detection of ringwoodite or ahrensite may require higher resolution techniques such as transmission electron microscopy compared to those employed in this study.

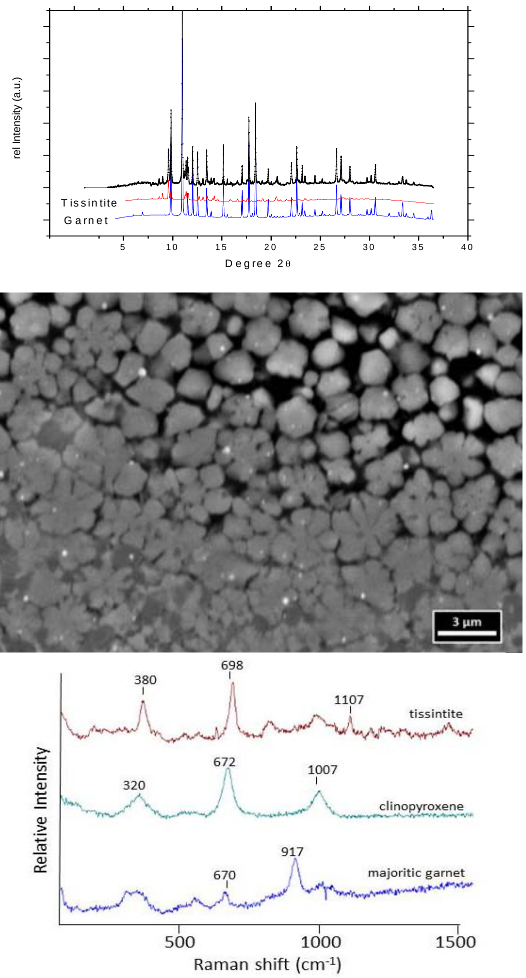

Figure 1. Top, micro-XRD data collected on the shock vein matrix. Middle, SEM BSE image of majoritic garnet, clinopyroxene and tiny Fe-sulphide spheres crystallized from shock melt. Bottom, Raman spectra of minerals associated with shock veins in NWA 101416.

Thicker portions of shock veins are dominated by granular textures of micrometer size crystals of garnet and pyroxene. EMP analyses collected on the coarsest grains (~2 µm) confirm that they are a pyrope-almandine-garnet with representative formula $(Mg_{1.39}Fe_{0.80}Ca_{0.61}Na_{0.14}Mn_{0.02})_{\Sigma 2}(Al_{1.35}Si_{0.40}Mg_{0.23}Ti_{0.03})_{\Sigma 2}Si_3O_{12}$. Silicon ranges from 3.39 to 3.42 cations per formula unit. Based on excess silicon in octahedral sites, this garnet contains a 39–42% majorite component. Diffraction data confirm presence of the majoritic garnet in the shock melt vein, as do 670 cm^{-1} and 917 cm^{-1} peak positions in Raman spectra. This majoritic garnet has crystallized with a diopside-rich pyroxene, with peaks in Raman spectra near 320, 673, 1007 cm^{-1}. In addition, a dense clinopyroxene was identified in the shock melt vein matrix. This pyroxene contains 30–50% of the Ca-Eskola component based on site-occupancies, similar to tissintite [3]. Garnet and dense clinopyroxene are the dominant phases in the shock melt vein although there is at least one example where these two phases are suppressed in favour of a clinopyroxene along the jadeite-tissintite join, with at least one other phase which matches calcium-ferrite type calcium-aluminate. Additional data are being collected in order to better understand the origin of this change in paragenesis.

Discussion and Conclusions: Of the ~85 martian meteorites currently in the world's collection, only two basalts preserve crystalline igneous feldspar – NWA 8159 [4] and NWA 10416 [this study]. This distinguishes these two meteorites from other martian basalts (shergottites) in which original igneous plagioclase has been completely shock-transformed. In NWA 8159, plagioclase (An_{54-65}) in non-veined regions is completely crystalline. In contrast, patchy isotropization of plagioclase (An_{59-67}) is observed in regions of NWA 10416 far from shock veins, which implies slightly higher but comparable shock conditions to those experienced by NWA 8159 (~16 GPa; [4]). In both meteorites grains close to the shock vein have been completely amorphized. Crystallization of high-pressure minerals throughout the mm-size veins (core-rim) implies that the shock melt crystallized at high pressure or during adiabatic pressure release. Modelling of the thermal history of this shock vein allows estimation of the time required for solidification (~100–500 ms). This implies a longer dwell time, τ, defined as the time the rock spent at high pressure, compared to shergottites such as Tissint where only the thinnest and therefore more rapidly quenched veins crystallize at high pressure [5]. High resolution numerical modeling of τ during impact ejection as a function of the impactor radius [6] demonstrates that τ varies as a function of depth and distance from the point of impact. This places more strongly shocked shergottites closer to the point of impact compared to NWA 10416. Using the scaling of [6] gives an impactor diameter of ~6 km, which would result in a larger crater compared to shergottites.

References: [1] Fritz et al. (2005) *MAPS*, 40, 1393– 1411.[2] Herd et al (2016) *LPS XLVII,* Companion Abstract. [3] Ma et al. (2015) *EPSL,* 422, 194–205. [4] Sharp et al (2015) *LPS XLVI*, Abstract #1939. [5] Walton et al (2014) *GCA* 140, 334-348. [6] Bowling et al. (2015) *LPS XLVI*, Abstract #2289.