The Northwest Africa 10416 olivine-phyric shergottite: A product of multiple impact events on Mars?

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Introduction: Martian meteorites record shock effects associated with hypervelocity impact events on their parent planet, manifest as shock deformation or transformation of igneous minerals. The timing of Mars ejection can be approximated by the CRE age; however, the timing of shock metamorphism has been addressed by few studies. Recently, the first shergottite to preserve crystalline igneous feldspar was reported [1]. In 2015, another martian olivine basalt, NWA 10416, was described [2]. As one of the few martian meteorites to preserve igneous feldspar, NWA 10416 records shock conditions distinct from those of other shergottites within which plagioclase has been amorphized or melted [3]. The purpose of this study is to characterize shock in NWA 10416.

Samples and Methods: Two thin sections were investigated using an optical microscope. BSE images were acquired using the Zeiss EVO MA SEM. Major and minor element abundances were measured with a JEOL 8900 EMP. A defocused electron beam (10 µm) was used to analyze beam-sensitive materials (10 nA, 15 kV) with a fully focused (1 µm) beam used for minerals (20 kV, 10 nA). Further phase characterization employed a micro-Raman spectrometer. The 100X objective of a microscope was used to focus the excitation laser beam (532 nm) to ~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 micro-XRD 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 μm^2 onto the sample surface. Diffraction data were collected in transmission geometry and by grid scans.

Results: Shock veins of variable width (~10 µm to 1.1 mm) cut across and shear igneous minerals. Plagioclase ($An_{59\text{-}67}$) in non-veined regions is crystalline and highly fractured including development of PDFs, with polysynthetic twinning. Patchy amorphization (4–8%) is observed with the degree amorphization increasing with proximity to shock veins. The only true maskelynite remaining in NWA 10416 is in the cores of the coarser, completely amorphized grains (150–350 µm) near shock veins. These cores are fracture-free glasses, yielding good totals (99.5–100.2 wt % oxides) with 4.744 to 4.993 cations on an 8-oxygen basis. The Raman spectrum contains a broad hump near 518 cm^{-1}. Plagioclase in direct contact with shock veins has been converted to tissintite. Also observed is an amorphous alteration product preferentially replacing maskelynite [2]; this material is enriched in Al, and depleted in Ca, Na and Si relative to labradorite. Analysis of this material gives consistently low totals (79.4–84.1 wt%), and it is extremely beam-sensitive and often associated with void spaces. Recalculation of EMP data assuming a smectite-type structure gives a formula consistent with beidellite, $(Ca_{0.36}K_{0.05})_{\Sigma=0.4}(Al_{1.99}Mg_{0.05}Fe_{0.05})_{\Sigma=2.1}(Si_{3.0}Al_{1.0})_{\Sigma=4}O_{10}(OH)_2(H_2O)_4$, a Ca-rich dioctahedral aluminosilicate smectite. Thin veins of calcite-filled fractures cut across "beidellite", shock veins and igneous minerals. Within the shock vein matrix the dominant silicate minerals are garnet and diopside, confirmed by EMP analyses, peak positions in the Raman spectrum and micro-XRD patterns. EMP analyses collected on garnet confirm that they are a pyrope-almandine-majorite garnet (~40% majorite).

Discussion and Conclusions: Shock effects recorded in NWA 10416 are distinct from most other shergottites in terms of: (1) the presence of crystalline igneous plagioclase with maskelynite formation restricted to shock vein margins, and (2) crystallization of high-pressure minerals (majoritic garnet + diopside) throughout mm-size shock veins. The former implies a lower peak shock pressure, ~16 GPa, compared to shergottites whose igneous feldspar has been completely shock-transformed [3]. The latter the 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]. A CRE of 1.05 ± 0.15 Ma from ^3He, ^{21}Ne and ^{38}Ar pairs launch of NWA 10416 with strongly shocked shergottites such as DaG 476 [5]. The discrepancy in shock pressure and duration between NWA 10416 and other shergottites does not imply ejection in distinct events, as these parameters have been shown to vary as a function of the position of the rock in the cratering process [6]. This places more strongly-shocked shergottites closer to the point of impact. However, if the maskelynite alteration product ("beidellite") identified in this study, can be shown to be preterrestrial, as alluded to by crosscutting relationships, then the history of this rock calls upon at least two impact and secondary alteration events.

References: [1] Sharp et al. 2015. Abstract #1939. 46th Lunar & Planetary Science Conference. [2] Herd et al. 2016. Abstract #2527. 47th Lunar & Planetary Science Conference. [3] Fritz et al. 2005. *Meteoritics & Planetary Science* 40:1393– 1411. [4] Walton et al. 2014. *Geochimica et Cosmochimica Acta* 140:334–348. [5] Cassata et al. 2016. Abstract #381. 26th Goldschmidt Conference. [6] Bowling et al. (2015) *LPS XLVI*, Abstract #2289.