A REVISED SHOCK HISTORY FOR THE YOUNGEST UNBRECCIATED LUNAR BASALT– NORTHWEST AFRICA 032. T. Mijajlovic[1], X. Xue[1] and E. L. Walton[1], [1] MacEwan University, Department of Physical Sciences, 10700 104 Ave, Edmonton, AB, T5J 2S2, Canada (waltone5@macewan.ca).

Introduction: Northwest Africa (NWA) 032 is considered to be the youngest radiometrically-dated mare basalt, with concordant Rb-Sr and Sm-Nd ages of 2.947 ± 0.016 Ga and 2.931 ± 0.092, respectively [1]. These ages are ~175 Ma older than those from ^{40}Ar-^{39}Ar (2.779 ± 0.014 Ga) [2]. NWA 032 contains a high modal abundance of pyroxene (50.7 vol%), plagioclase (29.4 vol%), and olivine (11.3 vol%) [3]. Measurement of the cosmogenic nuclides present in NWA 032 suggest an Earth-Moon transfer age of 0.5 Ma, typical of lunar meteorites [3]. The texture is that of an unbrecciated porphyritic basalt, with olivine as the most abundant phenocryst type. Olivine phenocrysts are zoned with Mg rich cores (Fo_{34-50}) and thin, discontinuous Fe-rich rims (Fo_{30}). Fine grained (≤ 1μm) elongated, tapered plagioclase crystals (An_{80-90}) are present within the groundmass, interspersed with pyroxene ($En_{1-25}Wo_{15-25}$) of similar shape and size. These two minerals occur in a plumose texture, radiating from a common nucleation point. Pyroxene may be categorized based on grain size as either groundmass (<1 μm), intermediate crystals (~50 μm) or larger phenocrysts (~100 μm) [3].

The mineralogy of NWA 032 makes it ideal for the study and classification of shock features based on the updated shock classification scheme [4], which relies on petrographic observations of deformation and transformation in olivine, pyroxene and plagioclase – three of the most abundant minerals in NWA 032. A previous description of shock effects in NWA 032 allowed for a shock pressure estimate of ~40-60 GPa [3]; however, the shock state of plagioclase feldspar (shock-amorphized vs crystalline) was inconclusive, owing to the fine grain size of this mineral (≤1μm). The purpose of our study is to characterize the shock deformation and transformation effects in NWA 032 using a combination of field emission scanning electron microscopy (FESEM) and Raman spectroscopy, focusing on the shock state of feldspar, as well as characterizing the crystallization products of shock melting. The latter have been demonstrated as useful criteria to evaluate shock conditions [5]. Our results more tightly constrain the shock history experienced by NWA 032.

Samples and Methods: One polished thin section of lunar meteorite NWA 032 was made available to this study through loan from the University of Alberta Meteorite Collection. Shock deformation effects such as mosaicism were assessed using a petrographic microscope where the optical properties of igneous minerals could be observed in reflected, transmitted polarized and crossed polarized illumination. Areas of interest were further characterized using high resolution backscattered electron (BSE) imaging. BSE images were collected with a 20 kV accelerating voltage using a ZEISS Sigma 300 FESEM at the University of Alberta. Mineral identification and composition were aided by acquisition of spot analyses using a Bruker energy-dispersive X-ray (EDX) spectrometer that is fitted on the FESEM. This EDX system has a dual silicon drift detector, each with an area of 60 mm^2, and an energy resolution of 123 eV. The structural state of phases (i.e., crystalline versus amorphous) was assessed using a Bruker SENTERRA Raman spectrometer at MacEwan University. This micro-Raman system uses a 532 nm Ar+ laser, which is focussed on the thin section surface using an objective lens. A 100X objective lens was used to achieve a laser spot size of ~1 μm. Spectral backgrounds were graphically reduced using commercial spectroscopy software. The RRUFF Raman online database and published spectra of pyroxene, olivine, plagioclase and maskelynite [5] were used to determine the expected vibrational modes for the phases analyzed.

Results: Elongated pyroxene crystals displayed thin, parallel bands spaced ~15 μm apart, identified as mechanical twins. Thin, parallel sets of open fissures with 3-5 μm spacing, are found heterogeneously distributed throughout phenocryst pyroxene grains. Both the intermediate elongate and the phenocryst pyroxene display undulatory extinction to weak mosaicism. Olivine contains planar fractures, which appear as open fissures spaced ~10 μm apart, and weak to moderate mosaicism.

Groundmass plagioclase grains displayed optical properties characteristic of isotopic materials (i.e., extinction under crossed polarized illumination). The Raman spectrum acquired from individual plagioclase grains contained none of expected peaks – a high intensity triplet between 484 cm^{-1} and 560 cm^{-1} and a distinct peak between 980 cm^{-1} and 1000 cm^{-1} [6] – expected of well crystalline Ca-rich plagioclase. Instead, acquired spectra contain broad features characteristic of an amorphous structure [6]. Textures indicating melting, such as flow lines or vesicles, were not observed in BSE images of the groundmass plagioclase.

Shock veins in NWA 032 occur as an anastomosing network of black, glassy veins cutting across the basaltic host rock. Offsets and displacement of igneous minerals are observed along vein margins. Shock vein width ranges from ~1 μm up to 100 μm. BSE imaging reveal internal textures that are dominantly glassy and schlieren-rich. Micrometer-size crystals nucleate off entrained mineral fragments and along shock veins margins. A range of greyscales was observed in BSE images between crystals, as well as within individual crystals (core to rim), suggesting that more than one phase is present, and that these have formed by nucleation and growth from a liquid. Major element composition from EDX spectra suggest both Mg-Fe-rich and Mg-Ca-Fe-rich silicates. Raman spectra acquired from these aphanitic minerals may be divided into two distinct spectral signatures in terms of their peak positions and intensities. One spectrum displays sharp, intense peaks at ~318 cm^{-1}, 384 cm^{-1}, 658 cm^{-1}, and 994 cm^{-1}, characteristic of clino- and orthopyroxene. The other spectrum showed a doublet at 810 cm^{-1} and 841cm^{-1}, characteristic of olivine. Regions of shock melting also include isolated, irregularly shaped pockets, heterogeneously distributed throughout the host rock. Like shock veins, internal textures of shock melt pockets are dominantly glassy and schlieren rich. Nucleation and growth of crystals are restricted to the margins of entrained igneous minerals. EDX and Raman spectra from these crystals are consistent with pyroxene and olivine. No high pressure compositional equivalents such as ringwoodite have been documented, despite acquisition of >40 spectra.

Discussion:

Shock Stage: Our assessment of the structural state of plagioclase in NWA 032, including a lack of peaks in the Raman spectrum and an absence of flow textures in BSE images, are consistent with maskelynite, the diaplectic glass of plagioclase composition. A shock stage for NWA 032 was determined using the updated classification scheme of [4] for mafic “M” rocks. The presence of planar fractures and mosaicism in olivine, mechanical twinning in pyroxene and transformation of plagioclase to maskelynite suggests a shock classification stage of M-S4 [4]. This shock stage indicates an equilibration shock pressure between 28 to 34 GPa and a post shock temperature of ~200-250 °C. These shock conditions are significantly lower than a previous estimate of 40-60 GPa and a post shock temperature of ~900-1100 °C [3].

Shock veins and shock melt pockets comprise 1-2 vol% of the host rock, with internal textures that are dominantly glassy. Olivine and pyroxene have crystallized from shock melt. These two minerals are generally considered low-pressure phases; however, experiments have shown they occur together at elevated pressures, up to 14 GPa [7]. This crystallization pressure is lower than our bulk shock pressure (28-35 GPa), and is consistent with the liquid remaining after pressure release and solidifying during decompression, or under ambient pressure conditions. Therefore, while yielding information on the crystallization history of shock melt in NWA 032, the quenched products of shock melting do not constrain the shock pressure of the meteorite as a whole.

Implications for the shock history: Most lunar meteorites have transfer times to Earth that are less than 1 Ma [8]. This transfer time is due to the escape velocity of the moon, 2.37 km/s, which is only sufficient to launch ejected material into an Earth-centered orbit that eventually degrades, causing the eventual meteorite to fall to Earth’s surface [9]. An increase in shock pressure may accelerate the material to 2.38 km/s, allowing it to escape the gravitational pull of the Earth-Moon system. In this latter impact scenario, the meteoroid is launched into an orbital trajectory around the Sun, increasing its cosmic exposure age and transfer time (>1 Ma), as well as significantly decreasing the likelihood of the material reaching Earth [9]. Based on the shock conditions experienced by NWA 032, described in this study, we have calculated the velocity of the sample during ejection to be 2.37 km/s. This velocity, coupled with the transfer age of 0.5 Ma [3], suggests the impact event that ejected NWA 032 was only sufficiently energetic to escape the lunar surface, but not the entirety of the Earth-Moon system. This shock history is consistent with our finding of a lower equilibration shock pressure (28-35 GPa; this study) than was previously estimated (40-60 GPa; [3]).

Conclusions: Constraining the temperature-pressure-time conditions of the impact that ejected NWA 032 from the moon is largely predicated on the shock state of plagioclase feldspar. The presence of maskelynite, confirmed by our study, constrains the shock pressures experienced by NWA 032 to ~28-35 GPa, corresponding to a post shock temperature of 200-250 °C. The presence of maskelynite within NWA 032 (this study), the lack of brecciation, and low solar wind contents [3], suggest NWA 032 experienced a single impact event that ejected it from the moon, during which the quenched shock melt present within the meteorite formed.

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