A REVISED SHOCK HISTORY FOR THE YOUNGEST UNBRECCIATED LUNAR BASALT– NORTHWEST AFRICA 032

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Introduction

Northwest Africa (NWA) 032 is 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]. Measurement of the cosmogenic nuclides present in NWA 032 suggest an Earth-Moon transfer age of 0.5 Ma, typical of lunar meteorites [2]. NWA 032 is an unbrecciated olivine-pyroxene-phyric basalt, with olivine, pyroxene and plagioclase as major minerals (Fig. 1). A previous description of shock effects in NWA 032 allowed for a shock pressure estimate of ~40-60 GPa [2]; however, the shock state of plagioclase feldspar (shock-amorphized vs crystalline) was inconclusive, owing to the fine grain size of this mineral (≤1 μm). The purpose of our study is to characterize the shock deformation and transformation effects in NWA 032 using field emission scanning electron microscopy (FESEM) and micro-Raman spectroscopy, focusing on the structural state of feldspar, shock deformation recorded in igneous olivine and pyroxene, as well as characterizing the crystallization products of shock melting. The latter have been demonstrated as useful criteria to evaluate shock conditions [3]. Our results more tightly constrain the shock history experienced by NWA 032.

Samples and Methods

Shock effects were assessed using a petrographic microscope, with identified areas of interest characterized in detail using a ZEISS Sigma 300 FESEM in BSE imaging mode at the University of Alberta. Mineral identification and composition were aided by acquisition of spot analyses using an EDX spectrometer fitted on the FESEM. The structural state of phases (i.e., crystalline versus amorphous) was assessed using a Bruker SENTERRA micro-Raman spectrometer. The RRUFF Raman online database and published spectra of pyroxene, olivine, plagioclase and maskelynite [4] were used to determine the expected vibrational modes for the phases analyzed.

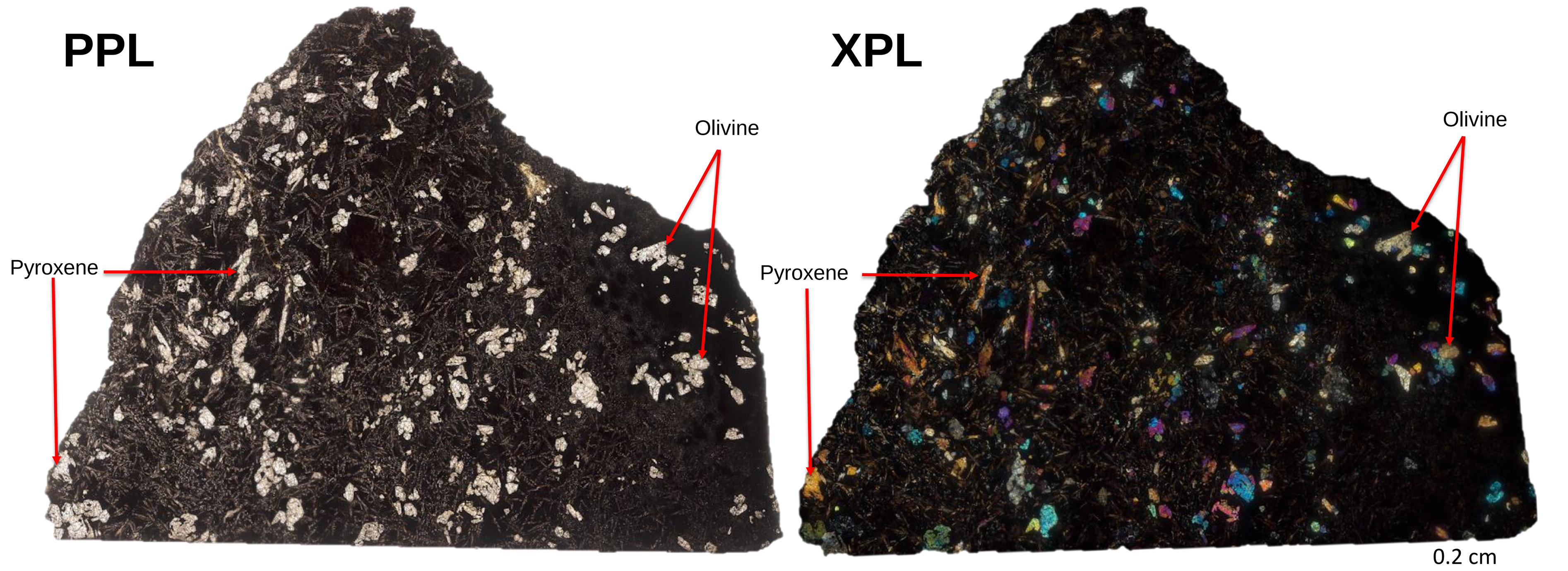

Fig. 1. Overview of the NWA 032 thin section investigated in this study, viewed under plane polarized light (PPL) and cross polarized light (XPL). Olivine-pyroxene phenocrysts (arrows) are embedded in a fine-grained groundmass of plumose plagioclase, pyroxene and oxides (Fig. 3). The thin section was made available to this study through loan from the University of Alberta Meteorite Collection.

Results

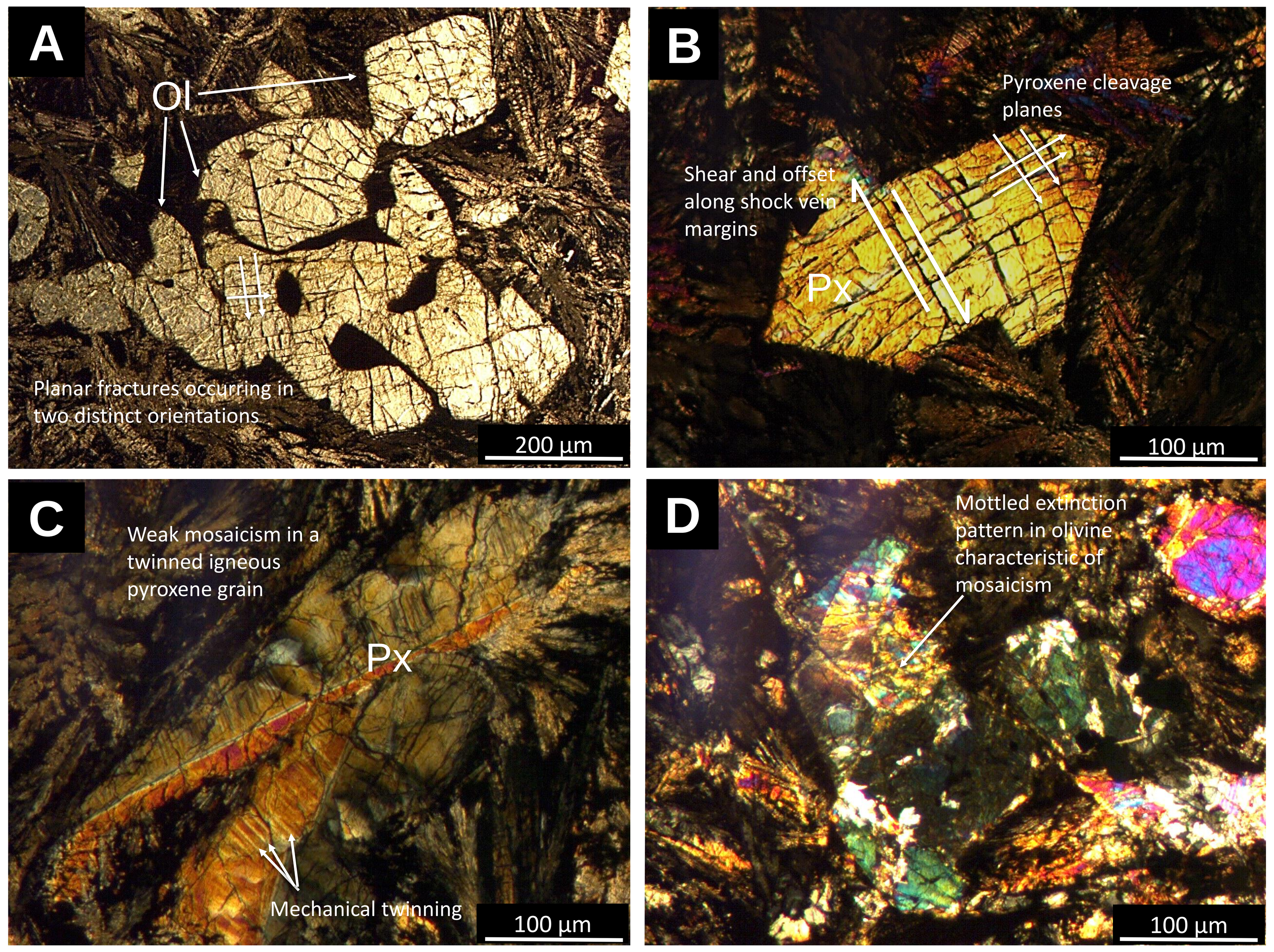

Fig. 2. Transmitted light images taken under plane light (A) cross polars (B-D) of A) olivine displaying planar fractures (arrows), B) a pyroxene phenocryst sheared and offset along a shock vein, showing typical pyroxene cleavage (2 planes @ 90°), C) pyroxene showing a simple twin (igneous), weak mosaicism (shock) and mechanical twinning (shock), and D) mosaicism in olivine. The open fissures in olivine were spaced approximately 10 μm apart and measured 3 μm wide. The fissures were heterogeneously distributed throughout the mineral with a maximum of two distinct orientations occurring within a single grain.

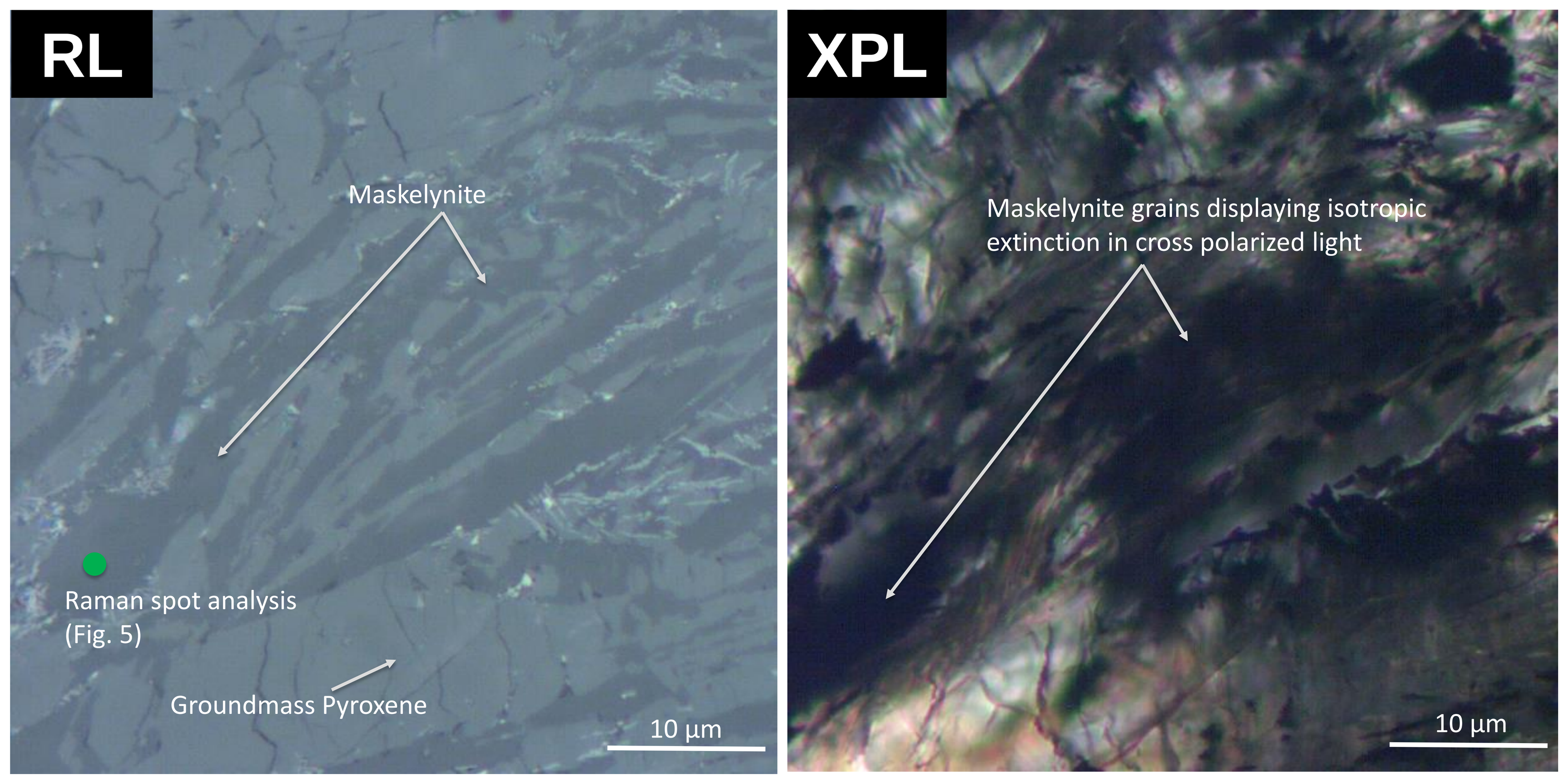

Fig. 3. Groundmass plagioclase grains larger than 1 μm were directly observable in reflected light (RL) when using the petrographic microscope. Once located as individual grains, the same areas displayed isotropic extinction in transmitted cross polarized light (XPL). Textures indicating melting, such as flow lines or vesicles, were not observed in any of the higher resolution BSE images of the groundmass plagioclase (not shown).

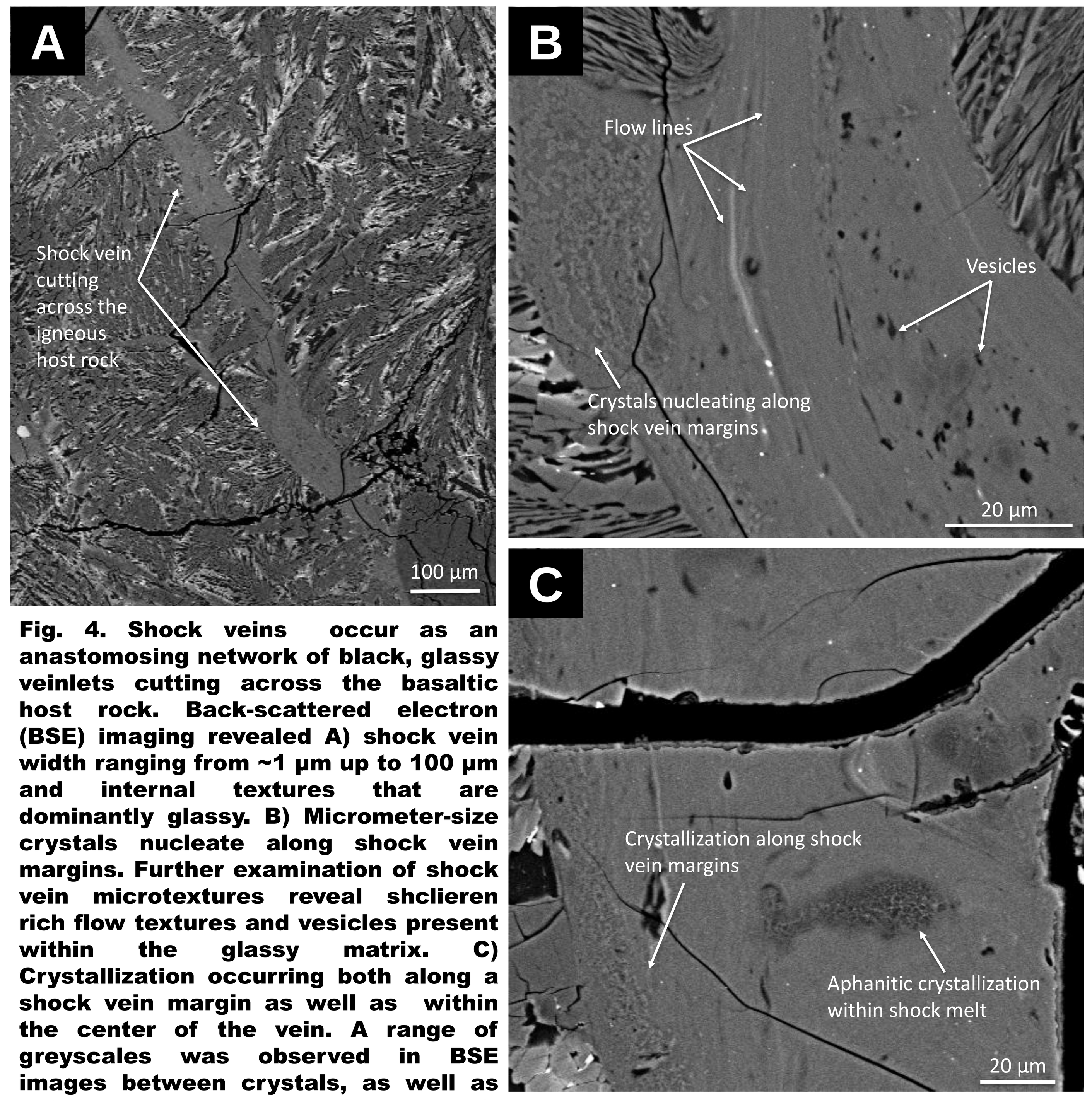

Fig. 4. Shock veins occur as an anastomosing network of black, glassy veinlets cutting across the basaltic host rock. Back-scattered electron (BSE) imaging revealed A) shock vein width ranging from ~1 μm up to 100 μm and internal textures that are dominantly glassy. B) Micrometer-size crystals nucleate along shock vein margins. Further examination of shock vein microtextures reveal schlieren rich flow textures and vesicles present within the glassy matrix. C) Crystallization occurring both along a shock vein margin as well as within the center of the vein. A range of greyscales was observed in BSE images between crystals, as well as with-in 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.

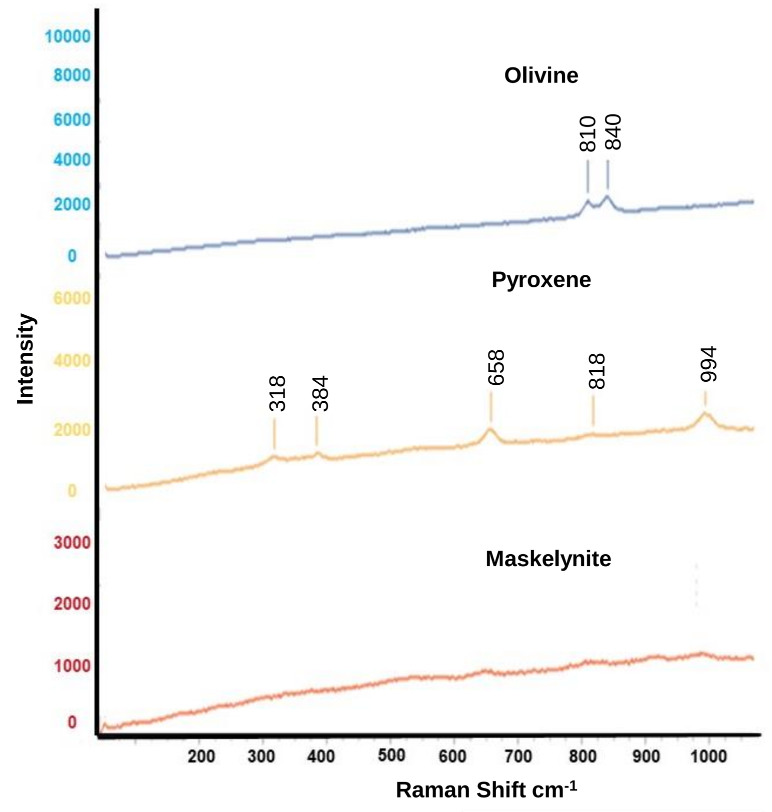

Fig. 5. Raman spectra acquired from the aphanitic minerals nucleating off the margins of shock veins may be divided into two distinct spectral signatures in terms of their peak positions and intensities. One spectrum displays sharp, intense peaks at ~318 cm^{-1}, 384 cm^{-1}, 658 cm^{-1}, and 994 cm^{-1}, characteristic of clino- and orthopyroxene. The other spectrum showed a doublet at 810 cm^{-1} and 841cm^{-1}, characteristic of olivine. 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} – expected of well crystalline Ca-rich plagioclase [4]. Instead, acquired spectra contain broad features characteristic of an amorphous structure [4].

Discussion

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 [3] 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 [3]. This shock stage indicates an equilibration shock pressure between 28 to 34 GPa and a post shock temperature of ~200-250 ºC. These shock conditions are significantly lower than a previous estimate of 40-60 GPa [2], which corresponds to a post shock temperature increase of ~900-1100 ºC [3]. Shock veins and shock melt pockets comprise 1-2 vol% of the host rock, with internal textures that are dominantly glassy (Fig. 3). Olivine and pyroxene have crystallized from shock melt (Fig. 3, 4). These two minerals are generally considered low-pressure phases; however, experiments have shown they occur together at elevated pressures, up to 14 GPa [5]. 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.

References: [1] Borg et al., 2009. Geochimica et Cosmochimica Acta 73 (13): 3963–80. [2] Fagan et al. 2002. MAPS 37 (3): 371–94. [3] Stöffler et al., 2018. MAPS 53 (1): 5–49. [4] Fritz J., Greshake A., and Stöffler D. 2005. Antarctic Meteorite Research 18: 96 – 116. [5] Gasparik (1992) J. Geophys. Res. 97, 15181-15188.