THE MULTI-STAGE COOLING HISTORY OF LUNAR METEORITE NWA 032 AS RECORDED BY PHENOCRYSTIC OLIVINE AND PYROXENE. P.V. Burger[1] , C.K. Shearer[1], J.J. Papike[1], [1]Institute of Meteoritics, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131 (pvburger@unm.edu).

Introduction – Lunar meteorite Northwest Africa (NWA) 032 is an unbrecciated mare basalt, discovered in 1999, whose modal mineralogy is characterized by phenocrystic olivine, pyroxene and chromite, with a groundmass containing feldspar, pyroxene, ilmenite, troilite and other trace metals [1]. Shock melt occurs in veins throughout the sample as well. Fagan et al. [1] observed that the major element chemistry of the sample is most similar to low-Ti basalts from Apollo 12 and 15, though it is enriched in the LREE, a characteristic more akin to Apollo 14 basalts. Radiogenic ages for this sample, based on Ar/Ar [1], and Rb/Sr and Sm/Nd [2] are concordant, ranging from 2.85 – 2.69 Ga. Fagan et al. suggest a relatively simple crystallization history for this sample, based on petrographic observations and thermodynamic modeling using the MELTS algorithm.

This study reexamines the petrographic characteristics of NWA 032 using a combination of backscattered electron imaging (BSE), wavelength dispersive (WDS) X-ray mapping and targeted quantitative electron microprobe analyses (EMP). In doing so, we seek to build on the comprehensive dataset by [1], and frequently allude that that study throughout this abstract. Specifically, we have focused on the crystallization history of the NWA 032 magma as recorded by phenocrystic olivine and pyroxene grains (as opposed to later intermediate and groundmass pyroxene, as described by [1]). Our observations describe previously undocumented zoning features in phenocrystic pyroxene grains, and their implication for the magma crystallization sequence.

Analytical Parameters – Initial inspection of NWA 032 was carried out using BSE on the JEOL 733 Superprobe, at the University of New Mexico. BSE images were used to

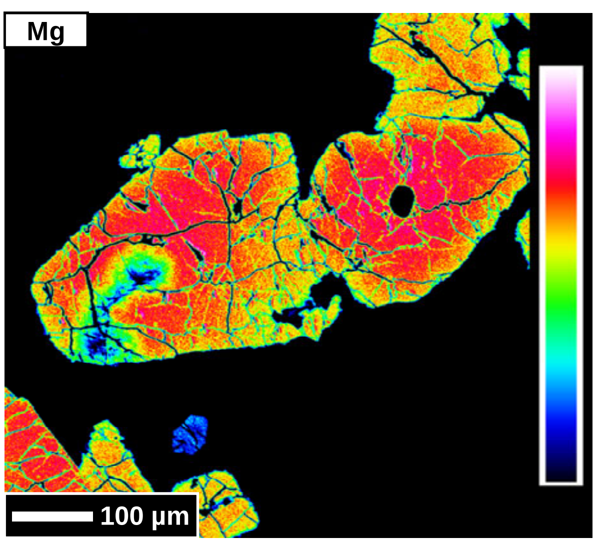

Figure 1. Magnesium WDS map of phenocrystic olivine in NWA 032, illustrating normal zoning from Mg-rich cores to Fe-rich rims. The Mg anomaly in the lower left of the grain is the result of previous SIMS work. Warmer colors indicate increasing X-ray intensity.

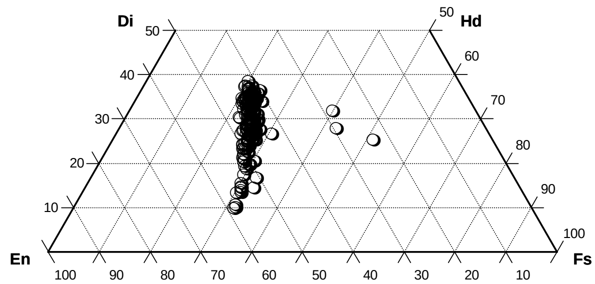

Figure 2. Pyroxene quadrilateral which is illustrates the major element chemistry of pyroxene phenocrysts in NWA 032.

(cont.) determine suitable regions to collect quantitative data and WDS X-ray maps. Quantitative data was collected using an accelerating voltage of 15 kV, a beam current of 20 nA and a spot size of ~1 µm. Taylor-brand mineral and metal standards were used for peak calibration. WDS mapping was conducted using an accelerating voltage of 15 kV and a beam current of 100 nA to maximize X-ray intensity.

Results – Initial petrographic observations are in agreement with those presented by [1]. Olivine phenocrysts measure up to 1.3 mm across their long dimension, with a euhedral-subhedral morphology. Grains demonstrate normal zoning (Fig. 1), from Mg-rich (Fo_{64}) cores towards more Fe-rich (Fo_{51}) compositions at crystal margins, with increased crystallization. According to [1], the Mg concentrations of the coarsest olivine cores in NWA 032 match those predicted for a melt of NWA 032 bulk rock composition [3].

Pyroxene phenocrysts suggest a more complicated history than initially suggested [1]. Phenocryst morphology is subhedral-anhedral; larger grains are similar in size to olivine phenocrysts, though smaller pyroxene phenocrysts are abundant as well. Some pyroxene phenocrysts share a common boundary with adjacent olivine phenocrysts. Quadrilateral pyroxene phenocryst chemistry is in agreement with the observations of [1]. Pyroxene likely nucleated about Mg-rich cores, and shows an apparent continuum toward more Ca-rich compositions (Fig. 2). Closer inspection of WDS Mg maps (Fig. 3) and comparison to quantitative EMP profiles (Fig. 4) illustrates that, rather than a zoning continuum, the chemistry of NWA 032 is more accurately characterized as an oscillation between zones of enriched Fe+Mg (pigeonite), and those enriched in Ca (augite). Furthermore, Al, Ti (Fig. 4) and Cr (not shown) also show a strong positive correlation with Ca, at lower concentrations, in pyroxene phenocrysts. This observation is logical in that Al, Ti and Cr are more compatible in the augite crystal structure [4, 5].

Discussion – The textures and chemistry of olivine and pyroxene phenocrysts in NWA 032 record an intricate crystallization sequence. As was suggested by [1], crystallization of the NWA 032 magma likely began with chromite and olivine. Growth zoning in olivine places constraints on the timescales of crystal growth, suggesting a period of 3.5-35 days for the largest olivine phenocrysts [1]. The observation

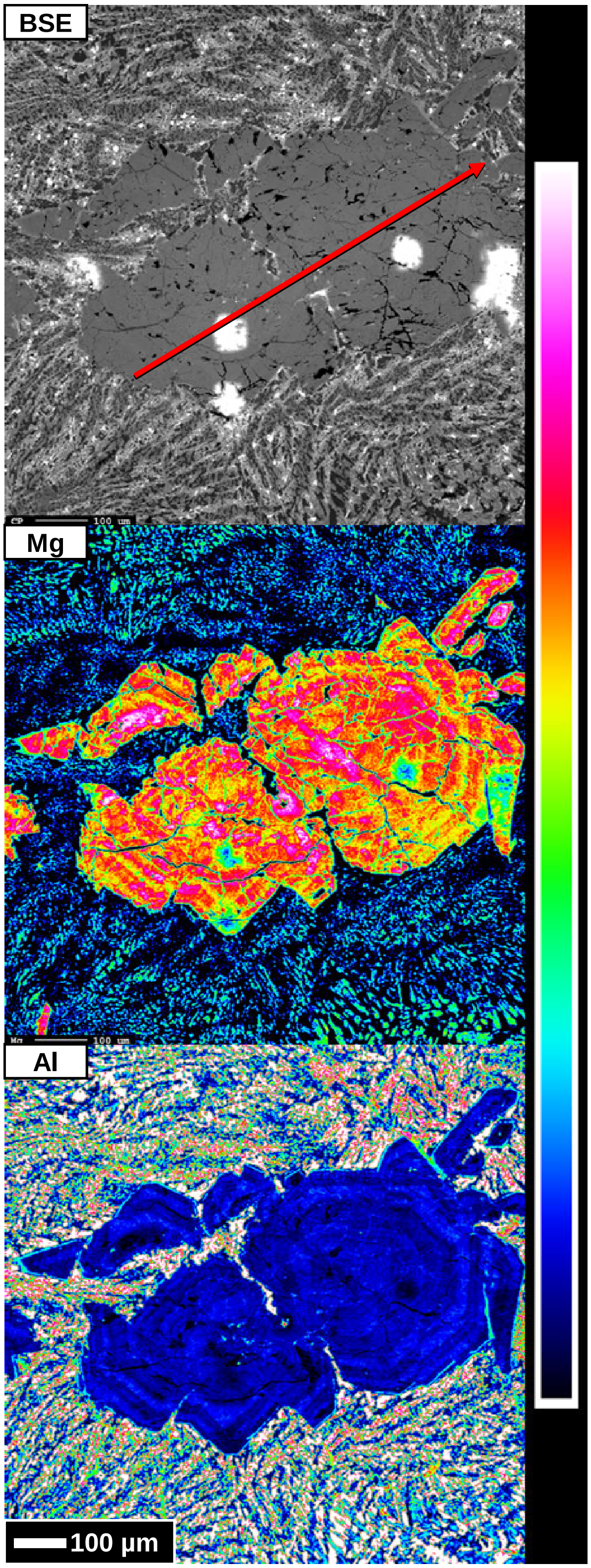

Figure 3. BSE and WDS maps of a pyroxene phenocryst in NWA 032; the quantitative EMP traverse is indicated by a red arrow in the BSE image. Bright halos in the BSE image indicate the location of previous SIMS analyses.

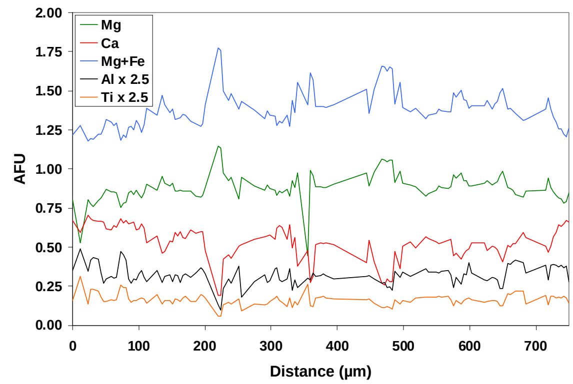

Figure 4. EMP rim to core to rim traverse of pyroxene phenocryst in NWA 032. The traverse path is illustrated in the BSE image in Fig. 3.

(cont.) that some olivine and pyroxene phenocrysts share a sutured boundary in this study and by [1] suggests that olivine and pyroxene co-crystallized during some point in this sample's growth history. While initial observations suggested that growth zoning in pyroxene phenocrysts is continuous, trending toward more Fe-rich compositions [1], our WDS maps (Fig. 3) and zoning profile (Fig. 4) illustrate that zoning is characterized by oscillatory bands. These oscillations are best described as an anti-correlation between Fe+Mg and Ca+Al+Ti (as well as Cr). This behavior indicates a second stage of crystallization. During the first stage, phenocrystic chromite and olivine crystallize, developing normal growth zoning, while in the second stage, possibly while magma was rising toward the surface, oscillatory zoning developed in pyroxene phenocrysts. The fact that Al and Ti are strongly correlated in these oscillatory growth bands, and the Ti/Al ratio both indicate that the Al content of the phenocrystic pyroxene is not the result of plagioclase crystallization. Rather, oscillatory zoning is likely the result of kinetic factors; future work will address this question.

In addition to phenocrystic pyroxene, [1] have characterized the fine-grained intergrowth of pyroxene and plagioclase in the matrix of NWA 032. The plumose intergrowth of these two minerals likely developed due to rapid cooling, following the eruption of the NWA 032-bearing magma.

References – [1] Fagan et al. (2002), MAPS, 37, 371-394. [2] Borg et al. (2007), MAPS, 42, A22-A22. [3] Roeder and Emslie. (1970), Contrib. Mineral. Petrol., 29, 275-289. [4] Karner et al. (2007), Am. Min., 92, 2002-2005. [5] Papike (2009), personal communication.