Disturbance of Pb-Pb ages of Apatites within Lunar Granulite Northwest Africa 3163 associated with Variations in Microtextural Domains. K. M. Lehman Franco[1], B. Wilson[2], K. T. Tait[3], R. Economos[1], E. Bell[4], [1]Roy M. Huffington Department of Earth Sciences, Southern Methodist University, P.O. Box 750395, Dallas, TX (kmlehman@mail.smu.edu), [2] Centre for Research in Earth and Space Science, York University,Toronto, ON, Canada (bjwilson@yorku.ca), [3]Royal Ontario Museum, Toronto, ON (ktait@rom.on.ca), University of California, LA, CA.

Introduction: In situ isotopic analyses of apatite $Ca_5(PO_4)_3$(F, Cl, OH) are critical to discerning the martian [e.g.,1] and lunar volatile budget [e.g., 2], identifying metasomatism [e.g., 3], characterizing magmatic sources, U-Pb and Pb-Pb geochronology, and may contain records of changing oxidation states of a magma [4]. These studies utilize apatite's nearly ubiquitous nature in silicic systems and the mineral's ability to concentrate U, Th, Pb, REE, water, and volatile elements (F, Cl, O, H, S) to address these topics [e.g., 5].

Understanding how impact can alter the isotopic composition is critical to interpreting the apatite results from meteorites and lunar samples. Previous studies have targeted specific microstructures within baddeleyite and zircon grains to more reliably decipher between U-Pb protolith ages and impact ages [6]. This study performs in situ Secondary Ionization Mass Spectrometry (SIMS) Pb and Cl isotope analyses of two >200 µm apatites in lunar meteorite NWA 3163 previously microstructurally characterized via electron backscatter diffraction (EBSD) [7] to evaluate two hypotheses. (1) Regions of the crystals displaying domains with higher portions of deformation as indicated by microfractures or nanocrystalline textures will display the most disturbed Pb-Pb ages. (2) Portions of the apatite grains with differing magnitudes of deformation will display measurable differences in $\delta^{37}Cl$.

Northwest Africa 3163 Description: NWA 3163 is classified as a granulitic anorthosite lunar meteorite [8]. This breccia contains clasts of gabbro and gabbro-anorthosite containing plagioclase (partially shocked to maskelynite), pyroxene, olivine, Fe-Ti oxide, and minor phosphate phases. Major and trace element compositions of NWA 3163 support a pristine ferroan anorthosite (FAN) protolith [6].

In situ $^{232}Th/^{208}Pb$ and $^{207}Pb/^{206}Pb$ dating of micro-baddleyite within the gabbroic clasts of NWA 3163 yielded a protolith age of 4328 ± 309 Ma and 4308 ± 18.6 Ma, respectively [6]. The Pb-Pb age is younger than the model Sr TR_D age of 4340 ± 57 Ma [8]. Ar-Ar dating identified at least two younger impact events, including the granulization event at 3322 ± 95 Ma and a younger impact at 1953 ± 26 Ma (McLeod et al., 2016).

NWA 3163 was shocked to an S4 or S5 state corresponding to shock pressures of >28 GPa [9]. The apatites specifically display microtextural features consistent with S5 shock [7].

Apatite Textural Domains: Wilson (2020) analyzed two large apatites (>200 µm) in anorthositic clasts of NWA 3163 using EBSD, Raman spectroscopy, and atom probe tomography to quantify the crystal structural integrity and highlight different domains of distorted crystal orientation or deformation microtextures. This work showed that both grains generally exhibit cataclastic deformation near the crystal edges while the interior exhibits a gradation in lattice misorientation (crystal plastic deformation). The largest apatite >300 µm exhibits up to 70° of misorientation. These apatites do not have evidence of post-impact recrystallization but rather show brittle flow near the edges of the grain and plastic deformation internally [7].

Methods: EBSD band contrast maps assess the degree of lattice disruption with poor band contrast (represented as black) representing nanofractures, amorphous or nanocrystalline materials. Strong band contrast is represented as white and is indicative of a lack of deformation. Utilizing the EBSD band contrast map from Wilson (2020), the magnitude of deformation was characterized by the loss of crystal integrity, represented by the portion of the spot that did not diffract electrons. These maps were utilized to develop the sampling strategy.

Isotopic analyses of Pb and Cl in the two main deformation domains (crystal plastic and cataclastic deformation) will allow us to evaluate if the unique microtextural subregions exhibit different Pb and Cl isotope ratios. Elemental maps were created using the Field Emission Scanning Electron Microscope (FE-SEM) and Energy Dispersive Spectrometer (EDS) at Southern Methodist University to highlight any compositional variations within the grains. FE-SEM analyses were performed at a working distance of 10 mm and an accelerating voltage of 15 kV. Cathodoluminescence (CL) imaging was also used to highlight any potential compositional zoning within the grains. No zoning was observed, but CL highlighted the plastic deformation observed in the Wilson (2020) study.

Pb isotope SIMS analyses were performed at the University of California, Los Angeles using the CAMECA ims1290. Samples were analyzed with the Hyperion II ion source using a 5nA $^{16}O^-$ primary beam and ~10µm spot size. SIMS spot locations were chosen in each grain to sample the different textural regions while avoiding large fractures. Twelve spots were analyzed on the larger grain, called Apatite 1. Specifically, five of the spots analyzed displayed textures consistent with cataclastic deformation. Five additional spots were analyzed on Apatite 2, one of which sampled a highly deformed cataclastic portion of the grain.

Results: Each of the grains displayed variations in the $^{207}Pb/^{206}Pb$ ratios and, in turn, the associated Pb-Pb age (Figure 1, Figure 2). Microtextural domains with primarily cataclastic deformation textures typically displayed the lowest $^{207}Pb/^{206}Pb$ ratios and youngest ages (Figure 2). The youngest Pb-Pb age 3964 ± 36 Ma is from a region with the lowest crystallinity (Figure 1). The regions with the highest crystal integrity had Pb-Pb ages of 4311 ± 16 Ma and 4319 ± 14 Ma, within error of the previous Pb-Pb age of the baddeleyite grains 4308 ± 18.6 Ma [8]. A mixing line is observed between the oldest Pb-Pb ages ~4320 Ma and the youngest Pb-Pb ages ~3960, but without further data we cannot confirm that the youngest age is an impact age. Some of the Pb-Pb data has evidence of terrestrial Pb contamination as the analyses migrate to higher $^{204}Pb/^{206}Pb$ ratios.

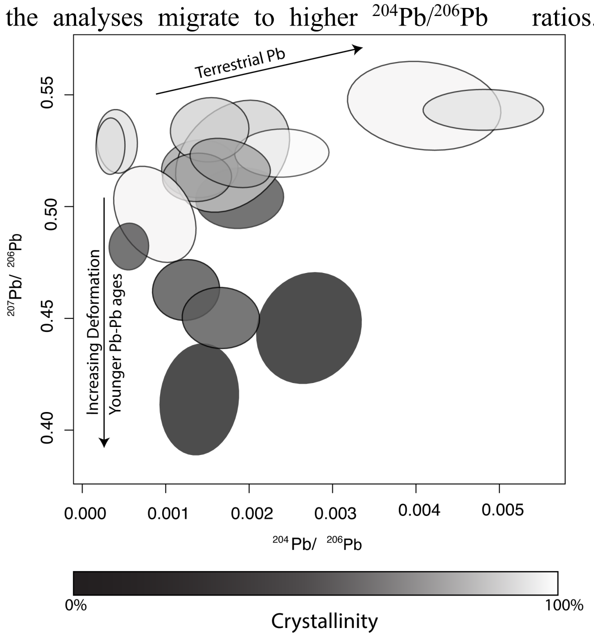

Figure 1: $^{207}Pb/^{206}Pb$ vs. $^{204}Pb/^{206}Pb$ diagram of the spot analyses of the two apatites in NWA 3163. Terrestrial Pb contamination is observed in some analyses increasing the $^{204}Pb/^{206}Pb$ ratio. The color of each error ellipsoid is associated with the percent of the spot analysis, which displayed cataclastic deformation. The regions with a lower percent of crystal integrity or higher percent of cataclastic deformation have lower $^{207}Pb/^{206}Pb$ ratios.

Discussion: Using EBSD microstructural characterization as a guide for in situ SIMS analysis can be powerful in deciphering between the magmatic ages of the apatites and secondary processes such as impact or metasomatism. The results suggest that cataclastic deformation leads to disturbance of the Pb-Pb ages. The regions with the lowest band contrast have ages around 3960 Ma potentially indicating a younger impact event. Despite the highly shocked nature of this meteorite, the regions that are plastically deformed do not show a significant isotopic variation, preserving the 4319 ± 14 Ma protolith Pb isotope ratios.

These results have two important implications. One, the agreement of the Pb-Pb ages of the two apatites with the Pb-Pb ages of baddeleyites support that the apatites are original to the FAN protolith. Two, the preservation of the formation age in the plastically deformed portions of the grains may indicate that these regions also preserved the original $\delta^{37}Cl$, a hypothesis that will be tested with $\delta^{37}Cl$ measurements via SIMS. These results are significant as no apatites have yet been found from ferroan anorthosite samples returned from the Apollo missions making these apatites critical to understanding the volatile budget and characterizing the magmatic sources of FAN suite.

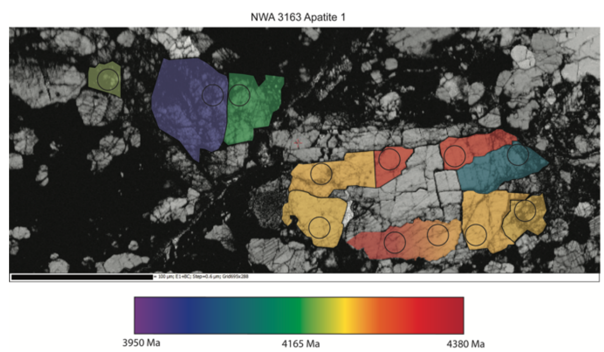

Figure 2: Variations in the apparent Pb-Pb ages of Apatite 1 are overlayed on top of an EBSD band contrast map from Wilson (2020). Dark regions in the EBSD band contrast represent regions that have a high degree of lattice disruption. Boundaries of the contiguous regions observed in SEM are outlined.

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References::

[1] Leshin L. A. (2000) *Geophysical Research Letters, 27, 14* 2017–2020. [2] Boyce J. W. et al. (2020) *Nature 466.7305,* 466-469. [3] McCubbin F. M. and Nekvasil H. (2008) *American Min. 51.11,* 676-684. [4] Economos R. et al. (2017) *Geochemica et Cosmochimica Acta 215,* 387-403. [5] Webster J. G. and Piccoli P. M. (2015) *Elements 11.3,* 177-182. [6] White L. F. et al. (2019) *Geosci. Frontiers 10.5,* 1841-1848. [7] Wilson B. JK. (2020) *M.S. Thesis, University of Toronto,* 1-41. [8] McLeod C.L. et al. (2016) *Geochemica et Cosmochimica Acta 187,* 350-374. [9] Stöffler D. et al. (2018) *Meteoritics & Planet. Sci. 53.1,* 5-49.