Sector-zoned pyroxenes in young lunar mare basalt, Northwest Africa (NWA) 8632: Insights into crystallization kinetics during late-stage volcanism on the Moon

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Introduction: Lunar volcanism peaked between 3.6-3.8 Ga but extended to ~1.0 Ga [1]. This extension of volcanic activity contradicts the Moon's size and consequence on planetary cooling that should have influenced the Moon to cease being geologically active early on in its history [2]. The conditions of late, lunar volcanism are still misunderstood and the availability of samples that represent a late (< 3.1 Ga) volcanic period [1] are limited to meteorites [3] and the Chang'e-5 basalts [4]. In the past, zonation patterns in major and minor elements have been used to understand the interaction between minerals and the surrounding melt [5,6]. NWA 8632 is an unbrecciated, lunar basaltic meteorite with a $^{40}Ar/^{39}Ar$ age of 2.877 Ga [7], thus, is a critical sample of post-peak lunar volcanism. In this study, we report sector-zoned pyroxenes within NWA 8632, a unique zoning pattern observed on Earth but rarely observed in lunar samples and use qualitative analyses to constrain the crystallization kinetics and magmatic dynamics of this mare basaltic sample.

Methods: Qualitative Kα X-ray element maps were collected using the JEOL 8200 electron microprobe at Rutgers University (RU) with operating conditions of 15kV accelerating voltage, 500nA beam current, 1µm step size, and a dwell time of 500-1000ms. Maps were processed using the ImageJ software.

Results: NWA 8632 has a porphyritic texture of olivine and pyroxene phenocrysts set in a fine-grained groundmass (GM) of olivine, pyroxene, and Fe-Ti-Cr oxides [7]. Sector-zoning occurs in euhedral phenocrystic pyroxene ranging from 285 to 665µm in length. "Hourglass-sectors" (Fig. 1a) are defined by depletion of Ti (Fig. 1b.-c.), Al, V, and Cr, and enrichment in Mn. These pyroxenes are observed as individual grains within the GM.

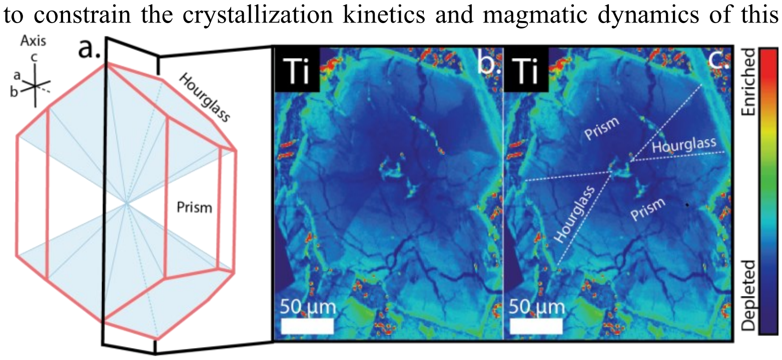

Fig. 1: a.) Graphic of sector-zoned pyroxene with hourglass (light blue), prism (white) sectors, and cutting plane (black) (adapted from [5]). b.) Ti-map of a sector-zoned pyroxene in NWA 8632 cut along the c-axis exposing depleted hourglass (c., white-dash) and slightly enriched prism sectors. This pyroxene also shows slight oscillatory zoning within prisms close to the enriched, quenched rims.

Discussion: Early studies proposed that sector-zoned pyroxenes crystallized under supercooled conditions but more recent work [5,8] found that sector-zoning can occur from low-degrees of undercooling at near-equilibrium conditions and slow cooling rates, fostering an environment for pyroxenes to grow to phenocrystic sizes with hourglass and prism sectors (Fig. 1b.,c.). Examples of such environments are slow, stagnant ascent or magma reservoir margins. NWA 8632 sector-zoned pyroxenes co-crystallized with olivine phenocrysts [7] that show oscillatory phosphorus (P) zoning in the core to mantle-rim regions, indication of a rapid change in temperature (T) that trapped immobile P during the same period of crystallization of sector-zoned pyroxenes. In addition, some sector-zoned pyroxenes display oscillatory zoning of Cr and Ti bands in the sectors and/or throughout the core-mantle and mantle-rim regions of the grain that could indicate magma chamber convection [6] or an eruption triggering event such as magma recharge [5]. Oscillatory zoning of major elements, however, is not observed, suggesting slower crystallization at more constant temperatures to allow major element diffusion. This suggests that an eruption triggering event is an unlikely source for the observed zoning pattern. Instead, the sector-zoned pyroxenes may have formed from a melt that experienced slow ascent at near-equilibrium conditions into a convecting magma chamber, before erupting to the lunar surface.

Conclusion: Sector-zoned pyroxenes provide a foundation for outlining the crystallization conditions of igneous samples. Combined with further analyses, these observations can be used to place constraints on the unique conditions of extended lunar volcanism. Future work includes obtaining quantitative compositions and isotopic analyses of the sector zones in order to fully understand the dynamics of the late-stage volcanism recorded by NWA 8632.

References: [1] Hiesinger et al. (2000) *JGR* 105, 29239-29275. [2] Joliff et al. (2006) *Rev. Mineral. Geochem.* 60. [3] Meteoritical Bulletin Database (as of 2023). [4] Li et al. (2021) *Nature* 600, 54-58. [5] Ubide et al. (2019) *GCA* 251, 265-283. [6] Elardo and Shearer (2014) *Am.Min.* 99, 355-3. [7] Fagan et al. (2018) *49th LPSC*, #2584. [8] Schwandt and Mckay (2006) *Am.Min.* 91, 1607–1615.