DISLOCATION-RICH OLIVINE IN APOLLO 12 OLIVINE BASALTS HAVE IMPLICATIONS FOR THEIR THERMAL HISTORIES AND FOR OUR UNDERSTANDING OF WATER AND VOLATILES IN THE MOON. J. P. Greenwood and T. F. Davoren, Dept. of Earth and Environmental Sciences, Wesleyan University, Middletown, CT 06459 USA (jgreenwood@wesleyan.edu; tdavoren@wesleyan.edu).

Introduction: The Apollo 12 olivine basalt collection is one of the most important records of magmatic activity from another planetary body. The consanguineous suite of samples are believed to represent one magma body, due to similarities in major and trace element chemistry. [1,2]. Due to their high normative olivine, it was recognized early on that these magmas must have been transporting/carrying more olivine than could have crystallized from a magma of their composition [3]. The seminal studies of Walker and colleagues on the experimental crystallization of Apollo 12 olivine basalts led to the recognition that their textures (from glassy vitrophyres to olivine cumulates) were due to differences in the cooling history of the Apollo 12 olivine basalt body [4,5]. They also determined thermal histories from assumptions of how the magmas stoped olivine during their crystallization [5]. In this century, the recognition of the importance of volatiles in lunar magmas has led to the use of olivine-hosted melt inclusions to determine water and volatile abundances of the entire Moon [6-9].

Central to the use of olivine-hosted melt inclusions as probes of the volatile contents of lunar magmas is the assumption that the olivine grains have: 1) crystallized from the magma being studied and 2) remained closed-systems since entrapment of the melt inclusions. Here we show that both of these assumptions are likely invalid for prior studies of volatiles in Apollo 12 olivine basalts [7-9]. Furthermore, our results call into question conclusions on the thermal history of Apollo 12 olivine basalts [5].

Methods: Optical and electron microscopy were used to study 20 sections of 17 different Apollo 12 olivine basalts. Critical results were obtained using EPMA and high-resolution X-ray mapping with 5 WDS detectors on the field emission Yale 'Hyperprobe'.

Results: In the Apollo 12 olivine basalt suite, three samples are vitrophyres (12008, 12009, and 12015), and the remainder (14 samples) are more slowly cooled olivine-rich basalts. In the 14 slowly-cooled basalts, we find symplectic chromite-ulvöspinel-pyroxene (CUSP) inclusions in cores of Mg-rich olivines (in samples where Fe-Mg are not completely equilibrated) [10,11]. We did not find CUSP inclusions in the three vitrophyres. Instead, we find that Mg-rich cores of large olivine grains are rich in dislocations (Fig. 1).

12008. Dislocations appear in Cr and Ti Kα X-ray mapping of olivine grains (Fig. 1). The dislocations show no surface features using secondary electron imaging. In our previous studies of CUSP inclusions in slowly cooled Apollo 12 olivine basalts, we have observed depletion zones of Cr, Al, Ti, and Ca in the vicinity of CUSP inclusions, suggesting that ingredients for symplectite formation are sourced locally, from the olivine grain the symplectites are forming in during subsolidus cooling [10,11]. Here, the dislocations appear to be acting as fast-diffusion pathways for Cr and Ti. A large pre-existing fracture shows Cr-enrichment, as well as a small (<5 µm) Cr-depletion zone on both sides of the fracture (Fig. 1). Chromite grains are observed at olivine-melt inclusion boundaries.

12009. We mapped three olivine grains in 12009. One had no dislocations, and the other two had few to moderate amounts of dislocations (grain with highest abundance shown in Fig. 1). A strong Cr-depletion zone can be seen on two sides of the large melt inclusion, likely due to the higher density of chromite grains seen on those same two sides of the olivine-melt inclusion boundary. We note that CUSP inclusions in more slowly-cooled Apollo 12 olivine basalts commonly had linear element depletion zones, appearing to highlight the importance of lattice planes for chemical diffusion in olivine [11]. Dislocations appear to have small Cr depletion zones associated with them in this sample.

12015. Dislocations in the olivine grain mapped in this sample are less abundant than in olivine grains from 12008 or 12009. The Cr-dressed dislocations appear more similar to what is seen in 12008, but with a lower density. Only a few chromite grains are seen at the olivine-melt inclusion boundary, but a general enrichment of Cr around the entire melt inclusion is seen. Cr depletion zones are not observed around this melt inclusion or near Cr-rich dislocations.

Discussion:

Origin of dislocations in Apollo 12 olivine basalts. Dislocations are extrinsic defects that require mechanical deformation of olivine grains. Magmas are not believed to support mechanical deformation, as the magma should flow. Dislocation-rich olivine grains have been rarely reported in terrestrial magmas, but they provide important context for our observations. They have been found in olivine picrites from Hawaii, and an origin as xenocrystic wall-rock olivine from the magma conduit or chamber, assimilated during magma transport was favored [12]. Dislocation-rich olivine grains were also found during drilling of mid-ocean ridge gabbros, wherein it was argued that the dislocation-rich olivines were deformed due to the forces of magma injection and then later assimilated [13].

For the Apollo 12 olivine basalts, either assimilation of wall-rock/conduit olivine from previous generations of the Apollo 12 olivine basalt magma, or deformation during the sheeting and diking intrusive magmatic events that likely preceded extrusion of the Apollo 12 olivine basalts, could explain the origin of Mg-, and dislocation-rich, olivine grain cores that we find in the three vitrophyres 12008, 12009, and 12015.

Implications for the thermal history of Apollo 12 olivine basalts. The Apollo 12 olivine basalts have long been recognized to have an excess of olivine. Previous studies favored crystal-settling [5], but here we propose that the high normative olivine in these basalts likely results from the assimilation of wallrock/conduit olivine, and that the Mg- and dislocation-rich olivine cores we find in 12008, 12009, and 12015 are representative of this assimilated, excess olivine.

Implications for water and volatiles in Apollo 12 olivine basalts and the lunar interior. Several studies have measured volatile elements in olivine-hosted melt inclusions from Mg-rich olivine grains in Apollo 12 vitrophyres and used these results to determine volatile contents of the lunar interior [7-9]. We postulate that these studies have likely analyzed melt inclusions in olivine xenocrysts, and their melt inclusions may not be appropriate for these purposes, as they violate the two principles for pristine olivine-hosted melt inclusions noted above.

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References: [1] Green D. H. et al. (1971) *EPSL* 13, 85-96. [2] Grove T. L. et al. (1973) *Proc. 4Th Lunar Sci. Conf.* 995-1011. [3] Kushiro I. and Haramura H. (1971) *Science* 171, 1235-1237. [4] Walker D. et al. (1976) *GSA Bull.* 87, 646-656. [5] Walker D. et al. (1976) *Proc. 7th Lunar Sci. Conf.* 1365-1389. [6] Hauri E. H. et al. (2011) *Science* 333 213-215. [7] Singer J. A. et al (2017) *Geochem. J.* 51, 95-104. [8] Chen Y. et al. (2015) *EPSL* 427, 37-46. [9] Ni P. et al. (2019) *GCA* 249, 17-41. [10] Davoren T. F. and Greenwood J. P. (2022) *LPSC LIII* abst#2057. [11] Davoren T. F. (2022) MSc. Wesleyan University. [12] Takahashi E. (2016) Fall AGU abst#V11B-2785. [13] Kennedy L. A. et al. (1996) Proc. ODP Sci. 147, 357-370.

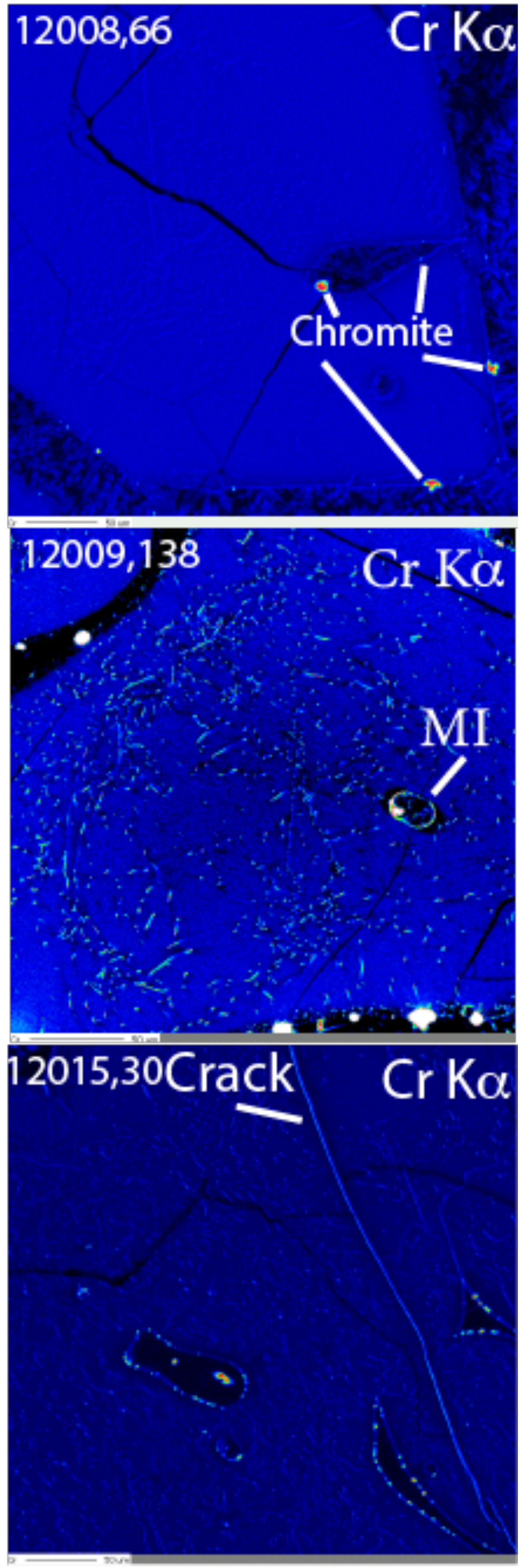

Figure 1. Cr Kα maps of 12008,66 (top), 12009,138 (middle), and 12015,30 (bottom). Olivine dominates the images. Dislocations are brighter and curvi-linear.