Chromite-Ulvöspinel-Pyroxene (CUSP) Inclusions in Apollo 12 Olivine Basalts. Thomas F. Davoren and James P. Greenwood, Earth and Environmental Sciences Dept., Wesleyan University, Middletown, CT 06459, USA (tdavoren@wesleyan.edu)

Introduction: The Apollo 12 olivine basalts are the only extraterrestrial suite of chemically related rocks in our collections and are believed to have formed in a large flow or sill [1, 2]. Experiments by *Walker et al. 1976* [2] were among the first dynamic crystallization experiments undertaken and were able to reproduce many of the chemical and textural features of the Apollo 12 olivine basalts, which vary in texture from vitrophyres to cumulates. Here we report on small (~1-10 µm in diameter) symplectic inclusions in Mg-rich regions of olivine grains in the Apollo 12 basalts. These Chromite-Ulvöspinel-Pyroxene (CUSP) inclusions were found in all but four of the olivine basalts from Apollo 12 and were first reported in some samples by [3].

To investigate if CUSP inclusions can be formed during cooling of the Apollo 12 olivine basalts, we obtained the original experimental charges of [3] (*D. Walker, pers. comm.*) and studied these samples for the presence and character of CUSP inclusions.

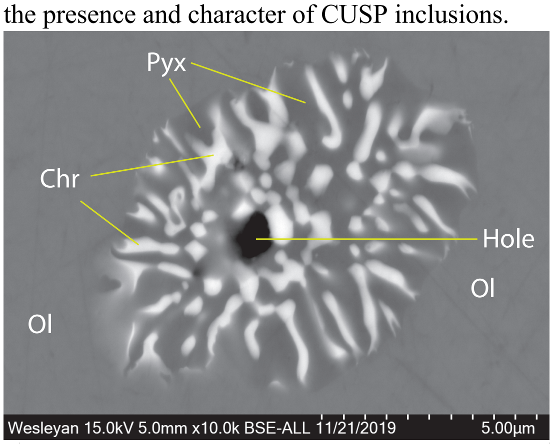


***Figure 1**: A CUSP inclusion in olivine grain P from sample 12018,76.*

Methods: A petrographic microscope is used to identify CUSP inclusions in olivine grains from thin sections of the olivine basalts. We then used Wesleyan University's Hitachi SU5000 FE-Scanning Electron Microscope (SEM) to verify existence of the different phases that make up the symplectite in the host olivine grain. Next, we use Yale University's JEOL JXA-8530F Electron Microprobe to create wave-dispersal-spectrometry (WDS) trace elemental maps of regions in olivine grains rich in CUSP inclusions. Size and density of CUSP inclusions from 3 grains in samples from [1] were calculated using Adobe Illustrator for comparison to results obtained on Apollo 12 olivine basalts. With Electron Microprobe X-Ray mapping of regions rich in CUSP inclusions, we obtain elemental maps that inform us about the paths various elements took through the host olivine lattice to nucleate and grow the symplectic CUSP inclusions. Kα WDS elemental maps of olivine grains reveal igneous zoning in olivine of Cr, Ti, Al, and P.

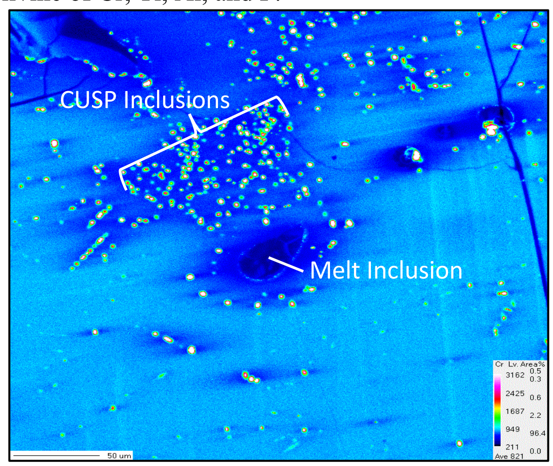
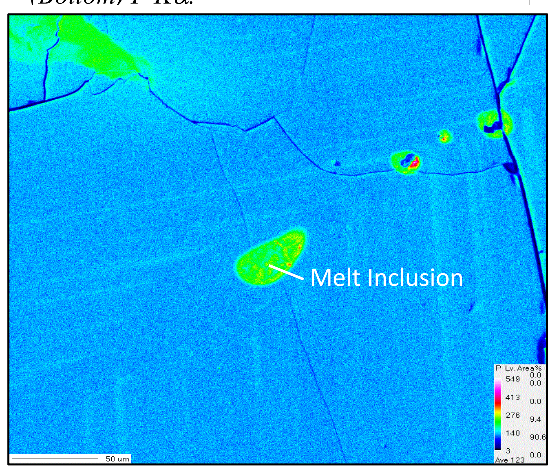


***Figure 2**: FE-EPMA WDS X-Ray mapping of grain B in sample 12004,55. (Top) Cr Kα. (Bottom) P Kα.*



Results: *CUSP Petrography in Olivine Basalts*: All CUSP inclusions were hosted in Mg-rich regions of olivine grains. CUSP inclusions are vermicular and composed of curving rods of chromite-ulvöspinel in a matrix of pyroxene (*Fig. 1*) [2]. With optical analysis, CUSP inclusions were found in 14 of the 18 Apollo 12 olivine basalts. Three samples that were void of symplectites were all olivine vitrophyres, and the one other sample,12006, was originally classified as a subophitic feldspathic basalt [4].

Most CUSP inclusions are between 2-5 μm in diameter, however larger symplectites occur in olivine grains from sample 12018 that are around 8-10 μm in diameter. Generally, these CUSP inclusions tend to get larger with slower cooling, however, sample 12018 is anomalous with its enormous CUSP inclusions at a relatively medium cooling depth (1.8 m above base). Larger CUSP inclusions tend to occur in areas with fewer symplectites, and conversely, smaller CUSPS occur in densely populated “hotspot” regions. Again, sample 12018 is unusual and has exceptionally few CUSP inclusions, hinting at the potential that clusters of smaller symplectites in olivine grains combining to form larger CUSP inclusions in less densely-populated regions.

Results: *CUSP Petrography in Walker et al.1976 Experiments:* This paper was one of the first studies to undertake dynamic crystallization experiments on lunar materials. Using laboratory-melted lunar basalt 12002 as starting material, the charges were heated to 1250°C in Fe capsules, cooled at various rates, and then quenched at various temperatures to create the textural range seen in the Apollo 12 olivine basalt suite. The systematic SEM analysis of olivine grains from these charges allowed for the identification of symplectic CUSP inclusions, indistinguishable from those found in lunar basalts.

Results: *Yale FE-WDS Mapping:* As seen in *Fig. 2 (top)*, CUSP inclusions are enriched in Cr from the center, outwards. The same trend is true in symplectites for Al, and Ti. Directly surrounding the symplectites, however, there is a halo of trace element depletion, ranging from circular to more oblong and stretched. *Fig. 2(top)* also shows two series of evenly spaced streaks of Cr element enrichment stretching across the Mg-rich regions of the grain, forming a point. This zoning is an igneous crystallization pattern comparable to the bands in the P Kα map (*Fig. 2 [bottom]*). P is not enriched or depleted within or around CUSP inclusions.

Discussion: Due to our hypothesized slow cooling requirement for the origin of these inclusions, those samples that were void of CUSP inclusions seem to cool too quickly to develop these features. This variation in cooling time is consistent with Walker ideas from *Walker et al., 1976*, allowing samples deeper in the magma body to cool slower than those on the “chill margin”. By getting access to the laboratory materials and the collection of the original experimental charges of [3], we determined that CUSP inclusions identical to lunar basalt symplectites in the experimental charges were able to form under slow cooling and/or with low quench temperatures. By cross-referencing the sample number with data from laboratory notebook of Dr. David Walker, we were able to determine that symplectites were created under controlled slow cooling (ln[-0.75 – 3.42] °C/hour) and/or low quench temperatures (1035-610 °C). *Fig. 3* displays both which experimental charges had olivine grains host to symplectites and the zone of cooling rate and quench T in which CUSP inclusions would likely be found.

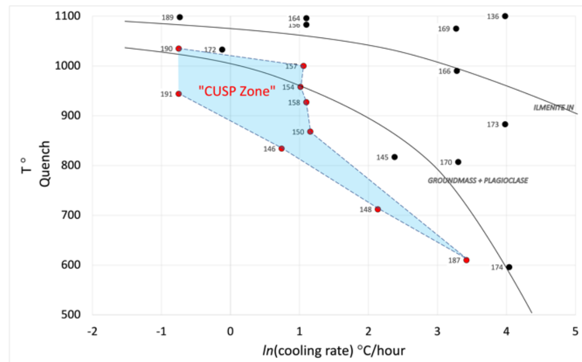


***Figure 3**: A recreation of a section of the experimental cooling figure from Walker et al., 1975 showing our hypothesized “CUSP Zone” (blue) that CUSP inclusions are expected to be hosted in. Samples in red contain CUSP inclusions, while black samples were not observed with any symplectites.*

Summary and Future Work: The CUSP inclusions found in lunar basalts seem to be indistinguishable from those formed under controlled cooling and quenching in *Walker et al., 1976*. As a rock undergoes slower cooling, the size of its CUSP inclusions seems to increase with a paired decrease in symplectite density. 12018, though, breaks this trend, for it has extremely large CUSP inclusions relative to its cooling rate. While slow cooling aids in the growth of CUSP inclusions, the genesis of these symplectites cannot rely on any external force such as water loss/gain, a change in fO_2, or a change in pressure since CUSP inclusions can be formed at 1 atm and reducing conditions. With more WDS maps being made using Yale University’s Electron Microprobe soon, we can compare abundances of trace elements in CUSP inclusion-rich regions in olivine grains from a range of cooling rates and proposed depths in the Apollo 12 basalt magma suite.

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References: [1] Walker. D. et al. (1976). Proc. Lunar Planet. Sci. Conf. 7, 1365–1389. [2] Walker. D. et al. (1976) Geological Society of America Bulletin v. 87, p. 646-656. [3] Roedder, E. and Weiblen P. W. (1970). Proc. 2nd Lunar Sci. Conf. 507. [4] Meyer, C. (2010). The Lunar Sample Compendium. LPSC 41, 1016.