THE ORIGIN OF CHROMITE SYMPLECTITES IN LUNAR TROCTOLITE 76535: A NEW LOOK AT AN OLD ROCK

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Introduction: Despite the highly Cr-depleted nature of its cumulus olivine (~140 ppm Cr_2O_3) relative to mare basalt olivine, pristine lunar troctolite 76535 contains significant Cr sporadically, but highly concentrated, in symplectite assemblages consisting of Mg-Al-chromite and two pyroxenes [1-4]. These symplectites occur primarily at olivine-plagioclase grain boundaries (e.g. Fig. 1a), but importantly, most grain boundaries are symplectite-free. The origin of symplectites in lunar rocks such as 76535 was a highly contentious topic in the mid-1970's [3]. Previously proposed symplectite formation mechanisms include crystallization of trapped interstitial melt and an olivine-plagioclase reaction including diffusion of Cr from cumulus olivine and/or remobilization of pre-existing cumulus chromite grains [1-5]; however the topic never saw a substantial resolution. The low Cr content of the cumulus olivine implies that Mg-suite magmas, and by inference their source material, were also low in Cr [6]. However, these symplectite formation mechanisms would imply that this Cr-depletion may be illusory.

With the goals of constraining the origin of the symplectites and the degree of Cr-depletion in Mg-suite magmas, we present a detailed petrologic and textural investigation of symplectites, as well as their relationships to intercumulus and primary cumulus phases. We have also investigated chromite veins (Fig. 1b), olivine-hosted melt inclusions (Fig. 1c) and intercumulus assemblages (Fig. 1d) in 76535 to determine what information they record in regards to the origin of the symplectites and the nature of the parental magma.

Analysis: Sample 76535 has experienced minimal shock and retains original, albeit metamorphic, textures and well-preserved symplectites. Several thin sections were analyzed in this study: 76535,46 ,56 and ,159. Prior to microbeam analyses, samples were documented via optical and electron microscopy to fully understand textural relationships and identify potential targets for subsequent analysis. Olivine, orthopyroxene (OPX), clinopyroxene (CPX), chromite, apatite and merrillite were analyzed for major and minor elements using the electron microprobe (EMP) at the University of New Mexico.

Results: Symplectites occur mostly along olivine-plagioclase grain boundaries, but most boundaries are free of symplectites. Figure 1a shows a typical symplectite at such a boundary. Symplectites are sometimes associated with discontinuous chromite veining along grain boundaries. Figure 1b shows a chromite vein with a small symplectite. Chromite veins along olivine-plagioclase boundaries often occur within a few tens of microns of chromite-free olivine-plagioclase boundaries. Chromite is not observed as discrete crystals or as inclusions in cumulus phases.

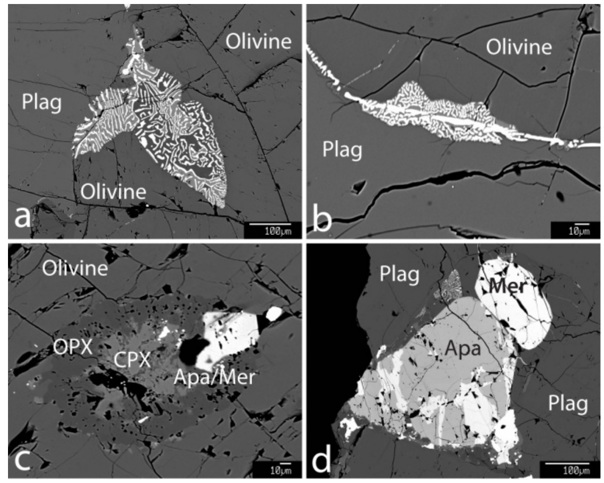

Figure 1: BSE images of a typical symplectite (a), an example of chromite veining with a small symplectite (b), an olivine-hosted melt inclusion (c), and an intercumulus assemblage (d) that contains a small symplectite.

Polycrystalline intercumulus assemblages also contain small symplectites (Fig. 1d); however olivine-hosted melt inclusions (MI) do not contain chromite. Both the MIs and intercumulus assemblages contain apatite-merrillite intergrowths. Apatite between the two textural occurrences is identical in terms of halogens. Other phases present in intercumulus assemblages include OPX, CPX, baddeleyite, zircon and Fe-Ni metal. Other phase in MIs include OPX, CPX, Fe-Ni metal, a K-Ba-Si-rich phase, and pyrochlore.

Olivine cores in 76535 uniformly contain ~140 ppm Cr_2O_3; however Figure 2 shows an EMP traverse from a symplectite-olivine contact into the olivine grain. At the contact, the olivine contains ~2800 ppm Cr_2O_3 and decreases in Cr_2O_3 with distance from the contact. A similar EMP traverse from a plagioclase contact into the same olivine grain shows no gradient.

Olivine-hosted melt inclusions are also low in Cr. Whereas OPX and CPX in symplectites contain an average of 7400 and 8100 ppm Cr_2O_3, respectively, OPX and CPX in the melt inclusions contain an average of 900 and 1200 ppm Cr_2O_3, respectively. Sample 76535 also contains large interstitial OPX grains that are similar in composition, including Cr_2O_3, to symplectite OPX.

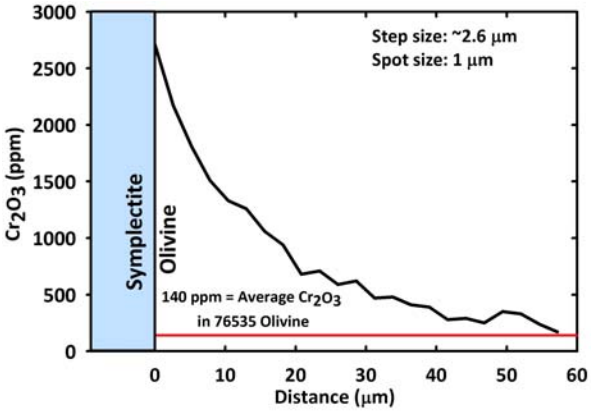

Figure 2: An EMP traverse away from a symplectite-olivine contact showing a gradient of Cr in the olivine. A similar traverse into a different area of the same olivine grain shows no gradient where it contacts plagioclase.

Discussion: In light of our detailed study of symplectites, MIs and intercumulus assemblages in 76535, we have reassessed previously proposed symplectite formation mechanisms. The crystallization of trapped intercumulus melt pockets was favored by [2, 5]. This mechanism would require significant adcumulus growth of plagioclase and olivine for a melt pocket to produce the large amount of chromite observed in symplectites. However, the symplectites exhibit textures more consistent with consumption of olivine and plagioclase in a mineral-mineral reaction [i.e. 7], with some symplectites preserving relic grain boundaries. Additionally, symplectites do not contain other minor phases (e.g. apatite, baddeleyite) that are indicative of intercumulus assemblages, which do seem to represent trapped melt pockets [e.g. 1-2, 4]. Based on these observations, we rule out crystallization of trapped melt.

Symplectite formation via a reaction between olivine and plagioclase [i.e. 7] that included diffusion of Cr from olivine or the remobilization of pre-existing chromite was preferred by [3-4] and [1], respectively. In the diffusion model, Cr in symplectite chromite is derived from originally more Cr-rich cumulus olivine. However, the Cr-gradient in Fig. 2 argues against this. Because olivine in contact with plagioclase displays no gradient, we interpret the gradient in Fig. 2 as a diffusion profile of Cr into olivine, not out of it. All olivine rims should show a gradient if diffusional loss was occurring. Additionally, olivine not in contact with symplectites is also low in Cr. This implies that the olivine was originally low in Cr, which is supported by the low Cr content of the MIs. Furthermore, reduced systems such as lunar magmas have Cr^{2+}/Cr^{3+} ratios near or greater than 1 [8-9]. Since olivine partitions the two valence states roughly equally [9], this would create the need for a Cr^{2+} oxidation mechanism to create the large amounts of Cr^{3+}-rich chromite. This, combined with the observation that olivine in chromite-saturated melts at low f_{O2} contain 1000's of ppm Cr_2O_3 [8-9], rules out diffusion of Cr from olivine.

The remobilization of pre-existing chromite is similarly argued against by the high-Cr content of olivine in equilibrium with chromite-saturated melts, low Cr-content of MIs, and the diffusion profile in Fig. 2. If primary chromite was present at grain boundaries, we would expect no diffusion profile, since equilibrium should be maintained during slow cooling and decreasing temperature favors lower Cr contents in the olivine [8, 9]. Furthermore, if the parental melt was saturated in chromite, the olivine should be much richer in Cr, and diffusional loss of that Cr is argued against above.

Failure of these symplectite formation mechanisms implies that open system addition of Cr to 76535 is required. We have evaluated three potential models for Cr addition: solid state addition of chromite, Cl-rich fluid metasomatism [i.e. 4], and metasomatism by a melt. Solid state addition may come in the form of differential settling of dense chromite from higher regions of the 76535 pluton. However, there are no chromite–rich samples of the Mg-suite that may represent such a region, and the mechanism by which chromite settles through a partially molten intrusion and stalls in the troctolite layer is unclear. A Cl-rich fluid has the potential to mobilize the typically immobile Cr^{3+} [e.g. 10]; however, such a fluid should also have re-equilibrated intercumulus apatite to more Cl-rich compositions than MI apatite. This is not the case and seems to rule out an exogenous Cl-rich fluid.

Chromite is, however, a near liquidus phase in many lunar basalts. Metasomatism of the 76535 pluton by a chromite-saturated melt provides a mechanism for adding Cr to the rock along cracks and grain boundaries (i.e. melt pathways), while preserving the halogen content of intercumulus apatite. Chromite would be deposited locally, resulting in the symplectite forming olivine-plagioclase reaction and local diffusion of Cr into olivine. Most olivine is unaffected, and retains its originally low Cr content, along with the shielded MIs. Although speculative, melt metasomatism appears to be the model with the fewest caveats. If correct, it would imply that the Mg-suite parental magmas were extremely low in Cr compared to mare basalts, a condition that would require further explanation [i.e. 6].

References: [1] Gooley et al. (1974) *GCA* ***38***, 1329-1339. [2] Dymek et al. (1975) *LPSC VI*, 301-341. [3] Bell et al. (1975) *LPSC VI*, 231-248. [4] McCallum and Schwartz (2001) *JGR* ***106***, 27,969-27,983. [5] Albee et al. (1975) *LPSC VI*, 1-3. [6] Elardo et al. (2011) *GCA* ***75***, 3024-3045. [7] Kushiro and Yoder (1966) *J. Petrol.* ***7***, 337-362. [8] Roeder and Reynolds (1991) *J. Petrol* ***32***, 909-934. [9] Hanson and Jones (1998) *Am. Min.* ***83,*** 669-684. [10] Klein-BenDavid et al. (2011) *Lithos* ***125***, 122-130