

## MECHANISMS FOR THE DEPLETION OF CHROMIUM IN MG-SUITE PARENTAL MAGMAS

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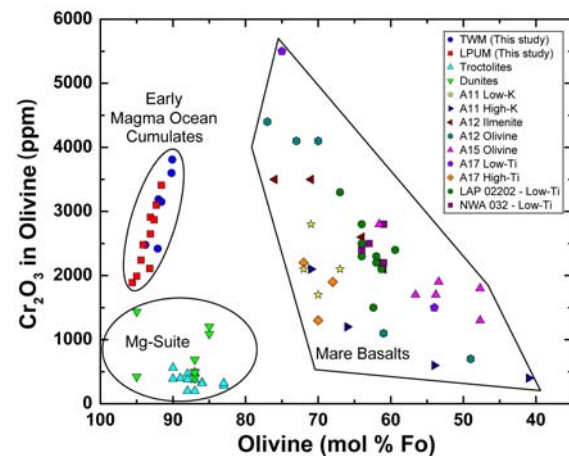
**Introduction:** The various cumulate lithologies of the lunar highlands Mg-suite represent the first period of crustal growth postdating the cessation of lunar magma ocean (LMO) crystallization [1,2]. They have been the topic of extensive study due to their unique chemistry; however, they have experienced extensive impact bombardment and re-equilibration, making identification of their source regions in the context of the LMO hypothesis difficult [1-3]. Although the mare basalts and picrite glasses have long been recognized as partial melts of the lunar mantle, only been more recently have models favoring early, Mg-rich LMO cumulates Mg-suite protoliths become more robust [2-4].

Several aspects of Mg-suite mineral chemistry and bulk composition have made reconstructing their history problematic. Their parental magmas had seemingly primitive major element characteristics, crystallizing olivine with a high Mg\* and Ca-rich plagioclase simultaneously, yet they were also highly enriched in incompatible trace elements (KREEP). Additionally, Mg-suite olivine contains substantially lower abundances of Ni, Co, and Cr relative to their more Fe-rich counterparts in mare basalts, contrary to the more primitive nature of Mg-suite parental magmas [2, 4]. The difficulty in explaining these chemical features stems from LMO crystallization models, which predict that early, Mg-rich LMO cumulates should have abundant Ni and Co and should also be Al- and incompatible element-poor [5].

However, significant progress has been made in understanding the source regions and processes that yielded the enigmatic Mg-suite's parental magmas. Although the precise physical conditions remain poorly constrained pending future work, these magmas could arise from Mg-rich LMO cumulates, transported to the base of the crust via density driven cumulate overturn, that undergo "mixing" with KREEP and crustal anorthosite [2,3]. Nickel and cobalt, typically very compatible in olivine, have recently been shown to be slightly incompatible in highly magnesian olivine [3, 4]. In this way, early crystallizing olivine in the LMO would be depleted in these elements relative to the olivine that formed the mare basalt source region.

A satisfactory explanation for Cr, however, has remained elusive. Elardo et al. [3] showed on the basis of LMO crystallization experiments that current estimates for a range of potential bulk composition of the Moon produce early, magnesian olivine far too rich in Cr to

be reasonable matches for the source(s) of Mg-suite magmas (Fig.1). In this work, we further examine early olivine-dominated LMO cumulates, report the olivine chemistry and Cr distribution in Mg-suite troctolites 76535 and 76335, and explore possible mechanisms that could deplete the Mg-suite parental magmas, or their source regions, in Cr.



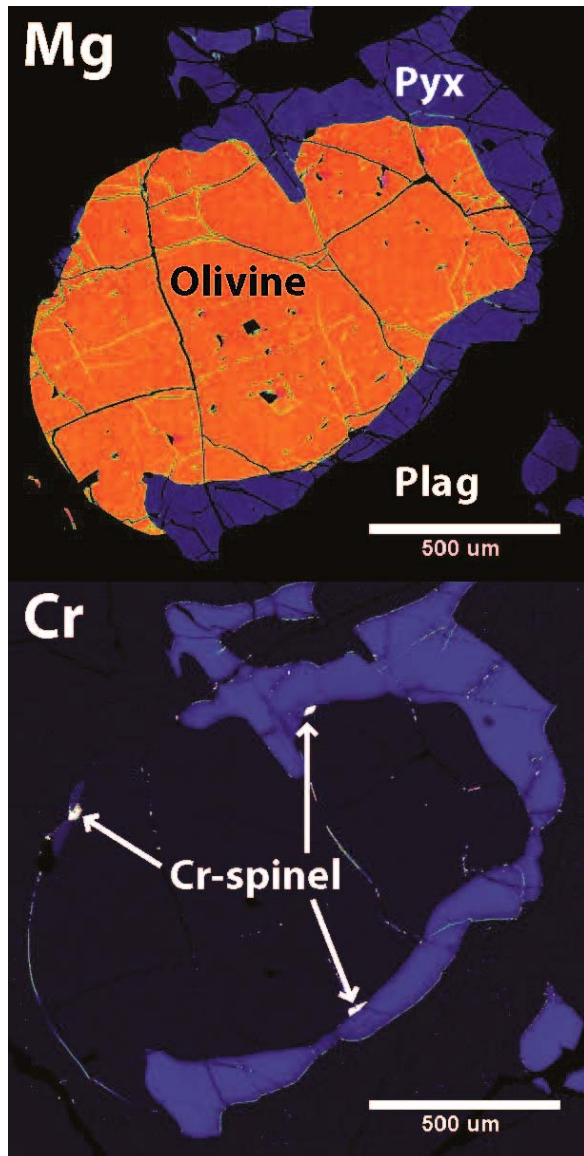
**Figure 1:** Plot of  $\text{Cr}_2\text{O}_3$  in olivine from Mg-suite rocks, mare basalts and experimental LMO cumulates vs. forsterite content. After [3] and references therein.

**Analytical conditions:** Olivine in lunar troctolites 76565, 159 and 76335, 54 was analyzed for major and minor elements using a JEOL JXA 8200 electron microprobe at the University of New Mexico. WDS elemental maps were obtained using the same instrument. Chemical analyses were made using an accelerating voltage of 15 keV and a beam current of 40 nA and WDS maps were made using the same accelerating voltage and beam current of 500 nA.

**Cr in the Mg-suite:** Because the mineral/melt partition coefficient for Cr in olivine is less than 1 (~0.3-0.7, varying with  $D_{\text{Mg}}$ ), it is clear from Fig. 1 that early LMO cumulates are too rich in Cr to produce partial melts capable of crystallizing the olivine in the Mg-suite cumulates. Therefore, additional processes must be invoked to explain the depletion.

**Spinel retention in the source:** Spinel retention in the Mg-suite restite could explain the low concentrations of Cr in their parental magmas much the same way it explains the low Cr concentration in MORBs.

However, for this to be the case, chromite would need to be an important early crystallizing phase in the



**Figure 2: WDS elemental maps of Mg and Cr in an olivine from troctolite 76535, 159.**

LMO. The LMO crystallization experiments of [3] show that this is very likely not the case, as chromite does not appear in the LMO crystallization sequence until almost 50% solid, and only at lower pressure (i.e. 1 GPa) in a refractory element enriched bulk Moon composition [5]. Invoking spinel retention in the source raises more questions than it answers.

*Early spinel crystallization:* Early crystallization of chromite from Mg-suite magmas at the low pressures of the lower to mid-level lunar crust would deplete the Mg-suite magmas in Cr. Small amounts of chromite may have co-crystallized with olivine in the dunites and troctolites, and this could be responsible for the decreasing Cr content with increasing Fo content of

olivine seen in those rocks. There is some petrographic evidence for this (Fig. 2). However, this relationship is also observed in the mare basalts, resulting in the negative trend in Fig. 1. Also, we interpret the chromite observed in Fig. 2 to be the result of exsolution, probably from pyroxene, but this is still under investigation. Early spinel crystallization seems unlikely as a cause of the Cr depletion.

*Multiple stages of melting:* Multiple stages of melt extraction from the Mg-suite source, in the absence of a Cr-sequestering phase, could lead to melts with low Cr abundances. However, if this were the case, we should observe a range of distinct Mg-suite cumulates from relatively Fe- and Cr-rich to the more Mg-rich, Cr-poor cumulates in the sample collection, representing melts from a source being depleted by multiple melting events. This range has not been observed.

*Core formation:* Although Cr remains lithophile at typical basaltic magmatic conditions, experiments by [6] showed that at low  $fO_2$  (i.e. IW -2.3), high temperatures, and in the presence of C and/or S, Cr exhibits increasingly siderophile behavior. If the Moon did indeed form a small Fe + S and/or C core, then this process could have depleted the LMO, and subsequently early forming olivine, in Cr (at least at the base of the LMO). There is currently no completely conclusive evidence for a lunar Fe core, but it has been suggested based on a number of lines of evidence [7]. Lunar core formation could be a viable mechanism to deplete early olivine cumulates in Cr.

*Overestimation of bulk lunar Cr:* Chromium in the lunar mantle has been constrained from the mare basalts and picrite glasses. However, this method makes the crucial assumption that the mare source region is representative of the entire lunar mantle. Olivine is the dominant phase for much of LMO crystallization, and its fractionation will concentrate Cr in the residual LMO. When the more pyroxene-rich mare basalt source regions formed, the LMO may have been significantly enriched in Cr relative to the starting bulk Moon value. If Cr in the bulk Moon has been overestimated due to this heterogeneity in the lunar mantle, then the low Cr contents of the more primitive Mg-suite source might reflect a lower bulk Moon Cr value.

**References:** [1] Hess (1994) *JGR*, 99, 19,083-19,093 [2] Shearer and Papike (2005) *GCA*, 69, 3445-3461 [3] Elardo et al. (in review) *GCA* [4] Longhi et al. (2010) *GCA*, 74, 784-798 [5] Taylor (1982) *Planetary science: A lunar perspective* [6] Chabot and Agee (2003) *GCA*, 67, 2077-2091 [7] Weiczorek et al. (2006) *New Views of the Moon*, Ch. 3, 221-364