ORIGIN OF THE MAGNESIAN SUITE CUMULATES.

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New melting calculations on various combinations of rock types formed in the lunar magma ocean suggest that the highly magnesian olivine characteristic of the magnesian suite cumulates ultimately derives from the earliest dunite cumulates of the magma ocean. However, the evolution from pure olivine deposited at the base of the magma ocean to olivine-plagioclase cumulates (magnesian suite troctolites) crystallized within the crust is complex. It involves overturn of the magma ocean (MO) cumulate pile, which brings the hottest cumulates to the base of the zone of mafic cumulates where melting and mixing (gravitational and impact) ensue. Low-degree, hybrid melts of a mixture of primary dunite, norite, and late-stage MO liquid have the necessary Ni, Co, Mg’, Al2O3, and REE to crystallize the distinctive lithologies of the magnesian suite.

An ion probe survey of lunar olivine compositions has shown that the most magnesian olivines have the lowest concentrations of Ni and Co [1], whereas the more ferroan primitive olivines in the mare basalt suite have the highest Ni and Co concentrations (Fig. 1). Calculation of olivine composition during crystallization of a deep magma ocean has shown that because of compositional effects on the olivine-liquid partition coefficients for Ni and Co, concentrations of these elements are relatively low at the onset of crystallization and that Ni increases to a maximum, while Co increases monotonically for most of the range of Mg’ [2]. The maximum in Ni concentration is situated on the high Mg’ (MgO/(MgO+FeO), molar) side of the mare basalt compositions These results explain the patterns of Ni and Co abundances in lunar olivines to a first approximation, but leave unexplained just how dunite, low in Ni and Co and buried at the base of the magma ocean, became plagioclase-saturated troctolite, also low in Ni and Co.

The simplest scenario for the magnesian suite is partial melting of primitive material. Segregation of the melt must take place at relatively low pressure (~0.5 GPa) in order to account for the observed troctolites with modal orthopyroxene [3,4]. Because the segregation pressure is relatively low, the olivine that crystallizes first from the segregated melt will be virtually identical to the residual olivine in the source. A 5% melt of the LPUM [4] composition (higher degrees of melting produce higher Ni and Co concentrations) was calculated, yielding 495 ppm Ni and 110 ppm Co in $fo_{90.2}$ olivine — concentrations that are clearly too high for the magnesian suite.

A better explanation may lie in magma ocean chemical evolution and dynamics. A magma ocean crystallizes from the bottom up, depositing a chemically and mineralogically zoned cumulate pile. Olivine-rich planetary compositions first crystallize a dunite layer, followed by a harzburgite layer, then a plagioclase-bearing norite, followed by gabbronorite. Density increases upwards with decreasing Mg’ and temperature throughout the ultramafic dunite and harzburgite layers, which become gravitationally unstable and overturn [5]. There is an abrupt decrease in density at the top of the ultramafic zone where plagioclase first appears. This decrease inhibits overturn of the mafic zone with respect to the ultramafic zone, although the mafic zone may overturn internally because of Mg’ decreasing upwards in silicates. Thus the lowermost norite with intermediate Mg’ is juxtaposed against hottest (1760° C), most magnesian olivine. Melting of the lower norite zone is likely to ensue, but the melt will not take on the character of the magnesian suite cumulates without the addition of a small amount of KREEP [6]. Late-stage MO liquid does not take on the characteristic negative Sm/Eu and Sm/Ti anomalies of KREEP until well after 99% crystallization [7], so mixing and/or assimilation of KREEP does not take place until MO crystallization is essentially complete. The Ni-Co crystallization traces of one hybridized liquid are shown as dashed curves in Fig. 1.

Thermal models of the effects of KREEP layers buried beneath a thick lunar crust predict extensive remelting of existing rock [8,9]. These results imply that a MO would take hundreds of millions of years to crystallize completely beneath a thick, early (anorthositic) insulating crust, especially if late-stage liquids were focused beneath the Procellarum KREEP Terrane (PKT, [10]). Yet some magnesian suite rocks with strong KREEP signatures [11] have crystallization ages probably within 50 and certainly within 100 million years of the formation of the Moon [12]. This suggests that a thick insulating crust was absent, allowing the latest stage liquid to crystallize extensively near to the surface. A floating anorthositic crust should have started to form after plagioclase reached saturation at about 80% crystallization of the MO at a time when thermal effects from enrichment of heat producing elements would be modest and certainly not focused globally. Thus the absence of an anorthositic crust beneath the PKT apparently had little to do with global focusing of residual liquid and formation of KREEP. Rather, the formation of a nearly global anorthositic crust may have been a post-MO feature facilitated by a dearth of residual liquid.

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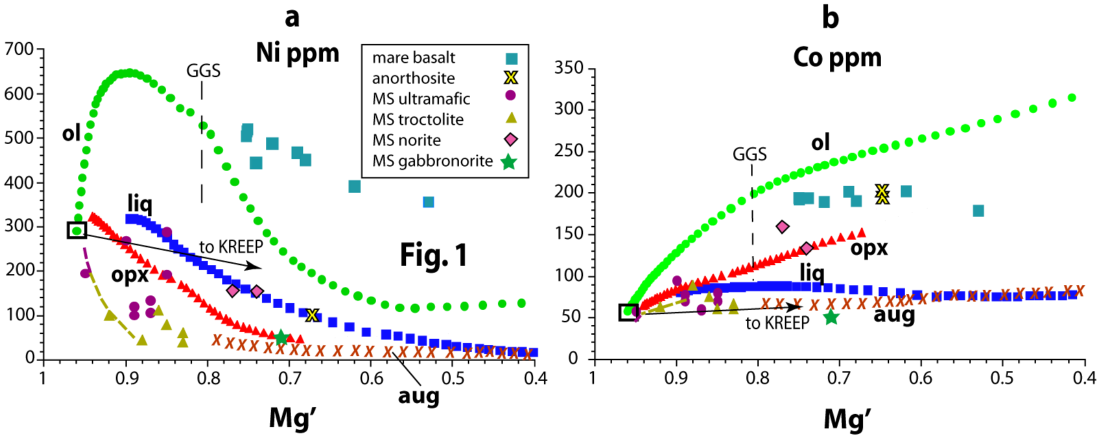

Figure 1. Calculation of Ni and Co variation during fractional crystallization of a magma ocean with LPUM [4] composition. Dashed curves are calculated evolution of hybrid (dunite-norite-KREEP) melt. Natural olivine compositions from [1].