MG-SUITE PLUTONS: IMPLICATIONS FOR MANTLE-DERIVED PRIMITIVE MAGMA SOURCE DEPTHS ON THE MOON. T.C. Prissel[1], S.W. Parman[1], J.W. Head[1], and L. Wilson[2]. [1]Department of Geological Sciences, Brown University, Providence, RI 02912 USA. [2]Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK (Tabb_Prissel@Brown.edu)

Introduction: Evidence for the earliest known volcanism on the Moon which post-dates the Lunar Magma Ocean (LMO) is found within the magnesian-suite (Mg-Suite) of rocks collected/returned during the Apollo era. Comprised of dunites, Mg-Al spinel bearing troctolites, troctolites, norites, and gabbronorites, Mg-suite rocks are most notably characterized by high Mg# (Mg/(Mg + Fe)) mafic silicates positively correlating with the An# (Ca/(Ca + Na)) of coexisting plagioclase [1]. A unique geochemical fingerprint ("primitive" major element chemistry combined with an "evolved" trace element signature) has led to a general consensus regarding the petrogenesis of the Mg-suite: following the differentiation of the LMO and formation of a ferroan anorthositic crust, partial melts from the earliest mafic cumulates are believed to have mixed with a residual KREEP (potassium, rare earth element, and phosphorus) layer on their way to forming plutons within the lunar crust [e.g. 2, 3]. Although this model fares well in explaining both the petrologic features and compositions of the Mg-suite, the question of how lunar magmas reach neutral buoyancy within the anorthositic crust is not a trivial one.

Prior to the recent update of crustal densities from the Gravity Recovery and Interior Laboratory (GRAIL) mission [4], [5] investigated the distribution of basaltic volcanism on the Moon as a function of magma buoyancy. They focused on mare volcanism and compositions, which have an average density of ~ 2945 kg/m^3 (calculated at 1 atm and respective liquidus temperatures). The authors assumed a two-layer model for the lunar crust and computed pre-GRAIL densities for the upper anorthositic and lower noritic crust with a majority of mare basalt densities falling somewhere in between the upper and lower crustal values. The authors then suggest those magmas whose densities lie between the upper and lower crustal densities erupt only when the upper anorthositic crust (density trap) is removed via impact excavation. With some caveats, this model adequately predicted the global distribution of basaltic volcanism on the Moon.

In general however, it is well known that all mantle-derived magmas will be positively buoyant relative to their source material. This initial positive buoyancy can be further driven by the overburden pressures exerted at the source region and may overcome neutral buoyancy encountered by the magma during its ascent [e.g. 6, 7]. What's more, we calculate the densities of recent models of Mg-suite parental liquid compositions [8] to be ~ 2699 kg/m^3, nearly 250 kg/m^3 lower than average mare basalt densities and well below the pre-GRAIL estimates for upper crustal densities (~ 2890 kg/m^3) [9]. Indeed, prior to the GRAIL measurements, such magmas would never have been expected to reach a state of neutral buoyancy within the anorthositic crust, instead erupting under all conditions of buoyancy-driven ascent.

However, no evidence for liquids parental to the Mg-suite has yet been observed on the lunar surface, implying intrusion rather than eruption. How then do low-density primitive magmas such as the liquids parental to the Mg-suite reach neutral buoyancy in the lunar crust? Data from GRAIL place the average bulk density of the lunar crust at considerably lower values (~ 2550 kg/m^3) [9]. Additionally, estimates of the overall average thickness of the lunar crust have decreased to ~ 34 – 43 km (from ~ 50 km). Here, we explore the potential scenarios for ascent and pluton emplacement of mantle-derived primitive melts on the Moon with updated crustal density measurements from GRAIL.

Model & Assumptions: We use the geophysical groundwork laid by [6] for modeling the ascent and emplacement of primitive magmas in the lunar crust. As [9] report an average bulk density of the entire lunar crust, a one-layer crustal model is employed. We assume that the crust-mantle interface is relatively flat with little to no vertical displacement in cross section. Next, we assume that as a mantle source melts, the magma generated forms a vertical column with uniform density, such that isostatic equilibrium between the pressures exerted at the source depth from a regional load equal the pressure of the magma column:

$$\rho_{mg} g z_{mg} = \rho_c g z_c + \rho_m g z_s \quad (1)$$

where $\rho_{mg}, \rho_c, \rho_m$ are the densities of the magma, crust, and mantle respectively, z_{mg}, z_c, z_s, represent the height of the magma column, crustal thickness, and source depth (distance from the crust-mantle interface to region of melting) respectively and g is the acceleration due to gravity. Rearranging (1) we can solve for the expected distance a magma will migrate as a function of its density, the relative densities of its surroundings, thickness of crust and source depth [10]:

$$z_{mg} = \frac{\rho_c z_c + \rho_m z_s}{\rho_{mg}} \quad (2)$$

Densities for a theoretical Mg-suite parental liquid composition [8], Apollo 15C green glass, Apollo 15 yellow glass, and Apollo 15 red glass were calculated at ~ 2699, 2823, 2941, and 3042 kg/m^3, respectively. The mare basalt compositions were used to show the effects of magmatic density on intrusion depth.

Results & Discussion: Table 1 summarizes the results from end member scenarios of a thick vs. thin anorthositic lunar crust. If in fact no liquids parental to the Mg-suite erupted to the lunar surface, results from both cases suggest extremely shallow source regions (no greater than 10 km for a thin crust, and no greater than 20 km for a thick crust), where any appreciably greater source depth should lead to the eruption of the parent liquid.

As previously stated, many models of Mg-suite parent compositions call upon a hybrid mixture of early mafic cumulates and a residual KREEP layer. Results from Table 1 may then constrain the depth of mixing for this process as well as the vertical extent of a potential KREEP layer. It should be noted that the density of KREEP basalt 15386 (~ 2700 kg/m^3) is nearly identical to the density of the theoretical Mg-suite parent composition used in this study. However, crystallization ages for KREEP basalts place them just prior to or contemporaneous with mare basaltic volcanism, distinctly younger than Mg-suite model ages [e.g. 11]. This suggests that the likelihood of magmatic intrusions vs. basaltic eruptions may be a function of time; i.e. the thermal evolution of the lunar crust.

Interestingly, a recent study [12] identified intrusive linear gravity anomalies with low-density contrasts from GRAIL data, suggestive of large lunar dike swarms. If the intrusions are indeed mafic, the authors suggest that a partially crystalline intrusion or a highly ductile or partially molten host rock would be required. If the latter case is true, these intrusions may be comprised of primitive compositions consistent with the Mg-suite. Additionally, a hotter less-dense lunar crust would not only aid in the trapping of primitive magmas, but also be more susceptible to assimilation as the host rock would be at or near its solidus temperature. This process (melt-rock reaction) has recently been identified as a likely mechanism for the petrogenesis of Mg-Al spinel-bearing lithologies on the Moon [e.g. 13, 14]. Moreover, the distinctly high Mg# of spinels in the newly discovered Mg-Al spinel anorthosite [refs] would be consistent with the melt-rock reaction between an Mg-suite parent liquid and hot anorthositic crust.

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	Lunar Crust	Lunar Mantle	
thickness (km)	43	z_s	
density (kg/m^3)	2550	3300	

	Depth below the lunar surface (km)			
z_s (km)	Mg-Suite	A15C GG	A15 YG	A15 RG
0	2.37	4.16	5.72	6.95
1	2.15	3.99	5.59	6.87
5	1.26	3.31	5.11	6.53
10	0.15	2.47	4.50	6.11
20	Erupts	0.78	3.28	5.26
100	to the	Erupts	Erupts	Erupts
400	surface	to surface	to surface	to surface

	Lunar Crust	Lunar Mantle	
thickness (km)	34	z_s	
density (kg/m^3)	2550	3300	

	Depth below the lunar surface (km)			
z_s (km)	Mg-Suite	A15C GG	A15 YG	A15 RG
0	1.88	3.29	4.52	5.50
1	1.65	3.12	4.40	5.41
5	0.76	2.44	3.91	5.07
10	Erupts	1.60	3.30	4.65
20	to	Erupts	2.08	3.80
100	the	to the	Erupts	Erupts
400	surface	surface	to surface	to surface

Table 1. Model results for magmatic intrusion depths below the lunar surface for an Mg-suite parental liquid, Apollo 15 green glass, Apollo 15 yellow glass, and Apollo 15 red glass as a function of source depth below the crust-mantle interface. Left table represents those results from "thicker" GRAIL estimates for the lunar crust with the right table representing results from a "thinner" crustal estimate.