

## LUNAR MAGMA OCEAN CRUST: IMPLICATIONS OF FeO CONTENTS IN PLAGIOCLASE

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**Introduction:** The Moon and its LMO began producing diverse cumulates within a few decades of the origin of the solar system. This differentiation produced the plagioclase cumulates that formed the lunar crust, the oldest portion of which is entirely anorthositic with >90% plagioclase of AN<sub>95-98</sub>. These anorthosites (named ferroan anorthosites FANs) are believed to make up the majority of the highlands and have olivine-pyroxene with Mg# of 75-50. The highlands also contain rocks in the Mg-rich group, mainly norites and troctolites, but also less-Mg-rich rocks such as alkali gabbros. Warren [1] in his seminal explanation of the Lunar Magma Ocean (LMO) suggested that it is unlikely that a series of rocks with modest plagioclase contents, such as the Mg-rich rocks, could have floated in any reasonable density magma (see [1] for an excellent review). Reasonably, FAN anorthosite group is more plausibly a series of flotation cumulates than is the Mg-rich group. It is thought that the Mg-rich rocks probably resulted as intrusions that were emplaced into an older, ferroan anorthosite portion of the crust. The FeO content of the highland rocks ranges from ~3-8 wt%, whereas those of the FAN suite are more restricted at 3-5 wt% FeO. For the sake of this study, let us assume that the FANs were definitely the result of LMO flotation. It is the compositions of the FAN suite rocks that are of particular interest here.

In brief, the FeO and other minor oxide contents of these plagioclases are anomalous, as well-documented by the exceptional studies of Bill Phinney [2-4]. The FeO content has significant implications for the interpretations of near-infrared spectral reflectivity data for the current lunar remote-sensing orbiters, especially the Moon Mineralogy Mapper [5] of Chandrayaan-1 (India), as well as for SELENE (Kaguya, Japan) [12].

### Anomalous FeO & MgO Contents of FAN Plag:

*Compilation of Data for Highland Plag* - A problem with gathering compositional data on plagioclase is the quality of the minor constituents such as FeO, MgO, and REEs [2-4]. However, McGee [6] has compiled such FeO and MgO chemistry for highland feldspars, as shown in Figure 1. It can be seen (Fig. 1) that the FeO and MgO contents of all lunar plagioclases are <1.0 wt%; but the highland plagioclases have these oxide contents <0.2 wt%. Furthermore, a recent compilation of just FAN plagioclases documented that they are mostly <0.1 wt%. These would appear to be particularly low since they supposedly began to crys-

tallize and float, to form the lunar crust, when approximately 75 % of the LMO had already crystallized.

### *Distribution Coefficient of FeO for Plagioclase /Melt:*

Considerable experimentation and examinations of natural terrestrial assemblages have been conducted to estimate the Kd of FeO between plagioclase and the melt from which it is crystallizing [1-3, 7-10]. The results of these studies are summarized in Figure 2, wherein it is apparent that the FeO Kd is ~0.03 for fO<sub>2</sub> conditions at I/W and below (i.e., lunar magmatic region). For example, a melt with 5 wt% FeO would be in equilibrium with plagioclase of 0.15 wt%, essentially what occurs with the lunar highland plagioclase.

### *Discrepancy Between Calculations and Observations:*

The LMO fractional crystallization has been modeled by Snyder et al. [11] using an initial value of 12 wt% FeO. At ~75 % crystallization, with all the previous crystallizing Mg-Fe olivine and pyroxene sinking in the LMO, plagioclase comes on the liquidus. At this point, the FeO composition of the remaining magma is predicted to be ~14 wt% FeO (Mg# ~60). Based upon the FeO Kd of plag/melt (= 0.03), the initial composition of the plagioclase that would be crystallizing and floating should be ~0.42 wt%. However, as shown in

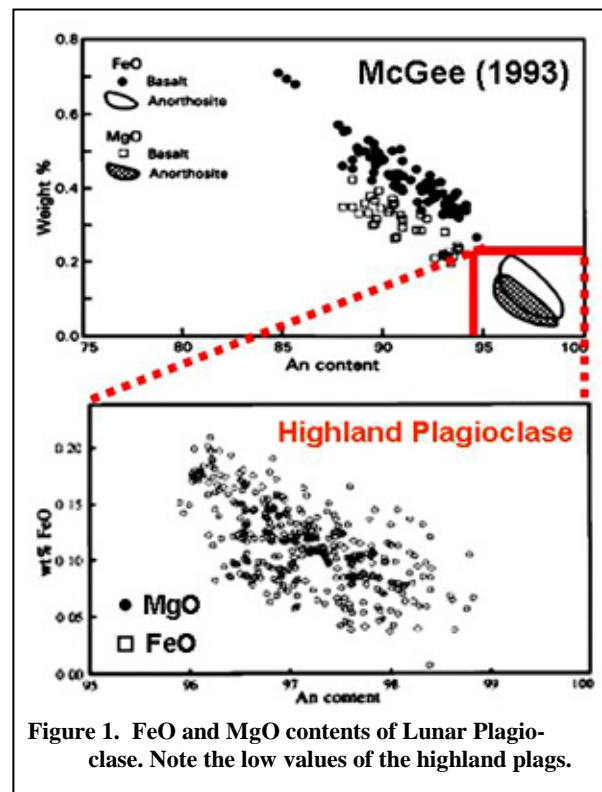


Figure 1. FeO and MgO contents of Lunar Plagioclase. Note the low values of the highland plags.

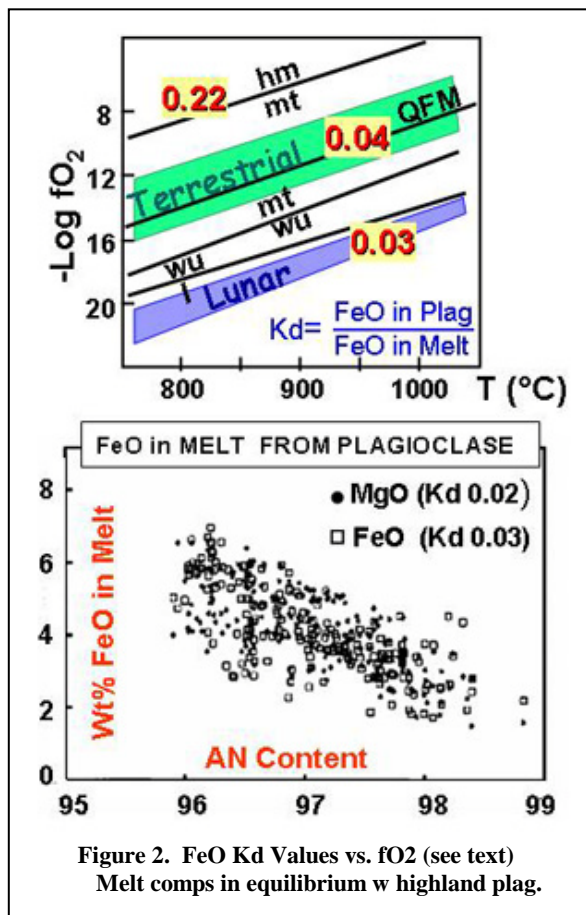


Figure 2. FeO Kd Values vs.  $f_{\text{O}_2}$  (see text)  
Melt comps in equilibrium w highland plag.

Figure 1, typical values for the highland plagioclases are  $\sim 0.12 \pm 0.08$  wt% FeO, with FAN plag being in the lower portion of this range. These are particularly low based upon values of equilibrium crystallization of FAN plagioclase from the LMO.

**Cause(s) for the Anomalously Low-FeO Contents of Highland Plagioclase:** As the LMO cooled and crystallization occurred, the loss of heat to the near-surface portions of the melt would be the driving force for the cooling. The balance between the radiogenic-heat input, the heat of crystallization, and the conductive heat-loss upward would factor into the overall cooling of the molten Moon. Adding to this the insulating effects of the mega-regolith, Warren [11] estimated that cooling to  $1000^\circ\text{C}$  at 20 km depth in the newly formed crust would take 10 to 50 m.y., and at 40 km, it would take 80 to 400 m.y. That is, *the crust of the LMO was a slowly cooling mass of mainly plagioclase, with minor olivine and pyroxene.*

**Results of Slow Cooling:** It has been pointed out for terrestrial anorthosite massifs that sub-solidus re-equilibration can occur for the FeO and MgO in plagioclase and olivine, pyroxene, and other Fe-Mg-bearing minerals during high-temperature metamor-

phism, as occurs with granulite-grade metamorphism [2-4]. This would seem to negate the calculations of the Fe-Mg contents of the melt from which the plagioclase has originally crystallized. It can be imagined that the same type of re-equilibration should have occurred with the LMO cumulates, at least for the more easily diffusive elements, such as Fe and Mg, but here due to the slow cooling of the crustal rocks.

The temperatures of magmatic melts on the Moon are  $100\text{-}200^\circ\text{C}$  higher than on Earth, due to the paucity of water in the lunar magmas. Therefore, the temperatures of crystallization of the LMO, being intrinsically higher, will result in an overall greater heat budget to the lunar crust at the time of formation. In addition, the cooling of the lunar surface is entirely by radiation, largely due to the lack of an effective atmosphere ( $10^{-12}$  torr) and absence of water. Thus, the radiative cooling of the lunar crust will proceed slower than a similar situation on Earth.

**SUMMARY:** The FeO and MgO compositions of highland plagioclase are approximately in equilibrium with its bulk composition. However, the original composition of the plagioclase at the instant of crystallization from the LMO melt was much higher by a factor of  $\sim 3$ . This is due to the sub-solidus re-equilibration of the plagioclase with its associated Fe-Mg silicate and oxide minerals. Inasmuch as plagioclase at different levels in the crust experienced different cooling rates, the observed FeO and MgO values today may differ by various amounts from total equilibrium of the present rock assemblage.

The bottom line to this study is that *the FeO and MgO compositions of lunar highland crustal plagioclase, particularly as seen by remote sensors on present-day orbiters, should currently be interpreted cautiously. These oxide contents in plagioclase may have little to no relationships to their original LMO-crystallization compositions.* Since crystalline plagioclase can now be detected and mapped remotely [5,12], however, the FeO and MgO content of crystalline plagioclase from both the FANs and the Mg-suite are well worth further investigation to determine what, if any, mysteries might be resolved for early crustal evolution.

**REFERENCES:** [1] Warren, P.H., 1985, Ann. Rev. EPS 13, 201-240; [2] Phinney, W.C., & D.A. Morrison, 1990, GCA 54, 1639-1654; [3] Phinney, W.C., 1991, Proc. 21<sup>st</sup> LPSC, 29-49; [4] Phinney, W.C., 1992, GCA 56, 1885-1895; [5] Pieters, C.M., et al., 2006, LPSC XXXVII, #1630; 2007, LPSC XXXVIII, #1295; 2009, these volumes; [6] McGee, J.J., 1993, JGR 98, 9089-9105; [7] Longhi, J. D. Walker, and J.F. Hays, 1976, Proc. 7<sup>th</sup> LSC, 1281-1300; [8] Sato, H., 1989, Proc. ODP - Sci. Results 111, 17-26; [9] Bindeman, I.N., A.M. Davis, and M.J. Drake, 1998, GCA 62, 1175-1193; [10] Aigner-Torres, M., J. Blundy, P. Ulmer, and T. Pettke, 2007, CMP 153, 647-667; [11] Snyder, G.S., L.A. Taylor, and C.R. Neal, 1992, GCA 56, 3809-3823; [12] Matsunaga, T., et al., 2008, GRL 35, L23201.