

ALKALI DEPLETION OF THE BULK MOON, IS IT REQUIRED? H. Nekvasil¹, A.E. Coraor², N. DiFrancesco¹, D.H. Lindsley¹, and G. Ustunisik³. ¹Department of Geosciences, Stony Brook University, Stony Brook, NY 11794-2100; ²Huntington High School, Huntington, NY 11743; ³American Museum of Natural History (Hanna.Nekvasil@stonybrook.edu).

Introduction: Studies of lunar pyroclastic glasses, apatite crystals, and melt inclusions [1-4] have indicated that the Moon is not the anhydrous body previously thought. This recognition, as well the similarities of several isotopic characteristics between the Moon and the Earth [e.g., [5],[6]], is shrinking the need for a large contribution of mass from the impactor during the Moon-forming process and motivating a reconsideration of process, rather than inherited characteristics, that could have led to observed differences between the Moon and the Earth.

Perhaps one of the most striking remaining petrologic differences between the Earth and Moon is the calcic anorthositic lunar Highlands crust. This lithology remains unique to the Moon and is considered the one primary lithology from the lunar magma ocean (LMO) that we have direct access to and its alkali-depleted nature is thought to characterize the Moon as a whole. However, the purported depletion of alkalis in the bulk Moon poses lingering conceptual difficulties when considering the formation of an anorthite-rich anorthosite flotation crust from a lunar magma ocean. The low alkali contents of proposed LMO compositions [e.g., [7],[8]] should produce late crystallization of anorthitic plagioclase. This causes three primary problems, first, it is hard to segregate a mineral that forms during the last 10-20% of crystallization; second, melt that has evolved from extensive ferromagnesian mineral precipitation before feldspar crystallization will be enriched in low density melt components, making it unlikely that plagioclase will float; and finally, if at late stages plagioclase is almost pure anorthite, then partial melting of any of these cumulate layers and/or of KREEP is unlikely to produce magmas that can give rise to the alkali suite rocks with their more sodic feldspar compositions or the alkali anorthosite with more intermediate plagioclase inferred to exist over a wide range of lunar terrains [9].

We have begun to question a fundamental tenet of the anorthositic crust. Is it possible to form an anorthite-rich anorthosite crust without strong alkali depletion of the bulk Moon? We have launched a multi-faceted investigation to take a new look at lunar plagioclase-bearing assemblages, and to evaluate the possibility of processes that might have given rise to alkali-depleted surface lithologies without requiring a highly alkali-depleted bulk Moon. The first set of inquiries involve the possibility of producing anorthitic anorthosite from LMO crystallization at low pressure,

as a surface veneer. This would allow the interior to be more sodic and enable the production of alkali suite rocks and alkali anorthosite.

Anorthite formation by alkali volatilization during low pressure crystallization of the LMO. Boiling of magmas at the lunar surface or in the near-surface environment can and has caused alkali loss. There is ample evidence of volatility of alkalis in vugs in lunar samples for example ([10], [11]), where intermediate composition plagioclase has been precipitated as a vapor deposit. Alkali loss at low pressure may be enhanced by dissolved Cl. Ustunisik et al. (this conference) reports on experiments that we have conducted at ~0.3 bars which indicate a greater loss of both Na and K from Cl-bearing melt. If this is extensive, it could obscure the alkali content of the primary magma and yield increasingly alkali-depleted mineral assemblages and residual melt. Lunar magmas show evidence (i.e., from apatite compositions [e.g., 2,3], Cl contents of glasses [1], chlorides as coatings on pyroclastic glass beads [e.g., 12], and chlorides as sublimates on lithologies such as Rusty Rock [13-15]) of having contained a significant amount of Cl.

Cl appears to play an additional role. Experiments by DiFrancesco et al. (this conference) on a Cl bearing 14053 composition has shown that when volatilization of Cl is exceeded by buildup of Cl in the melt due to crystallization of Cl-free minerals in a Highlands basalt such as 14053, the high density of the low-silica residual liquids will likely allow plagioclase to float. This implies that a secondary anorthositic crust could form locally on the surface, one that is independent of the LMO and the high density residual liquid could drain to deeper levels within the crust.

Importantly, there is no need to call upon *extensive* alkali loss by vaporization at/near the lunar surface in order to produce anorthitic plagioclase from a Na₂O-bearing parental magma, since several subtle aspects of plagioclase stability work in favor of high An content in plagioclase at shallow levels.

The effect of low pressure on plagioclase composition. It has been long recognized that anorthite stability decreases strongly with pressure (e.g., [16],[17]). Unless the activity-composition relations for the Ab and An components of the melt also change strongly with pressure, An destabilization will affect the plagioclase melting loop, causing the anorthite content of the plagioclase crystallizing to be

more anorthitic at low pressure for a given Ab content of the melt. In this way, plagioclase forming at or close to the lunar surface will be more anorthitic, even without Na loss due to volatilization, relative to that crystallizing at depth in the LMO. In this way, a shallow calcic crust of the LMO could be produced without requiring that the bulk of the LMO have sodium contents low enough to produce anorthitic plagioclase.

- **Two-plagioclase/melt equilibria.** A more complicated consequence of low pressure crystallization, is the predicted presence of a three-phase line (or surface in the more complex multi-component space), caused by the Bøggild and Huttenlocher solvi (Fig. 1, modified from [18]). This allows anorthite to crystallize from a magma that is in equilibrium with bytownite (e.g., An₈₆₋₈₈). In fact, such a three-phase line may explain the observed coexistence of two plagioclase phases (An₈₆ and An₉₄) with no intermediate compositions and no textural differences, ranging in size from phenocrysts to microlites as observed in 14310 [19]. Importantly, there is also a major discontinuity in Or content in these plagioclases [19]; Or component may widen the immiscibility gap from that of Fig. 1.

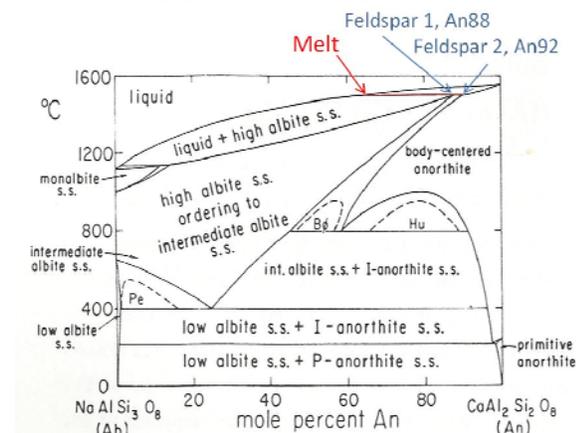


Figure 1. Hypothetical phase diagram for plagioclase phase stability idealized to first order transformations. Modified from [18].

The fact that this sample is considered an impact melt, indicates that neither the parent lithology, nor the daughter melt was strongly Na-depleted.

- **Azeotrope-controlled plagioclase evolution.** Our slow-cooling experiments in which degassing and crystallization have been coupled (DiFrancesco et al. this conference) show the formation of reversely zoned plagioclase; specifically, reverse zoning of the same magnitude as that described in natural lunar anorthosites (e.g., [20]). This reverse zoning and the formation of increasingly anorthitic plagioclase upon cooling does not require extensive degassing, if there is an azeotrope in the feldspar system (Fig. 2). In this

case, for bulk Ab contents of a magma near the azeotrope, but on the albitic side, plagioclase would show the expected Ab enrichment with dropping temperature. However, at shallow levels this same magma undergoing slight sodium loss may show plagioclase evolution towards more anorthitic compositions with dropping temperature. An azeotrope as shown in Fig. 2, would arise from strong positive deviations from ideality in the melt. Lunar compositions that show liquid/liquid immiscibility at low pressures lends support to the possibility of such an azeotrope.

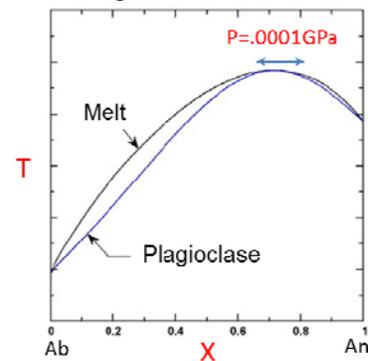


Figure 2. Schematic of azeotrope in the system Ab-An with a thermal maximum arising from strong positive deviations from ideality in the melt. Small losses of Na during degassing can cause the melt to move to the right of the azeotrope (in thin region of the

blue arrow) and dropping temperature will then produce anorthitic plagioclase and reverse zoning simply by cooling.

We have conducted experiments to determine the melt compositional controls on the formation of an azeotrope by focusing on the spinel-saturated plagioclase system at low bulk Na₂O contents for both Mg and Fe-bearing systems at 1 bar. Programmed cooling experiments in the system Forsterite-An₉₅Ab₅ have yielded spinel and normally zoned plagioclase and shown no azeotrope in this compositional region. Experiments in the system Fayalite-An₉₅Ab₅ are ongoing and the results will be reported.

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