PRODUCTION OF THE LUNAR MAGMA OCEAN BY FRACTIONATION OF THE INTERIOR

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INTRODUCTION

Prior treatments of the early lunar differentiation event (the "Lunar Magma Ocean") have generally assumed that the magma was produced by completely and instantaneously melting the outer portion of the Moon\(^1\). Although a useful simplification at the time, this picture is clearly unrealistic. The timescale for the heat generation that produced this event (probably on the order of \(10^5\)–\(10^7\) years) is shorter than the inferred duration of at least some of the resulting magma\(^2\) but probably much longer than the timescale for segregation of partial melt into a magma body. If, as seems likely, the distribution of the heat sources (of as yet uncertain nature) which produced this melt event is reasonably even throughout the Moon, one is led to the expectation that the magma ocean formed gradually over the heat generation event by fractional melting of some significant portion of the lunar interior. The melting was fractional because segregation of melt is rapid when above the solidus, and it was of great extent because mass motions accompanying such an event would significantly rearrange the outer layers of the Moon.

If one accepts the assumptions just described, one is lead to the following scenario. At stage 1, the first partial melt reaches the lunar surface. Exposed to space, it cools rapidly and produces a temporary crust of chill margin. The chill margin, continually fragmented by the still-continuing meteoritic bombardment and sub-surface magma motions, is denser than the magma and its fragments sink and remelt. This process allows the heat of the thin initial ocean to escape rapidly, carrying the magma ocean interior through its normal crystallization sequence and producing a crystal slurry of olivines, pyroxenes, and plagioclase. The olivines and pyroxenes sink, and the plagioclase floats to the top and replaces the fragmenting and sinking chill margin\(^3\). This situation is illustrated in Figure 1.

Thus begins stage 2, wherein a surface layer of floating slabs, boulders, pebbles and rockbergs composed mostly of plagioclase now begins to obstruct the rapid escape of heat from the magma. This process is cartooned in Figure 2. As the floating layer thickens, the loss of heat is reduced below the level equivalent to the potential enthalpy of crystallization carried in by the magma still erupting from the interior. Since this new magma does not necessarily have anorthite at its liquidus, it generally must crystallize -- liberating heat -- before it (or the resultant mixture of new and old magma) can be in equilibrium with the floating plagioclase. This excess heat which must be lost in order to maintain the floating plagioclase will melt and thin the crust until the rate of heat conduction through the crust matches the influx of excess heat of crystallization. Thus the floating crust at this stage will be very thin in order to maintain the magma body at the composition where anorthite is just on the liquidus, even though the thickness of the magma body may become very large. (As an example, if excess heat -- due to olivine solidification before anorthite -- equivalent to \(1/30\) of the lunar volume is delivered over \(10^6\) years, considering heat lost only by conduction leads to a \(10\ m\) crustal thickness. Actually the result of meteoric impacts and other thin spots will be to allow much of the crust to be thicker.) As the influx of new magma slows, the crust can thicken synchronously.

As the primordial heat sources die down and the influx of new magma ceases, stage 3 begins. Now the crust is released from the heat flux maintenance constraint, and can thicken as the magma ocean slowly fractionates into cumulates and additional crustal material as shown in Figure 3. This process should proceed in a manner similar to the instantaneously produced magma ocean considered previously\(^4\). Now, however, the volume of the magma ocean at the beginning of this stage is

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dependent on the composition of the melt originally fractionated from the lunar interior as well as its initial volume. Also, the floor beneath the magma ocean at the beginning of this stage may be composed of a thick layer of (largely olivine) cumulates produced during stage 2. Most importantly, the magma ocean composition at the beginning of this stage is highly modified from the bulk lunar composition for two reasons: the initial fractionation that produced the magma (depicted in olivine, for example) and the subsequent fractionation (more olivine depletion) superimposed upon this composition as the magma body adjusts itself to keep anorthite at the liquidus.

NUMERICAL MODELS

Numerical models of stages 2 and 3 (stage 1 is considered philosophically important but transitory and negligible in bulk impact) have been constructed in which the major element \( (\text{Al}_{2}\text{O}_{3}, \text{FeO}, \text{MgO}, \text{CaO}, \text{SiO}_2) \) chemistry of the two stages of fractionation was computed. Pressure- and composition-dependent equations for solid-phase co-equilibria\(^5\) were solved self-consistently with equations giving solid compositions as functions of magma composition\(^6\) together with the heat and mass balance equations to yield equilibrium crystallization sequences for each given bulk composition and pressure. Fractionation was modeled by finding the appropriate step in the equilibrium crystallization sequence (equivalent, of course, to an equilibrium melting sequence but reversed) and removing the appropriate phases, thus changing the system composition to be used in successive loops of the computation.

RESULTS AND DISCUSSION

As one would expect, stages 2 and 3 are distinct geochemical regimes. The exact nature of these regimes is affected strongly by the bulk lunar composition assumed and the extent of melting in the underlying lunar interior. However some qualitative generalizations can be made. If the degree of partial melting of the primitive lunar interior is small, the fractionated magma will be sufficiently rich in Al and Ca that very little cumulus crystallization will be necessary to keep the magma ocean saturated in anorthite. In such a case, stage 2 will still last as long as the heat sources producing it, but it will result in only a small cumulus production, with stage 3 yielding the bulk of the crust production.

This is the case in the model which produced Figure 4. Here a Taylor-Jakes composition\(^7\) and a relative melt volume fraction of 30% (corresponding to a 200 km deep magma ocean) was assumed. The enrichment in Al and Ca is great enough that anorthite is near the zero-pressure liquidus of the erupting magma throughout the heat generation epoch. This enrichment is sufficient to produce an anorthositic layer that is thicker than the estimated 50-70 depth of the lunar crust, indicating that the chosen bulk lunar composition may contain too much Ca and Al. Also apparent is the high degree of FeO enrichment of the initial magma composition, which leads to very iron-rich cumulates, particularly at the last stages of magma ocean crystallization. These last-produced cumulates would likely not remain emplaced for long, but would ascend to the lunar interior via subsolidus flow\(^8\).

If, by contrast, the melting of the Moon was extensive enough to introduce an important fraction of mafic minerals into the erupting magma, the stage 2 cumulates would be fairly extensive. The composition of the erupting magma would be correspondingly less exotic, however. Such a situation would occur if the entire Moon partially melted to the extent of producing a 300 km deep magma ocean, or even a shallow ocean if a correspondingly smaller fraction of the Moon was the source region. Therefore, further exploration of the range of rock compositions that can be produced with this model compared with the returned sample analyses may thus constrain the original bulk lunar composition.