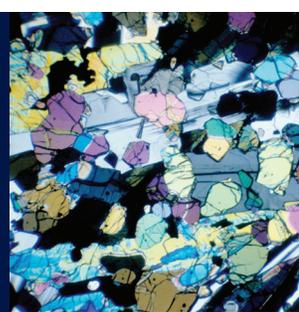


Lunar Mare Volcanism: Where Did the Magmas Come From?

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1811-5209/08/0005-0029\$2.50 DOI: 10.2113/gselements.5.1.29



The first rocks to be returned from the Moon by the Apollo 11 astronauts were basalts from the mare basins. Analysis of these rocks led to the hypothesis that the mare lavas were remelts of a lunar interior that had experienced an early, profound chemical differentiation event produced by crystallization of a planet-wide lunar magma ocean. As Apollo missions continued to explore and sample the lunar surface, an increasingly diverse suite of mare volcanic rocks was discovered. Mare magmatism is concentrated in the time interval of 3.8 to 3.0 billion years before present. Among the samples were tiny, glassy spheres of ultramafic composition that formed during volcanic fire-fountain eruptions into the cold lunar vacuum. The results of high-pressure and high-temperature laboratory melting experiments on lunar mare basalts and volcanic glasses, along with geochemical evidence and physical modeling, affirm that remelting of the solidified products of a deep magma ocean still provides the best explanation for lunar maria magmas. However, the initial depth of the lunar magma ocean, the physical processes that accompanied solidification, and the heat source for remelting cumulates to form these late basaltic outpourings remain incompletely understood and present challenging problems for current researchers.

KEYWORDS: Moon, mare basalt, magma ocean, ultramafic glass, experimental petrology

Lunar mare basalts are unique among our samples of basalts from the terrestrial planets, which include rocks from Mars and samples from a handful of small and chemically differentiated asteroids, in two important respects. First, like basaltic magmas on Earth, lunar basalts were produced by partial melting of the Moon's deep interior. However, unlike Earth's basaltic magmas, the nature of the deep source material that was remelted remains enigmatic, and the heat sources and melting processes are not completely understood. Second, the diversity in composition displayed by the mare volcanic products is unprecedented for mantle melts. The mare lavas provide evidence of the variations in composition, processes, and temperature with time. This brief review will describe what is known about the remarkable volcanic rocks from the Moon's surface and what unanswered questions remain about the processes that led to their origin.

DISCOVERING THE COMPOSITIONAL VARIABILITY OF MOON ROCKS

The first Apollo astronauts were impressed by the difference between the younger mare and older highland terrains on the Moon (Fig. 1). The flat, dark mare plains are flooded

with basalt, while the older highland terrains appear much lighter in color. The samples returned from the Apollo 11 landing site in Mare Tranquillitatis were basalts and lunar soils that included material that had been transported from the surrounding highland terrain by meteorite impacts. The chemical composition and the mineralogical constitution of the Apollo 11 basalts and soils led the first investigators of lunar samples to formulate the startling hypothesis that the entire surface of the Moon was once covered by a deep magma ocean that solidified and underwent chemical differentiation (Wood et al. 1970; Smith et al. 1970; Philpotts and Schnetzler 1970). The soil samples from the older highland terrains consisted of plagioclase feldspar rich in Ca and Al. This led Wood et al. (1970) and Smith et al. (1970) to postulate that the lunar highlands were plagioclase-rich and produced by

flotation of plagioclase in a magma ocean, leading to the formation of an early lunar crust.

In addition to soils, Apollo 11 returned mare basalts that possessed unusual major- and trace-element characteristics compared to terrestrial lavas (Fig. 2) and distinctive trace-element signatures (Philpotts and Schnetzler 1970). These chemical characteristics were consistent with a source that had experienced a differentiation event in which plagioclase, olivine, and pyroxenes were crystallizing together. The plagioclase separated from the magma, olivine, and pyroxene by floating, to form a lunar crust ~61 km thick (Taylor 1975).

The most compelling evidence comes from the fact that during melting processes the rare earth elements (REE) generally exhibit a systematic behavior. The REE are normally trivalent and are excluded from olivine and pyroxene (expected to be the dominant minerals in the deep source region of most planetary interiors); therefore, the REE are concentrated in the magma in a systematic manner that is controlled by their ionic radius. The mare lavas from the Apollo 11 and 12 landing sites exhibited an anomalous behavior in their REE-abundance variations. All the REE were enriched in the basalts relative to a normalizing standard (Fig. 2c, d) but europium (Eu) was strongly depleted relative to the other REE. This Eu anomaly could be explained if there was a prior crystallization event involving plagioclase. Under the reducing conditions of

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FIGURE 1 View of Mare Ingenii taken by the Apollo 15 astronauts on the far side of the Moon, from the Command Module. The Apollo 15 mission was the first of three multiday, geology-intensive Apollo missions. The large mare basalt-filled crater is Thomson, at 119 km across. A reflection from the spacecraft window runs across the picture diagonally. PHOTO NASA

lunar magma-ocean solidification, Eu was divalent and its ionic radius allowed it to substitute for Ca in the plagioclase crystal structure. Thus, the Eu anomaly indicates that the source of the mare lavas was melted under reducing conditions and had experienced plagioclase crystallization.

MAGMA-OCEAN CUMULATE REMELTING HYPOTHESIS

Much of our knowledge of the chemistry and mineralogical constitution of the Earth's mantle comes from studies of terrestrial basalts, which are melts derived from the mantle. Similarly, most of our knowledge of the lunar interior comes from studies of mare basalts, though they are

compositionally more diverse than their terrestrial counterparts. Experimental studies of the melting relations at high pressure and high temperature of the Apollo 11 (Ringwood and Essene 1970) and Apollo 12 (Green et al. 1971) lavas showed that Mg,Fe silicates were the first minerals to crystallize when the mare basalt cooled to its liquidus (i.e. the temperature at which the first crystal forms from the melt). At low pressures (FIG. 3A), olivine was the liquidus phase, and at higher pressures, pyroxene was the first phase to crystallize; at the transition, there was a point on the liquidus known as the multiple-saturation point where both phases crystallized simultaneously. This point of multiple saturation can have significance under some conditions and can indicate the depth, temperature, and minerals left behind after the melt was last equilibrated with a solid assemblage. Most importantly, plagioclase was nowhere near the liquidus. In fact, plagioclase crystallized only after a significant temperature interval and only at low pressure. Plagioclase should be on the liquidus if it was present in the source region during the melting event, as the Eu anomaly seemed to indicate, yet olivine and pyroxene were the only high-pressure liquidus phases. This evidence strengthened the arguments that the Eu-rich lunar crust was involved in a Moon-wide melting and differentiation event. Thus, the source of the mare lavas was composed of minerals that had been in equilibrium with plagioclase when they crystallized and had inherited their negative Eu anomaly from this prior magma-ocean-processing event.

LUNAR MAGMA OCEANOGRAPHY

As mare lavas from Apollo 12 and highland crustal rocks from Apollo 14 were returned and analyzed, the significance of the unusual compositional characteristics of mare basalts was reinforced. Taylor and Jakes (1974) proposed a quantitative model by postulating the thickness and compositional variation of sunken cumulates in the magma

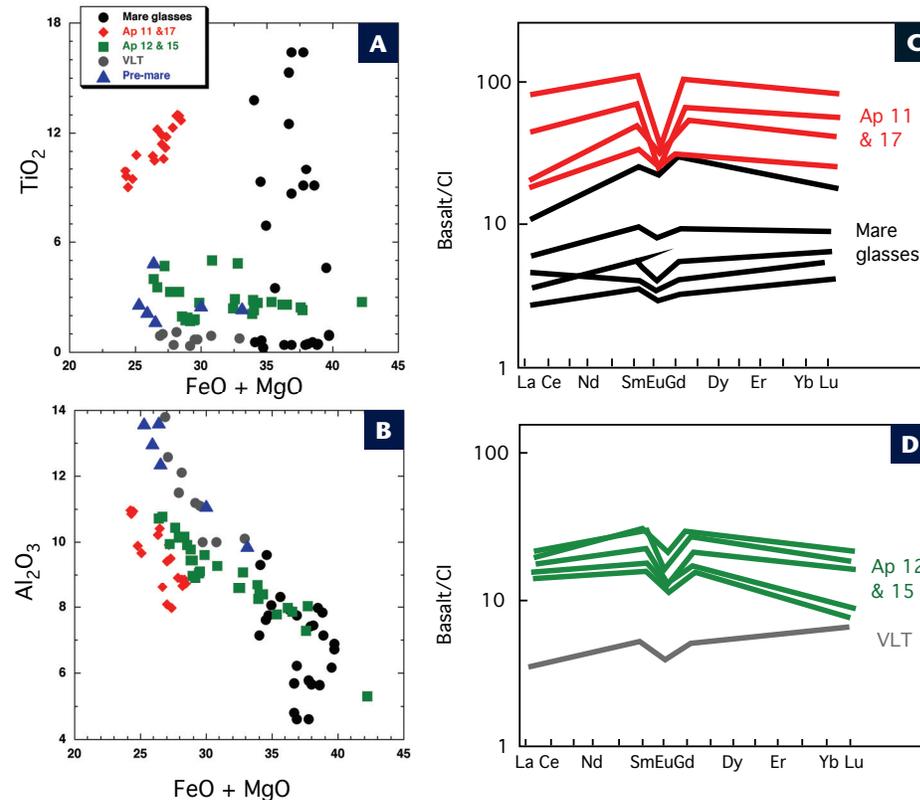


FIGURE 2 Compositional characteristics of the mare basalts (four groups) and lunar ultramafic glasses ("mare glasses"). (A) MgO + FeO versus TiO₂ content (in wt%). For comparison, terrestrial and Martian basalts have TiO₂ contents below 2 wt% at MgO + FeO near 20 wt%. (B) Al₂O₃ versus MgO + FeO (in wt%). Terrestrial basalts would plot at Al₂O₃ values between 16 and 18 wt%. Martian lavas would overlap with the mare basalts at low Al₂O₃. (C) and (D) Chondrite-normalized rare earth element plots comparing the compositions of mare ultramafic glasses with those of mare basalts.

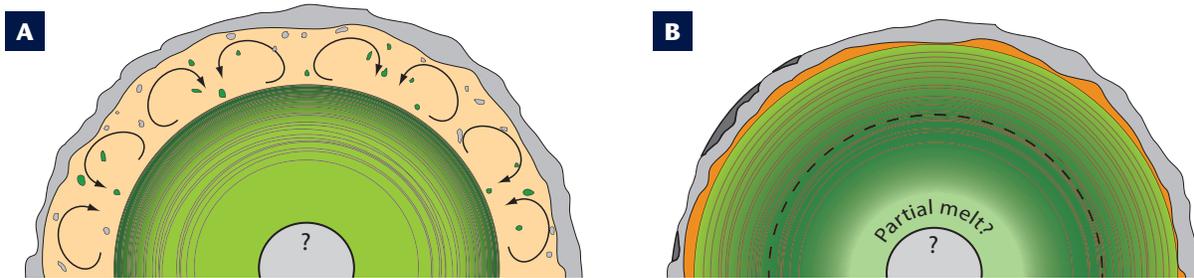


FIGURE 4 Schematic cross sections of the Moon during early (A) and late (B) stages of magma-ocean crystallization. Early in the solidification (A), buoyant plagioclase (grey) floats to the top of the convecting magma ocean (light brown) to make up a crust, while denser olivine and pyroxene crystals sink to the bottom to form a cumulate pile (green). The completely solidified lunar magma ocean (B) contains cumulates that have overturned in response to gravitational instabilities. The last dregs of the magma ocean became very enriched in TiO_2 (orange), leading to the crystallization of cumulates containing the TiO_2 -rich minerals ilmenite (FeTiO_3) and spinel (Fe_2TiO_4). The dashed line in (B) marks the location of a seismic anomaly, and the partial melt zone corresponds to a zone of attenuation seen from deep moonquakes (Jolliff et al. 2006).

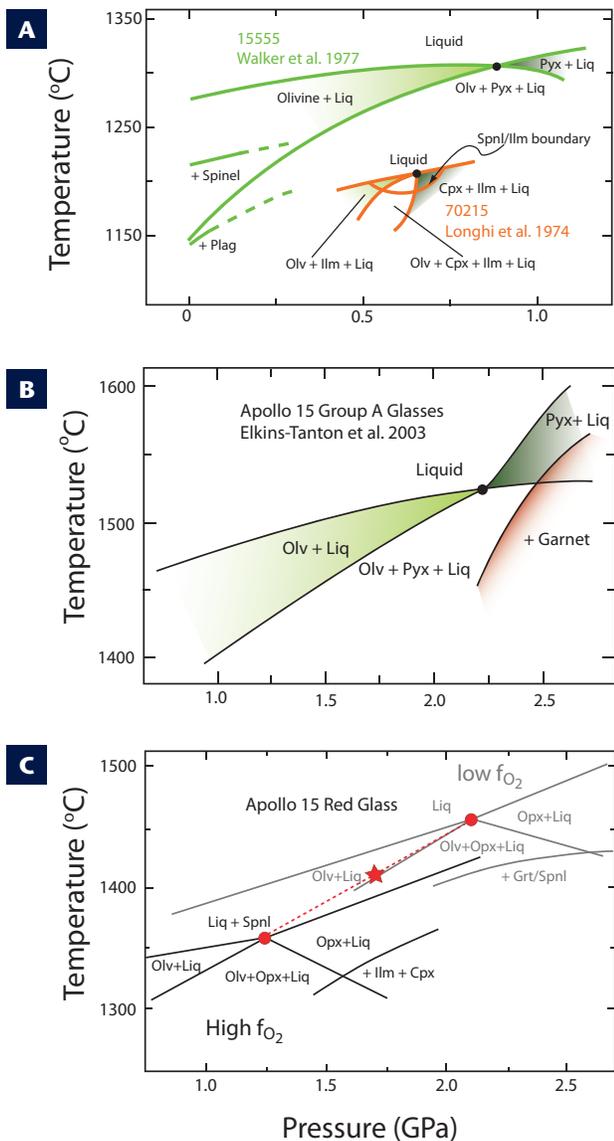


FIGURE 3 Phase diagrams for lunar mare basalts and ultramafic glasses showing the melting and crystallization behavior as a function of pressure and temperature. (A) Phase relations for Apollo 15 low-Ti mare basalt 15555 and Apollo 17 high-Ti basalt 70215 illustrate the low-pressure (lower than the ultramafic glasses) multiple-saturation, characteristic of the mare basalts and indicative of possible shallow reequilibration. (B) Apollo 15 low-Ti ultramafic glass ($\text{TiO}_2 = 0.25 \text{ wt\%}$) shows multiple saturation at high pressure, consistent with melting of cumulates at the base of the magma-ocean cumulate pile. (C) Apollo 15 red glass ($\text{TiO}_2 = 13.8 \text{ wt\%}$) shows the effects of oxidation state on its multiple-saturation pressures. At the inferred low oxidation state of the lunar interior, the high pressure of multiple saturation is inconsistent with melting of TiO_2 -rich cumulates that are at shallow depths in the cumulate pile.

ocean. They estimated the mass of highland crust rich in floated plagioclase and calculated the complementary mass of sunken olivine + pyroxene cumulates that would be required to make a whole-Moon bulk composition. They concluded that a 300 km deep Moon-wide magma ocean existed during the early history of the Moon (Fig. 4).

Also, a suite of pre-mare basalts was recognized (Taylor et al. 1983) at the Apollo 14 and Luna 16 sites; this suite records volcanic events ranging from 4.3 to 3.95 billion years ago. The origin of these pre-mare lavas is still debated, but they are probably volcanic equivalents of the magmas that form the lunar highlands crust (Mg-suite; Taylor 2009 this issue). Evidence of this pre-mare volcanism is obscured by the intense cratering event that bombarded the highlands until ~3.9 billion years ago (Norman 2009 this issue).

During the Apollo 15, 16, and 17 missions, the astronauts carried out detailed, multiday geologic examinations. This fieldwork was very successful and returned an abundance of interesting samples that were studied to refine the magma-ocean hypothesis. All the mare basalts had a negative Eu anomaly (Fig. 2c, d). Also, during the course of this lunar fieldwork, the astronauts discovered two completely unexpected volcanic deposits. They consisted of beads of volcanic glass. The first deposit, at Apollo 15, was composed of a layer of bright green glass beads ~100 microns in diameter. At the Apollo 17 site, geologist-astronaut Harrison "Jack" Schmitt found a deposit of orange glass spheres (Fig. 5A). These glasses formed by unique volcanic processes, whereby a fire fountain of very hot magma ($>1450^\circ\text{C}$; e.g. Elkins-Tanton et al. 2003) (Fig. 3B) was erupted into the lunar vacuum; the magma was rapidly cooled to glass in flight and was then deposited as a blanket on the lunar surface. As the Apollo samples were closely scrutinized, it was discovered that the glassy beads produced by these volcanic eruptions were ubiquitous in every lunar soil (Delano 1986). The glasses also showed a very broad range of compositional variation (Delano 1986; Fig. 2). In contrast to most of the mare lavas, the glasses were ultramafic (the sum $\text{FeO} + \text{MgO}$ in the glasses was $>35 \text{ wt\%}$), and glasses of this composition are unknown on Earth). The lunar ultramafic glasses constitute some of the highest-temperature magmas erupted in our solar system. Their liquidus temperatures are greater than 1450°C . In contrast, modern



FIGURE 5 Photomicrographs of lunar mare basalts and glasses. **(A)** Apollo 17 orange glass (sample 74220, 346). Horizontal width is 0.5 mm, plane-polarized light. **(B)** A rapidly cooled Apollo 15 quartz-normative basalt (sample 15595). Shown in this field of view are rapidly grown, skeletal pyroxene crystals set in a microcrystalline groundmass of glass and fine-grained pyroxene, plagioclase, and oxide minerals. Horizontal dimension of the photomicrograph (crossed polarizers) is ~2 mm. **(C)** A coarsely crystalline Apollo 12 low-Ti that basalt crystallized in the interior of a 10-meter-thick lava flow (sample 12005,40). This sample was probably excavated by a later meteorite impact, thrown into the mare basin, and subsequently picked up by the Apollo 12 astronauts. Horizontal dimension of the photomicrograph (crossed polarizers) is ~2 mm. Brightly colored grains are olivine and pyroxene; grey is plagioclase.

terrestrial basalts have liquidus temperatures of 1200 to 1250°C. One of the striking compositional variables was the TiO₂ content, which ranged from <0.25 wt% to >16 wt%. This compositional characteristic also correlated with color: the low TiO₂ glasses were green (e.g. Apollo 15), and the color progressed from yellow to orange (e.g. Apollo 17) to red to black as TiO₂ increased. All of the glasses also had a negative Eu anomaly (Shearer and Papike 1993; Fig. 2c). Thus, the ultramafic glasses on the Moon also show compositional characteristics that are consistent with melting of a body that had experienced a series of extensive, prior chemical differentiation events.

UNIQUENESS OF THE LUNAR MARE BASALT SUITE

In their textural characteristics, the mare basalts and ultramafic glasses record a dramatic variability in eruptive mechanisms, starting with the unique volcanic glasses that were rapidly chilled in the airless lunar atmosphere during violent eruptions (Fig. 5A). Other samples record the rapid cooling experienced at the outer “chill” margins of mare lava flows (Fig. 5B). Finally, several coarsely crystalline samples of basalt represent mare lavas that cooled slowly in the thick flows covering the mare plains (Fig. 5C).

On Earth, the compositions of basalt reflect a partial melting process that occurs in the Earth’s upper mantle. Although the melting conditions vary (e.g. temperature, pressure, and the presence or absence of H₂O are important variables), the source material is relatively uniform mantle peridotite. The same is true of Mars. This stands in stark contrast to the Moon, where the Al₂O₃ and TiO₂ variations in lunar basalts illustrate the necessity for a source region that is dramatically variable in composition. The ranges of TiO₂ contents in Earth basalts and Martian lavas are small, reflecting the uniform compositional characteristics of the source material. Terrestrial mantle peridotite is an olivine- and pyroxene-rich rock low in TiO₂ and is the dominant rock type in the upper mantle. In general, the origin of basalts on Earth can be explained by the melting of a mantle source composed of this rock type variably modi-

fied by a continuum of chemical enrichment and depletion events that have occurred over the 4.5 billion years of Earth history. In contrast, the lunar mare lavas and glasses preserve compositional characteristics that indicate a singular and more profound prior chemical differentiation event—the cooling and crystallization of the lunar magma ocean.

MODELS FOR THE ORIGIN OF MARE BASALTS AND ULTRAMAFIC GLASSES

The magma-ocean cumulate model explained mare basalts by a cumulate remelting process. In this model, the crystals that sank in the magma ocean and accumulated at its base were remelted. As the magma ocean crystallized from the bottom and top, the composition of the leftover magma changed in response to the composition of the minerals removed, which caused a progressive change in the compositions of minerals that accumulated at the base of the magma ocean (Fig. 4). To produce the mare basalts, these accumulated crystals were then remelted at some depth, forming a magma that was further differentiated in the lunar crust/mantle and erupted in the mare basins. The composition of the mare magma would then reflect the composition of the source minerals and the depth and temperature of melting. This model had some successes early on, but soon encountered difficulties.

On the success side, the mare basalts could be fitted into a consistent model. The high-TiO₂ basalts were in equilibrium with a plausible cumulate mineral assemblage at shallow depths in the Moon (Fig. 3A). This fitted with an origin as remelts of the last stages of cumulate formation at the top of the accumulated crystal pile and just beneath the floated-plagioclase crust. During these last stages of crystallization, TiO₂ would have been very enriched in the magma-ocean melt dregs, because earlier-crystallizing minerals (olivine, pyroxene, and plagioclase) excluded this component from their crystal structures and enriched it in the melt. Also concentrated in this late-stage liquid were heat-producing elements, the so-called lunar KREEP component. The Apollo 11 and 17 high-TiO₂ basalts were multiphase saturated at shallow depths and were thus the remelts of the shallow, late-stage cumulates (Fig. 3A). The Apollo 12 and 15 low-TiO₂ basalts were saturated with olivine + pyroxene residual sources at greater depth and were thus derived from deeper in the cumulate pile, where only olivine and pyroxene were crystallizing and accumulating (Fig. 3A).

The model failed to explain the origin of lunar high-TiO₂ ultramafic glasses. These glasses have high-pressure multiple saturation points that depend on the oxidation state of the source region and that place the source at a depth in the Moon greater than the shallow depth of the TiO₂-rich cumulates predicted for a normal magma-ocean solidification process (Delano 1980; Krawczynski and Grove 2008;

FIG. 3c). To explain this discrepancy, some process must have occurred after the magma ocean had solidified. Hess and Parmentier (1995) proposed a solution to this problem. The later, shallower cumulate layers in the solidified magma ocean would have been denser than the underlying cumulate layers (Zhong et al. 2000). A possible consequence of this arrangement is that after magma-ocean solidification had stopped, the denser layers became gravitationally unstable and sank through the underlying layers, leading to overturning and potential remelting of the cumulates. Thus, the high-TiO₂ ultramafic-glass might represent the liquid formed by remelting of the cumulate material that had been displaced to greater depth by gravitational overturn.

However, this explanation for the depth of the high-TiO₂ ultramafic source encountered additional problems. The high density and compressibility of the high-TiO₂ ultramafic magma (Fig. 6) meant that if it formed at the depth inferred by the high-pressure melting experiments, the melt would be negatively buoyant and would sink to greater depths rather than erupt (Circone and Agee 1996). Elkins-Tanton et al. (2002) explored the possibilities for lunar overturn and concluded that melts of the high-TiO₂ cumulate layer would have produced a negatively buoyant liquid even at shallow depths. They postulated that the high-TiO₂ ultramafic glasses formed from mixed source regions where the remelts hybridized at depths shallow enough to allow any melt that might be produced to ascend through the Moon's interior and erupt. In this scenario, the high-pressure melting relations no longer provide information on the phases left behind after melting and indicate that only a single residual mineral would remain. Thus, the conditions of multiple saturation no longer constrain the depth of melting (Fig. 6).

THE REMAINING CHALLENGES

One of the unsolved enigmas concerning the origin of the mare basalts is the source of the heat that remelted the lunar interior. Although mare volcanism started 4.3 billion years ago and may have continued until 1 billion years ago, the bulk of volcanism was confined to the interval of 3.8 to 3 billion years ago, which is separated in time from the magma-ocean solidification by at least 0.5 billion years. The mechanisms for this increase in magmatic activity are currently not understood. The temperature in the Moon's interior at the depth of origin for these basalts would have cooled conductively to a value well below that necessary to remelt the cumulates. Because the Moon is depleted in radioactive, heat-producing elements (such as potassium), during its post-magma-ocean thermal evolution, it rapidly developed a cold, thick outer layer (lithosphere) that cooled the cumulate layers to well below their melting temperature. At the same time, a deep (~1000 km) molten interior formed (Solomon and Longhi 1977).

The most likely source of heat for remelting the cold magma-ocean cumulate layers is an influx of hot, deep magma (Elkins-Tanton et al. 2003) or some other later external perturbation that resulted in heating. Possibilities for external perturbations include the late heavy meteorite bombardment that ended about 3.9 billion years ago (Elkins-Tanton et al. 2004) and tidal friction caused by the orbital coevolution of the Earth–Moon system (Touma and Wisdom 1998; Garrick-Bethell et al. 2006). However, the timing of this frictional-heating event cannot yet be estimated.

Also, the extent of the early melting event that led to the magma ocean is not completely settled. Estimates for the depth of the early magma ocean range from 300–500 km (similar to the early Taylor and Jakes model depth) to an entirely molten early Moon, possibly as a consequence of the giant impact event that most likely led to the formation of the Earth–Moon system. The main variable here is the bulk chemical composition of the Moon, which remains unknown. The thickness of the lunar crust is now well known thanks to gravity models (Zuber et al. 1994) and ranges from 20 to 120 km. Thus, the minimum depth of the magma ocean can be obtained by estimating how much of the whole Moon had to melt in order to produce the observed crustal thickness.

So, the story of the mare basalts is not yet finished. As modeling studies explore the early evolution of the Moon's cooling and solidification, we should gain a better understanding of the Moon's thermal evolution as a result of magma-ocean processes, giant impacts, and heating by tidal friction. As we continue the petrologic and geochemical examination of the mare samples, we will refine our estimates of the bulk composition of the Moon and understand better the involvement of a deep melt from the lunar interior in the process of mare basalt generation (Boyett and Carlson 2007). The upcoming GRAIL mission (www.jpl.nasa.gov/news/news.cfm?release=2007-145) will provide new gravity data that will reveal much about the structure and composition of the Moon. We predict that new insights will emerge from continued theoretical studies, geochemical and experimental studies of lunar samples, and future missions to explore the Moon.

ACKNOWLEDGMENTS

The authors thank J. Delano for his encouragement and assistance in preparing this review. We also thank J. Longhi and Y. Liang for constructive reviews. This work was supported by NASA Grant NNG06G167G. ■

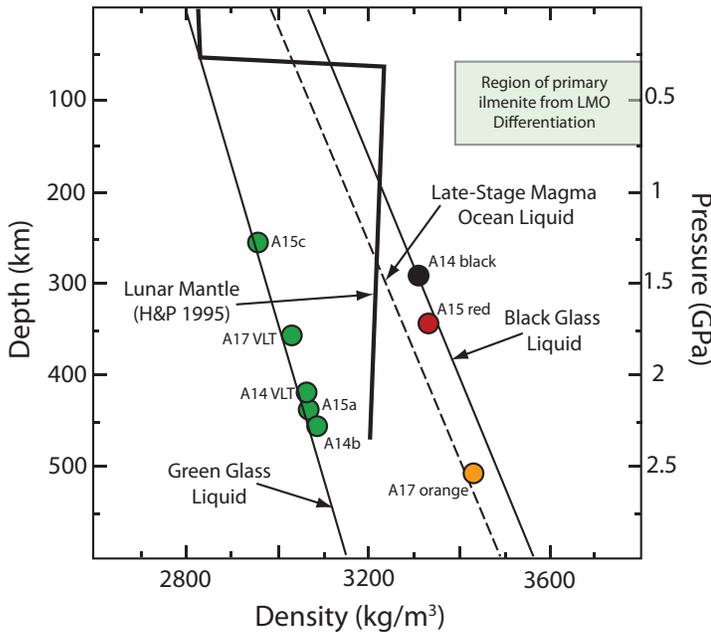


FIGURE 6 Depth of multiple saturation for ultramafic glasses plotted against the predicted density of the liquid and compared with the estimated density of the lunar interior (lunar mantle). Liquids less dense than their surroundings can ascend and erupt on the surface. Liquids denser than their surrounding country rocks will sink to greater depths and would not be expected to ascend and erupt. The lunar mantle relations are from Hess and Parmentier (1995); LMO: lunar magma ocean.

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