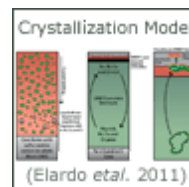



[About PSRD](#)
[Archive](#)
[Search](#)
[Subscribe](#)
[Glossary](#)
[Comments](#)

Headline Article

August 8, 2011

Crystallizing the Lunar Magma Ocean



--- Lab experiments help test ideas for the Moon's chemical composition and how its crust formed.

Written by G. Jeffrey Taylor

Hawai'i Institute of Geophysics and Planetology

A central tenet of lunar science is that the Moon was surrounded by a huge ocean of magma when it formed. Originally thought to be a few hundred kilometers deep, lunar scientists now think that the entire Moon was initially molten. Numerous geochemical models have been constructed for the crystallization of the **magma ocean**. All the calculations use computer programs based on experimental data, but these necessitate some simplifications. Stephen Elardo, David Draper, and Charles Shearer (all at the University of New Mexico, though Draper has moved to the Johnson Space Center) are tackling the problem differently by doing a series of high-temperature experiments at different pressures and two different starting compositions to improve our understanding of how the magma ocean crystallized.

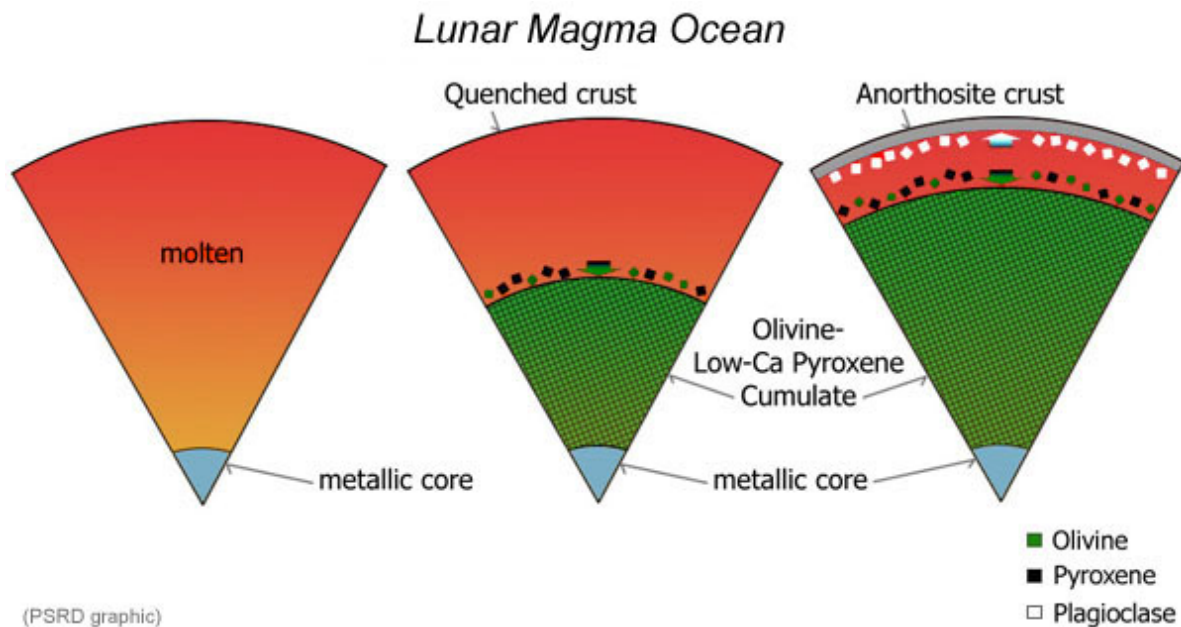
Their first results show that both starting compositions (one enriched in aluminum and other **refractory** elements and one not enriched compared to Earth) produce an extensive **olivine**-rich cumulate pile inside the Moon that rests on a metallic iron core. The composition with the higher aluminum concentration produces a thicker crust than does the other composition, raising the possibility that we can determine the bulk composition of the Moon by pinning down the thickness of the primary crust of the Moon. The olivine deposit is less dense than the overlying rock, so would likely slowly move as large blobs before stalling at the base of the crust. Once there it could react with feldspar-rich rock and **KREEP** (dregs from extensive magma ocean crystallization) to produce the magmas that gave rise to the numerous igneous rock bodies known as the magnesian suite.

Reference:

- Elardo S. M., Draper D. S., and Shearer C. K. (2011) Lunar Magma Ocean Crystallization Revisited: Bulk Composition, Early Cumulate Mineralogy, and the Source Regions of the Highlands Mg-suite. *Geochimica et Cosmochimica Acta*, v. 75, p. 3024-3045, doi: 10.1016/j.gca.2011.02.033.
- **PSRDpresents:** Crystallizing the Lunar Magma Ocean --**Short Slide Summary** (with accompanying notes).

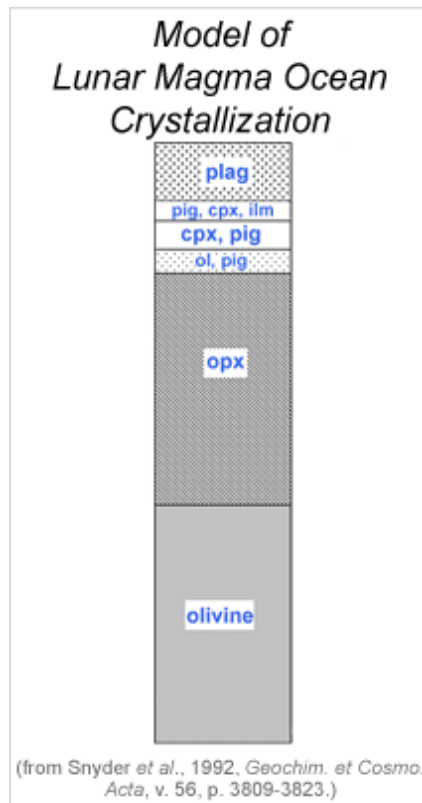
The Lunar Magma Ocean

The composition of the lunar crust indicates that the little body was almost completely molten when it formed. This central precept of lunar science is consistent with formation of the Moon by a giant impact, which would have led to rapid accumulation of molten material orbiting the proto-Earth. Cosmochemists do not yet understand the magma ocean system in detail. They do know that it must have been wildly complicated! Seeing through the complexity is one of the reasons Elardo and his colleagues are taking a new approach to understanding the crystallization of the lunar magma ocean. (Find a brief review of the evidence for the lunar magma ocean in "The Moon as a Model" section of [PSRD](#) article: [A Primordial and Complicated Magma Ocean on Mars.](#))



The idea that the Moon melted substantially (probably completely) when it formed, nicknamed the "magma ocean concept," is an important theory in lunar and planetary science. These three panels, from left to right, illustrate the lunar magma ocean theory. The basic idea suggests that as the molten Moon crystallized, minerals less dense than the magma floated and the heavier ones sank. The lighter minerals formed the primary crust of the Moon. Of course, the real magma ocean was much more complicated than this simple picture.

Like all magmas, the magma ocean did not crystallize all its minerals at once. It followed a sequence determined by its chemical composition and the pressure within it. Cosmochemists have calculated the order in which minerals crystallized and how mineral formation affected the chemical composition of the remaining magma. One such calculation, by Greg Snyder, Larry Taylor (University of Tennessee), and Clive Neal (University of Notre Dame), is shown in the diagram below. Not shown is that the last magma remaining would have concentrations of elements that are not incorporated into most of the minerals that crystallized; geochemists call such elements **incompatible**. Thus, elements such as potassium (K), phosphorus (P), and the rare earth elements (REE) became progressively more abundant in the magma as it crystallized, finally approaching 100 times that of the original, bulk Moon composition and making the important KREEP component that winds up in many types of lunar rocks.



Results of a cosmochemical calculation showing crystallization sequences of the lunar magma ocean, a vertical view, with the first-formed crystals closest to the bottom. Plagioclase feldspar begins to form after about 75% of the magma has crystallized, and ends up floating, so appears at the top. The region labeled "pig, cpx, ilm" would contain pigeonite (pig), high-calcium clinopyroxene (cpx), and ilmenite (ilm), and would have high concentrations of zirconium, rare earth elements, and other elements that do not enter olivine, orthopyroxene (opx), or plagioclase (plag).

Crystallization Experiments

To tame some of the complexity in our understanding of the magma ocean, Steve Elardo, Dave Draper, and Chip Shearer did a series of laboratory experiments at high temperatures and pressures. Their goal was to more fully understand the crystallization of the huge molten system. They used the latest experimental apparatus to achieve the conditions in the deepest parts of the lunar interior, at temperatures up to 1800°C (3272°F) and pressures up to 4 gigapascals (which corresponds to about 40,000 times the atmospheric pressure at the surface of the Earth, and is almost the pressure at the boundary with the metallic lunar core).

Multi-anvil Press*QUICKpress*

(Courtesy of Stephen Elardo, Univ. of New Mexico.)

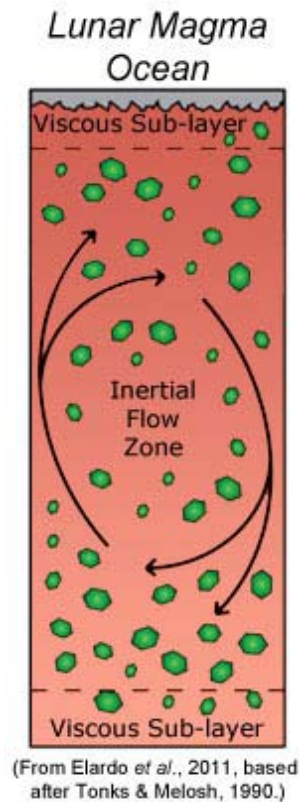
Photographs of the two types of high-pressure equipment used in the experiments. The runs at the highest pressure (4 GPa) were done using a multi-anvil press, shown at left. This machine allows pressures up to about 11 GPa (400 thousand times the pressure at Earth's surface). It uses octahedral devices that are squeezed between tungsten carbide cubes. Steve Elardo is pictured next to the other machine (right), a Depths of the Earth QUICKpress, which uses a piston and cylinder technique to obtain pressures up to about 2.5 GPa. (Steve's grease-decorated lab coat shows why scientists need them when working in the lab.)

Steve Elardo had the gear to do the experiments, but he needed to know the starting composition of the magma ocean. That seems easy: Just use the composition of the entire rocky Moon. Several attempts have been made to determine the whole-Moon composition, but they do not agree closely. They do, however, fall into two convenient categories: One group of estimates claims that the Moon is enriched in **refractory** elements (those that boil at high temperatures, such as calcium and aluminum) by about 50% compared to Earth; S. Ross Taylor (Australian National University) has championed this view, and the composition is nicknamed TWM (for Taylor Whole Moon). The other group claims that the abundances of refractory elements are the same in the Earth and Moon. This estimate is named LPUM (Lunar Primitive Upper Mantle); its chief proponent has been John Longhi (Lamont-Doherty Earth Observatory, Columbia University), and I think it ought to be nicknamed LLPUM for Longhi's Lunar Primitive Upper Mantle.



Elardo and colleagues did the experiments using both compositions, figuring they might be able to use the results to establish ways to test which compositional model is correct. For a discussion of the two main lunar compositional suggestions, see **PSRD** article: **Two Views of the Moon's Composition**.

A basic assumption that the team makes and that drove how they designed their experiments is that the initial magma ocean was thoroughly mixed. This would allow crystals formed in it to continuously and thoroughly communicate with each other and the magma, a process called equilibrium crystallization. This assumption stems from fluid dynamic arguments made by several investigators, but most thoroughly in 1990 by Brian Tonks (now at BYU-Idaho) and Jay Melosh (now at Purdue University). Tonks and Melosh calculated that the lunar magma ocean was convecting turbulently and had the capacity to entrain crystals in a circulating region and maintain that capacity until it was 50% crystallized. In interpreting their experimental data, Elardo and coworkers assume equilibrium crystallization for the first 50% of crystallization.



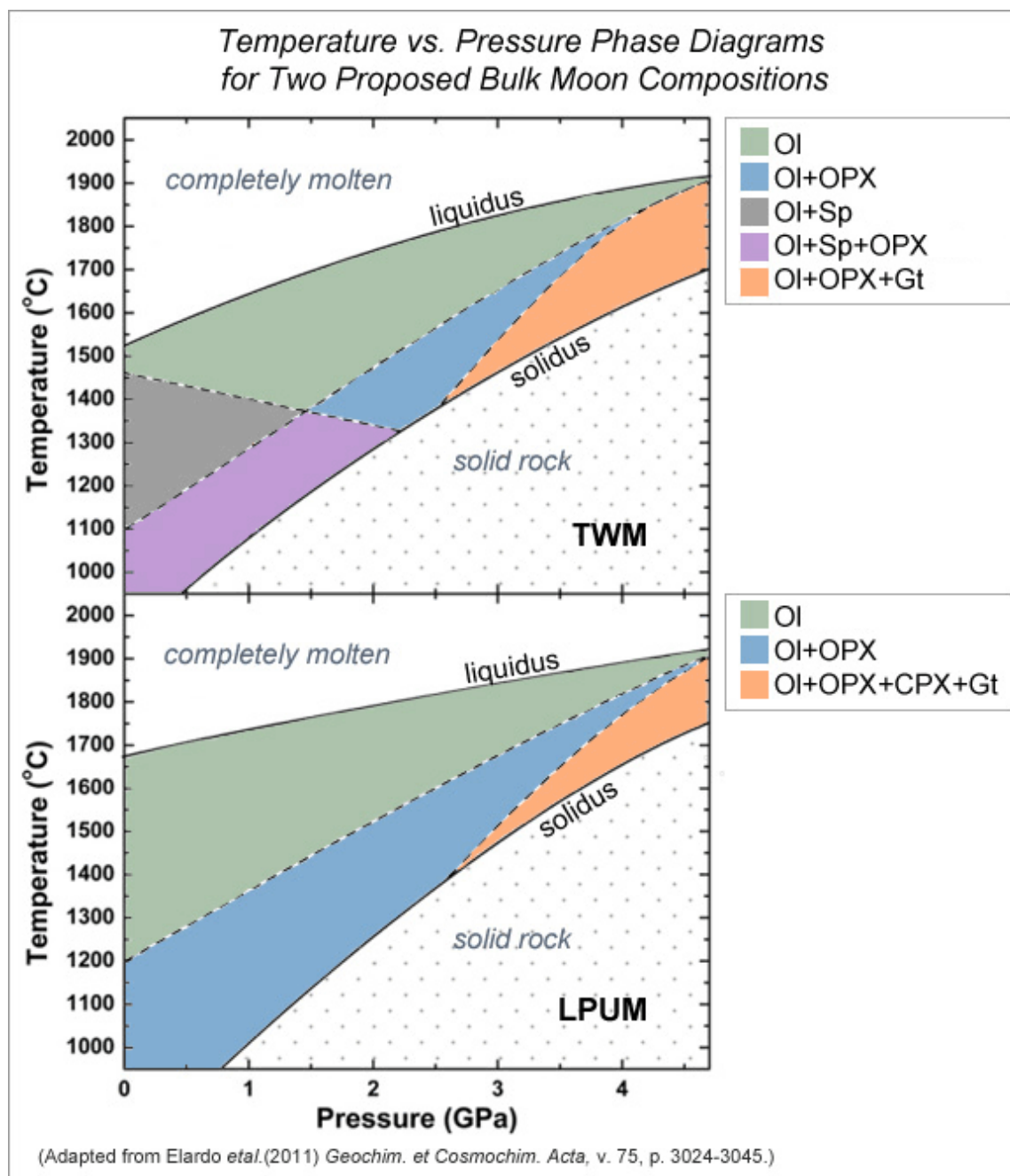
The lunar magma ocean is characterized by vigorous convection that suspends crystals until they are large enough to sink, which happens at about 50% crystallization. Somewhat gentler conditions prevail in small regions near the top and bottom of the magma ocean.

Experimental Results

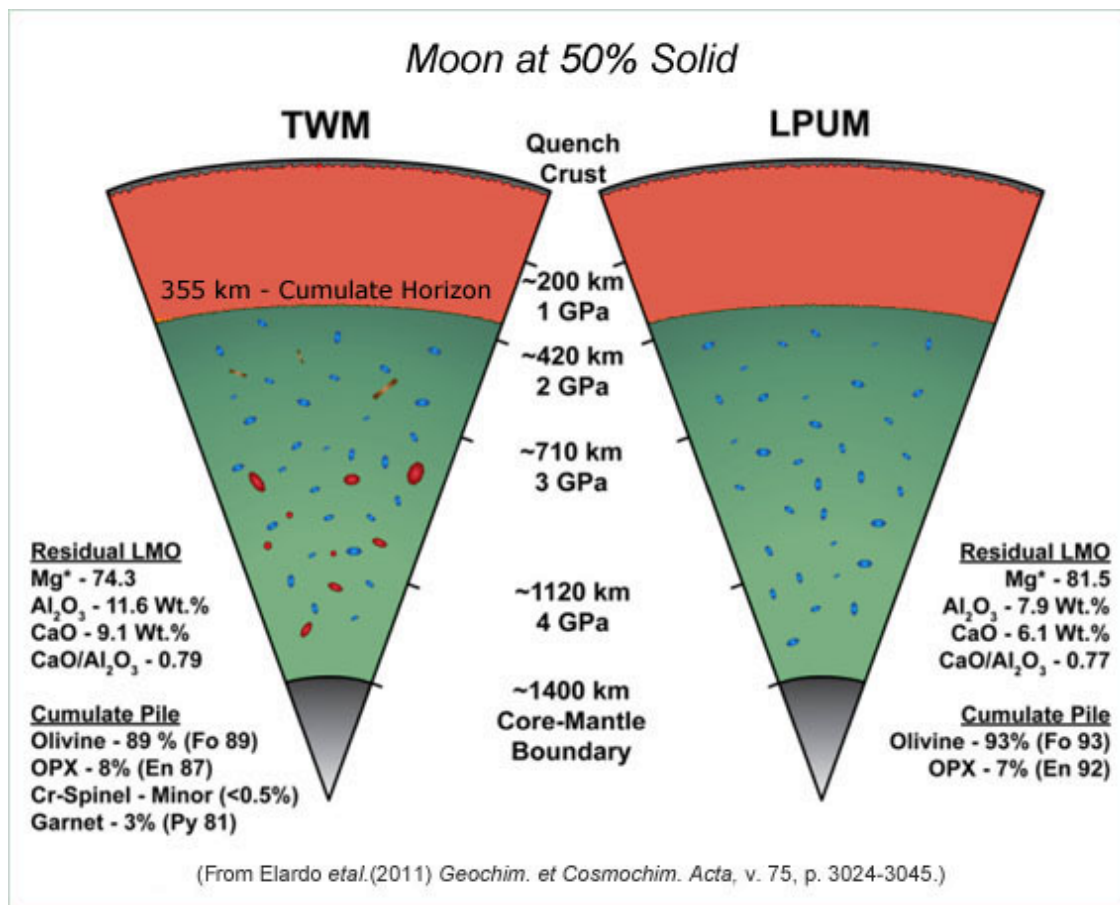
The figures below summarize the results from a total of 27 experiments, each lasting between two and four hours, followed by many hours of optical microscopy, and electron and secondary ion microprobe analyses. The temperature versus pressure diagrams show which minerals are present in the magmas at any given combination of temperature and pressure.

Olivine is the first mineral to form in magmas with either the TWM or LPUM compositions, as indicated by the big green fields near the liquidus. Its eventual accumulation leads to a thick layer of rock dominated by it (see second diagram below). The interesting thing is the presence of garnet in both compositions at higher pressure. However, the TWM composition precipitates garnet earlier and at lower pressures, so it ends up in the pile of accumulated crystals once they sink. If garnet were unambiguously detected in the deep lunar interior, it would favor the refractory-rich TWM composition.

The TWM, with its high aluminum content, precipitates spinel (an aluminum-rich mineral) after olivine below about 2 GPa. Even more significant, the magma left over after 50% of it has crystallized contains enough aluminum to crystallize 50% more plagioclase feldspar than does the LPUM composition. This implies that the TWM composition should have produced a larger anorthosite floatation crust, which may be a way to test the two compositional models once lunar scientists refine their understanding of the composition and thickness of the lunar crust.



Temperature versus pressure diagrams based on Steve Elardo's experiments for the Taylor Whole Moon (TWM) and Lunar Primitive Upper Mantle (LPUM) compositions. The diagrams show which minerals are present at different temperatures and pressures. Everything is liquid above the "liquidus" curve and everything is solid rock below the "solidus" curve. The crystallization order at a given pressure can be determined by following a straight line from the liquidus to the solidus. A major difference in the two compositions is the presence of the spinel (an aluminum-rich mineral) at less than 2 GPa in the TWM composition, but not in the LPUM composition. This reflects the higher aluminum in the TWM composition.



Cross section of the Moon after 50% crystallization of magmas with the TWM (left) and LPUM (right) compositions. In both cases, the solid pile of accumulated crystals ("cumulate pile") is composed mostly of olivine, with a smaller amount of orthopyroxene and even smaller amounts of spinel and garnet (depicted as orange and bluish blebs in the green cumulate pile). The mineral abundance calculations are based on the temperature-pressure diagram above. The orange region on top is the residual magma ocean after 50% crystallization. The big difference between the two compositions is the higher Al₂O₃ content in the TWM composition compared to the LPUM composition (11.6 wt% vs 7.9 wt%) and in the CaO concentration (9.1 wt% vs 6.1 wt%), another refractory element enriched in the TWM composition.

Buoyant Blobs and Magnesium Magmas

The Mg-suite of lunar rocks has the disturbing, paradoxical properties of high magnesian (Mg) to iron (Fe) ratios and high concentrations of incompatible trace elements (incompatible because they concentrate in magmas, not in major minerals). In typical crystallizing magmas, early-formed cumulates have high Mg/Fe, but low incompatible trace element abundances. By the time the trace element concentrations have increased substantially, the Mg/Fe has plummeted. Geochemical lore developed for many decades of rock studies says that high Mg/Fe coupled with high incompatible trace elements is inconsistent. So how did those Mg-suite magmas form?

Cosmochemists have been pondering this question since the Mg-suite was identified in the early 1970s. Several distinct ideas were proposed over the years, but were gradually narrowed down to two main ones. Both involve turnover of the magma ocean cumulate pile. All those early magnesian olivine crystals have lower densities than those formed later, especially during the last 25% of magma ocean crystallization. Lower density below higher density rock is not a stable situation, so the denser ones sink and the lighter ones rise, changing positions in a complicated, disorderly way. (Hot rocks, while solid, are quite plastic, so they flow.)

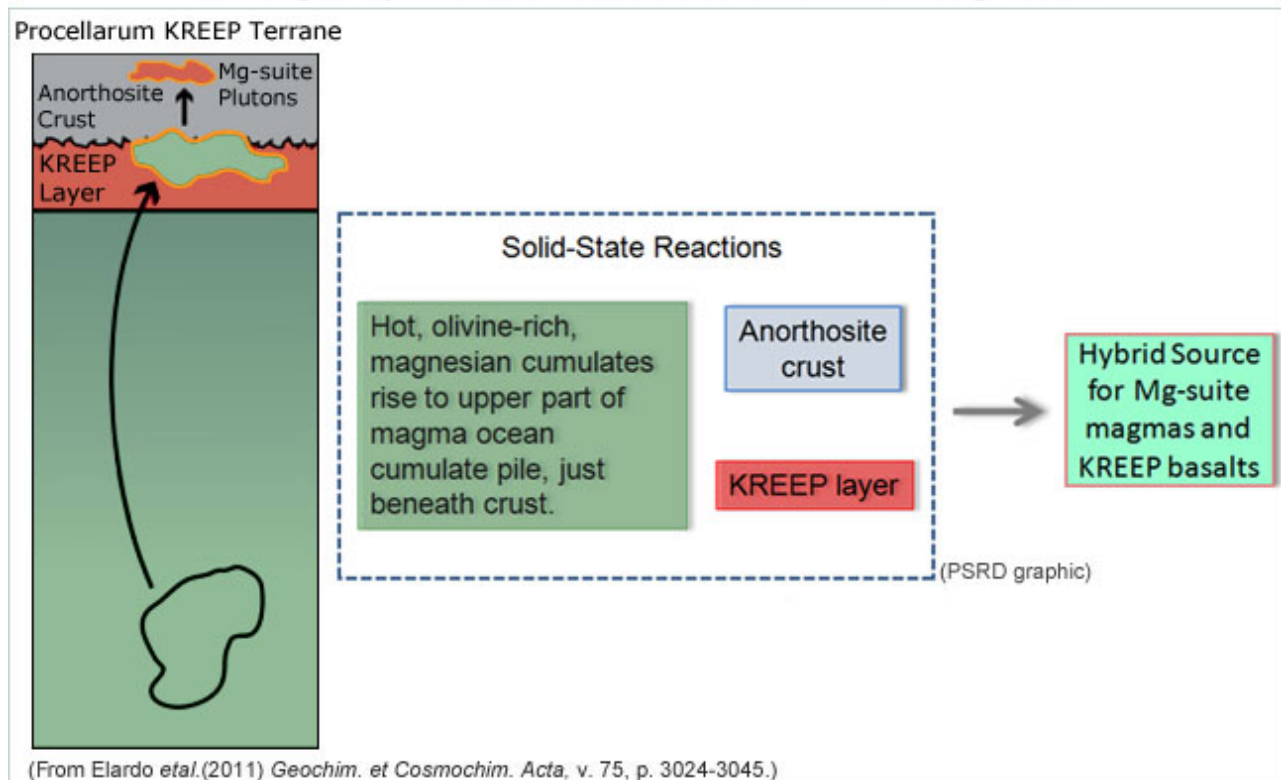
One reasonable idea for formation of the Mg-suite is that the rising cumulates partially melt as they rise

because of decreasing pressure, and the magma (which has high Mg/Fe) stalls at the base of the crust where it reacts with the KREEP layer (rich in incompatible trace elements and the last liquid remaining from the magma ocean) and the anorthosite crust. The KREEP provides the trace elements and the anorthosite provides Al_2O_3 to make the magmas rich enough in Al_2O_3 to crystallize plagioclase feldspar simultaneously with olivine or pyroxene, like the Mg-suite magmas were. But there's a problem. As pointed out in detail by Paul Hess (Brown University) in a 1994 paper, assimilation of anorthosite rock requires that some of the magma crystallizes in order to have enough heat to dissolve the feldspar. (Heat is released by crystallization.) Unfortunately, this decreases the Mg/Fe of the magma so much that it moves outside of the Mg-suite range.

The other idea is that overturn drags the KREEP layer down into the lunar mantle where it reacts with rising plumes of early, magnesian, olivine-rich cumulates. The added heat from decay of potassium, uranium, and thorium in KREEP causes partial melting, making magmas high in Mg/Fe and high in trace elements. However, the magmas must still assimilate aluminum (and calcium) from the anorthosite crust to produce magmas that crystallize enough plagioclase, which would cause the Mg/Fe ratio to decrease, so problems remain.

Elardo and coworkers suggest a way around the problem with assimilation causing an unacceptable decrease in Mg/Fe. They propose that rising diapirs of low-density, magnesian, olivine-rich early cumulates rise up through the overlying magma ocean products, stopping only when they reach the base of the crust where they nestle close to both KREEP and anorthosite. This gives them ample opportunity to slowly exchange elements in the solid state (possibly helped by small amounts of magma). As the system heats up, the hybrid source partially melts to produce Mg-suite magmas that rise into and onto the crust. Because no crystallization is required during the reactions among the olivine-rich diapirs, KREEP, and anorthosite, the high Mg/Fe is preserved. Though details need to be worked out, it is a fresh idea that will be evaluated like all the others.

Rising Diapir Model and Formation of the Mg-Suite



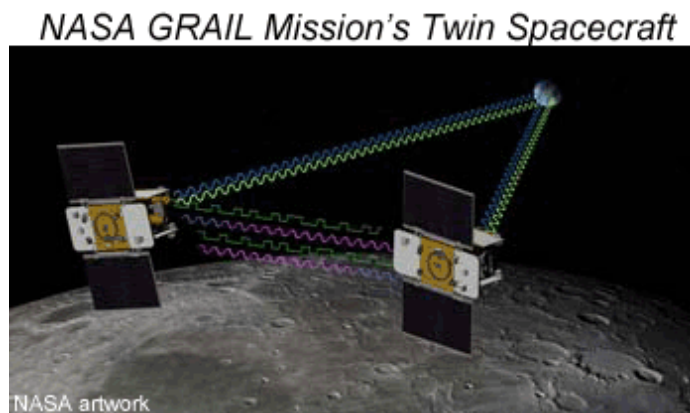
(Left) Model devised by Elardo, Draper, and Shearer for creation of a hybrid, shallow source for production of Mg-suite magmas. **(Right)** Schematic showing how the three major magma ocean products could react to make a hybrid source for the Mg-suite magmas. Rising magnesian cumulates from the magma ocean slowly smash into the KREEP layer (last magma ocean magma remaining, and possibly still partly molten) and near the anorthosite crust where all three react to

form a hybrid rock. This rock subsequently partially melts to produce the Mg-suite magmas, which are characterized by high Mg/Fe, high concentrations of incompatible trace elements such as the rare earths, and crystallize plagioclase feldspar and either olivine or pyroxene at about the same time.

Testing Ideas

Steve Elardo's work points out ways to test our estimates of the Moon's chemical composition. Specifically, the experiments show that the aluminum- and calcium-rich TWM composition produces a much thicker plagioclase-rich crust than does the more Earthlike LPUM composition. In addition, the TWM composition is aluminous enough to have formed the mineral garnet in its interior.

A new mission scheduled for launch in early September, 2011 will be able to assess the thickness and density variations (hence feldspar content) of the crust. Called GRAIL, the mission uses two spacecraft that follow each other in an orbit 50 kilometers above the lunar surface. The spacecraft will be separated by a distance of 175 to 225 kilometers. High-precision radio communication devices allow the spacecraft to determine the distance between them precisely. Because the distance is affected by tiny variations in the lunar gravity field, geophysicists will be able to determine the structure of the lunar crust and interior. These new data will be combined with existing remote sensing and sample analysis data to allow us to test compositional models in detail.



Artist concept of GRAIL mission. GRAIL will fly twin spacecraft in tandem orbits around the moon for several months to measure its gravity field in unprecedented detail, allowing us to test models for lunar composition, mantle dynamics, crustal magmatic evolution, and the structure of large impact basins.

Additional Resources

Links open in a new window.

- **PSRDpresents:** Crystallizing the Lunar Magma Ocean --**Short Slide Summary** (with accompanying notes).
- Elardo S. M., Draper D. S., and Shearer C. K. (2011) Lunar Magma Ocean Crystallization Revisited: Bulk Composition, Early Cumulate Mineralogy, and the Source Regions of the Highlands Mg-suite. *Geochimica et Cosmochimica Acta*, v. 75, p. 3024-3045, doi: 10.1016/j.gca.2011.02.033. [[NASA ADS entry](#)]
- **GRAIL mission homepage.**
- Hess P. C. (1994) Petrogenesis of Lunar Troctolites. *Journal of Geophysical Research*, v. 99, p. 19083-19093.
- Snyder G. A., Taylor L. A., and Neal C. R. (1992) A Chemical Model for Generating the Sources of

Mare Basalts: Combined Equilibrium and Fractional Crystallization of the Lunar Magmasphere. *Geochimica et Cosmochimica Acta*, v. 56, p. 3809-3823.

- Taylor, G. J. (March, 2006) A Primordial and Complicated Ocean of Magma on Mars. *Planetary Science Research Discoveries*. http://www.psr.d.hawaii.edu/Mar06/mars_magmaOcean.html.
- Taylor, G. J. (April, 2007) Two Views of the Moon's Composition. *Planetary Science Research Discoveries*. <http://www.psr.d.hawaii.edu/April07/Moon2Views.html>.
- Tonks W. B. and Melosh H. J. (1990) The physics of crystal settling and suspension in a turbulent magma ocean. Origin of the Earth. Oxford Univ. Press, New York, NY.



[[About PSRD](#) | [Archive](#) | [CosmoSparks](#) | [Search](#) | [Subscribe](#)]

[[Glossary](#) | [General Resources](#) | [Comments](#) | [Top of page](#)] [!\[\]\(a870788d6ed9b8fd294b7654a8c8526b_img.jpg\) Share](#)

2011

<http://www.psr.d.hawaii.edu>

psrd@higp.hawaii.edu