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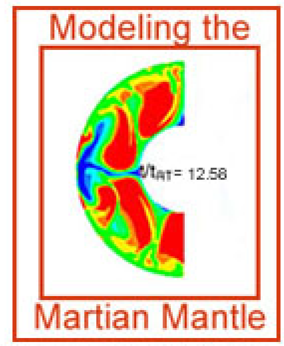

Elkins-Tanton, L. T., S. E. Zaranek, E. M. Parmentier, and P. C. Hess (2005) *EPSL*, v. 236, p. 1-12.

A Primordial and Complicated Ocean of Magma on Mars

--- Geophysical and geochemical calculations indicate that total melting of Mars during its formation could have led to large-scale heterogeneities in its mantle.

Written by G. Jeffrey Taylor
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It seems almost certain that the Moon was surrounded by an ocean of magma when it formed. This important idea has been applied to the other terrestrial planets and even to asteroids. Linda (Lindy) Elkins-Tanton and colleagues Mark Parmentier, Paul Hess, and Sarah Zaranek at Brown University, and Lars Borg and David Draper (University of New Mexico) have examined the chemical and physical consequences of magma ocean crystallization on Mars. Elkins-Tanton has focused on the fate of the pile of crystals created during solidification of a magma ocean over a thousand kilometers thick. Crystallization causes the minerals that form first to lie beneath those formed later. The deepest minerals are also less dense than the overlying minerals. This is an unstable situation: the low-density rocks would have a tendency to rise while the high-density rocks would have a tendency to sink. Although we think of rocks as solid and hard, when hot and under pressure, they flow like liquids. They do not flow fast, but they do flow like ultra-gooey liquids (about a factor of 100 million billion times gooier than ketchup at room temperature). Thus, the heavy layers sink and the light layers rise, producing a complicated Martian mantle with chemical characteristics like those cosmochemists infer from studies of Martian meteorites. The sinking of relatively cool rocks from the top of the crystallized pile cools the boundary between the metallic core and the mantle, causing motions inside the core to produce the early, strong magnetic field of Mars.

References:

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- Elkins-Tanton, L. T., E. M. Parmentier, and P. C. Hess (2005) Possible formation of ancient crust on Mars through magma ocean processes. *Journal of Geophysical Research,* v. 110, E12S01, doi:10.1029/2005JE002480.
- Elkins-Tanton, L. T., S. E. Zaranek, E. M. Parmentier, and P. C. Hess (2005) Early magnetic field and magmatic activity on Mars from magma ocean cumulate overturn. *Earth and Planetary Science Letters,* v. 236, p. 1-12.

An Exceptionally Brief History of Mars

Mars was a geologically happenin' place during its first billion years of existence, and particularly during its first 50 million years or so. Substantial early melting caused formation of a metallic core, silicate mantle, and at least half of the rocky crust within 50 million years after the planet formed. Metallic iron dribbled to the center to make a metallic core within about 15 million years after the formation of the solar system. These early events are recorded by the isotopes in Martian meteorites [see **PSRD** article Magma and Water on Mars], by the presence of highly-cratered terrain in the highlands and underlying the smooth northern plains, and by magnetized regions in the most ancient terrain. This early activity may have been driven by rapid accretion of Mars from countless smaller objects, a manufacturing process that might have taken only a million years after the beginning of the solar system.

After the initial pulse of melting, much of the igneous and tectonic activity focused around the Tharsis region, home of prominent volcanoes on Mars. Tharsis is a huge bulge in the crust, pushed up by forces below and decorated with volcanoes and lava flows. Magmas may have heated the crust, releasing water to form vast valley networks. Volcanism spewed large quantities of water and carbon dioxide into the atmosphere, further helping to erode the surface, though how much was eroded by rain and for what length of time water could have been stable is not known. Much of the construction of Tharsis was complete by the end of the Noachian period, well over 3 billion years ago. Volcanism and water-related processes have been intermittent since then.

Because so much happened during the first billion years, cosmochemists are particularly interested in it. This applies especially to the first 50 million years, when the planet underwent its initial differentiation into metallic core, silicate mantle, and primary crust. Because the planet probably formed rapidly, it might have melted like the Moon did. This early melting would have set the stage for the subsequent geologic history of Mars. In other words, it's a big deal, hence the interest in this event by Lars Borg and Dave Draper, and Lindy Elkins-Tanton and her colleagues.

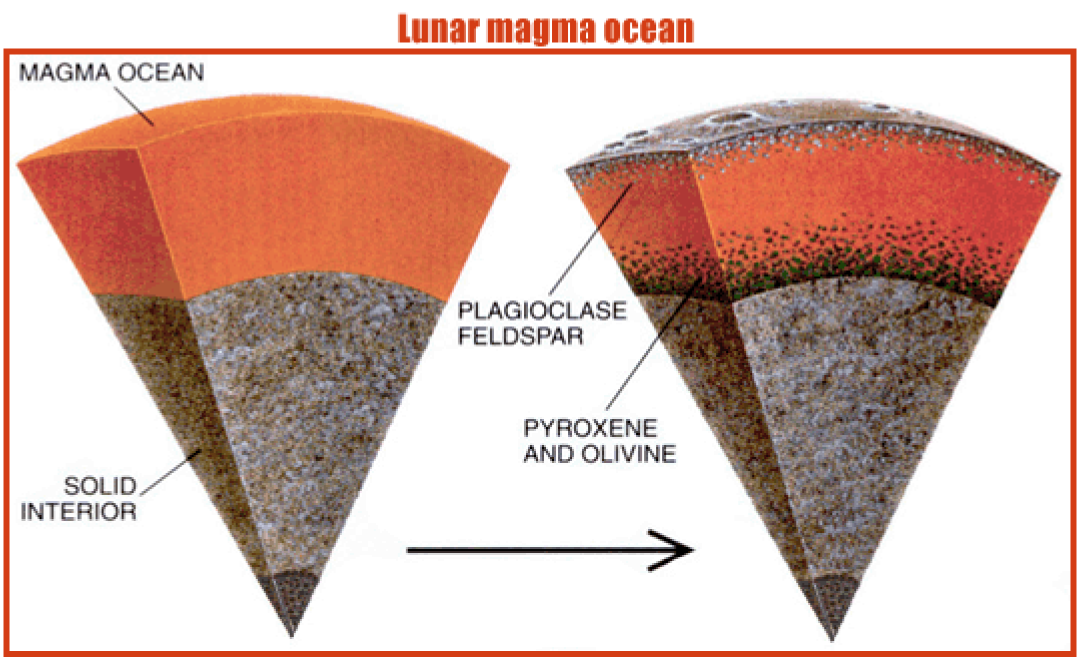
The Moon as a Model

Lunar samples brought to Earth by Apollo astronauts changed the way we look at the early history of the Moon and inner planets. Before astronauts collected the first samples, we knew little about the Moon's chemical composition. We did know from careful geologic mapping using telescopic and then Lunar Orbiter photography the relative sequence of geological events that shaped its surface, but we did not know the ages of rocks in the highlands or when lavas made the maria. In fact, we did not know for sure that the lunar maria (the dark areas on Moon) were composed of lava flows. Cosmochemists were shocked when they looked at the samples returned by the first piloted lunar landing, Apollo 11. In the charcoal gray grit scooped up by Neil Armstrong and Buzz Aldrin were white rock fragments a few millimeters across. They were clearly different from the other rock fragments, which were either pieces of lava flows demolished by impacts or mixtures of rocks (breccias) formed when impacts compacted lunar regolith.

Everybody who examined the soil samples in detail noted the white fragments and showed that they were quite different from the basalts that make up the Sea of Tranquility. The white fragments were made almost entirely of one mineral, plagioclase feldspar. Such rocks are called "anorthosite." In a bold leap, John Wood, then at the Smithsonian Astrophysical Observatory, suggested that the anorthosite fragments were tossed to the Apollo 11 landing site by impacts in the highlands. He claimed that not only were the nearby highlands composed of anorthosite, but all the highlands were. How could such a large area be composed of one rock type? Wood took another bold leap and said that when the Moon formed it melted, producing a huge ocean of magma around it. Plagioclase, a low-density mineral, floated to the top, while denser minerals sank. The millimeter-sized anorthosite rock fragments were pieces of the primary lunar crust.

(John Wood)

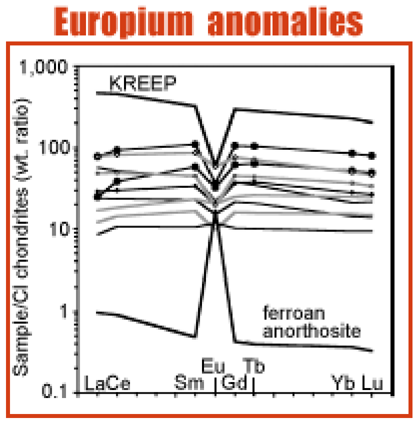
The photograph on the **left** shows a collection of 2 to 4 millimeter rock fragments sieved from an Apollo 11 soil sample by John Wood and his colleagues at the Smithsonian Astrophysical Observatory in 1969. Most fragments are dark basalts or impact breccias, but pieces of white, feldspar-rich rock are also present (near the millimeter-scale bar). These sparked Wood's imagination, leading to the idea of the lunar magma ocean.



(Adapted from G. J. Taylor (1994) The scientific legacy of Apollo, *Scientific American*, v. 271, p. 40-47.)

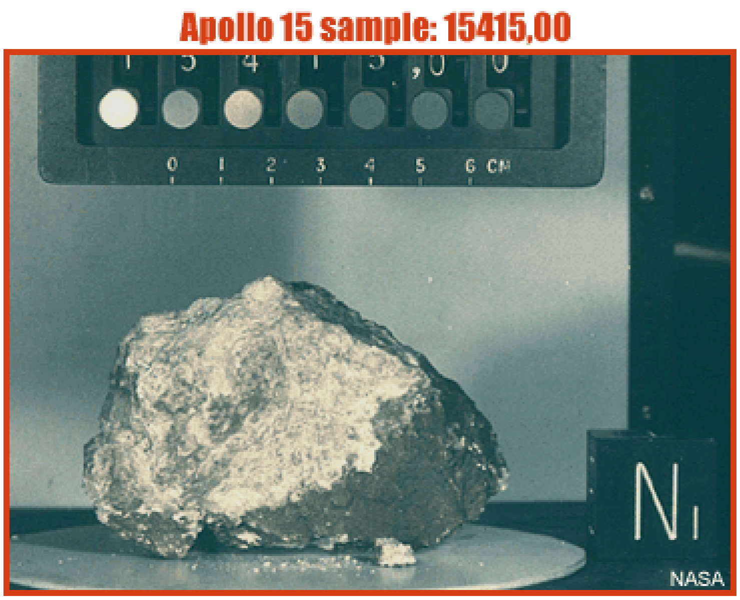
In the ocean of magma covering the baby Moon, lightweight minerals floated and heavy ones sank. The lighter minerals formed the crust of the Moon.

The magma ocean was an imaginative idea, and there was some other evidence for it. The Apollo 11 basalts provided one bit of evidence. Cosmochemists found that some chemical characteristics of mare basalts were complementary to those of anorthosites. This suggested that the regions in the deep interior of the Moon where the basalt lavas formed by partial melting were part of the same magma from which the anorthosites formed. Since the mare basalts formed at depths of hundreds of kilometers, the magma must have been hundreds of kilometers thick. A prominent example of such complementary chemical features is the abundance of europium, which is depleted in mare basalts and enriched in anorthosite. Further evidence was provided by the presence of abundant anorthosite at the Apollo 16 landing site in the lunar highlands.



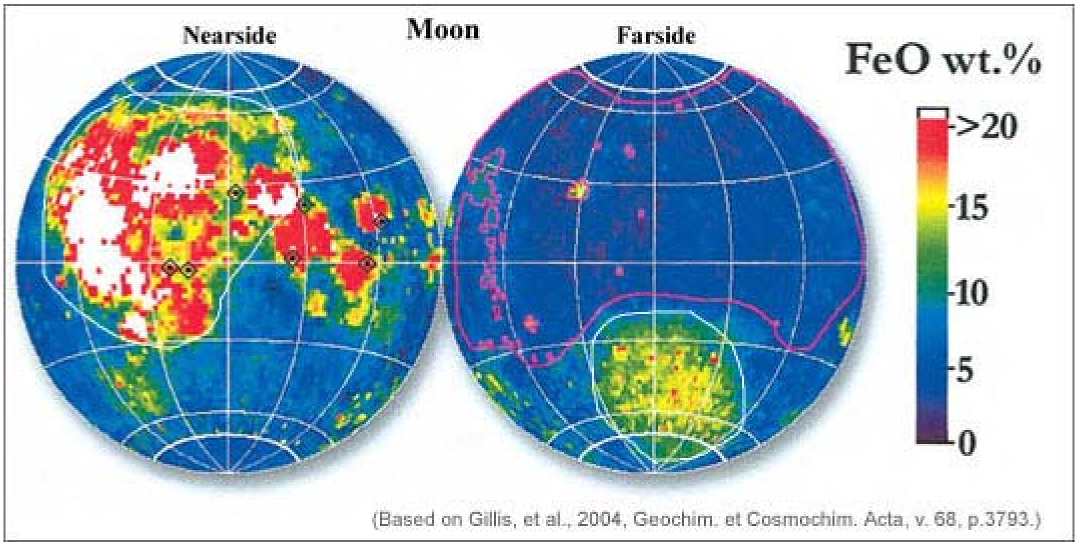
(Adapted from Warren, P. (2004)The Moon, in *Treatise on Geochemistry*, v. 1.)

Plot of the abundances of the rare earth elements for lunar anorthosites, mare basalts, and KREEP. Note the large, positive europium (Eu) anomaly in the anorthosite. The mare basalts have negative Eu anomalies, indicating that the minerals making up their source regions in the lunar mantle formed in a magma from which plagioclase feldspar (the main constituent in anorthosite) had been removed. The negative anomaly in KREEP is even more severe, consistent with it representing the last dregs of magma ocean crystallization.



Photograph of the first large anorthosite sample returned from the Moon, rock 15415, collected during the Apollo 15 mission. Apollo 16 returned lots of anorthosite samples.

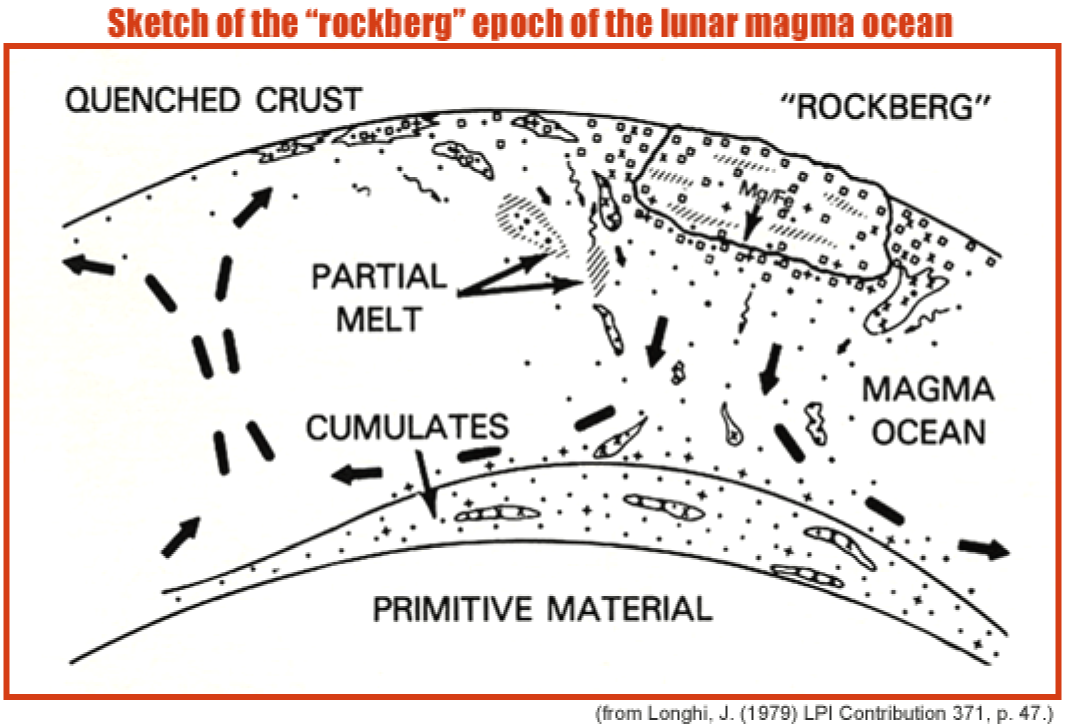
In spite of this early success, we still lacked the most basic evidence: proof that the ancient highlands are made of anorthosite. The Clementine mission (1994) and my colleague Paul Lucey (University of Hawaii) solved this problem. Clementine snapped pictures of the entire lunar surface. Lucey, using Apollo landing sites and returned soils as ground truth, figured out how to convert the intensity of reflected light to the concentration of FeO [see **PSRD** article Moonbeams and Elements]. Anorthosite is composed chiefly of feldspar, which has very little FeO. It does contain some minerals with FeO, so anorthosite might contain a few percent FeO. The maps produced from the Clementine data show huge regions of the highlands, especially on the farside, that contain between 2 and 6 wt% FeO, with an average about 4 wt%, as predicted by the magma ocean hypothesis. Measurements by the Lunar Prospector mission confirmed the Clementine measurements.



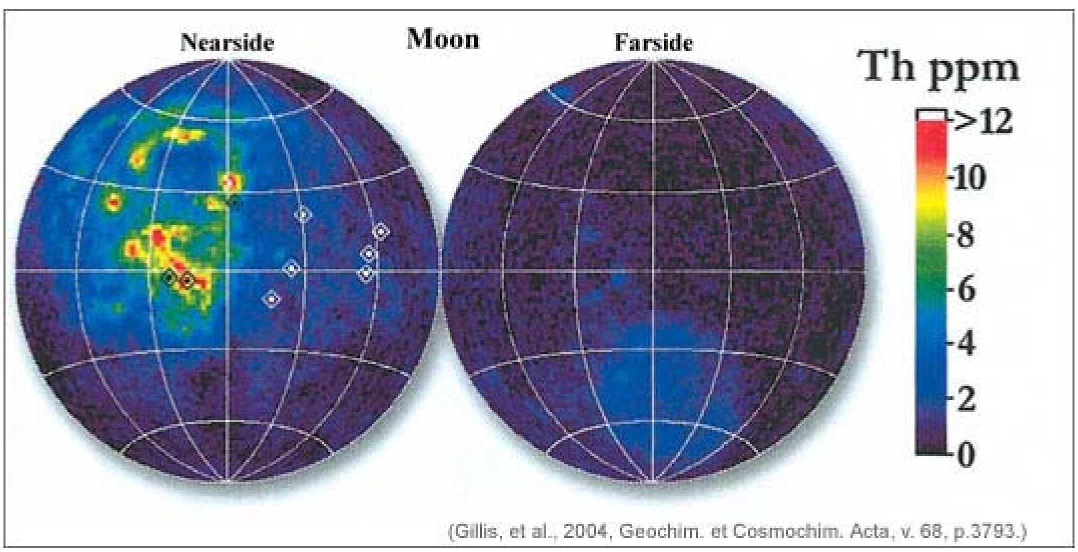
The maps, above, show the concentration of FeO on the Moon, as determined from Clementine data using a technique developed by Paul Lucey (University of Hawai'i) and updated by Jeff Gillis-Davis (previously at Washington University in St. Louis and now at the University of Hawai'i), Brad Jolliff, and Randy Korotev (both at Washington University in St. Louis). Low FeO translates into high Al_2O_3, consistent with the presence of lots of anorthosite, as predicted by the magma ocean hypothesis.

Once the magma ocean idea became entrenched in our thinking, cosmochemists began to examine the processes that could have operated in it. They began with knowledge gained from studies of layered intrusions on Earth. These are large bodies of magma that solidified far beneath the surface. As they cooled, minerals formed distinctive layers, some looking a bit like sediments deposited by rivers, but in this case the rivers were masses of swirling magma. However, a big difference was in scale. Terrestrial layered intrusions perhaps reach 8 kilometers in thickness and range in area from 100 km^2 (Skaergård, E. Greendland for example) to 66,000 km^2 (Bushveld, S. Africa). The lunar magma ocean was globe encircling and hundreds of kilometers deep. The terrestrial examples took us only so far.

Cosmochemists depicted numerous processes operating in the magma ocean. It would have crystallized substantially at its base because of the higher pressure there. It would have been vigorously convecting, preventing minerals from settling until the magma became choked with crystals. Once plagioclase floated to the top, it would begin to form a crust, creating what John Longhi (now at Columbia University) called rockbergs. There would have been reactions at the margins of the rockbergs, changing the composition of the magma. As the base solidified, residual, highly-evolved magma would have oozed upwards, mixing with the overlying magma, or even traveled through the magma all the way to the growing crust to crystallize there. As crystallization proceeded the magma became richer in a group of elements that do not readily concentrate in the major minerals forming from the magma (olivine, pyroxene, plagioclase, and ilmenite). They became greatly enriched in the leftover magma ocean. These elements include potassium (K), rare earth elements (REE), and phosphorus (P). This leftover stuff became a prominent constituent of many rocks returned from the Moon, and received the nickname KREEP. Paul Warren and John Wasson (University of California, Los Angeles) called the very last leftover magma "urKREEP," using a German prefix that means "primary." UrKREEP was also rich in thorium (Th), which allowed the Lunar Prospector mission to use its gamma ray spectrometer to map its distribution. For obscure reasons, thorium is concentrated on the lunar nearside.

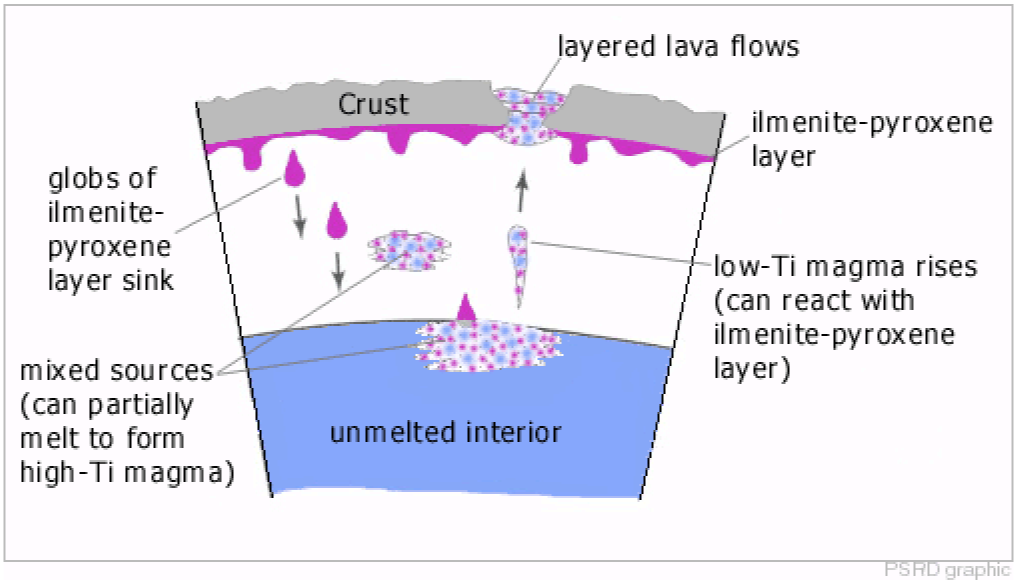


This is John Longhi's 1979 sketch of the processes operating in the lunar magma ocean. Even this complicated diagram is probably an oversimplified view of what happens in a huge body of magma.



Thorium (Th) is not distributed uniformly on the Moon. Somehow it and other elements that are not readily incorporated into major minerals ended up concentrated in one region of the Moon.

Once the magma ocean had crystallized, it would have been less dense at the bottom than at the top because the first minerals to form would have had higher magnesium to iron ratios. For example, olivine ranges in density from 3.2 if it is Mg_2SiO_4 to 4.3 if it is Fe_2SiO_4. The density of the olivine crystallizing from the magma ocean did not reach either extreme value, but there was a significant difference between the lower and upper portions of the accumulated pile of crystals. Pyroxene behaves the same way, and once ilmenite ($FeTiO_3$) crystallized (density from 4.5 to 5) the rocks on top would have been quite dense, resulting in a tendency for the whole pile to overturn. Although mostly solid, the hot rocks would have been ductile enough to move slowly upwards and downwards, forming a more stable, but complicated lunar interior.



Dense, titanium-rich rock might have sank through the underlying rock in the lunar mantle, while low-density rocks rose, scrambling the lunar mantle.

Cosmochemists have investigated the consequences of a magma ocean encompassing the primitive Earth and asteroids. Detailed models for Mars have only recently been discussed. This work is driven in part by our growing understanding of the chemical characteristics of Martian meteorites.

A Geochemical View of the Martian Magma Ocean

The Moon has a primary crust made of anorthosite, formed by plagioclase feldspar floating in its magma ocean. We do not observe this on Mars, but should we expect to see it? If not, what should we see? In other words, how do we test whether there was a magma ocean or not on Mars? Borg and Draper, and Elkins-Tanton and her colleagues have focused on the properties of the Martian mantle we infer from Martian meteorites. Although we have only about 30 of these important rocks and all but one are among the youngest rocks on Mars (all less than 1.3 billion years old), they still contain high-fidelity information about the mantle and when it formed. As detailed in the **PSRD** article The Multifarious Martian Mantle, the shergottite group of Martian meteorites indicates that there are at least two distinct reservoirs in the mantle. They have the characteristics outlined in the table below.

Enriched Reservoir	high La/Yb low Sm/Nd ($-\varepsilon_{Nd}$) high Rb (high $^{87}Sr/^{86}Sr$) oxidized
Depleted Reservoir	low La/Yb high Sm/Nd ($+\varepsilon_{Nd}$) low Rb (low $^{87}Sr/^{86}Sr$) reduced

There are other reservoirs as well, such as those that manufactured the nakhlite group of Martian meteorites and another that produced the 4.5 billion year old ALH 84001 meteorite, but the shergottite-producing regions give cosmochemists modeling a Martian magma ocean something to use as a test. Another important feature is that the regions of the mantle in which the Martian meteorites formed are depleted in aluminum compared to terrestrial basalts. Magma ocean models must account for that as well.

Mars is much larger than the Moon, causing the pressure inside Mars to be higher than in the Moon. This greatly affects calculations of crystallization in a magma ocean on Mars compared to the Moon--the deeper the magma ocean, the higher the pressure in it. In a Martian magma ocean deeper than several hundred kilometers, high pressure minerals such as garnet form. This greatly changes the course of crystallization compared to the lunar magma ocean. Garnet can contain a hefty amount of aluminum, which ends up deposited at depth. It is not available to make an anorthosite crust as on the Moon. Furthermore, garnet and other minerals affect the concentrations of trace elements in the magma ocean as it crystallizes. Fortunately, all this can be modeled mathematically using experimental data as a basis.

When modeling the lunar magma ocean, cosmochemists used a thorough knowledge of the order in which minerals crystallize in magma at low pressure. There are good computer programs available that enable these calculations. Unfortunately, such computer programs are not available for higher-pressures systems like those inside Mars. Besides that, experimental coverage at the right range of pressures is not thorough enough. This means that the crystallization sequence is not known as well as it is for the Moon. As a result, Borg and Draper had to make some reasonable guesses based on cosmochemical savvy.

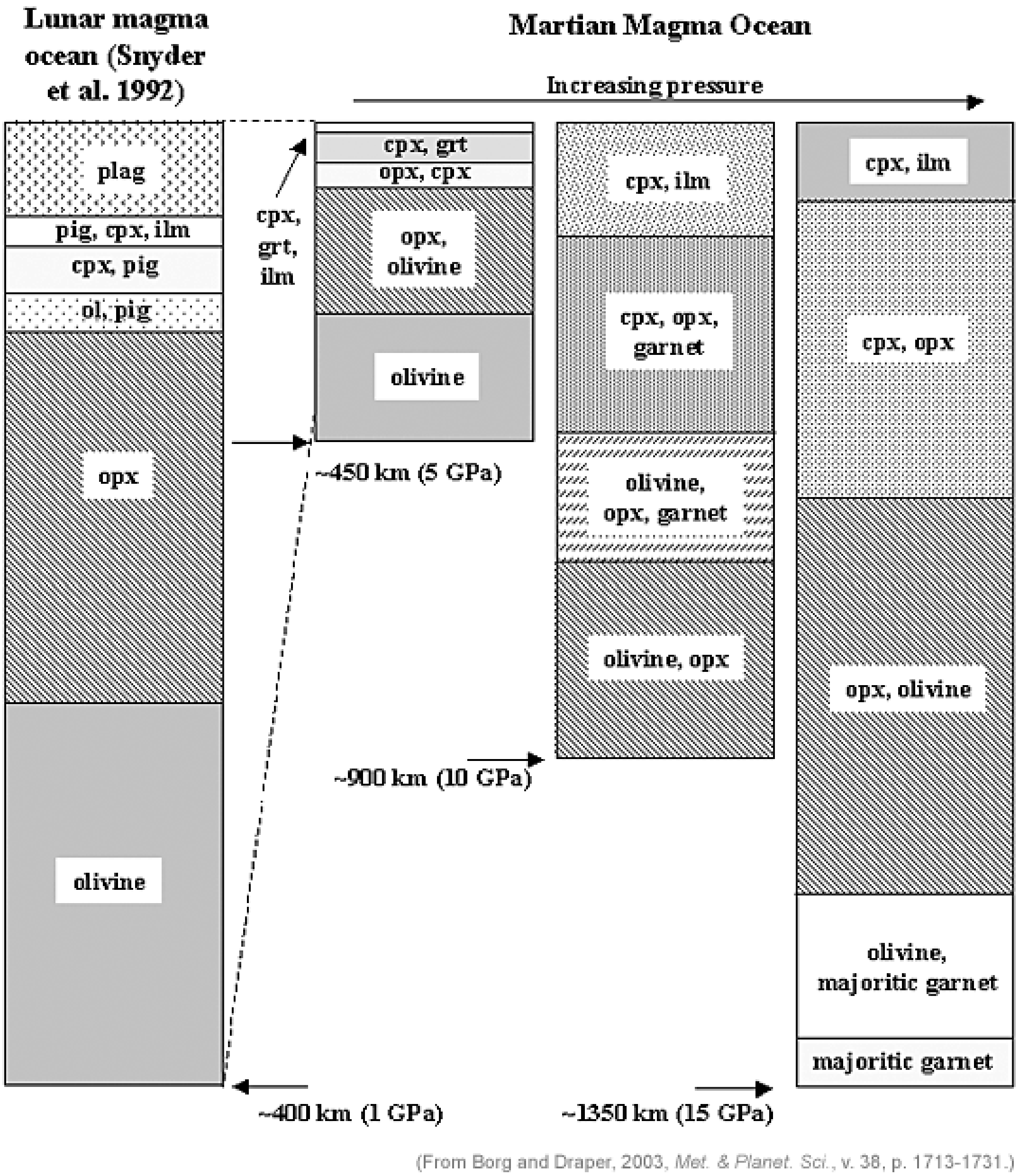
Fortunately, Dave Draper, Carl Agee (University of New Mexico), and their colleagues have been working to fill in gaps in the experimental database at high pressure. Many experimental studies done at high temperature and pressure had used a composition not close enough to what cosmochemists think Mars has. (Of course, that composition is a bit uncertain, too!) The major difference is the dissimilarity in the concentration of iron oxide compared to Earth and the Allende meteorite, the subjects of other experimental studies. Draper is a skilled experimentalist. He takes samples of silicate material (rocky stuff) and puts them in an experimental apparatus that heats and squeezes the sample. The pressure in his experiments reached 150,000 times that at the surface of the Earth at a temperature as high as 2000 Celsius.

Multi-anvil Press

(Courtesy of High Pressure Lab, Institute of Meteoritics, UNM.)

Dave Draper and his colleagues used this hydraulic device for experiments at high pressure and high temperature. The sample is contained in between ceramic octahedra located inside tungsten carbide cubes, which are placed inside a cylindrical module. The press then squeezes it all to the desired pressure. This photo was taken in 2002 when the apparatus was located at the Johnson Space Center. Standing next to the press is Jana Berlin, an undergraduate participant in the Summer Intern Program run by the Lunar and Planetary Institute [website]. More details of the apparatus, which is now at the University of New Mexico, can be found at the high-pressure laboratory's [website]. The lab was moved to UNM from the Johnson Space Center. (The construction of the new lab and moving the equipment makes an interesting story.)

The experiments filled in gaps in our knowledge of what minerals crystallize at different pressures inside Mars. The picture is not complete, but it is a reasonably detailed sketch. It allowed Borg and Draper to determine the crystallization sequence in a Martian magma ocean, hence to trace the way elemental concentrations changed as each layer crystallized from the magma. They studied three cases: shallow, medium, and deep magma oceans (see diagram below).

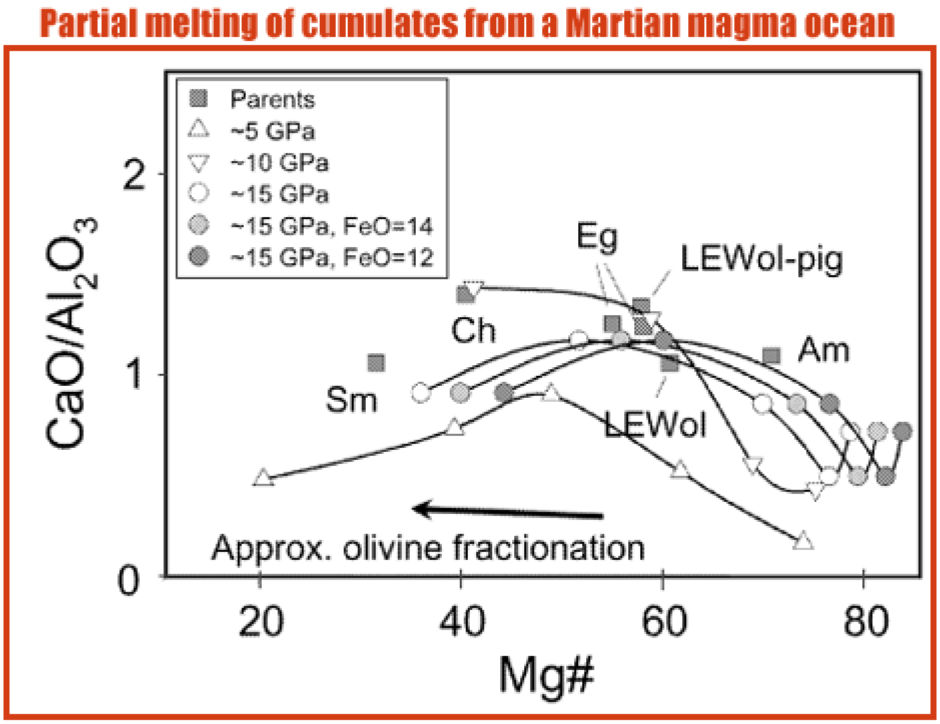


Cartoon showing crystallization sequences, on the left, of the lunar magma ocean (calculated by Greg Snyder, then at the University of Tennessee) and, on the right, three Martian magma oceans with different depths, hence pressures. Higher pressure in deeper oceans results in different distributions of the elements. Borg and Draper do not intend these diagrams to represent the precise layering developed in a magma ocean because accumulated layers may not be uniform around the entire globe and because, as discussed below, they might rise or sink depending on their densities.

Borg and Draper calculated how the concentrations of major elements changed with magma ocean crystallization and accumulation of the crystallizing minerals. In a separate set of calculations they assessed how the concentrations of trace elements changed in the layers of accumulating minerals and in the leftover magma. The leftover magma, which cosmochemists typically dub "residual magma" or "trapped liquid," plays a critical role in the chemical characteristics of the magma produced by subsequent melting of cumulate layers. Borg and Draper compared these calculated magmas to the compositions of Martian meteorites or the estimated compositions of the primary magmas of the Martian meteorite lava flows.

The Martian meteorites are characterized by a depletion of aluminum oxide (Al_2O_3) compared to typical basalts on Earth. This is usually expressed as the ratio CaO/Al_2O_3. The calculations indicate that Martian meteorite magmas cannot be made by cumulate rocks that formed in a shallow, low-pressure magma ocean. Such conditions lead to lower CaO/Al_2O_3 ratios than observed in the Martian meteorites. This suggests to Borg and

Draper that garnet (formed at high pressure) must have crystallized to remove aluminum from the magma. Recent results from the Mars Exploration Rovers suggest that not all Martian rocks have high CaO/Al_2O_3. These might represent magmas formed in portions of the mantle that were not depleted in aluminum. Alternatively, they might have formed much longer ago than were the Martian meteorite magmas. Their formation might have removed more aluminum than calcium from the mantle, leaving behind a depleted mantle containing high CaO/Al_2O_3 from which the young Martian meteorites formed.



(from Borg and Draper (2003) *Meteoritics & Planetary Sci*, v. 38, p. 1720, Fig. 5a.)

This graph shows how the ratio of calcium oxide to aluminum oxide would vary as a function of the ratio of magnesium oxide to magnesium oxide plus iron oxide (Mg#) during partial melting of cumulates from a Martian magma ocean. The letters denote assorted estimates of the magmas that gave rise to some of the Martian meteorites. Cumulates formed at low pressure do not produce magmas (bottom line) with sufficiently high CaO/Al_2O_3, but those formed at high pressure do. This suggests that the magma ocean on Mars was deep, allowing formation of garnet, which sops up aluminum. This leaves the overlying rock depleted in aluminum and having high CaO/Al_2O_3.

The trace element calculations were done only for the deep magma ocean case because that is required to explain the CaO/Al_2O_3 ratio. Borg and Draper show that magmas representing the distinctive reservoirs discussed above could form by various combinations of cumulate minerals and trapped liquids. The results are not perfect, perhaps indicating additional complexities need to be taken into account. For example, potassium in calculated magmas does not match those of Martian meteorites. This might indicate that a potassium-bearing mineral (such as phlogopite) formed and affected trace element distributions. However, Borg and Draper tested this idea, too. They found no combination of minerals that could explain all the discrepancies at once. If potassium worked out, then tantalum, for example, did not.

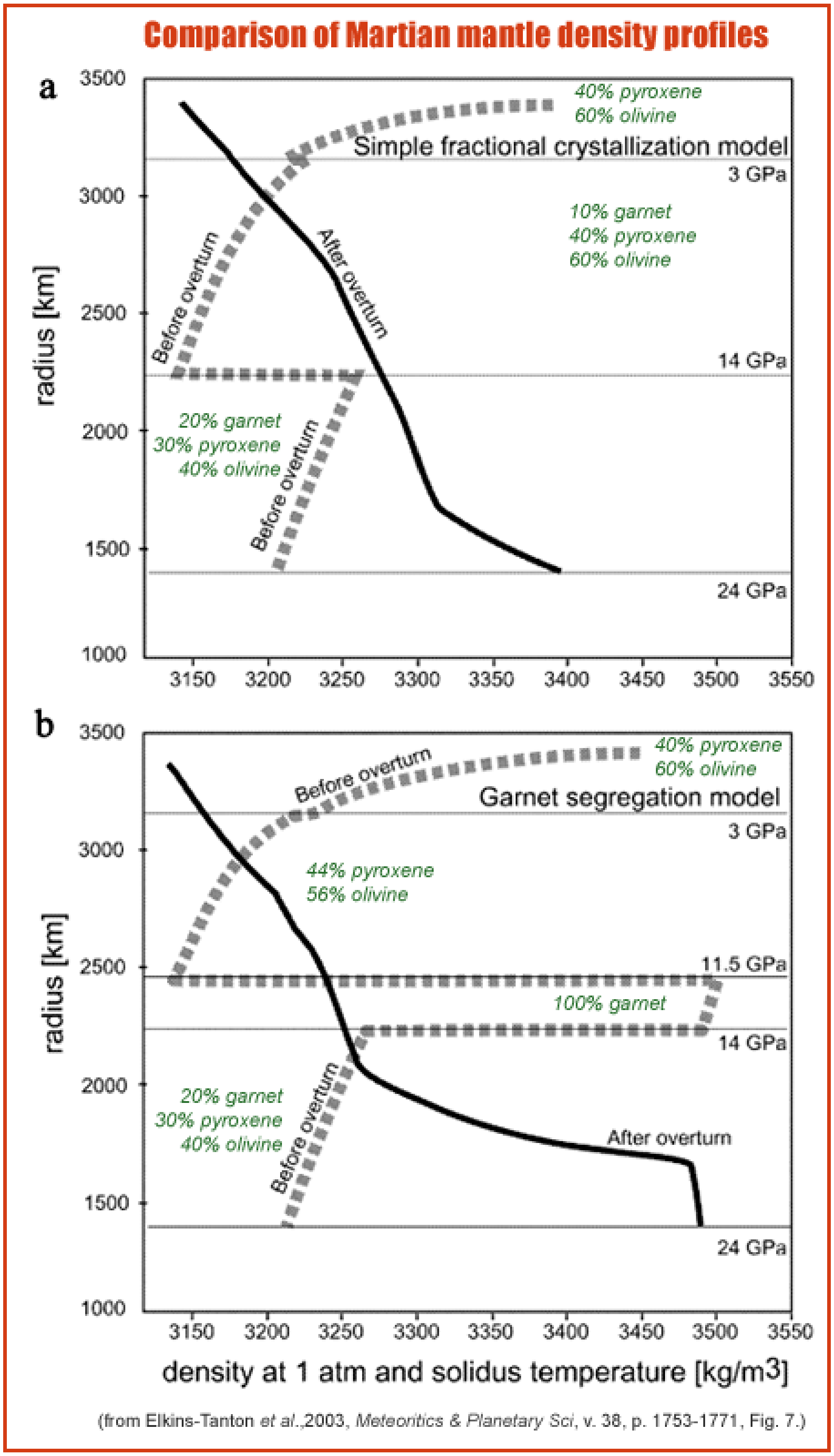
After publication of the 2003 paper by Borg and Draper, Dave Draper and his colleague Carl Agee reported on a series of high-pressure experiments using H-chondrites as starting materials. These experiments led them to conclude that the bulk composition of the rocky portion of Mars (hence of the original magma ocean) may have contained less iron oxide than cosmochemists have thought previously. This led Draper to run his magma ocean calculations again, using the slightly lower iron oxide concentration (12 or 14 wt%, rather than 18 wt%). The match with Martian meteorites is even better than before. It still explains the high ratio of CaO to Al_2O_3. And, the less iron-rich mantle reproduces a property called the moment of inertia factor. This factor was determined with great accuracy from measurements during the Pathfinder mission of how the pole of Mars changes the direction it is pointing. It assesses the distribution of mass inside the planet. The previous calculations with higher iron oxide also reproduce the moment of inertia factor, but this new calculation is even closer.

None of these calculations prove that a magma ocean existed on Mars, but they show that it is feasible. And complicated. The geochemical calculations are quite intricate, yet oversimplify what must have happened in a Martian magma ocean and afterwards. Some of that afterwards story is told by Lindy Elkins-Tanton and her colleagues.

A Geophysical View of the Martian Magma Ocean

Planets are dynamic. As a Martian magma ocean crystallized, the lowermost layers would have lower density than did layers higher up. This gradient in density is caused by the compositional changes in the magma as it evolves during crystallization. One major factor is that the ratio of iron to magnesium in olivine and pyroxene increases as the magma crystallizes. Fe/Mg decreases with depth in the crystallized magma ocean. There would be a tendency for lower layers to rise, the way blobs rise from the bottom of those sometimes fashionable but never classy lava lamps. Lindy Elkins-Tanton and her colleagues have studied the nature of this overturn.

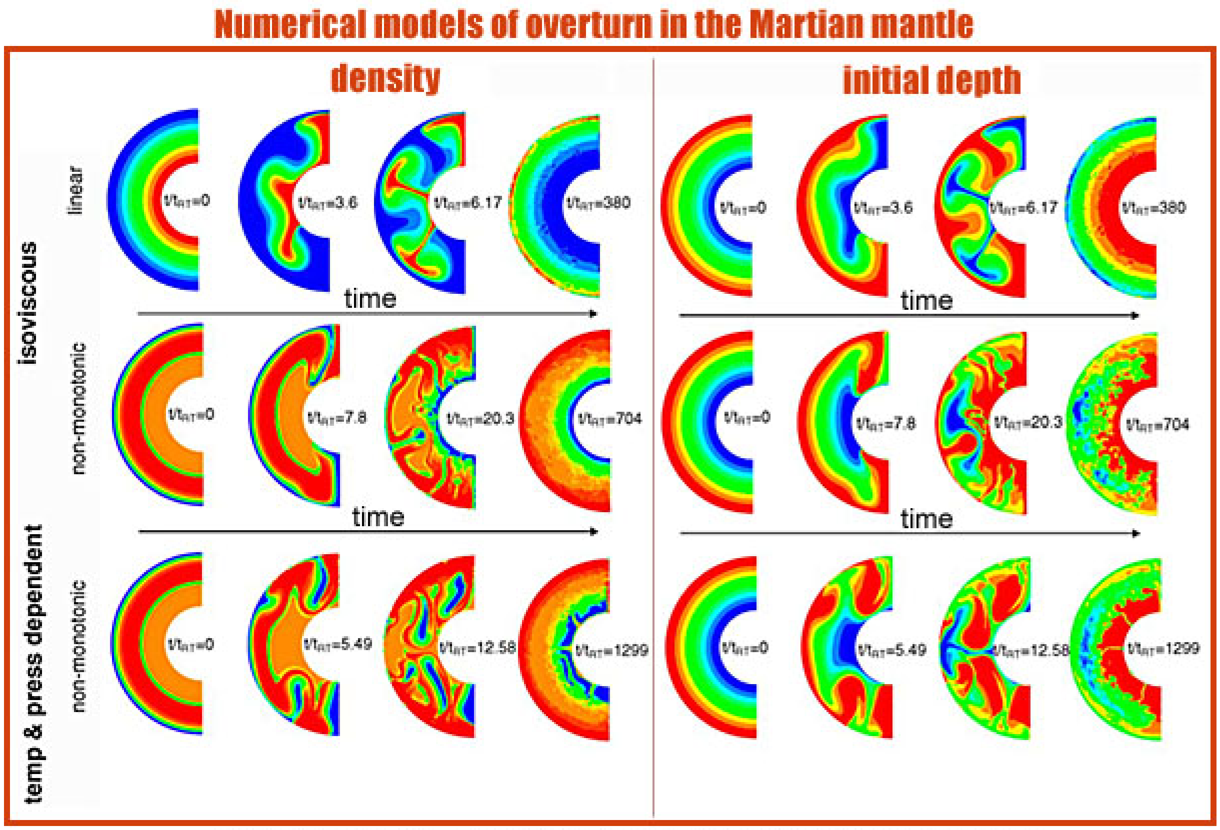
The first step in calculating the overturn of a magma ocean cumulate pile is to make the pile in the first place. This is much more complicated than assessing an order of crystallization. You have to worry about how the crystals separate and whether they are swept up in the convective flow that must accompany cooling of a huge, globe-encircling body of magma. There is an exquisite body of literature evaluating crystallization in magma bodies. It describes fluid dynamic theory, field observations of large layered igneous intrusions, and laboratory experiments. In spite of all this research, our understanding is not complete. Nevertheless, it allowed Elkins-Tanton to calculate two reasonable cases for the distribution of minerals and the density variation with depth after magma ocean crystallization. These are summarized in the diagram below.



Estimate of how the density of the Martian mantle varied with depth right after magma ocean crystallization and after it overturned. Elkins-Tanton tested two cases. In one case crystals settle in the general order in which they crystallize and with the densest at the bottom. In the other case, some of the garnet accumulates at the pressure at which it is dense enough to settle, but the other minerals (olivine and pyroxene) are buoyant and remain entrained in the remaining liquid. The garnet forms a dense layer in the middle of the pre-overturn mantle. The density variations (hence the abundances of minerals with depth) would probably not have been uniform around the entire planet.

Modeling the crystallization of a magma ocean is tricky. So is modeling the overturn of the products of that crystallization. The rate and duration of overturn is dependent on other factors besides density. A calculation must include consideration of temperature because density, crystal structure, and compressibility all depend on temperature. The extent to which a mineral becomes denser with pressure (compressibility) is also important. So is the stability of high pressure minerals: as a portion of mantle rises, some minerals transform to lower density forms, impeding ascent. On top of all that, the viscosity of the flowing mantle rock changes with pressure and temperature. It is one complicated physics problem!

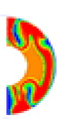
Lindy Elkin-Tanton's colleague at Brown University, Sarah Zaranek, produced highly illustrative visualizations of the overturn (see below). They show that when the mantle is finished overturning, the result is not simply an orderly rearrangement of the layers. It is a messy process that produces lateral heterogeneities, unless the viscosity is constant throughout the mantle and throughout the overturn event (which was almost certainly not the case). Lateral variations in composition would produce complicated variations in rock compositions on Mars, which is observed by instruments on the Mars Odyssey spacecraft.



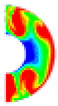
(from Elkins-Tanton, *et al.*, 2005, *Earth and Planetary Science Letters*, v. 236, p. 1-12, fig. 3.)

These colorful models of the Martian mantle show evolution of density stratification and movement (colored layers) after crystallization. As overturn occurs (see lefthand side), the dense upper layers sink and the less dense lower layers rise. The final product is a complicated mixture of materials. On the righthand side of the figure, we can track the initial location of a layer and see where it ends up in the complicated Martian mantle.

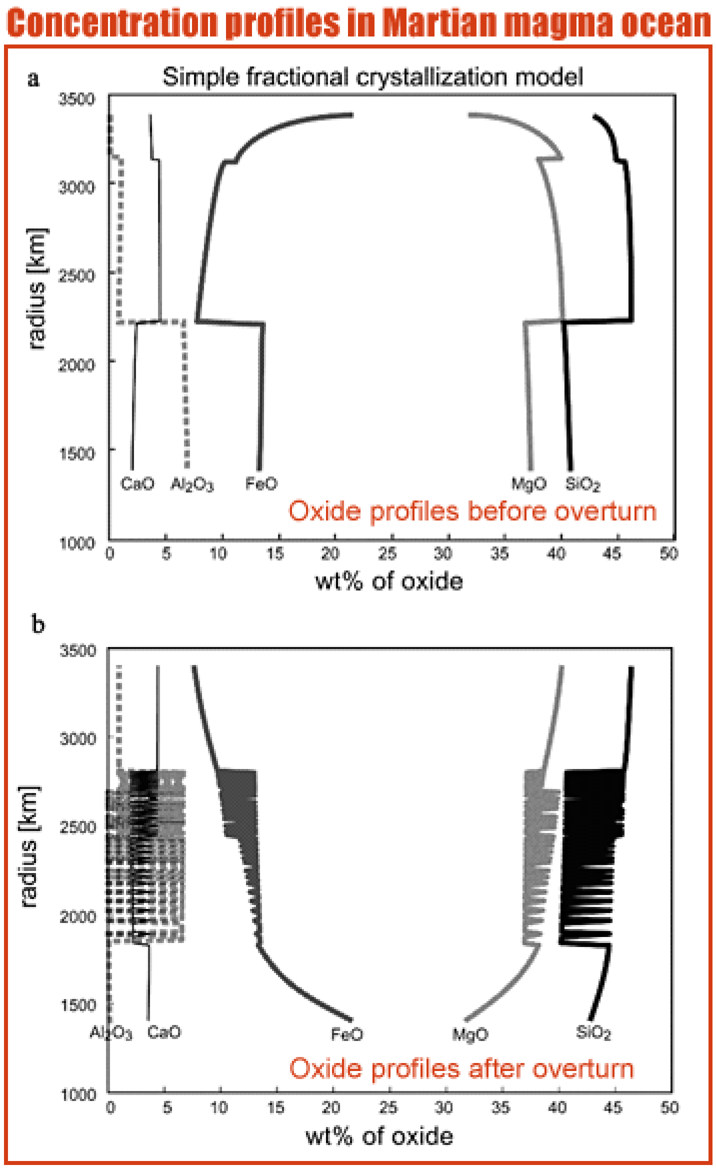
The two movies, linked below, show what happens with overturning of a cumulate Martian mantle with temperature- and pressure-dependent flow and deformation of the materials. These are animations of the bottom row of figures shown above.



+ View Movie 1 Initial layering in density, a proxy for composition, after magma ocean crystallization is shown by different colored layers. As overturn occurs, the dense upper layers sink and the less dense lower layers rise. The final product is a complicated mixture of materials.


+ View Movie 2 In this movie we can track the initial location of a layer and see where it ends up in the complicated Martian mantle. As shown in Video 1 of initial density layering, the final product again is complicated.

Another result of the calculations of crystallization and overturn is graphs of the concentrations of the main oxides that make up Martian crustal rocks. These show significant variations in oxide concentrations with depth. After overturn, these concentrations are completely different. In the middle mantle they oscillate back and forth, indicating significant scrambling of the mantle, as shown in the movies above. There are two distinct regions with different Al_2O_3 concentrations that could subsequently melt to produce most of the Martian meteorites (low in Al_2O_3) and crustal rocks at the Pathfinder, Spirit, and Opportunity landing sites.



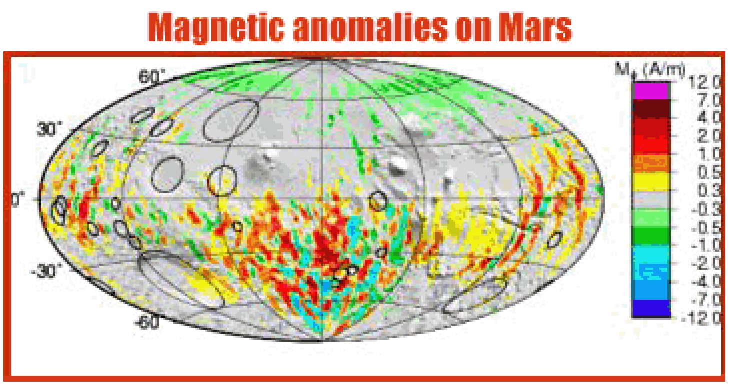
(from Elkins-Tanton *et al.*,2003, *Meteoritics & Planetary Sci*, v. 38, p. 1764.)

Compositional stratification resulting from crystallization of a Martian magma ocean (without formation of a pure garnet layer). Original concentration profiles are drastically altered and there is a mixed-up region in the middle. Partial melting of different regions of the mantle will produce several types of magma, giving rise to a variety of igneous rocks.

Elkins-Tanton and her coworkers and Lars Borg and Dave Draper also investigated the distribution of trace elements in different regions of the mantle, and mathematically melted the mantle to produce magmas. The results are consistent with the picture being painted by Martian meteorites and surface rocks. These sketches show that there is a wide variety of mantle compositional regions and that they formed early in the history of Mars. Elkins-Tanton suggests that the Shergottite group of Martian meteorites could have formed from a shallow region of the mantle that is depleted in Al_2O_3, whereas igneous rocks analyzed at the Pathfinder and Mars Exploration Rover sites formed from deeper regions of the mantle richer in Al_2O_3. It makes a nice, consistent story.

Spin-off: Driving the Early Martian Magnetic Field

Models of mantle overturn explain how we can get the diversity of igneous rocks observed on Mars. But wait, there's more. The models may also explain what created an early magnetic field on Mars. Magnetic measurements by a magnetometer onboard the Mars Global Surveyor spacecraft showed that there are regions of the ancient, heavily cratered highlands of Mars that have significant magnetic anomalies--areas with stronger than average magnetic fields. The fields are recorded by magnetic minerals in rocks.



(Benoit Langlais, 2003, Goddard Space Flight Center, NASA)

Map of the magnetic field strength on Mars. Red colors indicate strong fields, other colors weaker fields. The strong fields occur in the Martian highlands--the oldest exposed parts of the crust.

Most geophysicists think that planetary magnetic fields are generated by convective motions inside metallic iron cores. The motions are driven by cooling of the core, which requires flow of heat into the mantle immediately above the core. Some of the mantle rock arrived as relatively cool cumulates from the upper parts of the magma ocean. This allows for significant flow of heat across the core-mantle boundary, driving convection in the core. However, the heat from the core raises the temperature of the mantle rock, as does heat released by decay of radioactive elements trapped in the cumulates. This slows down the heat flow, inhibiting and then stopping the core dynamo. Elkins-Tanton and her colleagues estimate that this takes between 15 and 150 million years. After that the magnetic field is much weaker. The areas with the magnetic anomalies, therefore, are the oldest on Mars. Other areas in the highlands either formed later or were modified significantly by intrusion of younger magma.

What Next?

The complex models developed by these two teams of cosmochemists and geophysicists make predictions about the types of magma produced on Mars. Continued searching for Martian meteorites in hot and cold deserts on Earth and continued analysis of igneous rocks on the Martian surface by orbital and landed spacecraft will allow tests of these predictions. If unpredicted rocks are found, the models can be modified and we will have learned more about magma ocean crystallization and overturn, and about subsequent partial melting and magma formation.

Artist's conception of the Mars Science Laboratory rover

The Mars Science Laboratory rover will be much larger than the Mars Exploration Rovers Spirit and Opportunity. It will be equipped with instruments that will make analyses of surface rocks and soils, including igneous rocks that can be used to test predictions made by geochemical-geophysical models of formation of the Martian mantle.

ANSMET field team bags a meteorite from the Miller Range icefields, Antarctica

2005-2006 ANSMET team members, Marie Keiding (Univeristy of Iceland), Gordon (Oz) Osinski (Canadian Space Agency), and Shaun Norman (ANSMET Mountaineer and Field Safety Leader) are shown collecting a meteorite from the Miller Range icefields. The continued search for meteorites in the cold desert of Antarctica and in hot deserts of northern Africa and elsewhere will continue to yield new Martian meteorites. Cosmochemists hope that new types are found, expanding our knowledge of the range of igneous rocks on Mars.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- Borg, L. E. and D. S. Draper (2003) A petrogenetic model for the origin and compositional variation of the martian basaltic meteorites. *Meteoritics and Planetary Science*, v. 38, p. 1713-1731.
- Elkins-Tanton, L. T., E. M. Parmentier, and P. C. Hess (2003) Magma ocean fractional crystallization and cumulate overturn in terrestrial planets: Implications for Mars. *Meteoritics and Planetary Science*, v. 38, p. 1753-1771.
- Elkins-Tanton, L. T., E. M. Parmentier, and P. C. Hess (2005) Possible formation of ancient crust on

Mars through magma ocean processes. *Journal of Geophysical Research*, v. 110, E12S01, doi:10.1029/2005JE002480.

- Elkins-Tanton, L. T., S. E. Zaranek, E. M. Parmentier, and P. C. Hess (2005) Early magnetic field and magmatic activity on Mars from magma ocean cumulate overturn. *Earth and Planetary Science Letters,* v. 236, p. 1-12.
- Taylor, G. J. (1997) Moonbeams and Elements. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/Oct97/MoonFeO.html
- Taylor, G. J. (2004) The Multifarious Martian Mantle. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/June04/martianMantle.html
- Taylor, G. J. (2005) Magma and Water on Mars. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/Dec05/Magma-WaterOnMars.html

Excellent recent reviews of Martian geological, geophysical, and geochemical evolution:

- Nimmo, F. and K. Tanaka (2005) Early crustal evolution of Mars. *Annual Reviews of Earth and Planetary Science,* v. 33, p. 133-161.
- Solomon, S. and many others (2005) New perspectives on ancient Mars. *Science,* v. 307, p. 1214-1220.

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