The Apollo Conundrum: The Moon Clearly Had a Magma Ocean. Did Earth?

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Abstract

When Apollo returned the first moonrocks, a major surprise was that the lunar highlands are built of a single mineral - feldspar. Feldspar crystals floating to the top of a moon-magma ocean can explain this composition. If accepted as a key early stage in lunar evolution, it is a logical leap to infer that Earth must have had a similar – or larger – magma ocean during its early evolution. (The gravitational impact energy per unit mass that is released during a planetesimal's accretion scales as GM/R.) The nagging problem with the inference that Earth passed through an early magma-ocean stage is that the oldest rocks on Earth show no direct signs of a magma ocean. Instead the petrology of the oldest preserved Earth rocks shows clear evidence that repeated events of small to medium degrees of partial melting and melt extraction, as opposed to pervasive fractional crystallization, has been the modus operandi of terrestrial differentiation. The big difficulty is how to effectively 'remix' the products of an early terrestrial magma ocean back into the quasi-uniform 'primordial' pyrolite/peridotite silicate lithology from which oceanic and continental crust are thought to have evolved by partial melting events. Here I propose that a partially molten silicate body is actually highly resistant to the formation of a magma ocean. Jing and Karato (2012)'s experiments imply that a silicate melt should absorb much more impact shock-energy than either a silicate solid or an iron solid/melt. In this case, impact energy will be heterogeneously added into the growing proto-Earth, with silicate partial melts being shock-compression-heated to their vaporization temperature before their surrounding silicate solids heat to their melting point. The growing partially molten planetary surface will tend to 'explode' during impact events, with each impact-induced-explosion using a relatively small mass of vaporized silicate partial melt to fragment and rework much larger masses of cold, shock-fractured overlying 'lithosphere'. This explosive-armour-like mode for silicate planetary accretion will strongly resist the magma ocean-mode of planetary differentiation. A magma ocean would only tend to form in the planetary body created from the accreting debris ring of a giant impact event, a Moon.

V43D-0117 The Apollo Conundrum: The Moon Clearly Had a Magma Ocean. Did Earth?

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Abstract:

When Apollo returned the first moonrocks, a major surprise was that the lunar highlands are largely made of feldspar. The magma ocean hypothesis explains this ubiquitous lunar building material as the crystals that floated to the top of a satellite-scale 'ocean' of molten moon-magma. If accepted as a key early stage in lunar evolution, it is an extremely logical leap to infer that Earth must have also had a magma ocean during its early evolution, since the gravitational impact energy per unit mass that is released during a planetesimal's accretion scales as GM/R, with Earth's ratio being 22 times larger than the Moon's.

The nagging problem with the inference that Earth passed through an early magma-ocean stage is that the oldest rocks on Earth show no direct signs of a magma ocean. Instead the petrology of the oldest preserved Earth rocks shows clear evidence that repeated events of small to medium degrees of partial melting and melt extraction, as opposed to pervasive fractional crystallization, has been the modus operandus of terrestrial differentiation. Many researchers have worked to build effective hypotheses to effectively 'remix' the products of an early terrestrial magma ocean back into a quasi-uniform 'primordial' pyrolite/peridotite silicate lithology from which oceanic and continental crust would evolve by partial melting events.

Here I propose a way out: What if a partially molten silicate body is actually highly resistant to the formation of a complete magma ocean? Jing and Karato (2011) show that a silicate melt will absorb much more impact shock-energy than either a silicate solid or an iron solid/melt. In this case, impact energy will be heterogeneously added into the growing proto-Earth, with silicate partial melts being shock-compression-heated to their vaporization temperature before their surrounding silicate solids heat to their melting point. The growing partially molten proto-planetary surface will tend to 'explode' during impact events, with each impact-induced-explosion using a relatively small mass of vaporized silicate partial melt to fragment and rework much larger masses of cold, shock-fractured overlying 'lithosphere'. This explosive-armor-like mode of silicate planetary accretion will strongly resist the magma ocean-mode of planetary differentiation. A magma ocean would only tend to form in the planetary body created from the rapidly accreting debris ring of a giant impact event, a Moon.

Apollo Rocks provide strong evidence for an early lunar magma ocean:

First and foremost, most highland surface rocks are nearly monomineralic, formed primarily (>90%) of anorthosite (Ca-plagioclase). This mineral has a lower density than other major minerals predicted to crystallize at low pressures from an Earth-like silicate magma, hence will tend to float to the top of a crystallizing silicate magma. Its ubiquitous presence at the Moon's surface was a strong argument that the Moon formed liquid enough for this mineral to effectively segregate towards the Moon's surface once it had crystallized.

Other evidence from Apollo-collected rocks suggested that the moon may have formed from density-stratified minerals that crystallized from a large magma ocean. For example, it was proposed that the source-rocks for later-stage KREEP melts were relatively dense and concentrated in radioactive elements, hence were buried/confined to a density horizon that could form below the anorthite upper crust yet above a denser olivine-pyroxene lunar 'mantle' layer that contained ~75% of the crystallized minerals. This layer heated up due to its high concentration of U, Th, and K, causing later melting that produced small amounts of KREEP basalts.

These twin arguments in favor of a lunar magma ocean were recognized early, and have stood the test of time, while later isotopic dating evidence has led to questioning the ultra-short timescale implied by simple convective models for the initial crystallization of a magma ocean.

Conventional Impact Accretion Scenarios predict the early Earth should have had one or more large magma oceans

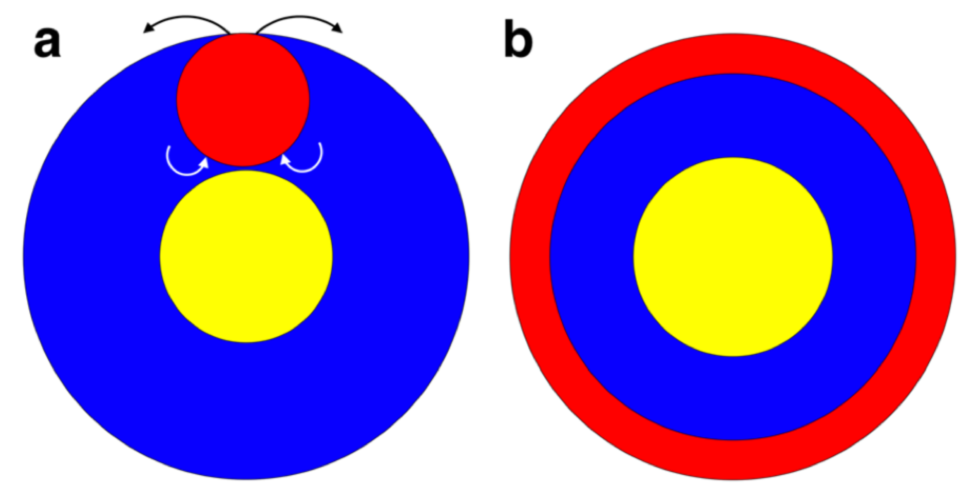


Fig. 1 Isostatic readjustment and lateral spreading of an initially spherical impact-induced melt pool (**a**) leading to global magma ocean formation (**b**). Due to the lower density of the melt (*red*) compared to the surrounding solid mantle (*blue*), the solid mantle rises isostatically beneath the melt pool (*white arrows*) by solid-state deformation and the melt spreads over the surface of the planetary embryo (*black arrows*).The proto-core is shown in *yellow*

Impact-induced melting during the accretion of the Earth has also been predicted to be large, based on conventional arguments that balance the energy released by impacts with the latent heat of melting of silicates and iron alloys (e.g., de Vries et al., 2016, from which the above figure was taken.). In particular, ultra-large moon-forming-like large impact events would be predicted to melt deep into the silicate mantle (de Vries et al., 2016).

But Early Earth Rocks and Cratonic Xenoliths contain no preserved record that the early Earth had a magma ocean

The curious thing is that preserved early Archaean rocks and old and younger cratonic xenoliths *contain zero evidence that their minerals ever experienced any magma-ocean events* that would involve total melting of a silicate body followed by sequential mineral crystallization events. This process would involve the well-understood fractional crystallization sequence of a 'Bowen crystallization path' of element-ratios in the crystallizing minerals — a pattern seen, for example, in the lunar anorthosite record. Instead the oldest preserved Earth record states that these rocks were all influenced by partial melting events that involve the selective fusion and removal of the 'easiest to melt' portion of a silicate protolith, with the more refractory material remaining in a solid-state (e.g. behaving as a restite). This view is implicit in all textbooks on Archaean petrology, and a continuous time-span of selective partial melting events is recorded in the Osmium-isotopes of mantle peridotites, with ages ranging from recent times for xenoliths sampled at mid-ocean ridges to the ages of presumed craton-forming partial melting events. The fact that this evidence is at odds with early magma-ocean differentiation event(s) for Earth has been quietly noted for a long time, with Grove and Bowring (1998) providing a thoughtful summary of the basic discord.

In essence, the terrestrial record states that the density-linked mineral segregation and stratification that the moon experienced in its magma ocean phase would need to have been almost *perfectly remixed* before Earth's magma ocean phase had ended. To reframe this issue in basic petrologic terms — the Mg/Fe ratios of the olivines and pyroxenes preserved in cratonic mantle xenoliths have the geochemical trends of these rocks being the residues to one or more partial melting events, and zero fractional crystallization events. The isotopic ages of craton-xenolith melting events are often even the same as the isotopic ages of the bulk of the overlying cratonic crustal rocks (cf. Pearson et al., 1995).

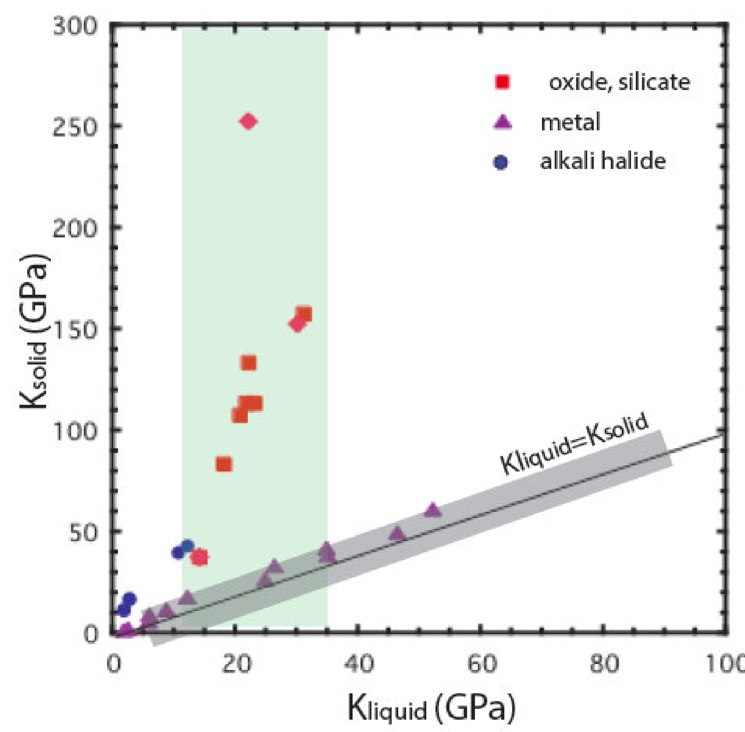
Siderophile abundances in Earth mantle minerals imply relatively low-pressure segregation of proto-Fe-core material from silicates

This evidence (cf. Rubie et al., 2011; Wood et al., 2006) is consistent with Earth not experiencing a deep planetary-scale magma ocean, but more complex magma ocean scenarios have been devised that can be consistent with this element-partitioning constraint (see de Vries et al., 2016).

But how could Earth have avoided major magma-ocean forming impact events?

What if shock heating in terrestrial impact events preferentially favored shock-energy being consumed by vaporization of pre-existing silicate partial melts over shock-heating of solid silicate minerals?

This behavior is implied by the unique measured compressional properties of silicate liquids, but not Fe-metal liquids (Jing and Karato, 2011)



The Grüneisen parameter $\gamma = \left(\frac{\partial \log T}{\partial \log \rho}\right)_{ad}$ decreases with compression in solids, but it increases with compression in silicate liquids, implying their intense heating upon compression. The implication is that it could be possible for pre-existing silicate partial melts to vaporize in an impact before their neighboring crystals shock-melted. The consequence would be 'explosions' during impact events associated with the vaporization of only a small volume of preexisting low-melt fraction partial melts — vapor + solid fragments instead of liquid magma ocean.

Tests and implications of this hypothesis for Earth and most-silicate bodies to have avoided planetary-scale magma-ocean forming events during their accretion:

- The Moon obviously DID still have a magma-ocean forming event. This was because it condensed from a cloud of rock + vapor ejecta created by the Moon-forming large impact. In this case (rapid gravitational collapse of a massive ejecta cloud that is thick enough to poorly radiate its internal heat) a large magma ocean would still naturally tend to form.
- The 'collisional erosion' hypothesis (O'Neill and Palme, 2008) proposed that the incompatible element depletion of both Earth and Moon relative to chondrites is due to the selective impact-removal of a small volume proto-crust surface layer that had been created by early partial melting and surface-wards melt migration. The same depletion pattern could actually be created by direct impact-linked removal of the vaporized small volume of silicate partial melts during the impact-accretion phase of Earth's genesis – e.g. the shared geochemical patterns of Earth and Moon relative to chondrites would reflect the selective vaporization and removal of small-degree sub-lithospheric partial melts during Earth's impact acrretion phase.
- TO DIRECTLY TEST this hypothesis with impact hydro-codes requires that they resolve the 'contact density discontinuity' created in most SPH discretization approaches (see extended discussion in the methods section of Hosono et al., 2019). This numerical artifact is why preexisting SPH simulations created liquid magma without significant vaporization of preexisting silicate partial melts.

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