Is lunar magma ocean (LMO) gone with the wind?

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The Moon is the only natural satellite of the Earth, and has been the subject of numerous works of arts, literature, mythology, astrology and astronomy for millennia. The scientific speculation of its origin has also been in the literature for centuries. But it is the manned landing of Apollo missions 11–17 (1969–1972) with returned lunar rocks and soils and the unmanned post-Apollo spacecraft with remote-sensing data that allow the development of geological models on the origin of the Moon, its internal structure and its subsequent histories [1].

Several models have been proposed for the origin of the Moon, but the single generally accepted model today is the ‘giant impact’ hypothesis [1]. It assumes that the Earth–Moon system formed as the result of a giant impact by a Mars-sized body that collided with the proto-Earth, blasting material into its orbit to form the Moon. This Moon formation mechanism would help explain the high angular momentum of the Earth–Moon system and the small size of the iron lunar core.

The energy released during such a giant impact would have been sufficient to melt the outer few hundreds of kilometers (<1000 km?) of the Moon, forming the postulated global lunar magma ocean (LMO; Fig. 1a). The evidence for this LMO hypothesis came from the highly anorthositic compositions of the lunar highland crust. The ‘anorthositic compositions’ refer to rocks dominated by CaO-rich plagioclase (CaAl2Si2O8), which is less dense than the magma and would float to form the lunar crust and highlands (Fig. 1b) [2]. This is the ‘plagioclase floatation hypothesis’. As noted [3], the ‘LMO hypothesis’ was initially based on a few anorthositic particles of Apollo 11 soil [2]. These two interdependent hypotheses are actually based on a single observation—the Moon’s anorthositic upper crust has
Figure 1. Cartoons illustrating the generally accepted ‘LMO hypothesis’. (a) The state of the LMO before crystallization with no Eu anomaly. (b) A snapshot of the LMO in the course of solidification by crystallizing dense olivine and pyroxene that sinks to form the lunar mantle and light plagioclase that floats to form the lunar crust (modified from http://www.lpi.usra.edu/). Not shown, but the KREEP would be the very last drops of residual melt (red) highly enriched in REEs and all other incompatible elements but low Eu and thus a strong negative Eu anomaly with Eu/Eu* ≪ 1.

A large positive Europium (Eu) anomaly. Eu is a rare earth element and a positive Eu anomaly means it is relatively more abundant than its neighboring rare earth elements Sm and Gd, i.e. Eu/Eu* = [EuN]/[SmN × GdN]^{0.5} > 1. This is because plagioclase prefers Eu over Sm and Gd during its crystallization from magma. Studies of the Apollo samples also show that basaltic rocks from the lunar Maria have a negative Eu anomaly, i.e. Eu/Eu* < 1. This observation has been used to further support the ‘LMO hypothesis’. Complementary to the plagioclase flotation, the dense mafic minerals olivine and pyroxene crystallized from the LMO would sink to form the lunar mantle with Eu/Eu* < 1 (Fig. 1b), whose subsequent melting would produce Maria basalts with inherited Eu/Eu* < 1. This forms the ‘cumulate origin hypothesis’ for the lunar mantle.

The Eu-anomaly-based ‘plagioclase flotation hypothesis’ for lunar crust and ‘cumulate hypothesis’ for lunar mantle are foundation to the ‘LMO hypothesis’. The dry ‘Moon hypothesis’ is considered as verification of the ‘LMO hypothesis’. In this short communication, we briefly summarize and further elaborate some key elements of the recent work by O’Hara and Niu [4] on the ‘LMO hypothesis’, and challenge that this single generally accepted hypothesis should be entirely reconsidered because its foundation is shaken and because the ‘dry Moon hypothesis’ has been proven to be problematic as emphatically pointed out from the very beginning of the Apollo program by the second author [5,6] and his 107-page meticulous review in 2000 [7].

The ‘wet’ vs. ‘dry’ Moon. As one of the NASA’s Principal Investigators of experimental petrology on returned lunar samples of Apollo missions, O’Hara and co-authors predicted in early 1970s that the Moon may have been a water-rich planet and may still be so in its interior [7] because water was required to explain the observed phase equilibria of lunar rocks. The best explanation was that partial melting of amphibole-bearing lunar mantle produced wet basaltic magmas. Such wet magmas underwent low-pressure gabbroic (plagioclase + clinopyroxene ± olivine ± titanium—iron-rich oxides) fractionation, effectively giving rise to the various rock types and lithologies of the Moon. The lack of hydrous minerals and depletion of volatile elements (including Na and varying species of S, C, F, Cl, etc.) in lunar samples simply resulted from volatilization loss during magma emplacement and volcanic eruption into the hard vacuum like ‘atmosphere’ of the Moon. Furthermore, the interpreted pyroclastic deposits on the Moon would offer a convincing line of evidence for wet magmas and hence wet lunar interior (abundant water and other volatiles). This ‘wet Moon’ view with experimental demonstrations has been in the literature for ∼45 years [7], but it has been entirely overlooked because this was a minority view that has been readily and quickly buried in the monopoly of the ‘LMO hypothesis’ [7,8]. The ability of analyzing abundant water and other volatiles in lunar glasses, minerals and melt inclusions in recent years [9–12] offers convincing evidence in support of the very old ‘wet’ Moon hypothesis, and effectively put the ‘dry Moon’ assumption to an end. For example, it has been demonstrated explicitly that the H₂O, F and S concentrations in the primitive lunar mantle source to be at least 110, 5.3 and 70 ppm, respectively, which are similar to those in terrestrial MORB mantle [12]. This casts doubt on the ‘giant impact hypothesis’ as all the volatiles would have been totally evaporated and severely questions the validity of the ‘LMO hypothesis’.

The Eu anomaly. The ‘plagioclase flotation hypothesis’ would be reasonable only if the lunar crust in general and the lunar highlands in particular all have Eu/Eu* > 1. However, this is not true [4,7]. If anything, there is a weak negative (Eu/Eu* < 1), not positive
(Eu/Eu* > 1), Eu anomaly for the lunar crust. The significant inverse correlations of Eu/Eu* with the abundances of incompatible elements such as Thorium (Th) of all the analyzed lunar samples (rocks and soils) suggest the likelihood that most lunar crustal materials have Eu/Eu* < 1 (Fig. 2a). Indeed, the gamma-ray spectrometer data [13] by the Lunar Prospector demonstrate that no more than ~4% of the global lunar crustal materials (rocks and soils) have Eu/Eu* > 1 (Fig. 2b). This straightforward observation denies the ‘plagioclase flotation hypothesis’ for the lunar crust. The weak negative (Eu/Eu* < 1) Eu anomaly in the Maria basalts is a straightforward consequence of cotectic crystallization of plagioclase + clinopyroxene + olivine rather than inherited from the assumed lunar mantle [4,7], which argues against the ‘cumulate hypothesis’ for the lunar mantle. All these further question the validity of the ‘LMO hypothesis’. The experimental studies also show the physical difficulty to separate plagioclase (to float) from the co-precipitating clinopyroxene + olivine (to sink) [7], making the ‘LMO hypothesis’ all the more feeble. It is possible that olivine and pyroxene might begin to crystallize to form much of the lunar mantle prior to plagioclase crystallization. This might partially reconcile the physical separation difficulty, but if so, there is no reason that the lunar mantle would have a negative Eu anomaly required by the ‘LMO hypothesis’.

A recent work claims the globally widespread pure anorthosite on the Moon [14], apparently in support of the ‘plagioclase flotation hypothesis’. However, this claim is inconsistent with the bulk lunar crust major element composition: 42.33 wt% SiO₂, 1.21 wt% TiO₂, 24.46 wt% Al₂O₃, 7.72 wt% FeO, 8.75 wt MgO and 15.17 wt% CaO and Mg⁺ (100·Mg/Mg + Fe) = 66.89 (or 69.18 if 10% total Fe is assumed to be Fe³⁺). This composition is equivalent to normative mineralogy of 66.74 wt% An (plagioclase), 6.92 wt% Di (clinopyroxene), 5.29 wt%
Hy (orthopyroxene), 18.39 wt% Ol (olivine) and 2.30 wt % II (ilmenite) [4]. This bulk lunar crustal composition is NOT anorthositic, but feldspathic basalt or feldspathic gabbroic composition only slightly more feldspathic than the oceanic lower crust bulk composition (despite the lost volatile elements like Na) [15]. To defend the ‘plagioclase flotation hypothesis’, one could argue that the globally high Th content [3] and thus the low Eu/Eu* (see Fig. 2) of the lunar crust may have resulted from compositional contamination by the lunar-wide basin formation ejecta [16], but this argument has no significance because the ‘plagioclase flotation hypothesis’ postulated since the Apollo program was based on lunar surface rocks already so contaminated in the early history of the Moon. Nevertheless, this contamination can help explain the observed ‘mechanical mixing’ of lunar compositional variation recognized by O’Hara and Niu [4].

While debate may continue for some time, we suggest that the ‘LMO hypothesis’ be abandoned because its foundation hypotheses (plagioclase flotation for lunar crust and mafic mineral sinking for lunar mantle) are tested to be false, and because its verifying ‘dry Moon hypothesis’ is also proven to be wrong. It follows that the ‘giant impact hypothesis’ for the origin of the Moon is severely questionable because abundant water and other volatiles remain well preserved in lunar rocks, supporting a wet, not a dry, Moon as advocated by O’Hara over 45 years ago. We emphasize that all the foregoing interdependent hypotheses need entire reconsideration in order to genuinely understand the origin and evolution of the Moon and its petrogenesis. It is beyond the scope of this short communication, but we suggest that more effort should be devoted to the effects of low pressure (due to the low gravity and thus relatively high mantle dT/dP) and hard vacuum ‘atmosphere’ on the lunar petrogenesis. As for the origin of the Moon, it is possible that the present-day angular momentum of the Earth–Moon system may not be used as a constraint and alternative possibilities may be explored [17]. An elegant review on the origin of the Moon from physical, chemical and isotopic perspectives is given by Halliday [18], and isotopic similarities of the Moon and the Earth offer constraints on physical models of Moon formation.

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REFERENCES

1. Jolliff, BL, Wieczorek, MA and Shearer, CK et al. (eds). Rev Mineral Geochem 2006; 60: 721.
2. Wood, JA, Dickey, JS and Marvin, UB et al. Lunar anorthosites and a geophysical model of the moon. In: Levinson, A. A. (ed) Proceedings of Apollo 11 Lunar Scientific Conference. New York: Pergammon Press, 1970, pp. 965–88.
3. Warren, PH. Annu Rev Earth Pl Sc 1985; 13: 201–40.
4. O’Hara, MJ and Niu, YL. Obvious problems in lunar petrogenesis and new perspectives. In: Foulger, GR, Lustrino, M and King, SD (eds). The Interdisciplinary Earth: A Volume in Honor of Don L Anderson: Geological Society of America Special Paper 514 and American Geophysical Union Special Publication, Vol. 71. 2015, pp. 339–66.
5. O’Hara, MJ. Endeavour 1970; 30: 3–7.
6. O’Hara, MJ. Nature 1970; 240: 95–6.
7. O’Hara, MJ. J Petrol 2000; 41: 1545–651.
8. Walker, D. J. Geophys Res 1983; 88: B17–25.
9. Saal, AE, Hauri, EH and Lo Cascio, M et al. Nature 2008; 454: 192–5.
10. Hauri, EH, Weinreich, T and Saal, AE et al. Science 2011; 333: 213–5.
11. Hui, HJ, Peslier, AH and Zhang, Y et al. Nat Geosci 2013: 6: 177–80.
12. Chen, Y, Zhang, Y and Liu, Y et al. Earth Planet Sc Lett 2015; 427: 37–46.
13. Prettyman, TH, Hagerty, JJ and Elphic, RC et al. J Geophys Res 2006; 111: E12007.
14. Ohtake, M, Matsunaga, T and Haruyama, J et al. Nature 2009; 461: 236–40.
15. Dick, HJB, Natland, JH and Alt, JC et al. Earth Planet Sc Lett 2000; 179: 31–51.
16. Petro, BE and Pieters, CM. Meteorit Planet Sci 2008; 43: 1517–92.
17. Cuk, M and Stewart, ST. Science 2012; 338: 1047–52.
18. Halliday, AN. Science 2012; 338: 1040–1.
19. Heiken, GH and Vaniman, DT French, BM (ed.). Lunar Sourcebook: a User’s Guide to the Moon. Cambridge: Cambridge University Press, 1991, 936.
20. Lawrence, DJ, Puetter, RC and Elphic, RC et al. Geophys Res Lett 2007; 34: L03201.
21. Heiken, GH and Vaniman, DT French, BM (ed.). Lunar Sourcebook: a User’s Guide to the Moon. Cambridge: Cambridge University Press, 1991, 936.