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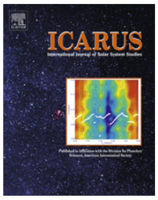

Composition of the lunar magma ocean constrained by the conditions for the crust formation

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ABSTRACT

The present study aims to constrain the composition of the initial lunar magma ocean (LMO) with fluid dynamic and thermodynamic consideration. A plausible range of the initial LMO composition is investigated by developing an incremental polybaric fractional crystallization model with variable fractionation efficiency to satisfy three conditions for the anorthosite crust formation: (1) the amount of anorthite crystallized from the LMO is abundant enough to form the crust with the observed thickness, (2) the Mg# (=Mg/(Mg + Fe)) of orthopyroxene crystallized with anorthite in the cooling LMO is consistent with that observed in the lunar highland rocks, ferroan anorthosite, and (3) crystallized anorthite separated to float in the turbulent LMO. A plausible range of FeO and Al_2O_3 contents of the bulk LMO is successfully constrained as a crescent region tight for FeO and loose for Al_2O_3. The FeO content must be higher than 1.3 times the bulk silicate Earth (BSE) and lower than 1.8 ×BSE unless the Al_2O_3 content of the Moon is extremely higher than the Earth. These upper and lower limits for FeO are positively correlated with the initial Al_2O_3 content and fractionation efficiency. The FeO–rich LMO composition may suggest that the circum-Earth disk just after the giant impact of the Earth–Moon system formation was more oxidizing or the impactor was richer in FeO than the Earth's mantle.

1. Introduction

The Moon preserves the records of early geologic events on its surface due to the small size and the absence of atmosphere and ocean, though such records had been erased on the Earth. The origin and evolution of the Moon are fundamental to understand the initial evolution of terrestrial planets and the formation of the Earth–Moon system.

The crust of the Moon has been investigated in detail by recent explorations. Petrologic, geochemical and geophysical observations suggest that ~35–55 km thick lunar crust is made up mainly of pure anorthite ($CaAl_2Si_2O_8$) (Ishihara et al., 2009; Lognonné et al., 2003; Wieczorek, 2006; Wieczorek et al., 2013). Geochronological studies show that the age of the highland anorthosite is 4.3–4.5 Ga (Borg et al., 1999; Nyquist et al., 2010), which suggests that anorthosites retain information about crustal formation just after its birth. The lunar anorthositic crust is thought to have formed by large-scale differentiation of a totally molten Moon (Smith et al., 1970; Wood et al., 1970), which was later named as the lunar magma ocean (LMO). The hypothesis of crust formation from the LMO has been supported by chronology of anorthosites (Nyquist et al., 1977; Nyquist and Shih, 1992), complementarity of Eu anomaly between highland anorthosites and mare basalts (Haskin et al., 1982; Morse, 1982; Ryder, 1982), and the presence of KREEP rocks that are enriched in compatible elements suggestive of extreme fractionation from the LMO (Dowty et al., 1976; Shih, 1977; Warren and Wasson, 1979).

The bulk chemical composition plays a key role on the evolution of the Moon, among which FeO and Al_2O_3 contents are specifically important: the FeO content affects (1) density and viscosity of melt, which control separation of minerals from the LMO, (2) chemical composition of olivine and pyroxenes, and (3) the bulk density and the moment of inertia, which depends on the amount of FeO in the mantle and the size of the metallic core. The Al_2O_3 content is also crucial in evolution of the LMO, because it affects the stability of anorthite, the major constituent of the highland crust, in the evolving LMO.

Previous workers have disputed whether the FeO and Al_2O_3 contents of the bulk Moon are similar to or richer than those of the Earth. Table 1 compares the previously estimated bulk silicate Moon, BSE, and CI-chondrite compositions. Although there are not significant differences among the estimations, the degree of enrichment of Al_2O_3 and FeO contents relative to the Earth shows considerable variations.

Longhi (2006) carried out mass balance calculations to estimate the bulk composition of the Moon on the basis of melting

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Table 1
Bulk compositions of the Moon estimated in previous studies. The compositions of the bulk silicate Earth (BSE) and a solar abundance are also shown for a comparison.

	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Mg#	FeO^c (×BSE)	$Al_2O_3{}^c$ (×BSE)
Longhi (2006)	46.1	0.17	3.9	0.50	7.6	0.13	38.3	3.2	0.05	0.003	0.90	0.9	0.9
Taylor (1982)	44.4	0.31	6.1	0.61	10.9	0.15	32.7	4.6	0.09	0.009	0.84	1.4	1.4
Warren (2005)	46.2	0.18	3.8	0.44	9.1	0.13	35.6	3.0	0.05	0.005	0.87	1.1	0.8
Khan et al. (2006)	45.5	n.d.	4.1	n.d.	12.5	n.d.	34.6	3.3	n.d.	n.d.	0.83	1.5	0.9
Buck and Toksoz (1980)	48.4	0.4	5.0	0.3	12.9	n.d.	29.0	3.8	0.15	n.d.	0.80	1.5	1.3
Lognonné et al. (2003)	53.5	n.d.	6.4	n.d.	13.3	n.d.	21.9	4.9	n.d.	n.d.	0.75	1.4	1.2
Jones and Delano (1989)	42.6	0.19	3.7	n.d.	13.6	0.19	37.1	3.0	n.d.	n.d.	0.83	1.78	0.9
O'Neill (1991)	44.6	0.17	3.9	0.47	12.4	0.17	35.1	3.3	0.05	n.d.	0.83	1.6	0.9
Ringwood (1979)	44.8	0.3	4.2	0.4	13.9	n.d.	32.7	3.7	0.05	n.d.	0.81	1.7	0.9
Snyder et al. (1992)	48.4	0.4	5.0	0.3	12.0	n.d.	29.9	3.8	0.13	0.04	0.82	1.4	1.0
BSE[a]	45.0	0.20	4.5	0.38	8.1	0.14	37.9	3.5	0.36	0.029	0.89	1.0	1.0
Solar abundance[b]	34.4	0.11	2.5	0.56	34.4	0.37	23.5	2.0	2.04	0.10	0.55	5.6	0.7

[a] McDonough and Sun (1995).
[b] Lodders (2003), n.d.: not determined.
[c] Enrichment factor compared to the Earth.

experiments (Longhi, 1992, 2003, 2005). The bulk Al_2O_3 content is estimated to be ~4 wt% being consistent with the source mantle composition for a low-Al_2O_3 magma, the green picritic glass, and is similar to the Earth's upper mantle. He also argued that the Mg# of the Moon is comparable to that of the Earth to generate the rocks of the magnesian suite. The bulk composition that Longhi estimated is called as Lunar Primitive Upper Mantle (LPUM). These estimates may be true for the mare basalts on the nearside of the Moon, but it is not known whether this estimation is applicable to the ancient magma ocean or the farside.

Taylor (1982) was the first who proposed that the Moon was more enriched in refractory elements than the Earth, which is called as Taylor Whole Moon (TWM). Using the bulk U content (~0.033 ppm) estimated from the heat flow measurement at the Apollo 15 and 17 sites (Keihm and Langseth, 1977; Langseth et al., 1976), Taylor estimated the Al_2O_3 content of the Moon to be 6.1 wt%. The FeO content was estimated to be 10–11 wt% from petrological requirements to generate the highland crust and the source regions of the mare basalts (Longhi, 2005; Taylor and Bence, 1975). This estimation may be valid only for the nearside of the Moon, which is known to be strongly concentrated in the heat source elements relative to the farside (Jolliff et al., 2000).

Warren (2005) estimated the bulk Al_2O_3 content of the Moon from the bulk Th content, which comes from the revised calibration of the Lunar Prospector gamma-ray data. On the basis of mass balance calculation using the compositional structure and thickness of the lunar crust, he estimated the Al_2O_3 contents to be 3.8 wt%, which was poorer than previous estimations. The value, however, may contain a considerable uncertainty, because the estimation is strongly dependent on the Th distribution in the lunar crust structure. The FeO content was estimated to be 9–10 wt% in order to be consistent with the high Mg# of olivine in the magnesian suite (0.87–0.90) (Warren, 1993). The magnesian suite, however, is a minor component of the Moon compared with the ferroan anorthosite, and it is not very convincing to argue that this rock intruded into the lunar crust from the LMO cumulates without any assimilation or melting. Warren (1990) was the first to emphasize the importance of FeO enrichment in the parent magma for anorthite flotation and argued that the ferroan anorthosite is really the magma ocean flotation product.

Khan et al. (2006) developed an inversion method to estimate mineralogy, mineral modal abundances, and thermal structure by using seismic data, lunar mass, and moment of inertia. They obtained a higher FeO content and lower Mg# than other estimations. The Al_2O_3 content is estimated to be ~4 wt%, which is similar to the terrestrial mantle, because a LMO composition with Al_2O_3 more than ~5 wt% produces more aluminous phase resulting in higher seismic velocity that is in disagreement with the seismic model (Kuskov and Kronrod, 1998). The results, however, may contain considerable errors, as the authors themselves point out, due to uncertainties in the electric conductivity measurements in spite of the highly sophisticated inversion method.

There are several other estimations as listed in Table 1. Ringwood (1979) estimated the bulk composition of the Moon by a pyrolite approach, mixing melt and residue components in appropriate proportions, which was used to estimate the mantle composition of the Earth. O'Neill (1991) and Jones and Delano (1989) estimated the bulk Moon composition based on models of geochemical evolution of the Moon. Lognonné et al. (2003) reevaluated the Apollo lunar seismic data to estimate seismic velocity, density, and temperature structures, as well as the bulk composition of the Moon by optimizing mixing ratios of several assumed distinct chemical reservoirs. Buck and Toksoz (1980) used seismic velocities of the crust and mantle, crustal thickness, and other geophysical data combined with a simple evolution models to estimate the bulk composition of the Moon. Snyder et al. (1992) modified the estimate of Buck and Toksoz (1980) to be consistent with the crustal thickness. These estimates are more or less dependent on formation models that are based on many unverified assumptions.

The bulk composition controls phase relations and separation of phases crystallized, which further controls residual melt composition, that is, evolution of the LMO. The effectiveness of crystal-melt separation is controlled by physical properties of phases, particularly those of melt. Therefore, it is important to estimate the bulk abundances of FeO and Al_2O_3 simultaneously and by global constraints, although they have been estimated independently and/or on the basis of local geochemical data in previous work.

In this study, we will estimate the bulk composition of the Moon by developing a new model for the conditions of anorthite flotation in the LMO to satisfy both physical and chemical constraints for anorthosite crust formation through thermodynamic and fluid dynamic consideration on anorthite flotation and accumulation in the LMO. The model has potential strength in that it depends on highly reliable global observations by recent explorations.

2. Method

2.1. Outline of the model

The anorthosite crust of the Moon suggests accumulation of anorthite, which was achieved by (1) the saturation of melt in the anorthite component at a certain stage of differentiation, (2) the abundance of anorthite crystallized in the LMO being large enough to form the observed crustal thickness, and (3) the physical