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Crystallization of the lunar magma ocean and the primordial mantle-crust differentiation of the Moon

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Abstract

We present crystallization experiments on silicate melt compositions related to the lunar magma ocean (LMO) and its evolution with cooling. Our approach aims at constraining the primordial internal differentiation of the Moon into mantle and crust. We used graphite capsules in piston cylinder (1.35–0.80 GPa) and internally-heated pressure vessels (<0.50 GPa), over 1580–1020 °C, and produced melt compositions using a stepwise approach that reproduces fractional crystallization. Using our new experimental dataset, we define phase equilibria and equations predicting the saturation of liquidus phases, magma temperature, and crystal/melt partitioning for major elements relevant for the crystallization of the LMO. These empirical expressions are then used in a forward model that predicts the liquid line of descent and crystallization products of a 600 km-thick magma ocean. Our results show that the effects of changes in the bulk composition on the sequence of crystallization are minor. Our experiments also show the crystallization of a silica phase at ca. 1080 °C and we suggest that this phase might have contributed to the building of the lower anorthositic crust. Calculation of crustal thickness clearly shows that a thin crust similar to that revealed by GRAIL cannot have been generated through solidification of whole Moon magma ocean. We discuss the role of magma ocean depth, trapped liquid fraction (with implication for the alumina budget in the mantle and the crust), and the efficiency of plagioclase flotation in producing the thin crust. We also constrain the potential range of pyroxene compositions that could be incorporated into the crust and show that delayed crustal building during ca. 4% LMO crystallization on the nearside of the Moon may explain the dichotomy for Mg-number. Finally, we show that the LMO can produce magnesian anorthosites during the first stages of plagioclase crystallization.

Keywords: Lunar crust; Anorthosite; Mantle; Experimental petrology; Phase equilibria; Liquid line of descent

1. INTRODUCTION

The origin of the Moon has been generally attributed to a giant impact between a planet and the proto-Earth that ejected into orbit material from which the Moon accreted (Hartmann and Davis, 1975; Stevenson, 1987; Cameron and Benz, 1991; Canup and Asphaug, 2001; Canup, 2012; Ćuk and Stewart, 2012). Energy liberated in the giant impact event was sufficient to produce melting of a substantial portion of the Moon, a likely cause of a "Lunar Magma Ocean" (LMO; e.g. Tonks and Melosh, 1993; Elkins-Tanton, 2012). The LMO developed early between 4.5 and 4.3 Ga though the time of its initiation and its exact duration remains controversial (Kleine et al., 2005; Nemchin et al., 2009; Taylor et al., 2009; Touboul et al.,

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2009; Elkins-Tanton et al., 2011; Gaffney and Borg, 2014). Its crystallization appears to have structured the Moon into a mantle and a crust (e.g. Smith et al., 1970; Wood et al., 1970; Warren, 1985). However, direct evidence on how the LMO evolved chemically and physically as it cooled and crystallized remains a major issue. Petrologic models for the solidification of the LMO have been derived mainly from thermodynamic phase relationships assuming either fractional or equilibrium crystallization or some combination of the two (Longhi, 1977, 1980; Snyder et al., 1992; Elkins-Tanton et al., 2011). A recent study has experimentally constrained the early cumulate mineralogy in the solidified magma ocean (Elardo et al., 2011). The role of water during crystallization of the lunar magma ocean has been invoked (Lin et al., 2016, 2017), although volatile depletion of the Moon compared to Earth is still a matter of debate (Sharp et al., 2010; Elkins-Tanton and Grove, 2011; Canup et al., 2015).

The original and canonical model for LMO solidification involves plagioclase flotation to the top of a denser LMO and formation of a global anorthositic crust underlain by complementary mafic cumulates (Warren, 1985; Shearer et al., 2006). This model has been criticized and arguments invoked against this scenario are the young age of the anorthosite (Borg et al., 2011), the existence of magnesian anorthosites (Gross et al., 2014), and heterogeneity in plagioclase trace element concentrations (Russell et al., 2014) that are difficult to produce during magma ocean crystallization. A magma ocean also appears unable to produce noritic assemblages soon after plagioclase saturation because of early saturation with augite (Longhi, 2003).

However, alternative processes proposed for the formation of the anorthosite crust on the Moon do not necessarily invalidate the existence of an initial magma ocean, which would have produced the source rocks for the production of anorthosite by remelting and serial magmatism (Longhi, 2003; Gross et al., 2014; Longhi and Ashwal, 1985). Primordial differentiation of the Moon during magma ocean crystallization is still largely accepted to have produced deep cumulate rocks forming the lunar mantle, the source for surficial mare basalts (Snyder et al., 1992; Münker, 2010; Barr and Grove, 2013; Hui et al., 2013a; Hallis et al., 2014; Brown and Grove, 2015). Extreme differentiation of the LMO has also been suggested to lead eventually to the formation of urKREEP and titanium-rich cumulates (Longhi, 1977; Warren and Wasson, 1979b; Warren, 1985).

To place new constraints on the evolution of the LMO and its crystallization products, we have performed a series of crystallization experiments at 1.35–0.08 GPa and temperatures in the range 1580–1020 °C. These experimental results constrain the liquidus phase boundaries along the liquid line of descent of 600 km-thick lunar magma oceans with variable bulk compositions. Experiments are combined with numerical models using forward approaches of fractional crystallization. Our study brings new information on the amount of alumina stored in the mantle, the timing for the saturation of plagioclase, and the resulting crustal thickness that is produced by solidification of the LMO. We also discuss the origin of the nearside-farside dichotomy for the composition of pyroxene in the anorthositic crust and the formation of magnesian anorthosites. Primordial crust-mantle differentiation of the Moon is the main focus of this paper, with the objective to provide direct insights into the primary compositional stratification of the lunar interior. Defining the initial state of the Moon is essential to understand its subsequent evolution and specifically potential cumulate overturn, remelting, and production of mare basalts and ultramafic glasses (Solomon and Longhi, 1977; Hess and Parmentier, 1995; Elkins Tanton et al., 2002).

2. COMPOSITION AND DEPTH OF THE LUNAR MAGMA OCEAN

2.1. Bulk Moon compositions

The bulk composition of the silicate portion of the Moon has been estimated using various approaches and selected compositions are presented in Table 1. The main discriminating criterion among proposed compositions is the Mg-number (molar MgO/(MgO + FeO)) and a variation in the abundance of refractory elements (Ca, Al). This variability ranges from close to or greater than that inferred for Earth. Refractory lithophile elements are supposed to be in chondritic proportions with one another but their enrichment relative to CI chondrites and to Earth has been debated (e.g. Warren, 2005; Taylor et al., 2006). Estimates for the alumina content of the bulk Moon compositions mainly depend on the estimated thickness and composition of the crust. Both of these are not fully constrained values. The two end-member model compositions are: the Taylor Whole Moon model (TWM; Taylor and Bence, 1975; Taylor, 1982), which has an Al_2O_3 content that is 1.5 higher compared to Earth mantle, and the Lunar Primitive Upper Mantle model (LPUM; Jones and Delano, 1989; Longhi, 2003; Warren, 2005), which has an Al_2O_3 content that is similar to the terrestrial primitive upper mantle of Hart and Zindler (1986) with depletion of the alkali content. A third category represented by the compositions of O'Neill (1991) and Wänke and Dreibus (1982) has terrestrial refractory elements but a lower Mg-number.

More recently, isotopic studies have shown a high degree of similarity between Earth and Moon, which tends to support that lunar material was mainly derived from Earth (Wiechert et al., 2001; Touboul et al., 2007; Zhang et al., 2012; Dauphas et al., 2014). Impact simulations involving larger impactors support the possible formation of a disk of Earth-like composition (Canup, 2012). Additionally, recent data provided by the dual Gravity Recovery and Interior Laboratory (GRAIL) spacecraft have shown that the density of the Moon's crust is significantly lower than generally assumed (Wieczorek et al., 2013). Consequently, the average crustal thickness is suggested to be thinner, which implies that the bulk refractory element composition of the Moon (mainly Ca and Al) is not enriched with respect to that of Earth.

Although recent data tends to favor Earth-like concentrations for refractory elements in bulk Moon compositions