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The effect of temperature distribution in the lunar mantle on the bulk composition of the Moon

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Abstract

The purpose of the present study is to evaluate the lunar bulk composition (BSM) and the composition of the three-layer mantle based on a joint inversion of lunar mass and moment of inertia, and the mantle seismic velocity profiles in combination with Gibbs free energy minimization. We obtained that regardless of the thermal state, BSM possess almost constant values of bulk FeO ~ 12-13 wt.% and MG# 80-81.5, which id significantly different from those of the bulk-silicate Earth (BSE). The FeO content and MG# are approximately identical in the upper and lower mantle. The abundance of SiO_2 slightly depends on the thermal state. On the contrary, there are two different groups for the lunar abundance of alumina depending on the thermal state: 1) Cold models of BSM (3-4.6 wt.% Al_2O_3) are comparable to the Al_2O_3 content for the BSE; 2) Hot models (bulk Al_2O_3 is 1.2 – 1.7 × BSE). The simulation results suggest that the lunar mantle is stratified by chemical composition.

1. Introduction

The chemical composition of the Moon should be considered as a fundamental geochemical constraint when testing cosmogonic models of its origin. One of the most important problems of lunar geochemistry is the determination of its bulk composition - mainly the concentrations of rock-forming oxides SiO_2, Al_2O_3, CaO, FeO and the MG# affecting mineralogy and physical properties (density (ρ), bulk (K_S) and shear (G) moduli, V_P and V_S) of the mantle. The purpose of this work is to evaluate these geochemical parameters and to construct a model of chemical composition of the Moon based on a joint inversion of lunar mass and moment of inertia, the mantle P-, S-velocity profiles and petrological models methods.

2. Data and method

We investigate the thermal state and chemical composition of the silicate portion of the Moon (crust + mantle; BSM) for the magma ocean model (wich implies that modern composition of uniformly mixed overlying shells is identical with the bulk composition of the magma ocean, and reflect the bulk composition of the silicate Moon). We consider a five-layer model of the internal structure of the Moon including the crust, three zones of the mantle (the upper (39-240 km), the middle (240-750 km) and the lower mantle (750 km - core)) and Fe-S core. The input parameters of the model are the lunar mass and moment of inertia [1], the composition, the mean density and thickness of the crust, the seismic P- and S-wave velocities in the mantle [2,3], the oxide concentration interval in the NaTiCFMAS system, the average density of the Fe-S core.

The modeling of the composition and physical properties of the Moon was performed in the NaTiCFMAS system using Monte Carlo method and Gibbs free energy minimization combined with a Mie-Grüneisen equation of state of minerals described in detail in our previous publications [4,5]. The following ranges of oxide concentrations in the mantle (wt.%) were considered: 25 ≤ MgO ≤ 45%, 40 ≤ SiO_2 ≤ 55%, 5 ≤ FeO ≤ 15%, 0.1 ≤ CaO, Al_2O_3 ≤ 7%, where the concentrations of Al_2O_3 and CaO are related by the dependence of CaO/Al_2O_3 ~ 0.8.

3. Results

Since the temperature at different depths is not exactly known [5,6], the mean volume mantle temperature T_{mean}, controlling the mantle mineral composition and physical properties, is chosen as an integral characteristic of the thermal state of the Moon, which for our model is calculated from the expression: $T_{\mathrm{mean}} = (T_u V_u + T_m V_m + T_l V_l)/(V_u + V_m + V_l)$, where T_u, T_m, T_l are the mean temperatures (ºC) in the three zones of the mantle, V_u, V_m, V_l are the volumes of the upper, middle and lower mantle. In terms of T_{mean}, all thermal models can be divided into "cold" ones with T_{mean} ~ 690-860ºC and "hot" ones with T_{mean} ~ 925-1075ºC (fig. 1).

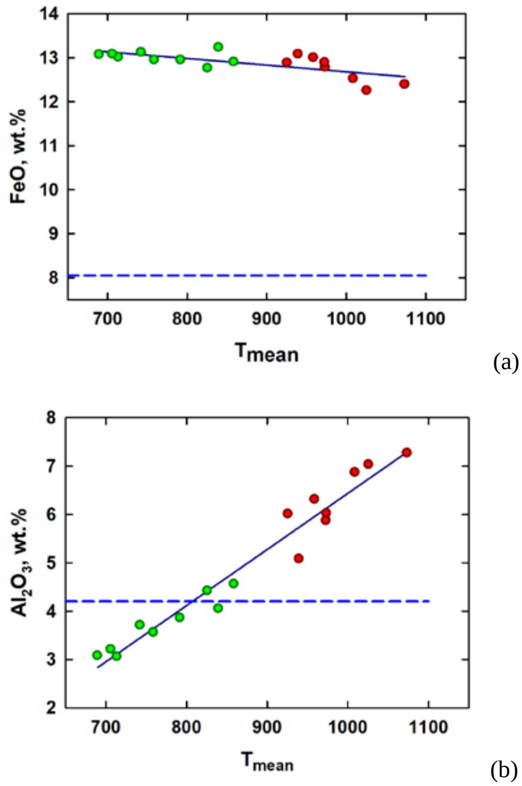

Figure 1: The contents of FeO, Al_2O_3, SiO_2 and MG# in the silicate portion of the Moon (mantle + crust) calculated from geodetic and seismic data as a function of mantle temperature (T_{mean}). Dots - the mean values of FeO (a) and Al_2O_3 (b) concentrations under the assumption of a normal distribution. Red color – "hot" models, green color – "cold" models. Dashed line - the parameters for BSE (Ringwood, 1977; McDonough, 1990, Dauphas et al., 2014).

3. Conclusions

Regardless of the thermal state, BSM is characterized by almost constant bulk FeO ~ 12-13 wt.% and MG# 80-81.5, which significantly differs from those for the bulk-silicate Earth (BSE). The FeO content of 11-14 wt.% and MG# 80-83 are approximately identical in the upper and lower mantle. The abundance of SiO_2 slightly depends on the thermal state and is 50-55% in the upper mantle and 45-50% in the lower mantle. On the contrary, there are two different groups for the lunar abundance of alumina depending on the thermal state: 1) Cold models of BSM (3-4.6 wt.% Al_2O_3) are comparable to the Al_2O_3 content for the BSE; 2) Hot models bulk Al_2O_3 is 1.2 – 1.7 × BSE. The results indicate a gradual increase in the alumina content from the upper mantle (1-2%) to the lower one up to 4-7 wt.% Al_2O_3 with a garnet amount up to ~20 wt.%. The simulation results suggest that the lunar mantle is stratified by chemical composition. However, the question of the similarity and / or difference in their composition with regard to the abundance of refractory elements remains unresolved and requires further research.

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