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GEOCHEMISTRY

Geochemical Constraints for the Bulk Composition of the Moon

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Abstract—The bulk composition of the silicate Moon (crust + mantle, BSM) is determined on the basis of inversion of gravitational and seismic data. It is shown that the mantle refractory oxides form two different groups depending on the thermal state. By the bulk Al_2O_3 content of ~3.0–4.6 wt %, the cold BSM models span the range of Al_2O_3 content of the silicate Earth (Bulk Silicate Earth, BSE), whereas the hot BSM models are significantly enriched in the Al_2O_3 content of ~5.1–7.3 wt % (Al_2O_3 content of ~1.2–1.7 × BSE) relative to BSE. In contrast, apart from the distribution of temperature, both BSM models are characterized by almost constant values of bulk FeO contents (~12.2–13.2 wt %) and MG# values (80.0–81.5), which are strongly distinct from those for BSE (~8 wt % FeO and 89 MG#). The results show that, for the geophysically possible distribution of temperatures, the silicate fraction of the Moon is enriched in FeO and depleted in MgO relative to BSE.

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The Moon is the first object of space studies among the planets and satellites of the Solar System and is the one space body (except for the Earth) that has yielded rock samples and reliable data on the velocities of seismic wave propagation and the gravitational, electromagnetic, and thermal fields. At the beginning of the 21st century, the Moon has again attracted close attention. The data on the content and distribution of chemical elements on the Moon's surface were provided by the Luna-16, -20, and -24 automatic stations and Apollo missions and were supplemented by remote data from the Clementine, Lunar Prospector, Lunar Reconnaissance Orbiter, Kaguya, Chang-E, and Chandrayaan spacecraft. However, the problem of the similar and/or distinct chemical composition of the Earth (Bulk Silicate Earth, BSE) and its satellite (Bulk Silicate Moon, BSM) still remains a matter of fierce debate [1, 2].

One of the most important tasks of the Moon's geochemistry is determination of its bulk composition: the concentrations of major oxides (SiO_2, Al_2O_3, FeO) and the Mg mole fraction (MG# = MgO/[MgO + FeO]), which affect the mineralogy, physical properties of the mantle, thermodynamics, and the dynamics of magma processing and crystallization of the lunar magma ocean (LMO). The aim of this study is estimation of these geochemical parameters on the basis of joint inversion of the geodetic, seismic, and petrological data using the Monte-Carlo method combined with minimization of the Gibbs free energy in the framework of the Na_2O–TiO_2–CaO–FeO–MgO–Al_2O_3–SiO_2 (NaTiCFMAS) system.

APPROACH

Because of the lack of samples of deep matter, the information on the Moon's composition can be deduced only indirectly, e.g., the analysis of basalts and volcanic glasses, as well as the assemblage of geophysical data. According to the Apollo seismic experiments and geodetic data of the GRAIL mission, we consider a five-layered model of the internal structure of a spherically symmetric Moon: a crust, a three-layered mantle, and an Fe–S core [3–8].

The current petrological–geochemical and geophysical models indicate stratification of the Moon by the chemical composition, which is typically related to the LMO hypothesis (which is usually considered to be the outer shell, subjected to partial melting [8–10]). However, the scale of the Moon's melting remains unclear. This is one of the unresolved problems of thermal and magmatic evolution of the Moon. The processing of data of Apollo seismic experiments implies the zonal structure of the mantle and the presence of several seismic boundaries of the Moon's interiors including a sharp jump in the velocities of *P*- and *S*-waves at a depth of 750 km [3]. We study the thermal state and the chemical composition of the BSM (crust

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