

INFERRING THE COMPOSITION AND THE SEISMIC PROPERTIES OF THE LUNAR MANTLE FROM BULK COMPOSITION AND GEOPHYSICAL DATA

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Thermodynamic modeling of phase relations and physical properties of multicomponent mineral systems was used to develop a method for solving the inverse problem of determining the composition, density, seismic velocities in the Lunar mantle from the totality of geophysical and petrological (bulk composition) evidence. The goal of the inversion procedure is to find the a self-consistent petrological-geophysical model the Moon that minimize the discrepancies between the calculated and well-known petrological and geophysical models.

Introduction: There are two approaches to obtain information on the composition and internal structure of a planet. The first approach consists in forward modeling - computer simulation of phase equilibria and thermoelastic properties at high pressures and temperatures and a comparison of the calculated density and seismic profiles with geophysical observations. A thermodynamic approach for computation of phase diagrams, equations of state of minerals, seismic properties and density from known thermodynamic conditions and mineralogies applied to the planetary interiors has been extensively described.

Another approach to solution of the problem of modeling the constitution of the planet consists in translating the observed gravity data and seismic velocity profiles into the temperature and composition models [1,2] (inverse problem). In this paper, we propose a new formulation for solution of this problem which consists in retrieving the density distribution, chemical composition, seismic velocities in the Lunar mantle from the geophysical and perological observations (bulk composition of the Moon).

Thermodynamic approach: From the thermodynamic standpoint, the composition and the physical state of the Moon can be characterized by several parameters determined from geochemical data and equations of state (ESs) of the multiphase mantle material. The apparatus of chemical thermodynamics allows one to use the bulk composition of rocks for a correct determination of the composition and physical properties of stable phase assemblages at high temperatures and pressures [3]. We use the method of the Gibbs free energy minimization adapted to calculations of phase equilibria in multisystems with phases of variable composition representing multicomponent solid solutions of minerals. The ESs of minerals are calculated in the Mie-Grüneisen-Debye quasiharmonic approximation, with the Born-Mayer potential approximating the ES potential part. Equilibrium compositions of phase assemblages, elastic wave velocities, and density were calculated with the use of the THERMOSEISM software complex

[3]. The database contains self-consistent data on such thermodynamic parameters as the enthalpy, entropy, heat capacity, Grüneisen parameter, thermal expansion, and bulk and shear moduli of minerals and on mixing parameters of solid solutions. For the computation of phase diagram for a given chemical composition, we have used the well-known equation for the Gibbs free energy.

Determination of the Composition and Mantle and Seismic Velocities in the middle and lower mantle:

The mass and moment-of-inertia factor and the hypothesis of chemical differentiation of the Moon as a result of partial melting of initially homogeneous material (hypothetical magma ocean) are used to model the internal structure of the Moon. We consider here a five-layer model of the internal structure of the Moon, including a silicate crust (H=50 km, $\rho=2.9 \text{ g cm}^{-3}$), a three-layer mantle at depths of 50-250 km (upper mantle), 250-625 km (middle mantle), 625 km - core-mantle boundary (lower mantle), and a Fe-10 wt.% S-core ($\rho=5.7 \text{ g cm}^{-3}$). The composition of the lower mantle is equal to bulk composition of the Moon. Crust model from Taylor (1982). Thermodynamic modeling of phase relations and physical properties in the multicomponent mineral system CaO-FeO-MgO-Al₂O₃-SiO₂ was used to develop a method for solving the inverse problem. The concentrations of major oxides for the entire mantle varied in the ranges $2 \leq \text{CaO}$ and $\text{Al}_2\text{O}_3 \leq 8\%$, $25 \leq \text{MgO} \leq 45\%$, $40 \leq \text{SiO}_2 \leq 54\%$, $6 \leq \text{FeO} \leq 20\%$. Thermal models were taken from Kuskov and Kronrod [1]. A Monte-Carlo inversion procedure has been used to estimate the distributions of the density and composition in the mantle and velocities in the middle and lower mantle and Fe-FeS core radii of the Moon from gravity measurements, bulk composition and seismic velocities in the upper mantle.

Results: We determine the permissible ranges of composition, mineralogy, velocities and density in the upper, middle and lower mantle as well as core sizes and masses. Table 1, 2 shows the geophysically and petrologically allowed ranges of composition and of P- and S-wave for geochemical models Taylor (1982), Galimov (2004). Ringwood (1979), Warren (2005) and the velocities of the seismic models in the lunar mantle [4-8]. The basic conclusion arising from this study is that the calculated velocities for all geochemical models may be expressed as follows $V_s= 4.40\text{-}4.48 \text{ km s}^{-1}$, $V_p=7.94\text{-}7.98 \text{ km s}^{-1}$ in the middle mantle and $V_s= 4.41\text{-}4.48 \text{ km s}^{-1}$, $V_p=8.03\text{-}8.14 \text{ km s}^{-1}$ in the lower mantle.

Table 1. Chemical composition in the Lunar mantle

Model	H (km)	Al ₂ O ₃	FeO	MgO	SiO ₂
Taylor (1982), Galimov (2004)	50-250	2.6	11.9	35.8	47.6
	250-625	5.2	14.8	35.2	40.5
	>625	6.1	12.9	32.3	43.8
Ringwood (1979)	50-250	1.7	13.4	37.9	45.7
	250-625	2.1	15.3	36.6	44.3
	>625	4.0	14.0 m	33.9	44.9
Warren (2005)	50-250	1.6	9.5	39.4	48.2
	250-625	2.5	11.8	37.2	46.5
	>625	4.1	10.2	35.3	46.9

Table 2. Seismic velocities in the Lunar mantle

Model	H, km	V _p , km/s	V _s , km/s
Goins et al. (1981)	60	7.75±0.15	4.57±0.10
	400	7.65±0.15	4.37±0.10
	480-1100	7.60±0.15	4.20±0.10
Nakamura (1983)	60-300	7.74±0.12	4.49±0.03
	300-500	7.46±0.25	4.25±0.10
	500-1000	8.26±0.40	4.65±0.16
Khan et al. (2000)	45-500	8.0±0.8	4.0±0.4
	500-750	9.0±1.9	5.5±0.9
	750-1000	11.0±2.1	6.0±0.7
Lognonné et al. (2003) Lognonné (2005)	30-300	7.75±0.15	4.53±0.15
	300-500	7.75±0.15	4.50±0.15
	500-750	7.50±0.30	4.35±0.30
	750-1000	7.90±0.30	4.20±0.30
Gagnepain-Beyneix et al. (2006)	40-240	7.65±0.06	4.44±0.04
	240-500	7.79±0.12	4.37±0.07
	500-750	7.62±0.22	4.40±0.11
	750-1000	8.15±0.23	4.50±0.10
Kuskov, Kronrod (1998)	60-300	7.67-7.80	4.45-4.51
	400	7.53-7.60	4.29-4.30
	800	8.17-8.20	4.50-4.51
Model Taylor (1982), Galimov (2004).	50-300	7.86	4.49
	300-625	7.98	4.40
	625-1000	8.14	4.46
Model Ringwood (1979)	50-300	7.88	4.80
	300-625	7.94	4.41
	625-1000	8.03	4.41
Model Warren (2005)	50-300	7.93	4.56
	300-625	7.98	4.48
	625-1000	8.09	4.48

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