ADJUSTMENT OF GEOPHYSICAL AND GEOCHEMICAL MODELS OF THE MOON.

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Introduction: A goal of the present study was to develop the most favourable model of the Moon matching both geophysical and geochemical data. We used Marcov chain Monte Carlo method MCMC (similar to [1]) for inversion of selenodetic and seismic data together with thermodynamic approach to calculate phase composition and physical properties (bulk and shear modulus) from chemical composition and temperature. Bulk concentrations of Fe and Al oxides were considered as geochemical constraints.

The model of the Moon: We applied viscoelastis spherically-symmetric 9-layers model of the Moon: megaregolith, crust, four mantle layers (mantle 1-3 – upper mantle, mantle 4 – lower mantle), low viscosity zone (LVZ), liquid outer core and solid inner core. Physical properties in each layer were assumed to be constant. The total number of model parameters was 22: thickness *t*, density ρ, shear modulus μ, bulk modulus κ and viscosity η in each layer, except mantle layers; for mantle layers - temperature in each mantle layer and main oxides concentrations (Al_2O_3, FeO, MgO) in upper mantle layers (ρ, μ and κ were calculated from temperature *T* and oxides concentrations). Some of model parameters were fixed. Crustal and megaregolith parameters: ρ_{crust} = 2590 kg/m^3 , h_{crust} = 34 km [2] (including megaregolith with 1 km thickness), Bulk and shear modulus in the crust were taken from [3]. The division of the mantle into layers was performed according to the model [4]: layers boundaries at the depths 250, 500 and 750 km. T in the mantle layers was also fixed. The shear modulus in the fluid outer core is fixed to 0 Pa. The bulk modulus of the outer core and elastic parameters of the inner core are fixed to the model values of [5]. The density of the solid inner core was taken from [6].

The main oxides concentrations were specified equal in first three upper mantle layers (mantle 1-3), concentrations in the lower mantle were calculated from magma ocean condition (mean oxide concentration in the upper layers C_{upper_mantle} + C_{crust} = lower mantle concentration (C_{lower_mantle})= bulk concentration in the silicate Moon (C_{bulk}), [7] et al.).

Geophysical data. We employed same geophysical data set as [1]: six selenodetically observed data – mean radius (*R*), mass (*M*), normalized mean solid moment of inertia (Is/MR^2), degree 2 potential tidal Love number *k*2 [8], and monthly and annual quality factors (*Qm* and *Qa*) [9].

Travel time (TT) data were taken from [10]: 302 data (177 *P* wave and 125 *S* wave) from 59 sources.

Geochemical models of bulk composition of the Moon (Al_2O_3 and FeO). Two types of geochemical models of the Moon were considered: 1 - bulk Al_20_3 in the Moon is similar to that of bulk Earth's silicate part: "mean" Al_2O_3 = 4,05 ± 0,36 wt.%; 2 – concentration of Al_2O_{3bulk} in the Moon is higher than in silicate Earth: "mean"Al_2O_3 = 5,91 ± 0,39 wt.%. For both types of models "mean" Fe_2O_3 = 12,25 ± 1,33 wt.% ([7, 11, 12] et al.).

Calculation of physical properties in the mantle. Density ρ, shear modulus μ and bulk modulus κ in mantle layers were calculated with thermodynamic modeling of phase relations and physical properties in five-component mineral system CaO-FeO-MgO-Al_2O_3-SiO_2. To calculate phase diagrams we implemented Gibbs free energy minimization technique with software and database THERMOSEISM [13]. We considered linear temperature profile with temperature from 600 ^oC at the depth of 150 km to 1200^{o}C at the depths 1000 km. Crustal composition was defined from [14].

Inversion. A Bayesian inversion approach is an effective method to solve for a nonlinear problem such as planetary internal structure modeling ([1, 11] et al.). This study utilizes Markov chain Monte Carlo (MCMC) algorithm to infer the parameters of the lunar internal structure. Then, the likelihood function *L*(*m*) is calculated ([1]).

Since the goal of this study was adjustment of geophysical and geochemical models of the Moon, we considered bulk chemical composition of the Moon as certain value similar to other observed data included into *L*(*m*). The main difference between [1] and this study is that in current study bulk Al_2O_3 and FeO concentrations are included into *L*(*m*) as observed data. As a result we expected to obtain probable model of the Moon wich in some way optimally corresponds to whole set of constraints.

Results. The results of inversion for main oxides concentrations are represented in fig.1, where only envelope of histogram bars is shown in the figure. Three variants of TT errors have been considered: 1) TT error from [10] – err1 (blue color), 2) TT from [10] multiplied by three – err3 (green color), 3) TT from [10] multiplied by nine – err9 (red color).

It is obviously (fig. 1) that though bulk concentrations of Al_2O_3 and FeO were included into $L(m)$ as observed data, in case of err1 a peak value of posterior probability is different from expected value (the difference is ~1 wt.%). For Al_2O_3 it means “transition” into another type of models (fig. 1a). Furthermore there is no normal distibution of model parameters. In case of err3 posterior distribution is normal or close to normal which conforms well with geochemical constraints. Further increasing of TT error (err9) leads to too wide range of MgO concentrations and seismic velocities (fig. 1).

Thus for err3 we have calculated models of the Moon consistent with both geochemical and geochemical constraints.

In the upper mantle (where the accuracy of TT estimation is the most precise because of large quantity of seismic events) calculated seismic velocities are in a good agreement with [4] model. However in the lower mantle layers calculated velocities appeared to be lower than those of [4] model. Furthemore the difference increases with depth: in the lowermost fourth layer (mantle 4) calculated from our model Vp is ~7,9 km/s (fig. 4c), whereas Vp [4] is 8,15+-0,23 km/s. However it should be noted that calculated velocieties are consistent with those from [15, table 1].

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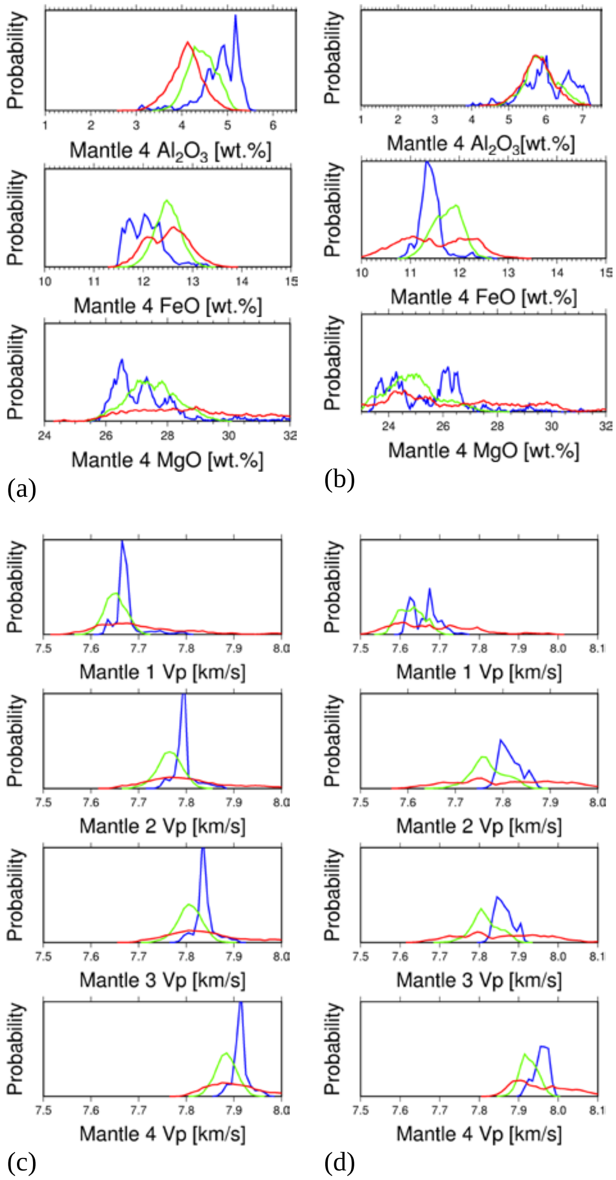

Fig.1 Posterior distribution of main oxides Al_2O_3, FeO, MgO (a, b) in the lowermost mantle layer Mantle 4 (= bulk oxides concentration) and seismic velocities Vp (c, d) in the mantle of the Moon for models: (a, c) type-1 (bulk Al_2O_3 = 4,05 ± 0,35 wt.% - similar to Earth’s), (b, d) type-2 (Al_2O_3 = 5,91 ± 0,39 wt.% - higher than Earth’s). Blue line – err1 (original TT error from [10]]). Green line – err3 (TT error from [10] multiplied by 3 , Red line – err9 (TT error from [10] multiplied by 9).

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