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Joint inversion of seismic and petrologic models for the thermal state of the Moon

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1. Introduction

Despite the extensive progress has been made in understanding the internal structure of the lunar mantle, one of the most difficult factors to determine is the present temperature of the lunar interior. Knowledge of chemical composition and thermal regime is essential for the correct interpretation of seismic data and for understanding the internal structure of the Moon. Temperature is not modeled directly. Seismic studies are probably the best tool to infer (indirectly) the thermal state of the Moon. We invert the Apollo P- and S-wave velocity models, together with lunar mass and moment of inertia, directly for the chemical composition and thermal state of the Moon. To place constraints on the temperature distribution in the lunar mantle, we have calculated a family of geotherms (selenotherms) from seismic velocities [1, 6], making various assumptions regarding the chemical composition of the upper and lower mantle.

2. Thermodynamic approach

The phase composition and physical properties of the mantle were modeled within the Na_2O-TiO_2-CaO-FeO-MgO-Al_2O_3-SiO_2 system including the non-ideal solid solution phases. For the computation of phase equilibrium relations, we have used a method of minimization of the total Gibbs free energy combined with a Mie-Grüneisen equation of state [4]. Our forward calculation of phase equilibria, seismic velocities and density and inverse calculation of temperature include anharmonic and anelastic parameters as well as mineral reaction effects [4, 5].

3. Results

Our seismically derived temperature models (Fig. 1) are much colder than temperatures found by Keihm and Langseth [2], which are based on heat flow and Th abundance measurements. We get the upper mantle heat flow value of 3.6 mW/m^2 [5], which is not consistent with heat fluxes in the range of 7-13 mW/m^2 found in [2].

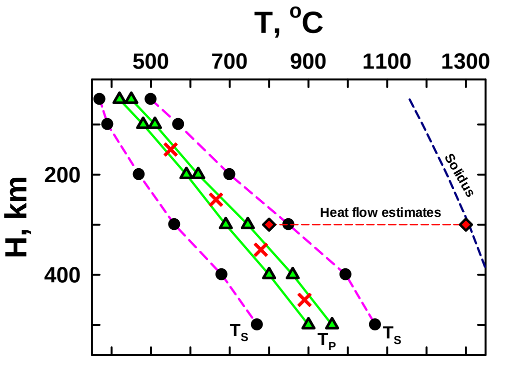


Figure 1: Upper mantle temperatures for the olivine-bearing pyroxenite model inferred from the mean P- and S-wave velocity models [1, 6]. Crosses correspond to the optimal mantle temperature [5]. The range of temperatures at 300 km depth estimated in [2] is marked by the diamonds.

The results of our inversion procedure indicate that upper and lower mantle compositions are strikingly different (Fig. 2). Compositional effects play a dominant role in determining the temperatures from seismic models (Fig. 3).

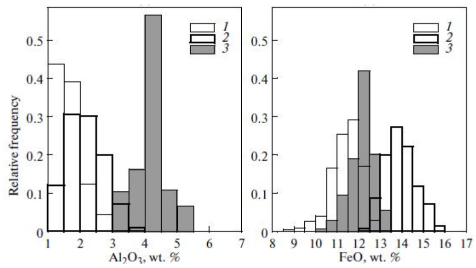


Figure 2. The content of Al_2O_3 and FeO in the mantle of the Moon constrained by the mass, moment of inertia and seismic velocities. 1, 2, 3 are the upper, middle and lower mantle, respectively.

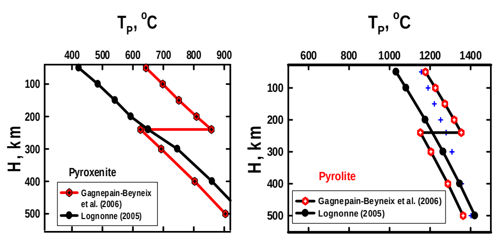
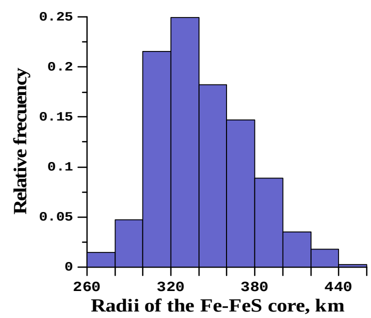


Figure 3: Upper mantle temperature estimates for pyroxenite and pyrolite [5].

The upper mantle may be composed of olivine-bearing pyroxenite; the inferred temperatures are well below the probable solidus condition, in accord with seismic evidence for a rigid lunar mantle. Temperatures inferred for a pyrolitic upper mantle are close or above the solidus. General increase in seismic velocities from the upper to the lower mantle is consistent with a change in bulk composition from a dominantly pyroxenite upper mantle depleted in Al and Ca (~2 wt% CaO and Al2O3) to a dominantly fertile lower mantle enriched in Al and Ca (~4-6 wt% CaO and Al2O3) with larger amounts of olivine, garnet and clinopyroxene. A pyrolitic model cannot be regarded as a geochemical-geophysical basis for the entire mantle of the Moon.

Radius of an iron–sulfide core (Fig. 4) estimated by the Monte-Carlo method (R(Fe–10%S core) = 340±30 km) agrees well with the previous estimates [3, 7].



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