Vestnik Otdelenia nauk o Zemle RAN, VOL. 3, NZ6058, doi:10.2205/2011NZ000188, 2011

Geochemical and geophysical constraints for Lunar thermal field

E. V. Kronrod, O. L. Kuskov, V. A. Kronrod
V. I. Vernadsky Institute of Geochemistry and Analytical Chemistry RAS, Moscow
kendr_ka@bk.ru

Key words: Moon, temperature, composition, thermodynamics.

Citation: Kronrod, E. V., O. L. Kuskov, V. A. Kronrod (2011), Geochemical and geophysical constraints for Lunar thermal field, *Vestn. Otd. nauk Zemle, 3*, NZ6058, doi:10.2205/2011NZ000188.

The thermal conditions currently estimate directly from heat flow and result of numerical simulation of lunar thermal history. Heat flow measurements in alighting areas of Apollo-15 and -17 were 21±3 and 16±2 mW/m^2,that is 3–4 times less than average heat flow through earth`s surface. Subsequently a great number of works about thermal history of the Moon were published. According to calculations, under accretion heat (at that time the hypothesis of co-accretion was dominant) and following warming of the Moon by radioactive elements the temperature of the outer layer of the Moon after ~1 billion years reached melting curve at depth about 500 km, that conforms to seismic data and depth of outflow of sea basalts. Deeper layers haven't been subjected to melting. At the present time the interpretation of heat flow estimations needs a revision. In proposed work were founded probable temperature distribution and its influence on the internal structure of the Moon.

The problem of thermal field estimation of the Moon was provisionally divided into two parts.

I. From seismic data for basic models of the Moon probable temperature distributions in mantle were found.
II. Under results of the part I, using the data of inertia moment, mass and seismic velocities we determine temperature distributions and basic oxide concentrations in the mantle of the Moon.

We should consider these tasks more particularly.

I. The temperature field of the Moon defines by instrumentality of the new method of inversion of seismic information into temperature distribution by using P- and S-velocity information. Correlation of geochemical and geophysical models of the Moon was done with the instrumentality of physic-chemical modeling. These methods make possible converting bulk composition models into equilibrium phase associations and conformed with them seismic and density characteristics, and converting velocity profiles into composition models and/or temperature distribution [*Kuskov and Kronrod*, 2007; *Kuskov, et al.*, 2006]. Phase associations and physical properties of lunar rock estimates from Gibbs free energy minimization method and mantle substance equation of state subject to phase changes, anharmonicity and inelasticity. Detailed method of conversation seismic data into temperature is described in [*Kuskov et al.*, 2006].

Converted temperature profile allows detect the preference of up and low mantle composition and estimate degree of certainty of lunar seismic composition. Three basic petrological models of the Moon were considered: olivinic pyroxenite (Ol–Px) [*Kuskov and Kronrod*, 1998], pyrolith [*McDonough*, 1990], Ca, Al-fertile composition (olivine–clinopyroxene–garnet – Ol–Cpx–Gar) [*Kuskov and Kronrod*, 2009].

As a result of moon's thermal field computational modeling geophysical and geochemical constraints of composition and temperature distribution in up and low mantle of the Moon were determined. Following conclusions were done:

(1) The influence of rock chemical composition is the most important parameter in conversion of seismic velocities into temperature effects. Calculated temperature for pyrolith composition in upper mantle exceeds solidus temperature (fig. 1b), that doesn't satisfy physic-chemical limitations. Depleted by pyroxenite composition (~2 mass.% CaO и Al_2O_3), satisfy limitations (fig. 1a). Low mantle composition can be presented by either pyrolith or association of olivine-clinopyroxene-garnet (fig.2).

(2) Pyroxenitic composition of upper mantle and olivine-clinopyroxene-garnet and/or pyrolithic composition of low mantle gives realistic temperature distribution (less than solidus) in all mantle of the Moon [*Kuskov and Kronrod*, 1998; *Kuskov and Kronrod*, 2009]. Temperature distribution on depth 50-1000 km can be described by approximate equation: $T(^oC) = 351 + 1718[1 - \exp(-0.00082 \cdot H)]$.

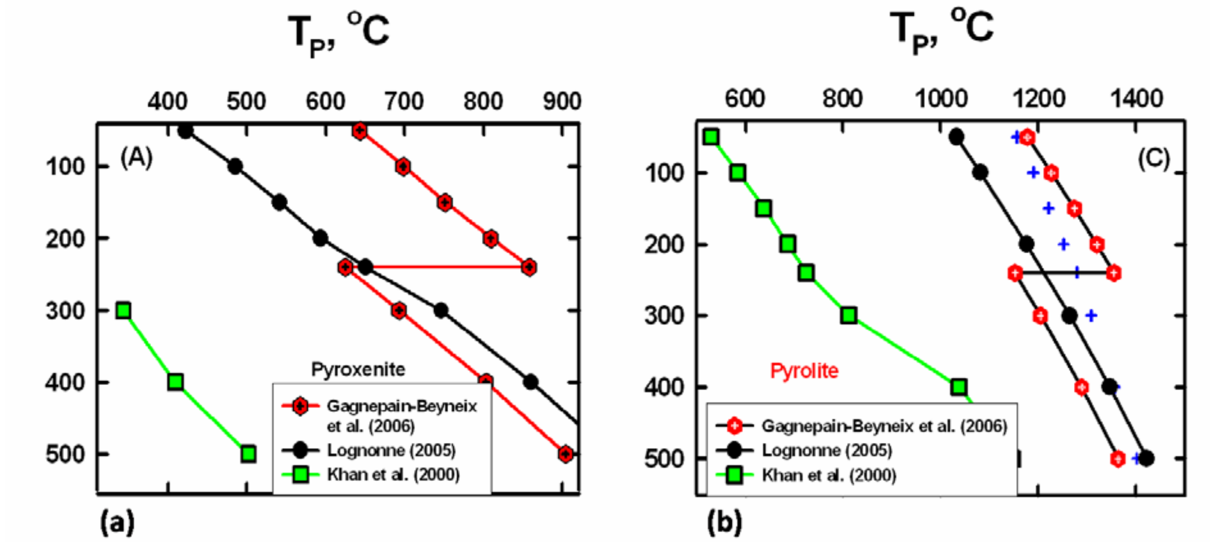

Fig. 1. Temperature distribution in the upper mantle of the Moon, derived from recent seismic data [*Kuskov and Kronrod*, 1999a; 1999b; *Kuskov et al.*, 2002] and geochemical constraints for pyroxenite composition. Seismic models for temperature calculation were taken from [*Kuskov and Kronrod*, 1999]. Temperature variations on parts with the same velocity depend on density changing with depth

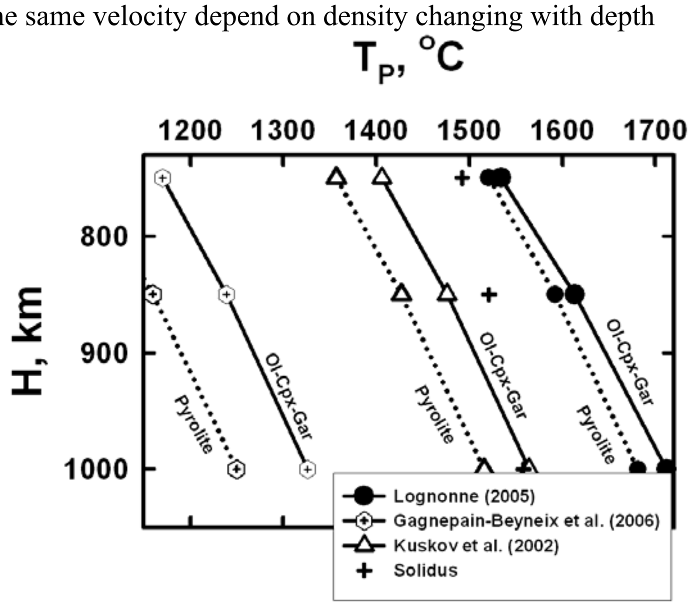

Fig. 2. Temperature distribution in low mantle of the Moon from seismic models [*Kuskov and Kronrod*, 1999; *Kuskov et al.*, 2002]. Compositional models are: pyroxenite, olivine–clinopyroxene–garnet and pyrolith. Solidus (crosses) marks data for pyroxenitic [*Kuskov et al*., 2002] and peridotitic [*McDonough*, 1995] composition

II. On the base of gravitation data (mass, moment of inertia) and seismic data (P- and S-velocities) using Monte-Carlo method all the lunar thermal state constraint set is analyzed. Consequently qualitative dependences between bulk composition, core size and lunar mantle temperature distribution were gained. Phase composition and physical properties of mantle calculation was done using Gibbs free energy minimization technique and equation of state of mantle substance in system CaO–FeO–MgO–Al_2O_3–SiO_2. Input data is: mass, radius, average density, moment of inertia of the Moon and seismic velocities in mantle. According to seismic data we propose that the model of the Moon consists of five spherical layers: crust, three-layered mantle (upper, middle and lower) and ferro-sulphidic core, measurements of which determine from calculations. Following parameters of model were considered: crust depth was taken in the interval of 40-55 km км, up-middle mantle boundary – 250–300 km., middle-lower mantle – 625–750 км. Mantle-core boundary defines from calculations.

Minimal temperature of the up mantle at depth 150 km (500 °C) was defined from numerical experiment. Maximal temperature in lower mantle at the depth of 1000 km set at 1400 °C (that is 150 °C less than solidus temperature). Estimations for different temperature profiles were done. The temperature for the upper mantle is set at 450-750 °C, for middle – 750–1200 °C, for lower – 950–1400 °C. As gradients of temperature in initial profiles were different, comparison of results was done for average temperature of the mantle.

$$T_{mean} =(T_{up}V_{up}+ T_{mid}V_{mid} +T_{low}V_{low})/(V_{up}+ V_{mid} +V_{low})$$

Indexes up, mid, low correspond to upper, middle and lower mantle, V – volume of corresponding mantle zone.

The results of modeling are represented in figs.1 and 2. Apparently, bulk composition considerably depends on T_{mean}. Increasing of temperature leads to FeO concentration decreasing and Al_2O, MgO increasing. Radius of the Moon core also slightly increases with temperature increasing.

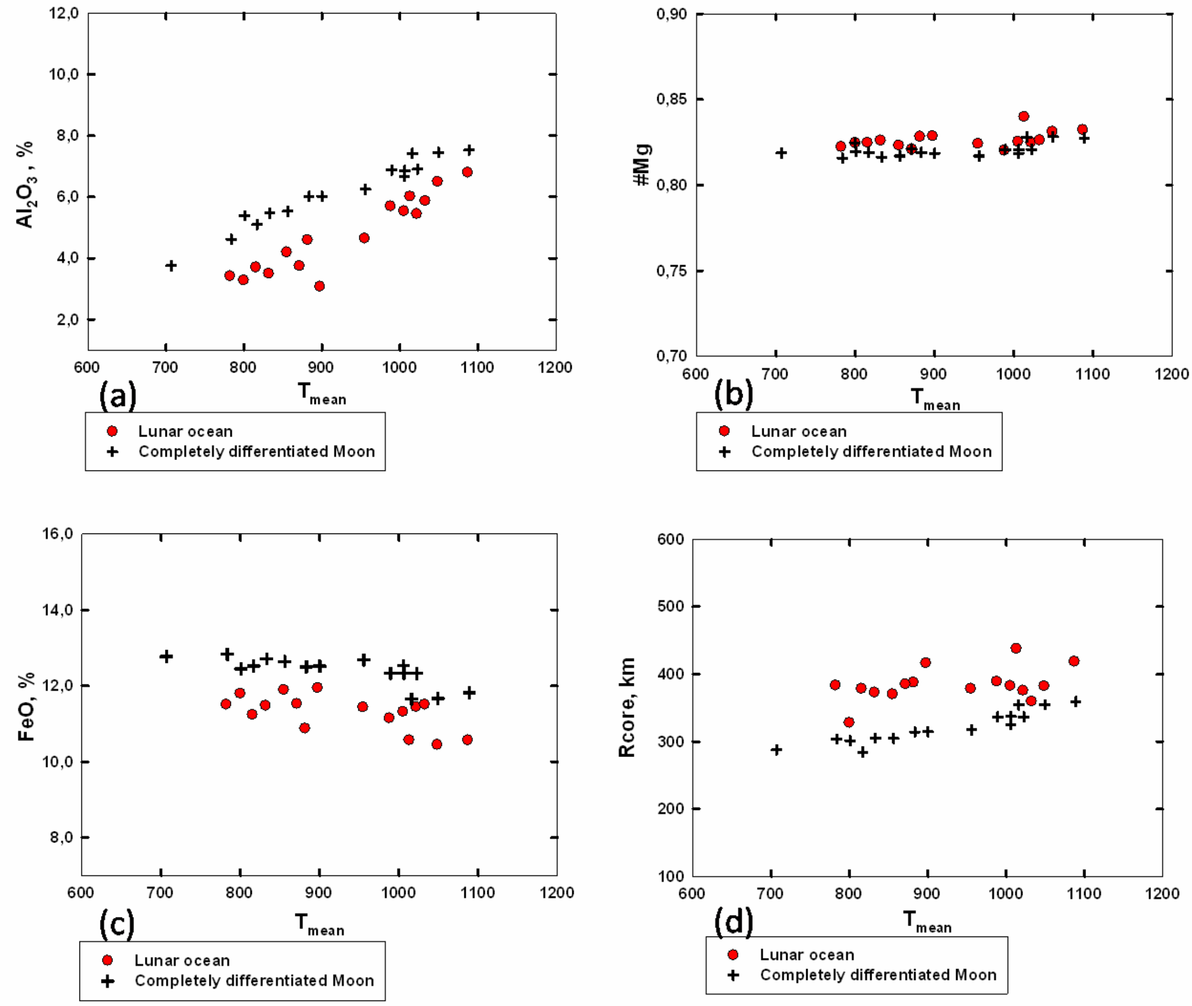

Fig 3. Concentration of Al_2O_3 (a) magnesia number (b), concentration of FeO (c) and core radius as functions of T_{mean}. Middle-lower mantle bound is 625 km

The results of researching show that for bulk composition estimating is necessary to set concrete thermal model or set heat flow limitations on the crust–mantle boundary.

By this part of work following conclusions can be done:

1. Temperature distribution in mantle of the Moon essentially influence on bulk composition of silicate Moon, in the first place on concentration Al_2O_3
2. The Moon is zonal stratified by composition.
3. Silicate Moon is essentially concentrated by oxide FeO (10.5–13 mas. %) and depleted by MgO (28.5–32.5 mas.%) in comparison with earth's mantle. Magnesia number lies in the range of 0.82–0.84

References

Kronrod, V. A., O. L. Kuskov (1997), Chemical composition, temperature and radius of the lunar core from geophysical evidence, *Geokhimiya* № 2, pp. 134–142.

Kronrod, V. A., O. L. Kuskov (1999), Temperature in the Moon's mantle from seismic data, *Izvestiya. Phys. Solid. Earth,* № 35, pp. 363–371.

Kronrod, V.A., O. L. Kuskov (2007), Modeling of the thermal structure of continental lithosphere, *Izv. Phys. Solid Earth, 43*, pp. 91–101.

Kuskov, O. L., V. A. Kronrod (1998), A model of the chemical differentiation of the Moon, *Petrology, vol 6*, pp. 564–582.

Kuskov, O. L., V. A. Kronrod (2009), Geochemical constraints on the model of the composition and thermal conditions of the Moon according to seismic data, *Izv. Phys. Solid Earth., vol 45*, pp. 753–768.

Kuskov, O. L., V. A. Kronrod, H. Annersten (2006), Inferring upper-mantle temperatures from seismic and geochemical constraints: Implications for Kaapvaal craton, *Earth Planet Sci. Lett., vol. 244*, pp. 133–154.

Kuskov, O. L., V. A. Kronrod, L. L. Hood (2002), Geochemical constraints on the seismic properties of the lunar mantle, *Phys. Earth Planet. Inter, vol. 134*, pp. 175–189

McDonough, W. F., S. –s Sun (1995), The composition of the Earth, *Chem. Geol., vol. 120*, pp. 23–253