EFFECT OF VARIABLE THERMAL CONDUCTIVITY ON LUNAR THERMAL EVOLUTION. Y. Zhao[1], A. P. van den Berg[1] and W. van Westrenen[1], [1]Faculty of Earth and Life Sciences, VU University Amsterdam, the Netherlands, email y.zhao@vu.nl

Introduction: The Moon is a relatively small planetary body. Its high surface-to-volume ratio suggests that it is expected to have cooled relatively rapidly. However, recent observations suggest that it still maintains a high temperature in its present-day interior [1, 2], raising questions about the mechanism(s) behind a delayed cooling. Temperature-dependent viscosity has been studied as a first-order factor [3] in controlling the rate of planetary cooling. The effect of variable thermal conductivity has been studied before for other planetary bodies [4, 5], but not the Moon.

The lunar crust is mainly composed of anorthositic plagioclase [6], with a small volume of mare basalt on parts of the surface. Both of these phases have a thermal conductivity of around 2 W/m/K [5, 7]. We consider the effect of variable conductivity in the lunar interior, including the low value in the lunar crust, and assess how it influences cooling history. This variable thermal conductivity is compared to a uniform value of 4 W/m/K, generally assumed for mantle materials and applied in many previous studies [4, 5, 8, 9].

An updated conductivity profile: To arrive at a more refined conductivity profile for the Moon, Hofmeister's [10] temperature- and pressure-dependent conductivity model for average mantle material is applied under lunar conditions. Temperature is obtained from the mantle convection models of [8]. Pressure is obtained from a depth-dependent gravity profile calculated from uniform mantle density and assuming an Fe-rich core radius of 350 km. Thermal expansivity decreases with depth and has a negative effect on conductivity. Results obtained from the GRAIL mission show that the lunar crust is 34-43 km thick [11]. In this study, we assume the crust has a thickness of 40 km, and a thermal conductivity of 2 W/m/K.

The resulting temperature- and pressure-dependent thermal conductivity profile changes during secular cooling. A few snapshots from model H1 (Table 1) are shown in Figure 1. As van den Berg et al. have calculated for the Earth [4, 9] and exoplanets [12], due to strong temperature dependence, conductivity in the thermal boundary layers (e.g. the lithosphere) decreases rapidly with increasing temperature. For the above-mentioned planets, conductivity increases with depth in the convective mantle, due to the dominance of pressure dependence over temperature dependence in the deeper mantle. This creates a low-conductivity zone (LCZ) at the base of the lithosphere [4, 9, 12], which affects the style and efficiency of planetary cool-

ing. On the contrary, in the Moon, the positive effect of pressure is significantly smaller due to the low gravity, decreasing with increasing depth. The negative effect of temperature almost cancels the positive effect of pressure in the bulk mantle. Although a sharp change of gradient is observed at the bottom of the lithosphere, it does not represent a clear minimum.

In our preliminary studies, we verify that the main influence of variable thermal conductivity on planetary cooling comes from the thermal boundary layers. The low conductivity in the lunar crust leads to overall high thermal resistance of the lithosphere, which acts as a strong resistor to the heat flow caused by the temperature contrast between the mantle and the surface.

Model setup: Convection equations are solved for an incompressible, infinite Prandtl number fluid, using the extended Boussinesq approximation. Modeling experiments are performed using a cylindrical finite element mesh with a total of 20000 elements.

Figure 1. Evolution through time of the variable thermal conductivity in the lunar mantle in model H1. The initial conductivity profile (red) is identical in the H models.
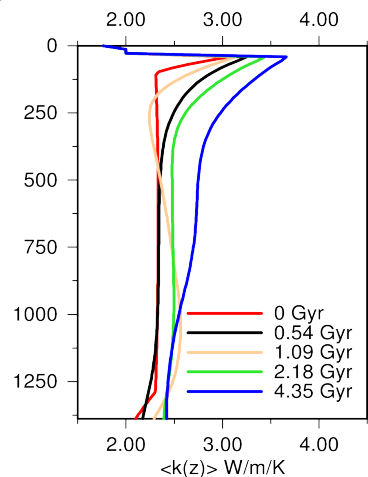
Our models start from the end of lunar magma ocean (LMO) solidification [13]. Density and the internal distribution of heat-producing elements are based on the stratified structure of the cumulates [13]. The initial temperature distribution follows a laterally homogeneous profile that increases linearly in the convective part of the bulk mantle. The rate of increase with depth is obtained from a linear approximation of a convecting lunar mantle in previous model results [8].

In our preliminary studies, the viscosity scale value is 1×10^{23} Pa s. This results in a Rayleigh number of 1.005×10^4.

A set of four models is used, summarized in Table 1. H1 and H2 use the variable conductivity model. They are compared to U1 and U2 which use a uniform conductivity of 4 W/m/K. H1 and U1 assume that the heat-producing elements of the KREEP layer remain in the lunar crust, whereas H2 and U2 assume they follow the ilmenite-bearing cumulates (IBC) in the mantle overturn after solidification of the LMO.

Table 1. Models used in this study. Unit of thermal conductivity is W/m/K.

Models	H1	H2	U1	U2
Conductivity model	k=k(z)	k=k(z)	k=4	k=4
Location of KREEP layer heat producing elements	crust	IBC layer	crust	IBC layer

Results and discussion:

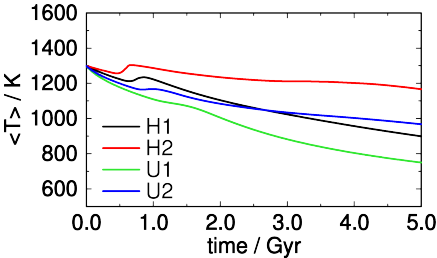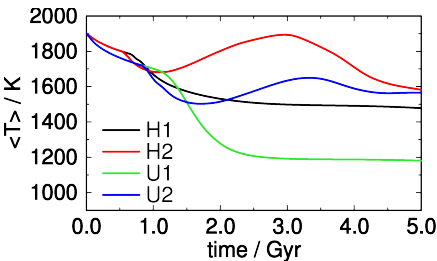*Figure 2. Evolution of average mantle temperatures.*

*Figure 3. Evolution of average core temperatures.*

The effect of variable conductivity can be seen by comparing the H models to the corresponding U models. The different conductivity models result in differences in present-day average mantle temperature of more than 100 K. This corresponds to a delay of cooling of 2 Gyr or more, for the H models to reach the same present-day mantle temperature. This means that variable thermal conductivity, including low values in the crust, is a significant controlling factor in the thermal evolution of the Moon.

Core temperature evolution is sensitive to both variable thermal conductivity and the location of the

KREEP layer heat production. Variable thermal conductivity moves the onset of mantle overturn back in time by more than 0.5 Gyr.

Figure 4. Heat flux across the core-mantle boundary, compared to the Q_{ad} criterion.
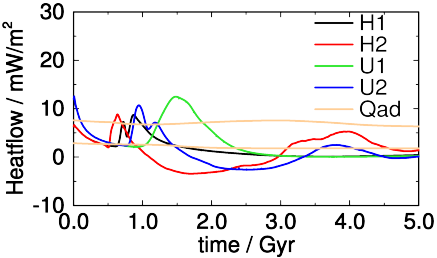
A variable conductivity does not result in significant differences in present-day surface heat flux. Core-mantle boundary heat flux is compared to a necessary condition of lunar dynamo, which computes the minimum amount of heat flow (Q_{ad}) out of the core to sustain an adiabat in the outer core [14]. Models with a variable conductivity in general imply an earlier time range of dynamo existence.

Conclusion: For small planetary bodies with a high surface-to-volume ratio, including the Moon, thermal conductivity in the lithosphere can be a strong limiting factor in their thermal evolution. The high concentrations of plagioclase in the lunar crust significantly increase thermal resistance of the lithosphere, and therefore insulate the convecting mantle.

Our results show that a variable conductivity profile predicts higher present-day mantle temperatures by more than 100 K, an early mantle overturn and an earlier dynamo existence.

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