ASYMMETRIC THERMAL EVOLUTION OF THE MOON.

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Introduction: The Moon possesses a clear dichotomy in geologic processes between the nearside and farside hemispheres [1]. The most pronounced expression of this dichotomy is the strong concentration of both radioactive heat sources [2,3] and mare basalts on the nearside hemipshere in a region known as the Procellarum KREEP Terrane (PKT). The apparent correlation between heat sources and basaltic eruptions implies a genetic relation between the two [4]. Apollo samples and remote sensing data suggest that the volumetrically insignificant mare basalts are not the direct carrier of the heat producing elements in the PKT, and that these elements are likely concentrated in the underlying crust [1]. If the entire crust were enriched in heat producing elements, this heat source could influence the Moon's post magma-ocean thermal evolution.

Past studies of the Moon's thermal evolution have made use of either spatially symmetric conditions [5,6], limited regions in space and/or time using simplified models [4,7] or the influence of ponctual external perturbations [8]. In this project, we use the 2 and 3 dimensional thermochemical convection code GAIA developped at the German Aerospace Center [9] to conduct a systematic study on the influence of an asymmetric distribution of crustal heat sources on the Moon's thermal and magmatic evolution.

Method: The code GAIA allows the calculation of both 2D cylindrical and fully 3D spherical simulations. It handles variable viscosity in both the radial and lateral directions, and the conservation equations of mass, momentum and energy are solved using the Boussinesq approximation and a Newtonian rheology. The equations also include latent heat consumption by partial melting as well as the subsequent change of density of the mantle residue. The extraction of heat sources from the mantle and ensuing crustal growth can also be monitored. For the initial aspects of this investigation, we focus on 2D cylindrical simulations, which are much less computationally intensive than full 3D simulations.

An asymmetry in heat production is imposed by concentrating KREEP below the crust in the PKT region. The bulk uranium content of the Moon is debated, with estimates from an Earth-like 20 ppb to almost twice this value of 35 ppb [10]. Initial simulations with bulk uranium abundances of 35 ppb led to excessively hot histories that are inconsistent with the observed volumes of mare basalts, and we instead concentrated on simulations with a 20 ppb bulk uranium concentration [4]. The abundances of heat producing elements in the highlands crust, PKT, and mantle, were taken from [4].

A suite of simulations were run using different intial conditions, and these were compared using several hemispherical averaged quantities, such as the melt fraction, lithospheric thickness, and heat flow at the surface and core mantle boundary. The predicted gravitational anomaly on the surface was also calculated, as this could influence crustal thickness modeling based on gravity and topography. Slices of the Moon's mantle at different times were also used to provide insight on convection patterns.

Results: One key result is that asymmetries in heat producing elements distribution that were created shortly after the Moon formed can have a long lasting influence on the thermal structure of the Moon. Figure 1 shows the thermal state of the Moon after 4.5 Ga of evolution for a representative case. Approximating the thickness of the elastic lithosphere by the 800 K isotherm [11], its present day value varies from approximately 50 km beneath the PKT to nearly 200 km on the farside. Such lateral variations would likely influence the tidal stresses in the lunar interior, and hence the locations of deep moonquakes on the two hemispheres.

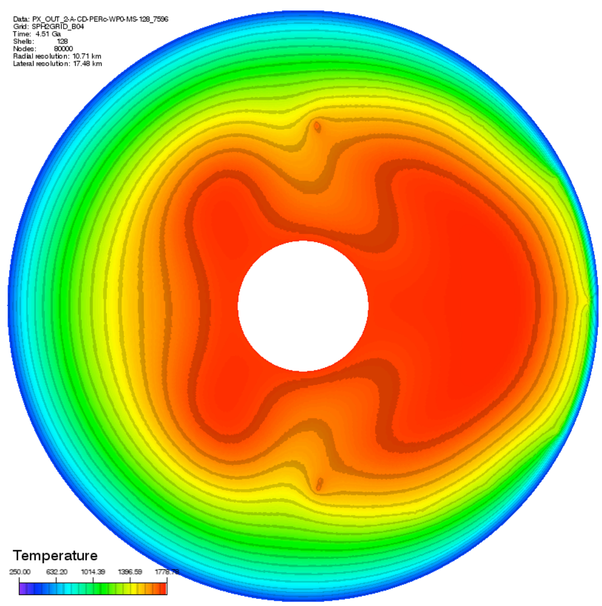

FIG. 1: Thermal state of the Moon after 4.5 Ga of evolution. The modeled PKT region is 40° of angular radius and was emplaced on the right hemisphere

Another stricking result is that it is possible to obtain large degrees of melting beneath the PKT while keeping the farside mantle mostly unmelted (Figure 2). These simulations also predict variations in the core-mantle boundary heat flow of about 1 mW/m^2 at the present day, and as large as 3 mW/m^2 in the past (Figure 3). As proposed by [12], such a degree-1 heat flow boundary condition for the core could power a dynamo, potentially explaining the existence of lunar magnetic anomalies and paleomagnetic measurements.

Finally, this thermal anomaly could have an important contribution to the long wavelength gravity field field of the Moon. Figure 4 shows variations in the radial gravity field for the present day as a function of angular distance from PKT. Such variations have not been taken into account in crustal thickness modeling of the Moon [13], and might help reconcile gravitational and seismological crustal thickness estimates [14,15]. Furthermore, present day lateral temperature variations could also bias seismological inversions for mantle composition.

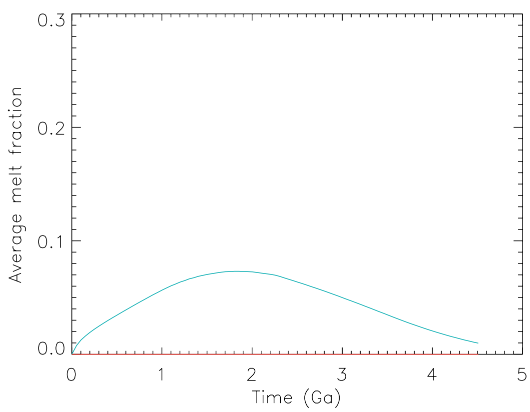

FIG. 2: Averaged melt fraction on the farside (red) and nearside (blue) hemispheres.

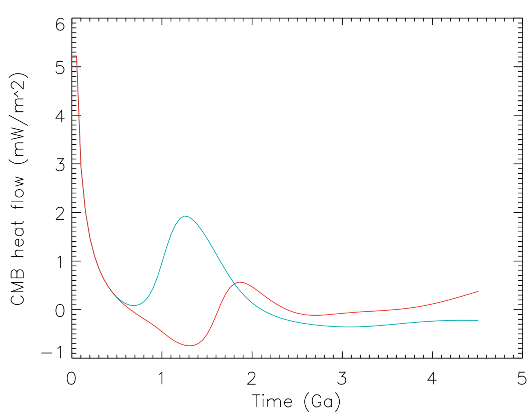

FIG. 3: Average heat flow out of the core on the farside (red) and nearside (blue) hemispheres.

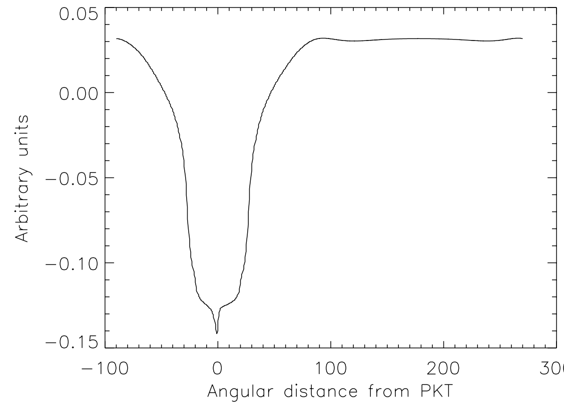

FIG. 4: Gravity anomaly as a function of angular distance from the PKT anomaly's center in arbitrary units.

Conclusion: Initial asymmetries in the concentration of heat sources in the PKT region of the Moon leads to long-lasting consequences that are visible to the present day: melt production and mare volcanism are localized on the nearside hemisphere, a degree-1 heat flow is imposed on the core-mantle boundary, and the thermal anomaly has a non-negligible effect on the gravitational field.

Future work will include an investigation of the effects of a stable mantle stratification due to mantle overturn following magma ocean crystallization. Such a stable stratification would slow down the already sluggish convection in the lunar mantle, and possibly strenghten the present observations. The effect of different initial crustal thicknesses, especially when introducing a difference between near and farside, as well as crust formation, will also be investigated.

Finally, as more computational power will be available, some simulations will be run in 3D to assess the effect of geometry.

Aknowledgements: The simulations were performed equally on IPGP's cluster Melian and on DLR's cluster pfcluster1.

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