THE ROLE OF BASIN-FORMING IMPACTS IN THE GLOBAL LUNAR EVOLUTION.

T. Rolf[1], M.-H. Zhu[2], K. Wünnemann[3], and S. C. Werner[1], [1]Centre for Earth Evolution and Dynamics, University of Oslo, Norway (tobias.rolf@geo.uio.no), [2]Space Science Institute, Macau University of Science and Technology, Taipa, Macau, [3]Museum für Naturkunde, Leibniz Institute for Earth Evolution and Biodiversity, Berlin, Germany

Introduction: A striking feature on the lunar surface is the population of impact basins a few dozens of which have been cataloged. These large-scale structures have diameters of several 100 to >2000 km and their signature is clearly visible in present-day observables such as the gravity field [1]. The chronology of lunar basins is essential for understanding the age of the lunar surface and its early evolution [2]. However, relatively little previous work has addressed the question, how large basin-forming impacts affected the internal evolution of the Moon, which is inevitably linked to the surface, e.g. via volcanism and heat loss.

Upon impact, the vast majority of the kinetic energy of the impactor is transferred to the target triggering a shock wave that propagates away from the point of impact. As a consequence material *(i)* is set into motion resulting in the excavation of a crater and *(ii)* is heated up and may even melt after release from shock pressure. Material that is expelled from the crater is deposited outside the basin forming a high-porosity, low-conductivity ejecta blanket. Its insulating properties have been suggested to modify surface heat flux [3], the longevity of magmatism [4] and lunar contraction history [5]. Most such studies have used a spatially and/or temporally uniform ejecta blanket, although its thickness may significantly vary [6].

However, most of the impact energy contributes to the heating of the interior [7] up to its solidus and may affect internal planetary dynamics [8] linked to surface magmatic processes [9].

Recently proposed global lunar evolution models [5,10] can explain various observations on the present-day Moon, but do not, or only partly, consider the thermal input of large basin-forming impacts. We take this as motivation to investigate in more detail the thermochemical evolution of the Moon coupled with its early bombardment.

Methodology: We use the mantle convection code *StagYY* [11] to model the long-term evolution of the Moon. It solves the equations for incompressible Stokes flow in a 3D spherical shell and includes temperature- and depth-dependent viscosity as well as (basaltic) melt production and extraction.

The general model evolution is largely controlled by the amount and distribution of radiogenic heat sources and the initial thermal state. Our preferred initial thermal profile has a 80 km surface boundary layer and then follows the solidus to a depth of 350 km below which the profile is adiabatic [10].

We use ~25 ppb as the bulk *U* content of the Moon, but take into account higher concentration in the lunar crust (top 50 km), and particularly in a 80° arc below the near-side crust, which represents the Procellarum KREEP terrane and allows us to account for the presently observed asymmetric structure of the Moon [10].

In order to investigate the role of impact processes, we consider an ejecta blanket with variable local thickness and degree of insulation as well as the impact-induced heat anomaly. The latter we determined by conducting a series of 2D axisymmetric impact simulations of varying basin size with the shock physics code *iSALE* [12,13] The results were then plugged into the 3D evolution model. For simplicity, we did not consider the effect of an oblique impact angle here and kept the impact velocity constant..

The thickness of the ejecta blanket is assumed to decrease with distance according to a power law, following recent studies on the Orientale basin [14,15]. Based on this assumption we can approximate ejecta thickness globally and convert it into an effective surface conductivity of the lunar regolith [5], which is subsequently used in the evolution model.

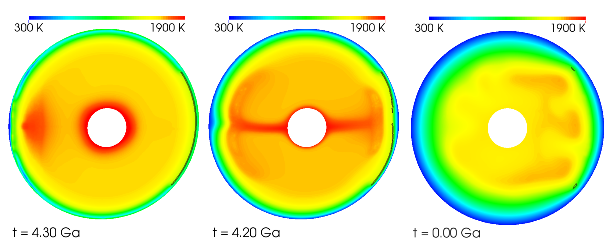

Fig. 1: Slices of mantle temperature in a case with an impact (2080 km basin) at 4.3 Ga on the farside (left), antipodal to the location of KREEP (right, black).

Results: In general, our preferred models match present-day surface heat flux (far-side ~12 mW/m^2, near-side ~16 mW/m^2, ~20 mW/m^2 above *KREEP*) and temperature profile from independent estimates reasonably well [3,16].

We focus here on an impact leading to a South Pole-Aitken-like basin (~2080 km), which may be considered as an end-member in lunar evolution. The impact (at 4.3 Ga) heats up a substantial volume of the lunar interior to above its solidus *(Fig. 1),* which generates a large melting event leading to crust formation and depletion in basalt of the residue.

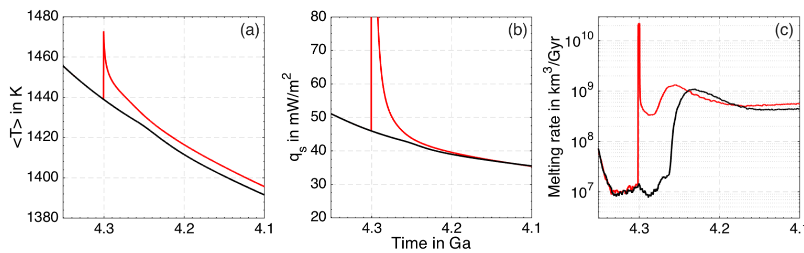

Fig. 2: (a) Global average mantle temperature, (b) surface heat flux, (c) melting rate during early evolution: (black) no impact, (red) impact case as in Fig. 1.

However, the initially strong temperature increase is rather short-lived and most of the global thermal anomaly vanishes within ~50 Myrs after the impact (*Fig. 2a*). This is because surface heat loss is strongly increased (*Fig. 2b)* due to enhanced thermal conduction and also because a lot of the shock-induced heat is used for latent heat consumption during strong melting after the impact *(Fig. 2c).* After 50-100 Myrs, heat flux has relaxed to the value observed without an impact.

Melt is still generated after that time (*Fig. 2c*), not due to the impact, but because of the arrival of hot upwellings hitting the base of the lithosphere (*Fig. 1*). The locations where such upwellings arrive is, however, affected by the impact (2 antipodal plumes with impact, 4 tetrahedral plumes without). This may contribute to the observable distribution of volcanic rocks.

A small remaining global thermal anomaly is maintained in the long-term evolution, possibly because the lunar interior is a bit more depleted due to the extraction of basalt after the large impact-induced melting event: the higher solidus of depleted material may lead to slightly lower melt production in the later evolution.

This remaining heat anomaly is much smaller than the uncertainty in proposed present selenotherms [16]; however, it can be enhanced by the ejecta blanket caused by the impact. Depending on the assumed thermal conductivity of the regolith, the blanket (although very thin far away from the basin rim) insulates the interior and causes up to 50 K globally elevated temperature at present-day, more than the remaining anomaly induced by the impact directly (*Fig. 2a*).

The effect of the ejecta blanket is furthermore enhanced if additional ejecta (from other basins) is considered to form a global layer: a few 100 meters of such a global *background blanket* lead to mantle temperatures globally increased by up to a few 100 K and enhance the amount and duration of magmatic activity, consistent with [4].

We tested various impact sizes and found that the effects reported above decrease with the observed basin size. This is not surprising since smaller impacts induce less heat, cause less melting, and deposit less ejecta on the surface. Additionally, we computed a case with a large impact at the end of the lunar bombardment (~3.7 Ga): here, somewhat less impact-induced melt is observed because of secular cooling of the whole Moon and the growth of the cold lunar lithosphere.

Finally, we have computed some cases, where we considered not only a single impact, but the 7 largest lunar basin-forming impacts at their respective locations and possible formation time. Preliminary results confirm the observations above. Effects are slightly stronger when several impact events are superimposed, but seem to be dominated by the largest event. Future work with different impact sequences will be performed to evaluate the effects of the bombardment history in more detail.

Conclusions: Our results indicate that shock-induced thermal anomalies can have strong temporary effects on mantle temperature, surface heat loss, and melt production. However, these effects are mostly short-living (<100 Myr). On the long-term, insulating ejecta may contribute stronger to lunar mantle temperature and surface heat flux, in particular if a global cover was formed, but the present-day thermal state is more likely to be controlled by the amount and distribution of heat-producing elements.

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