THERMAL AND CHEMICAL CONSEQUENCES OF LARGE IMPACTS ON THE LUNAR INTERIOR.

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Introduction: Combined models for mantle thermochemical evolution and impact-induced shock heating show that large basin-forming impacts can have profound long-term effects on the interior dynamics of terrestrial planetary bodies [1, 2]. The Moon's interior evolution was likely affected by such large impact events. As the South Pole–Aitken (SPA) basin is the largest and most ancient recognizable lunar impact basin [3], the SPA impact likely had the most pronounced influence on lunar evolution. Accordingly, we investigate the potential significance of impacts through modeling of thermal heating associated SPA; specifically, the SPA impact will be simulated using a combined shock heating and thermochemical evolution model. Results will be interpreted in the context of lunar observational data and predictions made by other models of the effects of lunar impacts, including the migration of magma ocean residuum [4] and antipodal seismic effects and fracturing [5, 6]. We are especially interested in the potential relationship between the SPA impact, the Procellarum KREEP Terrane (PKT), and mare basalts on the lunar nearside (Figure 1). This abstract presents preliminary shock-heating calculation results for the SPA impact and a first-order estimation of lunar thermochemical evolution following emplacement of a generalized spherical temperature anomaly, as well as a discussion of related models and their significance.

Shock Heating Model: To calculate shock-induced heating, the Hugoniot release method from [1] is used. The initial density of the lunar material is assumed to be constant with depth. As we are primarily interested in near-surface effects, we do not consider depth-dependent variations in density and pressure in the model. Figure 2 shows a 2D cross-section of the impact-induced thermal anomaly. We assume that resulting temperatures in excess of the mantle solidus can be approximated as the solidus due to greater efficiency of thermal convection in liquids compared to solids as discussed in [2].

Instantaneous Effects of the SPA Impact: Parameterizing the SPA impact based on previous work [8–10] in our shock heating model indicates that the impact generated an isobaric core (IC) with a radius of ~60 km centered at a depth of ~25 km, outside of which shock pressure and heating decay rapidly with distance from the IC center [7]. Temperature increase exceeds 500 K up to a distance of ~800 km and 100 K up to a distance of ~1700 km. The subsequent evolution of this induced thermal anomaly will depend on the thermal and chemical state of the Moon at the time of the SPA impact [8, 9] which can be examined through thermochemical evolution models of the Moon.

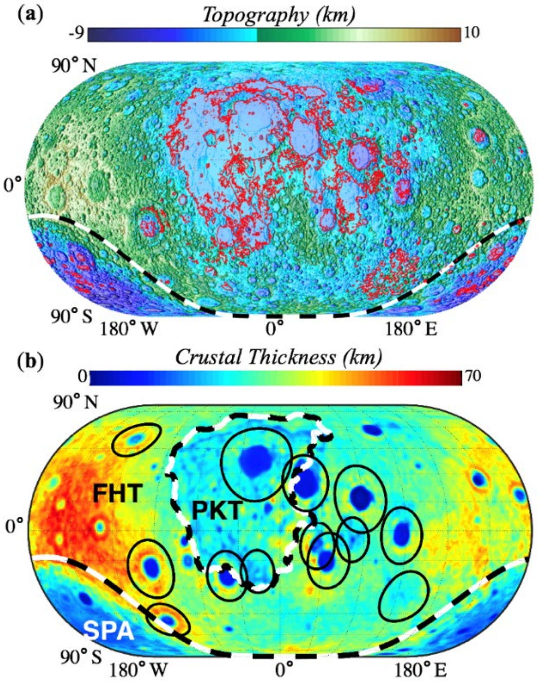

Figure 1: Lunar maps of (**a**) topography with surface volcanic deposits (outlined in red; [10]), and (**b**) crustal thickness [11]. The Feldspathic Highlands Terrane (FHT), South Pole–Aitken (SPA) basin, and Procellarum KREEP Terrane (PKT) are labeled and delineated in black and white, and basins with diameters larger than 650 km are outlined (b). Modified after [8].

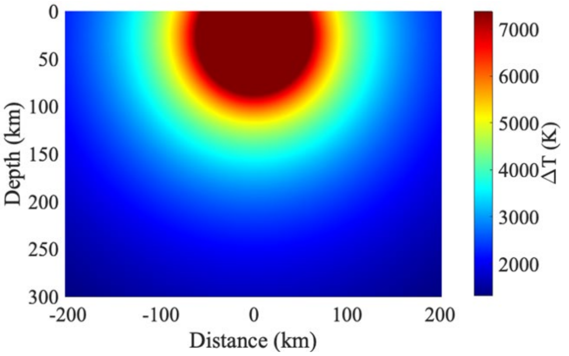

Figure 2: 2D instantaneous temperature increase associated with the SPA impact as determined by the Hugoniot release method [1]. ΔT is the shock-induced increase in temperature. Impact parameters are from [12, 13]. Dark-red region at center of the thermal anomaly is the isobaric core (IC).

Lunar Mantle Thermochemical Evolution: To model thermochemical evolution of the lunar interior, the 3D finite element code CitcomS [14, 15] is used with nominal lunar parameters [13] to solve the nondimensionalized conservation equations for mass, momentum, and energy. The mantle is assumed incompressible, viscosity is temperature-dependent, and the Prandtl number is assumed infinite.

By ~500 Myr after the emplacement of a generalized spherical temperature anomaly into a lunar mantle of uniform temperature, the thermal anomaly has spread laterally beneath the surface and a single mantle upwelling at the core-mantle boundary has formed.

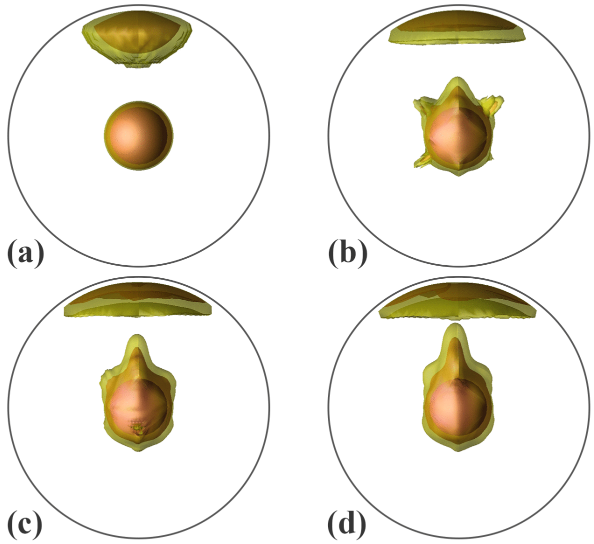

Figure 3: Development of mantle convection plumes in the lunar interior after (**a**) 0 Myr, (**b**) 160 Myr, (**c**) 320 Myr, and (**d**) 480 Myr. Two temperature isosurfaces are shown. Static sphere at center represents the core.

Potential Effects of Large Impacts: As SPA is the largest and oldest recognized lunar impact basin [3], the effects of its formation may have had the most profound influence among all lunar impacts on the evolution of the Moon. Previous work using 2D convection modeling [16] suggests that convection may have been initiated by impact-induced heating in an initially stagnant lunar interior, so the impact event which formed SPA may have contributed significantly to early lunar convection patterns. Other proposed pre-Nectarian impact basins, such as Fecunditatis and Australe North, likely would have formed by ~4.3 Ga [17, 3], prior to the final crystallization of the magma ocean residuum [18, 19]. If these features are of impact origin, this suggests that these impacts probably occurred at a time when the lunar interior was still quite hot, and had the greatest potential to affect the final distribution of the magma ocean residuum (i.e. urKREEP). There is some evidence that even an Imbrium-sized impact would only serve to concentrate residuum near the resulting basin while an SPA-sized impact would cause it to migrate away from the basin laterally and vertically [4, 9]. Previous modeling work [9] also sets precedence for the lateral migration of the lunar magma ocean residuum toward the antipode of a large impact in a warm Moon. This idea will be further investigated in future modeling.

Large impacts may also have a direct effect on the surface, seismically disrupting the region antipodal to the impact site and creating fractures that would facilitate magma ascent [5, 6] as well as transport of residual melt from the magma ocean. Possible antipodal fracturing as a result of the SPA impact could therefore contribute to the predominance of maria on the lunar nearside, especially within the PKT.

Discussion: The combined effects of interior convective patterns, near-surface material transport, and antipodal seismic effects induced by large, basin-forming lunar impacts may have played an important role in lunar evolution. Of particular interest is the potential relationship between large impact events and concentration of KREEP material within the PKT, and the subsequent eruption of KREEP-rich mare basalts primarily within this region (Fig. 1). Combined shock heating and thermochemical evolution modeling will allow us to further assess the role of large impacts in the origin and hemispheric dichotomy of lunar maria and in the evolution of the Moon's interior.

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