INFLUENCE OF BASIN IMPACT HEATING ON VISCOUS RELAXATION OF TOPOGRAPHY AND THERMAL INTERIOR STATE.

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Introduction: Similarly sized lunar basins exhibit a predictable trend in the depth-to-diameter ratios, with older basins revealing shallower topographic profiles than their younger counterparts [1]. Given the predicted high temperatures from accretionary heat for the early Moon [2], it is expected viscous relaxation more pervasively influenced the evolution of impact basin topography in early lunar history [3,4]. Additionally, viscous relaxation may have been further enhanced by near-surface KREEP and possible water reservoirs. Analyses of very-low-Ti glasses and lunar melt inclusions present compelling evidence that water concentrations of at least 260 ppm were present in parts of the lunar interior prior to 3 Ga [5,6]. The existence of a water-enriched near-surface layer is predicted by the lunar magma ocean model [7], wherein water would be enriched along with the incompatible elements to form a wet layer enhanced in radioactive elements (KREEP) beneath the lunar crust [8,9]. It has been hypothesized that this layer, all or in part, may have foundered and/or mixed with other cumulates during the suspected overturn of the lunar magma ocean [10,11]. Herein, we investigate the effects of impact heating and compositional heterogeneities in the lunar interior, with implications for the viscous relaxation of lunar topography.

Methods: The conservation equations of mass, momentum, and energy are solved by a modified version of CitcomS, a three-dimensional spherical, finite-element thermal evolution model [12,13]. Based on previous thermochemical evolution models [14,15], we initialize our models with representative lunar density profiles and uniform mantle radioactive heating rates. Our temperature- and depth-dependent rheology is referenced to a temperature of 1800 K and viscosity of 10^{20} Pa-s with a maximum viscosity variation of factor 10^5. Melt generated from the impact heating is not considered for the models herein.

At less than 50 Myr after the model start, impact-related heating is incorporated as a single pulse at the northern pole of the sphere. Based on the final basin diameter [16] and nominal impact parameters for the Moon [17] our modified version of CitcomS estimates the impact heating associated with shock-increased pressure via the Hugoniot equations [18,19].

Impact Heating: To gauge the possible effect of the initial mantle thermal state on the evolution of the impact-induced thermal anomaly we examine two potential end-member thermal scenarios: an initially warm and cool mantle at the time of impact. The former may be applicable for basins that impacted early in lunar history (e.g., South Pole-Aitken and possibly other pre-Nectarian basins) or nearside basins that formed into crust with KREEP-rich material below (e.g., Imbrium).

South Pole-Aitken Basin: We model the impact heating associated with the 2400-km diameter South Pole-Aitken (SPA) basin [16] and find the subsequent evolution of the induced thermal anomaly is dependent on the thermal state of the mantle at the time of impact. For a warm mantle initialized at a temperature of ~1700 K, the material heated by the SPA impact rises upward and spreads laterally beneath the crust underneath more than half of the planet (Fig. 1a, b). This scenario has low viscosities that allow for convective heat loss of the SPA-related impact heat. However, for the case of a cooler mantle initialized at a temperature of ~1000 K, the mantle material heated by the impact remains localized beneath the basin with only modest lateral spreading, and conductively cools with time as shown in Fig. 1c, d.

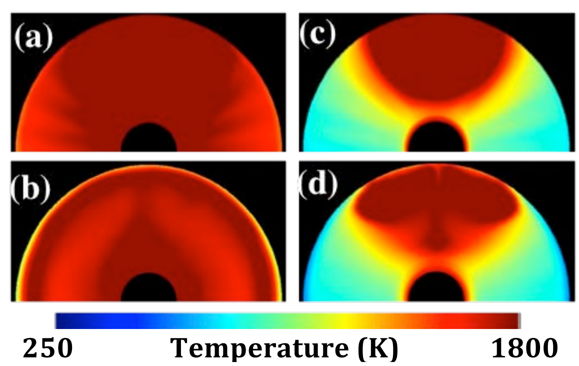

Figure 1. Hemisphere view of modeled impact heating associated with the SPA basin-forming impact. The modeled impact occurs at the center of hemisphere. The temperature for an SPA impact into a surface underlain with an initially warm mantle (~1700 K) is shown at (**a**) 1 Myr and (**b**) 100 Myr after impact. The temperature for an SPA-scale impact into a surface underlain with an initially cool (~1000 K) mantle is shown at (**c**) 1 Myr and (**d**) 100 Myr after impact.

Imbrium Basin: Investigating a smaller impact such as that responsible for the Imbrium basin, we find similar results – an impact into a surface overlaying a warm mantle results in a long-lived regional thermal anomaly centered on the impact site that spreads over an area much larger than the basin itself. This resultant thermal anomaly laterally spans ~20% of the area beneath the crust at 150 Myr after impact (Fig. 2a, b). In contrast, an impact into a colder mantle remains localized beneath the basin (Fig. 2c, d).

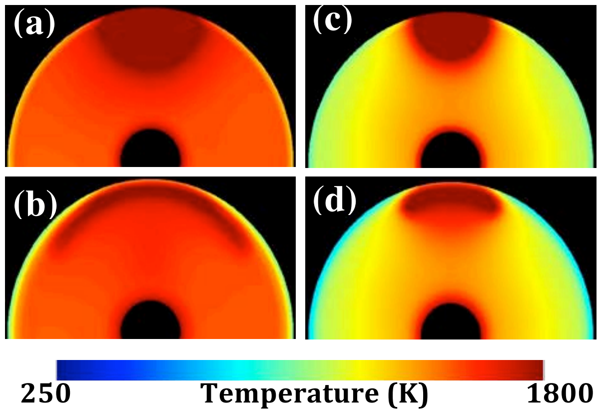

Figure 2. Hemisphere view of modeled impact heating associated with the Imbrium basin-forming impact. The modeled impact occurs at the center of hemisphere. The temperature for an Imbrium impact into a surface underlain with an initially warm (1500 K) mantle is shown at (**a**) 1 Myr and (**b**) 150 Myr after impact. The temperature for an Imbrium-scale impact into a surface underlain with an initially cool (1100 K) mantle is shown at (**c**) 1 Myr and (**d**) 150 Myr after impact.

Implications for Viscous Relaxation of Topography: Our results of impact heating suggest impacts into surfaces underlain by a colder mantle may result in thermal anomalies localized to the central excavation cavity (i.e., [20]), with lower temperatures and lower viscosities in the surrounding crust inhibiting crustal flow and impeding basin relaxation. Alternatively, impacts into surfaces underlain by a warmer mantle tend to result in thermal anomalies that extend beyond the central excavation cavity and would have a greater effect on the viscous relaxation of basin structures and other regional physiographic structures.

Though our models only directly consider the effect of initial mantle temperature, the temperature is a proxy for the viscosity (i.e., an increase in temperature corresponds to a decrease in viscosity). Accordingly, any mechanism capable of generating a regional reduction in viscosity could also promote the convective transport of the impact-related thermal anomaly observed in Figs 1, 2.

A potential source of viscosity reduction may be the existence of a water- and KREEP-enriched near-surface layer as predicted by the lunar magma ocean model [7]. From experimental studies of the Earth's upper mantle, small amounts (~40 ppm) of water (i.e., hydrogen) can result in a viscosity reduction factor in excess of 10^2 [21]. The reduced viscosity due to local water enrichment in combination with the increased temperatures associated with radioactive heating could have provided a sufficient reduction in the mantle viscosity to allow for impact-generated thermal anomalies to extend beyond their respective central excavation cavities.

Thus, if such a layer remained beneath the surface of the nearside KREEP terrane, basin impacts in this region may have more pervasively influenced the viscous relaxation of surface features due to the enhanced radioactive heating of the mantle and potential reduction in viscosity due to the presence of water.

Additionally, all basins forming early in lunar history when the mantle was sufficiently warm, would have also likely enhanced viscous relaxation of their respective regional surface features.

Conclusions: Large-scale basin-forming impacts into warmer targets likely contributed to regional-scale thermal anomalies and resultant viscous relaxation of surface topography. A warmer mantle is more likely to have existed for basins that formed early in lunar history (i.e., pre-Nectarian age basins) or basins that formed in regions with enhanced heat flow and higher concentrations of water (i.e., KREEP terrane). The effects of more pervasive viscous relaxation as a result of the thermal anomaly generated by impacts should be observable as relatively subdued terrain in regions near the oldest basins and those basins near the KREEP terrane. These results have important implications for understanding the differences in crustal structure between Imbrium and Orientale, and between pre-Nectarian and later basins.

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