WAS AN EPOCH OF LUNAR MAGMATISM TRIGGERED BY THE SOUTH POLE-AITKEN BASIN IMPACT?

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Introduction: A compilation (Fig. 1) of zircon analyses [1-6] indicate there was a particularly large magmatic epoch 4.30-4.36 Ga. Zircon is found in a diverse suite of magmatic lithologies (anorthosite, troctolite, gabbro-norite, quartz-monzodiorite, granites, felsites) and in impact breccias that incorporate clasts of those lithologies. The zircon crystals are derived from Apollo landing sites spanning a distance of 1758 km (Apollo 12 to Apollo 17), an area of 878,750 km^2, and involve impact basin deposits that were excavated from depths up to ~60 km (by the Imbrium impact) – providing extensive sampling of magmatic rocks in the nearside crust. The 4.30-4.36 Ga peak in zircon ages is similar to several other ages [7-9], including an urKREEP average model age of 4.368 ± 0.029 Ga [10]. The latter has been interpreted to represent the solidification of the lunar magma ocean, although it is difficult to reconcile that model with ancient lunar zircon ages (up to 4.417 ± 0.007 Ga) without a very complicated petrogenetic model [10].

Lunar Magmatism Hypothesis (LMH): As an alternative, we hypothesize that the magmatic epoch was triggered by the immense, 2500-km-diameter South Pole-Aitken basin impact on the lunar farside, which is the oldest, largest, and deepest impact basin on the Moon. Hydrocode simulations of the South Pole-Aitken impact [11] indicate mantle melting on the farside, leading to an immense differentiated magmatic system [12,13]. Simulations [11,14] also show the impact generated sharp pressure anomalies in the mantle beneath the lunar nearside crust and correspondingly large displacements, strains, and stress changes. Additional modeling shows that those pressure anomalies would have accelerated the ascent of mantle partial melts, producing a concentrated magmatic epoch among nearside lithologies too.

Modeling the SPA Impact and the Magmatic Response. The observed dimensions, gravity structure, and distribution of lithologies of the South Pole-Aitken basin are best fit with a hydrocode impact model using a 170 km diameter asteroid hitting the Moon vertically at 10 km/s [11], or one slightly larger for an oblique impact [14]. In this model, the pre-impact thermal structure of the Moon is such that the lower crust and upper mantle temperatures are at or very close to the solidus between a depth of ~25 and 560 km – the vestige of the Moon's magma ocean.

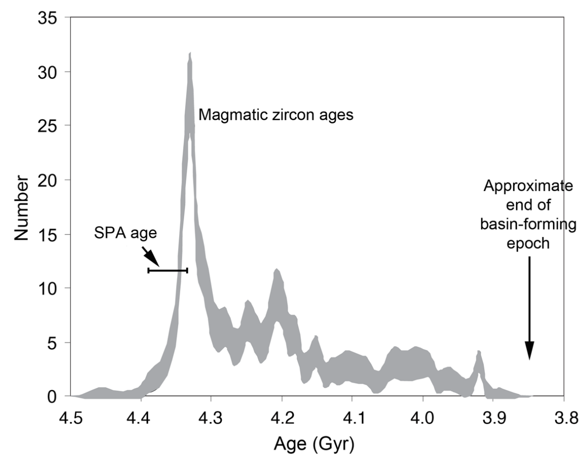

Fig. 1. Distribution of zircon crystallization ages that reflect the production of magma on the Moon [1-6]; the estimated SPA age is from [22].

Here we have extended our analysis of those hydrocode results to evaluate the consequences of the impact on the entire sphere of the Moon, including the upper mantle beneath the nearside crust. Pressure and stress waves generated by the impact event radiated around the Moon, beginning with the shock wave and followed by a train of high-amplitude surface waves. The pressure in the initial shock wave exceeded ~400 MPa (above the lithostatic load) in the upper mantle across the entire Moon; wave focusing would have increased the stress magnitude in a zone around the impact antipode by perhaps as much as an order of magnitude (Fig. 2), depending on the angle of impact [14] and asymmetries in the Moon's figure and internal structure at the time of impact [15]. The consequences of the South Pole-Aitken basin impact were felt around the Moon for hours after the initial shock wave arrived. In particular, the presence of a weak asthenosphere leads to large deformation of the crust during the formation of the basin. Oscillations of the crater floor inside the basin send a series of high-amplitude gravity waves around the Moon, causing displacements of ~1 km and shear stresses sufficient to cause pervasive fracturing of the crust.

The globally distributed dynamic stress changes would have had a profound effect on melt migration by creating new pathways and enhancing forces that drive melt ascent. In addition to pervasive large-scale fracturing [14], the impact would have catalyzed melt migration at all scales. Estimates of magma ascent velocity and effective buoyancy in dikes [16,17] can be derived from vertical gradients in horizontal stresses via analysis of pressure balances across the dike [18]. For typical locations on the lunar nearside, the averaged stress state during a vertical opening event indicates positive velocities in the lower crust and negative velocities in the upper crust. These findings predict the formation of an intrusive horizon in the lower crust.

Discussion and Final Observations: Thus, we propose the South Pole-Aitken impact mobilized melt around the whole Moon, particularly beneath the antipodal lunar nearside surface that is the provenance of the Apollo sample suite, accounting for the observed spike in magmatic zircon ages. Effectively, the process has the capacity to perturb the normal ascent of partial mantle melts and accelerate them upward, creating a magmatic pulse or cluster of magmatic events over a timescale of several millions of years to produce the observed age spike (Fig. 1).

This process is distinct from the proposed concept of decompression melting beneath the floor of an impact crater [19], a process that fails to generate melt in most impact events [20], with the possible exception of the largest basin-size events. While that process and the processes described here may have enhanced the mobility of melt beneath the South Pole-Aitken impact site, only the process described here has the capacity to generate a period of enhanced magmatism on the lunar nearside.

The 10 km/s impact velocity in our hydrocode model of the South Pole-Aitken basin impact is consistent with an independent assessment of average impact velocities (9 km/s) at that time in lunar history based on the size distribution of craters [21]. A calibration of crater densities on the most ancient portions of the floor of South Pole-Aitken basin also implies an age of 4.33 to 4.39 Ga [22], consistent with the timing needed to generate the subsequent magmatic pulse (Fig. 1). Confirming an age of the South Pole-Aitken basin will be a good test of our hypothesis and is one more reason for a South Pole-Aitken basin sample return mission [23,24].

Interestingly, recent analyses of the production of impact melt within the South Pole-Aitken basin [13] suggest the basin-forming impact event occurred prior to mantle overturn on the Moon. If so, then the same mantle perturbations proposed here to produce an enhanced period of magmatism may have also provided the activation energy needed to initiate that overturn, produce adiabatic melting [25], and further enhanced the amount of magmatism.

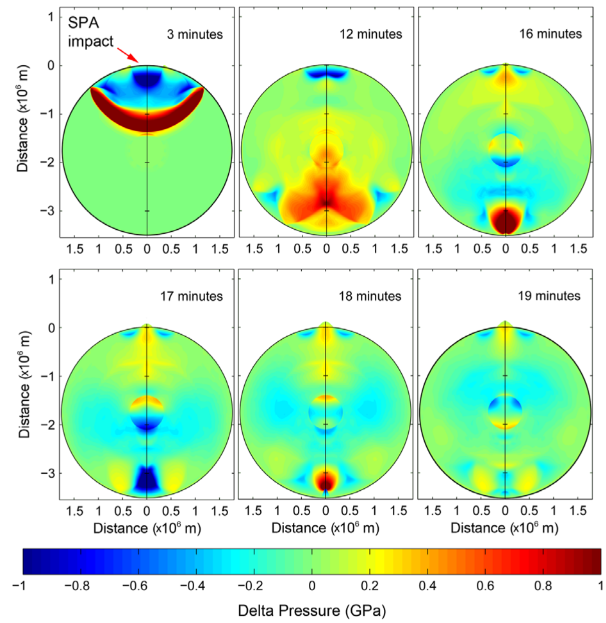

Fig. 2. Pressure variation relative to the initial lithostatic pressure at 3, 12, 16, 17, 18, and 19 minutes after impact. The nearside is at the bottom of each panel.

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