AGE OF THE LUNAR SOUTH POLE-AITKEN BASIN.

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Introduction: The South Pole-Aitken basin (SPA) is the largest and oldest lunar basin [1], yet its absolute age is unknown. An absolute age for SPA would help constrain the early impactor flux in the inner solar system and test the late heavy bombardment hypothesis. Given the basin's large size, it is reasonable to suspect that some of SPA's ejecta may be present in the Apollo sample collection. To test this idea, we focus on a sample with a great depth of origin, and a low shock pressure history: lunar troctolite 76535. Using iSALE hydrocode modeling, we demonstrate that SPA is the only viable basin that could have excavated 76535.

Sample 76535: Troctolite 76535 is one of the most well-studied lunar samples, but its origin has never been established. It was collected randomly in a soil rake sample near the base of North Massif, and has a mass of 155 g. $^{40}Ar/^{39}Ar$ analysis places its age at 4.25 ± 0.01 Ga with no disturbances [2].

Depth of origin: Symplectite mineral assemblages in 76535 equilibrated at 850 ± 50 °C, at pressures of 220-250 MPa [3]. These pressures imply depths of origin of 47 to 58 km, assuming crustal thickness densities ranging from 2850 to 2550 kg/m^3 [4], a mantle density of 3200 kg/m^3, and a crustal thickness of 40 km. We can also estimate the depth independently from the sample's cooling rate of 3.9 °C/My, which was recently derived using the ages and closure temperatures of four different chronometers [5]. The rate implies cooling from a solidus of ~1125 °C to the ambient temperature of 500 °C (inferred by [6]) in 160 My. This timescale implies depths of 56-70 km, using two different thermal diffusion relationships. In the remainder of this work, we assume the depth of formation is 45-65 km.

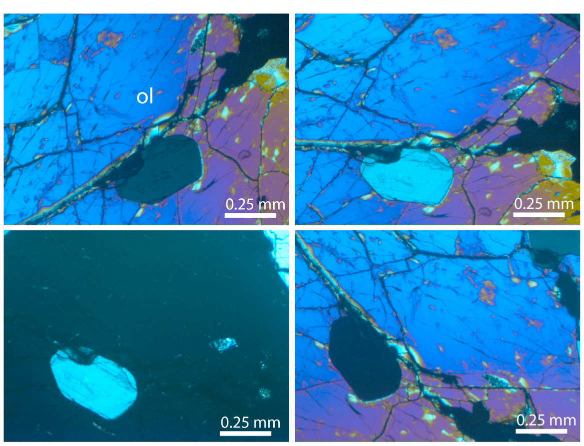

Figure 1. Olivines in 76535 exhibit sharp extinction, implying peak shock levels < 6 GPa.

Shock pressure history: No petrologic indications of shock have been reported in 76535 [7,8]. However, to better quantify an upper bound on its peak shock level, we examined olivines in 76535, which are particularly susceptible to shock deformation [9]. We found no evidence of undulatory extinction in more than ten olivine grains, implying no plastic deformation, and therefore peak shock pressures below the Hugoniot elastic limit, which begins at 6 GPa in olivine, depending on crystal orientation [10] (Fig. 1). This is consistent with other work that suggests that undulatory extinction appears at 4-5 GPa [11]. Therefore, we conclude the rock was not shocked above 6 GPa.

Simulation of SPA formation: We examined ten of the Moon's largest undated basins [11-13] to identify candidates that could have excavated 76535. The three largest are: SPA, Fecunditatis, and Australe (with no evidence that Tranquillitatis is a basin). Using the iSALE-2D hydrocode, we modeled the formation of the latter two basins (which are similarly sized) as the result of a 90-km diameter impactor with a speed of 17 km/s, consistent with previous modeling results [13] (Fig. 2). We modeled SPA using a 200 km impactor with a speed of 10 km/s, consistent with previous modeling work [14], and also with a speed of 17 km/s.

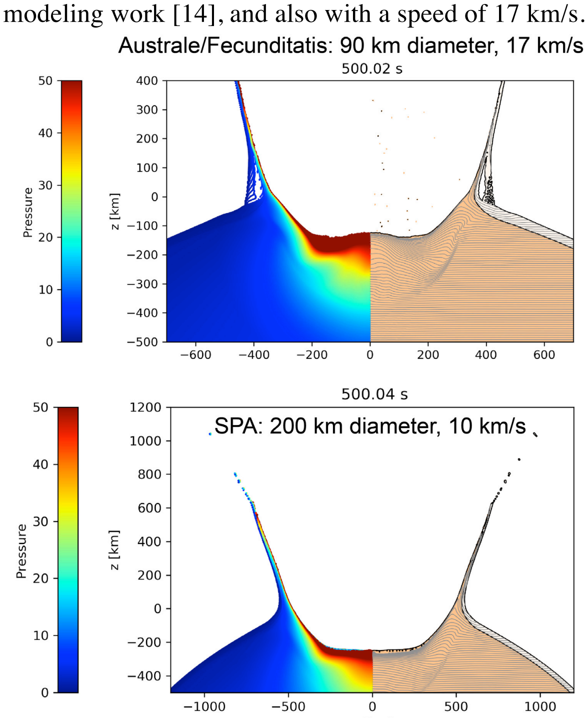

Figure 2: iSALE simulation of the formation of Australe/Fecunditatis class (top) and SPA class (bottom) basins.

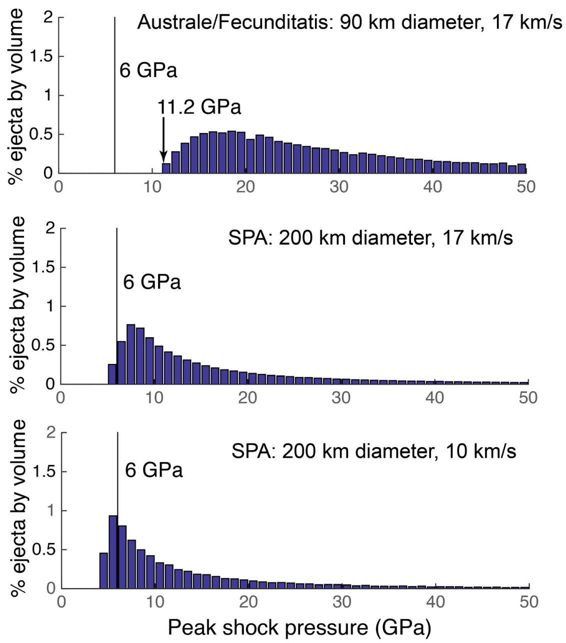

Figure 3. Peak shock pressures for ejecta from 45-65 km depth. Only SPA-class basins can excavate material from such depths with peak shock pressures <6 GPa.

Ejecta characteristics. We find that only SPA-class basins can excavate material from the relevant depth and shock pressure range for 76535 (Fig. 3). The lowest shock pressure achieved for Fecunditatis/Australe class basins is 11.2 GPa (from 45-65 km). The large scale required of the excavation event helps rule out a smaller source basin that was subsequently overprinted by Imbrium or other basins. However, for the SPA-class basins, ejecta with shock levels <6 GPa are deposited only locally, in a small annulus within the basin (550-580 km radius, but outside the melt cavity radius ~500 km [14], Fig. 4). Therefore, transport of 76535 to the Apollo 17 site must have been by a secondary cratering process that retained 76535's low shock state. While this may seem implausible, lunar meteorites make their way to Earth from weakly shocked spalled surface rocks [15], and non-local materials have often been found at Apollo sites [e.g. 16].

Secondary transport of 76535: Assuming a single event brought 76535 from the SPA ejecta annulus to the Apollo 17 site, the minimum launch speed required is ~2.3 km/s (for a 67° launch angle). This is close to escape speed (2.38 km/s), and speeds much greater than 2.3 km/s have long flights, yielding nearly global coverage. We performed high-resolution iSALE simulations of smaller impacts (i.e., 40-km diameter craters) to determine the amount of material removed by near-surface spall at speeds and shock pressures relevant for 76535. We find that a limited regime around the impactor is appropriately spalled (at 67°), concluding it is plausible for 76535 to have been transported to the Apollo 17 site. Calculating the probability of finding a sample like 76535 during all of the Apollo missions is difficult, but we will present statistical and geophysical arguments that can help assess its feasibility.

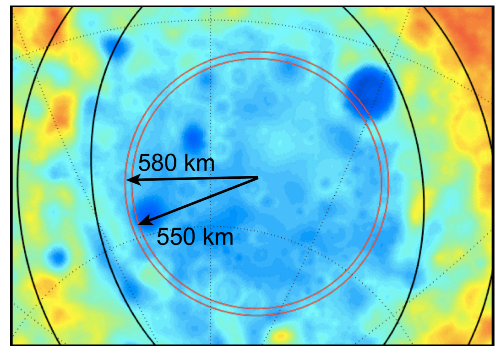

Figure 4: Crustal thickness map of SPA (blue to red: 0 to 80 km) [4]. Ejecta from 45-65 km depth, shocked to <6 GPa, falls within the red annulus indicated.

Absolute age of SPA: Since SPA represents the only viable source of 76535, we can infer its age to be the sample's $^{40}Ar/^{39}Ar$ age of 4.25 ± 0.01 Ga [2]. This age is identical to the SPA crater count age of 4.26 ± 0.03 Ga previously reported [17], within uncertainties, when one assumes the lunar chronology function of [18]. Because the crater chronology function of [18] before ~3.6 Ga is semilog-linear and monotonically increasing, there are important implications for the flux of impactors in the early solar system.

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