THE SYNERGETIC EFFECT OF THE POTENTIAL PROCELLARUM AND THE SOUTH-POLE AITKEN IMPACT ON THE FORMATION OF THE LUNAR NEARSIDE-FARSIDE ASYMMETRIES. T. Liu[1], L. Allibert[1], R. Luther[1], K. Wünnemann[1,2], M.-H. Zhu[3,4] and T. M. Davison[5], [1]Museum für Naturkunde Berlin, Leibniz Institute for Evolution and Biodiversity Science, Germany (tiantian.liu@mfn.berlin), [2]Freie Universität Berlin, Germany, [3]State Key Laboratory of Lunar and Planetary Sciences, Macau University of Science and Technology, Macau, China, [4]CNSA Macau Center for Space Exploration and Science, Macau, China, [5]Impacts & Astromaterials Research Centre, Department of Earth Science and Engineering, Imperial College London, London, UK.

Introduction: The largest and oldest known impact basin on the Moon is the South Pole Aitken (SPA) basin. It is only outranked by the Procellarum structure that was potentially also formed by impact [7,9]. The latter has been related to unresolved questions regarding the striking asymmetries between the lunar nearside and farside in composition, topography, and crustal thickness [1-3].

Recent GRAIL observations show that the farside crust is ~20-km thicker than the nearside crust [4]. Additionally, Kaguya remote sensing data show that the thick crust on the farside highlands has at least two layers consisting of a mafic-rich layer covering the primary crust [5], and a large area of the nearside exhibits low-Ca pyroxene that may result from a large impact [6]. The given crustal structure supports the idea that the lunar nearside-farside asymmetries may be the result of a giant Procellarum impact on the nearside [7] or a mega basin striding the whole nearside hemisphere [8].

Previous studies using numerical modeling [9] or scaled models [8] were carried out to investigate how the formation of such mega basin affected the evolution of the lunar crust. However, neither considered the influence of the subsequent SPA impact that, although significantly smaller, certainly had the potential to add to the global shaping of lunar crust. After the two stochastic events in the lunar history, the formation of Procellarum and SPA, at least 30 basin-forming impacts and a large number of smaller impacts became the predominant process contributing to the crustal evolution.

Understanding the formation mechanism of nearside-farside asymmetries is critical to constrain the crystallization of the magma ocean and the formation of the lunar crust. Here we propose a new idea, namely that the succession of two giant impact events, Procellarum and SPA, substantially shaped the initial structure of the asymmetric nearside-farside crust and the subsequent cumulative impact mixing added to it. This is the first quantitative attempt to reconstruct the consequences of these two early major events followed by the long-term impact mixing. The final simulation results represent the estimated present-day crustal distribution to be compared with the observations including both the crustal thickness distribution and mineral composition.

Methods: We assume that the Procellarum impact (*step 1*) occurred prior to the SPA-forming impact (*step 2*) [7, 9]. Subsequently, the successive impact gardening (*step 3*) caused additional mixing of the ejecta deposits of the two giant events composed of the mantle and crustal components. The observations of the scarcity of mantle components on the farside highlands indicate a shallow excavation depth, which suggests rather shallow impact angles for both the Procellarum and the SPA impact.

Step 1: Procellarum impact. We use a three-dimensional modeling approach, the iSALE-3D code [10], to simulate the formation of the proposed Procellarum impact event and vary projectile size, impact velocity, and impact angle. We approximate the Moon by a 3,500-km-diameter sphere consisting of a 700-km diameter iron core and a dunite mantle. Due to the high computational demands, the relatively large cell size of ~20 km is taken, and hence the crustal layer (~ 50 km) is not resolved explicitly as a separate layer. All materials were described by ANEOS-derived equation of state tables [11-14] and strength models used by [15]. The impact angle ranges from the most frequent value of 45° to 15°. To match the extend of the observed Procellarum structure (~2000-km transient crater radius; ~2800-km final crater radius; [7, 9]), we also vary impactor radius (200, 360, and 480 km) and impact velocity (10-18 km/s).

We track the ejecta trajectories and their locations using Lagrangian tracers. When a tracer moves above the preimpact target surface, it is considered as ejecta and its launch time, angle, and velocity are recorded. Using the hyperparabolic function, we estimate the elliptical trajectory of the given ejecta angles and velocities and calculate their landing position on the surface. To calculate the final deposition, we then consider the process of local mixing (the entrainment of local material into ejecta blanket upon landing) and post-emplacement motion (ground motion as a result of the collapse of the transient cavity and subsequent modification process). The ejecta thickness distribution along the distance from the impact site is calculated based on the final position of the ejecta according to the number of tracers (i.e., mass) located at a given distance assuming the initial density of the material. The provenance depth of the ejected materials is also recorded by tracers. Assuming that the material from the top 50 km originates from the primary crust, the proportion of the crustal component in the ejecta is estimated (see Figure 1 for an example of results in the case of a given impact).

Step 2: SPA impact. Davison et al. (2022) [16] did systematic studies on the SPA formation as an oblique impact using high-resolution iSALE-3D code. Their simulations considered different thermal profiles, impact angles, and compositionally distinct layers for the Moon and the impactor, and address their effect on final crater structure, ejecta production and impactor's fate. As the provenance depth of the ejecta deposits is also recorded in their modeling results, we can trace back the zone from where the ejected materials originate. Since the Procellarum impact is chronologically older than the SPA event, we thus assume the SPA impact target has a 3-layer structure consisting of a thick Procellarum ejecta on the top, the underlying primary crustal layer and the deeper mantle material, where the composition and thickness of the top Procellarum layer are derived from the step 1 simulation. Combining the recorded provenance depth of the SPA ejecta from [16] and the composition of the assumed 3-layer impact target, the composition of the SPA ejecta is recalculated.

Step 3: Impact mixing. Liu et al. (2020) [17] developed a spatially-resolved numerical model to investigate the material diffusion with the long-term impact mixing. Taking the material composition from *step 1* and *step 2* as the initial surface of the impact mixing model, we are able to track how the material composition has evolved until the present day.

Expected results and conclusions: We tweaked the free parameters of the Procellarum and the SPA impact (e.g., projectile size, impact angle, and impact velocity) until the modeling results reproduce the observed crustal thickness asymmetry and the surface distribution of plagioclase (the typical crustal component). For example, it shows that the crustal thickness to the west of Procellarum terrain is about 10 km thicker than that to the east. It could be caused by the asymmetric emplacement of the Procellarum ejecta. Taking the result in Figure 1 as an example, the Procellarum ejecta could explain such extra thicker curst if it was distributed over the western area. In addition, the large-scale SPA impact event suggests that deep mantle materials are exposed at the surface, which, however, does not agree with observations. It could also be explained by the emplacement of a thick layer of Procellarum ejecta in the area where subsequently the SPA impact occurred. This layer impedes the SPA impactor to penetrate through the crust deep into the mantle. As can be also seen from Figure 1, if Procellarum ejecta with a thickness of ~10 km were emplaced at the SPA impact target region, the excavation of deeper mantle materials and its depositon on the surface becomes less likely.

Systematic simulations including the Procellarum impact, the SPA impact and the subsequent impact mixing will quantitatively estimate the integrated outcome of two early major events. The results can shed light on the crustal formation and evolution history. In addition, comparisons with observations will allow for discrimination between impact scenarios for the SPA-forming event, which is itself controversial issue.

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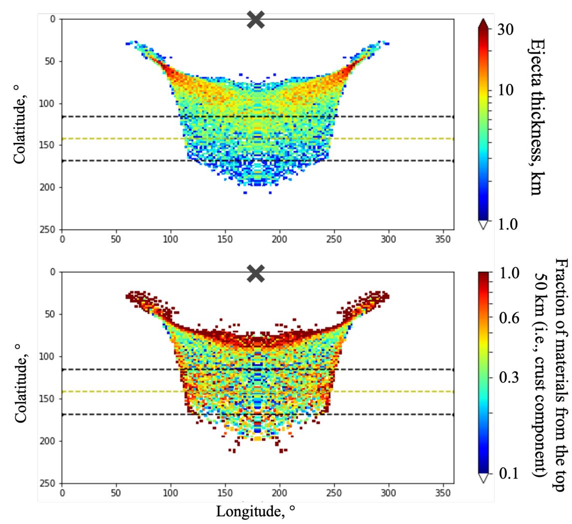

Figure 1. Distribution of Procellarum ejecta thickness (upper) and the composition of the ejecta deposit (lower) based on the simulation considering impact angle of 30°, impact velocity of 18 km/s and projectile diameter of 470 km. Cross mark indicates the contact point of the Procellarum impact. The outlined horizontal region presents the possible target region of the SPA impact.