SOUTH POLE-AITKEN BASIN MAY CONTRIBUTE INSIGNIFICANTLY TO THE LATE ACCRETION OF THE MOON. M.-H. Zhu[1,2], K. Wünnemann[2,5], A. Morbidelli[3], N. Artemieva[4], [1]Space Science Institute, Macau University of Science and Technology, Macau (mhzhu@must.edu.mo); [2]Museum für Naturkunde, Berlin, Germany; [3]Observatoire de la Côte d'Azur, Nice, France; [4]Planetary Science Institute, Tucson, USA; [5]Freie Universität Berlin, Berlin, Germany.

Introduction: The South Pole-Aitken (SPA) basin has a semimajor axis (a) of 1200 km and semininor axis (b) of 1028 km with a tilt angle of -18.8° [1]. As one of the oldest and largest basins with a distinct surface expression on the Moon, the SPA basin is thought to have significantly affected the formation of farside highlands [2], magnetic anomalies [3], and true polar wander [4]. Thus, understanding its formation is crucial to constrain the Moon's early impact history, interior structure, and thermal evolution. According to its elliptical ratio (a/b = 1.17), SPA was likely formed by an object with diameter (D) > 200-300 km obliquely travelling from south to north [1, 5, 6]. Although several studies have already been done [3, 5-8], the formation of SPA and its effects on the Moon's early evolution remains enigmatic. Using a series of quantitative numerical modeling of oblique impacts on the Moon constrained by the gravity models from the GRAIL mission [9], we propose that the SPA basin was formed by a Vesta-sized impactor with an impact angle of 15°-20° on the early Moon.

Possibility of a Vesta-sized impactor hitting the early Moon: The bulk HSEs of the Moon, mainly attributed by post-core-formation late accretion, is estimated to be ~ 2.1×10^{19} kg [10]. During impacts, a projectile typically implants ~ 60% of its material into the Moon with the rest escaping from the Moon's gravity [11]. Thus, the Moon should have accreted ~ 3.5×10^{19} kg of materials. Assuming a size frequency distribution of projectiles analog to that of the main belt asteroids [12], this amount of material implies that ~ 15,200 km-sized objects should have hit the Moon. This number is ~ 1.3% of the total number of km-sized asteroids in the main belt, therefore, the probability of a Vesta-sized asteroid hitting the Moon is also 1.3%. However, the extrapolation backward in time of the decay of lunar bombardment rate over the last 4.1 Gy [13] suggests that the Moon accreted a mass ~ 5-10 times larger than that inferred from the HSE content. These two pieces of information can be reconciled if some projectiles were differentiated and their cores merged with the lunar core, or if the lunar HSEs have been sequestered only since the crystallization of the lunar magma ocean [14]. If the total amount of projectiles hitting the Moon was 10 times larger than usually considered, the collision probability of a Vesta-like impactor also grows by a factor of ~10 times. In addition, the majority of projectiles impacting the early Moon were planetesimals leftovers from the main phase of terrestrial planet formation [15]. Although the size distribution of the planetesimals is uncertain, it is thought that more mass was contained in large objects. As the large impacts on the early Moon are stochastic, therefore, a Vesta-sized body hitting on the early Moon is not unlikely.

Numerical modeling of SPA formation: We use the iSALE-3D shock-physics code [16] to simulate the oblique impact event. We assume the Moon as a 3,500-km-diameter sphere with 700-km-diameter iron core. We use dunite to represent the mantle, on top of which 30 km and 50 km-thick material is used to represent the crustal layer [17]. The cell size was 10 km throughout the entire modeling domain. As the possible age of SPA is ~ 200 Ma after the Moon formation [15, 18], we assume the Moon was still warm at the time of the SPA impact. The differentiated impactor, with a dunite mantle and iron core, hit the Moon with velocity of 10-25 kms^{-1}. We vary the impact angle between 10° and 60° and impactor diameter from 200 km to 800 km.

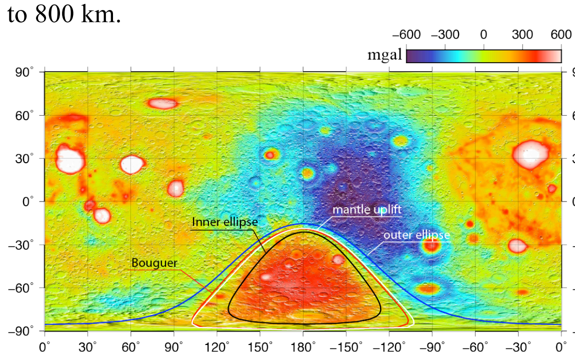

Fig. 1 Bouguer anomaly map from GRAIL with a rotation of 18.8° and offset of SPA center (longitude) to 180°. The out/inner topographic ellipse, BGA boundary, and mantle uplift boundary (crust, 50 km) from the best-fit model are also plotted.

For large impact basins on the Moon, the Bouguer gravity anomaly (BGA) in the basin center (see Fig. 1) is mainly caused by the mantle uplift during the collapse of a transient crater [19]. The size of BGA corresponds to the size of mantle uplift [20]. In the case of SPA, its inner depression is covered by the massive mafic materials from subsequent geologic activities, making its BGA formation complicated. However, the elliptical shape of its BGA boundary (2130 km x 1790 km, a/b = 1.19, see Fig. 1), located between the inner and outer topographic ellipses where no obvious mafic material is presented, indicates that the mantle uplift may dominate its BGA. Thus, we use the BGA boundary derived from GRAIL data to constrain our model. Based on this assumption, the outer boundary of the mantle uplift in the best-fit model ought to correspond to the observed BGA.

Results and Discussions: Fig. 2 illustrates the SPA basin-forming process for an impactor of 630 km in diameter with an impact velocity of 18 kms^{-1} hitting the Moon (crust, 50 km) at an angle of 20^o. The general outcome is that the projectile strips the Moon's crust and exposes the mantle within the basin (A); the central peak, initially arisen at the impact site and consisting of crust and mantle material, eventually collapses and displaces its material in downrange direction within the basin (B, C). These displaced materials thicken the crust in downrange within the basin.

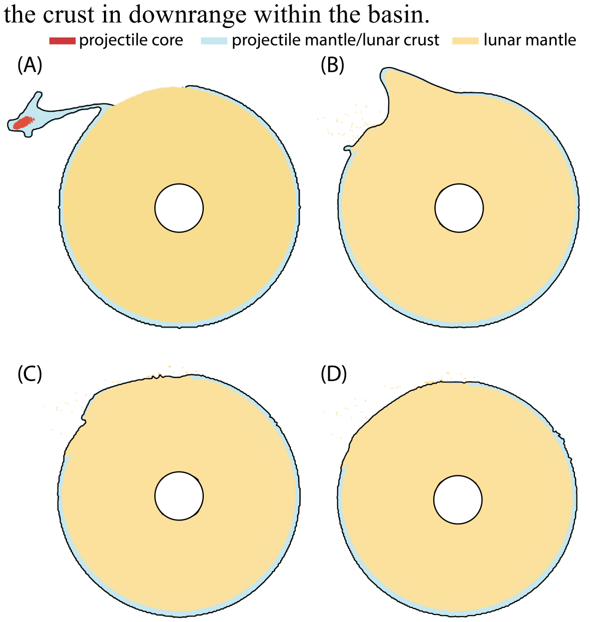

Fig. 2 Snapshots of an oblique impact (D ~ 630 km and v ~ 18 km s^{-1}) for the formation of the SPA basin. The impact site is at the top; the impact angle is 20^o to local horizon.

The best-fit model produces a transient cavity with a diameter of ~1400 km, in agreement with early estimates (e.g., [21]). The impact excavates materials up to a depth of ~140 km, producing a large volume of ejecta. Crustal materials near the impact site are ejected with velocities almost similar to the velocity of the impactor (~18 kms^{-1}) and, therefore, escape from the Moon's gravity field. However, most of the excavated materials have relatively low velocities and are eventually deposited outside the transient cavity but within the final basin. Only a small fraction of excavated materials deposits on the farside highlands, forming an ejecta layer with an average thickness of ~1 km. The ejecta layer on the farside highlands from the best-fit model is much thinner than the expected thickness (~5-10 km) forming a two-layer structure [22], suggesting that it is unlikely that the SPA excavation created the farside highlands [2].

Within the basin, the material on the top layer consists of the upper mantle material with some fractions of the crust and impactor mantle materials. Due to the high shock pressure produced by the impact, most materials within the basin are melted, forming a pool with an average depth of ~ 200 km. Such a melt pool would have likely differentiated, which supports the assumption that the crust within the SPA basin represents a secondary crust derived from the differentiation of the melt pool [23].

The low part of the impactor interacting with the Moon is significantly decelerated by shearing along the surface; the upper part continues its motion nearly unaffected. Part of the decelerated impactor material is mixed into the ejecta and the lunar mantle. In comparison with the total mass of the impactor, only a small fraction (~7%) is added to the Moon. The upper part (~93% in mass) of the impactor experiences strong pressure gradients and strain rates, resulting in the fragmentation of the impactor [24]. Due to the high velocity of these fragments, they escape the Earth/Moon's system, but may hit the Moon again within some time interval. However, the efficiency of re-impact depends on ejecta fragment size [25, 26]. Assuming a cumulative slope of -2.85 [24], the size distribution of the fragments predicts that there are ~ 220 objects with D > 18 km ejected from the Moon during the SPA impact. A few of these bodies may re-impact the Moon within ~10 Ma [25] and form basins with D > 300 km. These re-impact events may explain the formation of basins with ages similar to the SPA basin according to the stratigraphic sequence [27].

References: [1] Garrick-Bethell & Zuber (2009) *Icarus*, *204*, 399. [2] Zuber et al. (1994) *Science*, *266*, 1839. [3] Wieczorek et al. (2012) *Science*, *335*, 1,212. [4] Keane & Matsuyama (2014) *GRL*, *41*, 6,610. [5] Schultz (1997) *LPSC*, 1787. [6] Schultz & Crawford (2011) *GSA*, *477*, 141. [7] Potter et al. (2012) *Icarus*, *220*, 730. [8] Melosh et al. (2017) *Geology*, *45*, 1,063. [9] Zuber et al. (2013) *Science*, *339*, 668. [10] Day et al. (2007) *Science*, *315*, 217. [11] Artemieva & Shuvalov (2008), *SSR*, *42*, 329. [12] Strom et al. (2005) *Science*, *305*, 1,847. [13] Neukum & Ivanov (1994) in *Hazards due to Comets and Asteroids*, 359. [14] Morbidelli et al. (2018) *Icarus*, in press. [15] Morbidelli et al. (2012) *EPSL*, *355*,144. [16] Elbeshausen et al. (2009) *Icarus*, *204*, 716. [17] Wieczorek et al. (2013) *Science*, *339*, 671. [18] Marchi et al. (2012), *EPSL*, *325*, 27. [19] Melosh et al. (2013) *Science, 340,* 1,552. [20] Neumann et al. (2015) *Sci. Adv.,* 1:e1500852. [21] Spudis et al. (1994) *Science*, *266*, 1,848. [22] Yamamoto et al. (2012) *GRL*, *39*, L13201. [23] Vaughan et al. (2014) *PSS*, *91*, 101. [24] Leinhardt & Stewart (2012) *AJ*, *745*, 79. [25] Bottke et al. (2015) *Science*, *348*, 321. [26] Marchi et al. (2017) *Nature Geosci*, *11*, 77. [27] Fassett et al. (2014) *JGR*, *117*, E00H06.