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RESEARCH ARTICLE
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**Key Points:**
- We report a detailed 3-D geological analysis of the nature and history of pre-Nectarian aged Von Kármán crater in the lunar South Pole-Aitken basin
- The region contains farside mare basalts affected by linear features and ejecta material from a wide range of surrounding craters
- Our geological analysis provides a framework for the Chang'E-4 mission to carry out in situ exploration

**Supporting Information:**
- Supporting Information S1
- Data Set S1
- Data Set S2
- Data Set S3

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# Geological Characteristics of Von Kármán Crater, Northwestern South Pole-Aitken Basin: Chang'E-4 Landing Site Region

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**Abstract** Von Kármán crater (diameter = ~186 km), lying in the northwestern South Pole-Aitken (SPA) basin, was formed in the pre-Nectarian. The Von Kármán crater floor was subsequently flooded with one or several generations of mare basalts during the Imbrian period. Numerous subsequent impact craters in the surrounding region delivered ejecta to the floor, together forming a rich sample of the SPA basin and farside geologic history. We studied in details the targeted landing region (45.0–46.0°S, 176.4–178.8°E) of the 2018 Chinese lunar mission Chang'E-4, within the Von Kármán crater. The topography of the landing region is generally flat at a baseline of ~60 m. Secondary craters and ejecta materials have covered most of the mare unit and can be traced back to at least four source craters (Finsen, Von Kármán L, Von Kármán L', and Antoniadi) based on preferential spatial orientations and crosscutting relationships. Extensive sinuous ridges and troughs are identified spatially related to *Ba Jie* crater (diameter = ~4 km). Reflectance spectral variations due to difference in both composition and physical properties are observed among the ejecta from various-sized craters on the mare unit. The composition trends were used together with crater scaling relationships and estimates of regolith thickness to reconstruct the subsurface stratigraphy. The results reveal a complex geological history of the landing region and set the framework for the in situ measurements of the CE-4 mission, which will provide unique insights into the compositions of farside mare basalt, SPA compositional zone including SPA compositional anomaly and Mg-pyroxene annulus, regolith evolution, and the lunar space environment.

**Plain Language Summary** The South Pole-Aitken (SPA) basin on the farside of the Moon is the largest known impact structure in the solar system. It is the key area to answer several important questions about the Moon, including its internal structure and thermal evolution. We outline the geologic history of an important area (Von Kármán crater) within SPA. In 2018, a new Chinese lunar mission Chang'E-4 (CE-4) will be the first to land in the Von Kármán crater, within the SPA basin. The scientific instruments of CE-4, mounted on a lander and a rover, will analyze both surface and subsurface of this farside region. Here we present a detailed geological study of the selected landing region of CE-4, based on remote sensing data of the Moon. Our study identified several targets of high scientific interests and proposes testable hypotheses for the CE-4 mission.

## 1. Introduction

The farside South Pole-Aitken (SPA) basin is the largest known impact structure on the Moon (Stuart-Alexander, 1978; Wilhelms et al., 1987). Its geology provides insights into the composition of the lower crust and upper mantle, the impact flux in early lunar history, the nature and evolution of basin-scale impact melt deposits, and the nature of large impact basins and their formation and modification processes (Garrick-Bethell & Zuber, 2009; Head et al., 1993; Moriarty & Pieters, 2018; Potter et al., 2012; Spudis et al., 1994; Vaughan & Head, 2014). The SPA basin has been studied with spectral observations (e.g., Ohtake et al., 2014; Pieters et al., 2001) and recently been subdivided into four distinct compositional zones based on Moon Mineralogy Mapper ($M^3$) data (Moriarty & Pieters, 2018): (1) a central ~700-km-wide SPA compositional anomaly (SPACA), which exhibits a strong Ca-pyroxene signature, which is different from typical mare basalts; (2) a Mg-Pyroxene Annulus, which

is characterized by Mg-rich pyroxenes; (3) a Heterogeneous Annulus, which exhibits mixing of localized pyroxene-rich units and feldspathic materials; and (4) the SPA Exterior, which is mafic-free and dominated by feldspathic materials. Pyroxene compositions in both the Heterogeneous Annulus and Mg-Pyroxene Annulus are similar. Moriarty and Pieters (2018) have indicated that the Mg-pyroxene unit is beneath the SPACA Ca-pyroxene unit from the stratigraphic relationships and central peak exposures among craters within SPACA. The material of Mg-Pyroxene Annulus was the main material excavated and melted by the SPA-forming event due to the relatively uniform composition and the great area, depth, and thickness of the Mg-Pyroxene Annulus. The extremely large size of the SPA basin strongly suggests that it has excavated subcrustal and mantle material (e.g., Melosh et al., 2017); however, the lack of evidence for widespread dunite or olivine-dominated mineral assemblages, and the dominance of Mg-pyroxenes in the basin interior, suggests that lunar mantle must include a significant Mg-pyroxene component (Moriarty & Pieters, 2018).

Von Kármán crater (diameter $D$ = 186 km; central coordinates as 44.4°S, 176.2°E; Figure 1a) lies within the Mg-Pyroxene Annulus, just northwest of the SPACA terrain. This crater is a pre-Nectarian crater (Losiak et al., 2009; Yingst et al., 2017), younger than the Von Kármán M basin ($D$ = 219 km; central coordinates as 49.4°S, 174.9°E), and older than the Leibnitz crater (diameter $D$ = 236 km; central coordinates as 38.2°S 179.3°E: Figures 1b and 1c; Yingst et al., 2017). Mare basalts flooded parts of the Von Kármán crater floor during the Imbrian Period (Pasckert et al., 2018; Wilhelms et al., 1979; Yingst & Head, 1997; Yingst et al., 2017), but a portion of the central peak remains exposed near the center of the crater (Figure 1d). Finsen crater (diameter $D$ = 73 km; central coordinates as 42.3°S, 182.3°E), Von Kármán L crater (diameter $D$ = 29 km; central coordinates as 47.8°S 177.9°E), and a similar-sized unnamed crater nearby (we informally denote it as Von Kármán L′ in this study) were formed subsequent to the Von Kármán crater (Wilhelms et al., 1979; Figure 1c). Relatively higher albedo linear features on the mare basalt of Von Kármán crater converge toward the crater Finsen (Figure 1b), which is located within the SPACA, suggesting that the SPACA material has been derived from Finsen crater.

In 2018, the Chinese lunar mission Chang'E-4 (CE-4; Wu et al., 2017) will explore the SPA basin. It will be the first in situ exploration of the farside of the Moon. The selected landing region for CE-4 (45°S–46°S, 176.4°E—178.8°E; Wu et al., 2017) is located on the southern floor of the Von Kármán crater. In situ exploration within the Von Kármán landing region will bring unprecedented imaging, spectral, radar, and low-frequency radio spectral data for the landing region, and it will greatly improve our understanding about the compositions of farside mare basalt, SPA compositional zones including SPA compositional anomaly and Mg-pyroxene annulus, regolith evolution, and the lunar space environment. Indeed, the U.S. National Research Council (2007) has identified key scientific priorities for future lunar exploration that can be addressed from the Von Kármán crater, including the possibility to study the existence and extent of differentiation of the SPA melt sheet (Morrison, 1998; Nakamura et al., 2009; Vaughan & Head, 2014) and possible exposed upper mantle materials (Melosh et al., 2017; Moriarty & Pieters, 2018). In this study, we have (1) investigated the geological characteristics of the landing region using available remote sensing data including topography, high-resolution imaging, and reflectance spectral data; (2) identified targets of high scientific interests; and (3) proposed testable hypothesis for the CE-4 mission.

## 2. Methods

### 2.1. Data Sets

We analyzed the local geology using the Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) mosaic (100 m/pixel) for regional context (Robinson et al., 2010), Kaguya Multiband Imager (MI) 750 nm reflectance mosaic (14 m/pixel) for albedo variations (Ohtake et al., 2008), Terrain Camera (TC) morning mosaic (7 m/pixel) for local context (Kato et al., 2010), and LROC Narrow Angle Camera (NAC) images (0.5–1.6 m/pixel) for small geological feature identification. Topographic analyses were performed using the merged digital elevation model (DEM) that is derived from the LRO Lunar Orbiter Laser Altimeter (LOLA; Smith et al., 2010) and Kaguya TC data (SLDEM: 59 m/pix; Barker et al., 2016). We produced a slope map for the landing region using SLDEM at a 59 m scale.

### 2.2. Regolith and Ejecta Thicknesses

We estimated the thickness of the regolith within the proposed landing area using NAC images that have incidence angles less than 55° following the method described in Quaide and Oberbeck (1968). Quaide

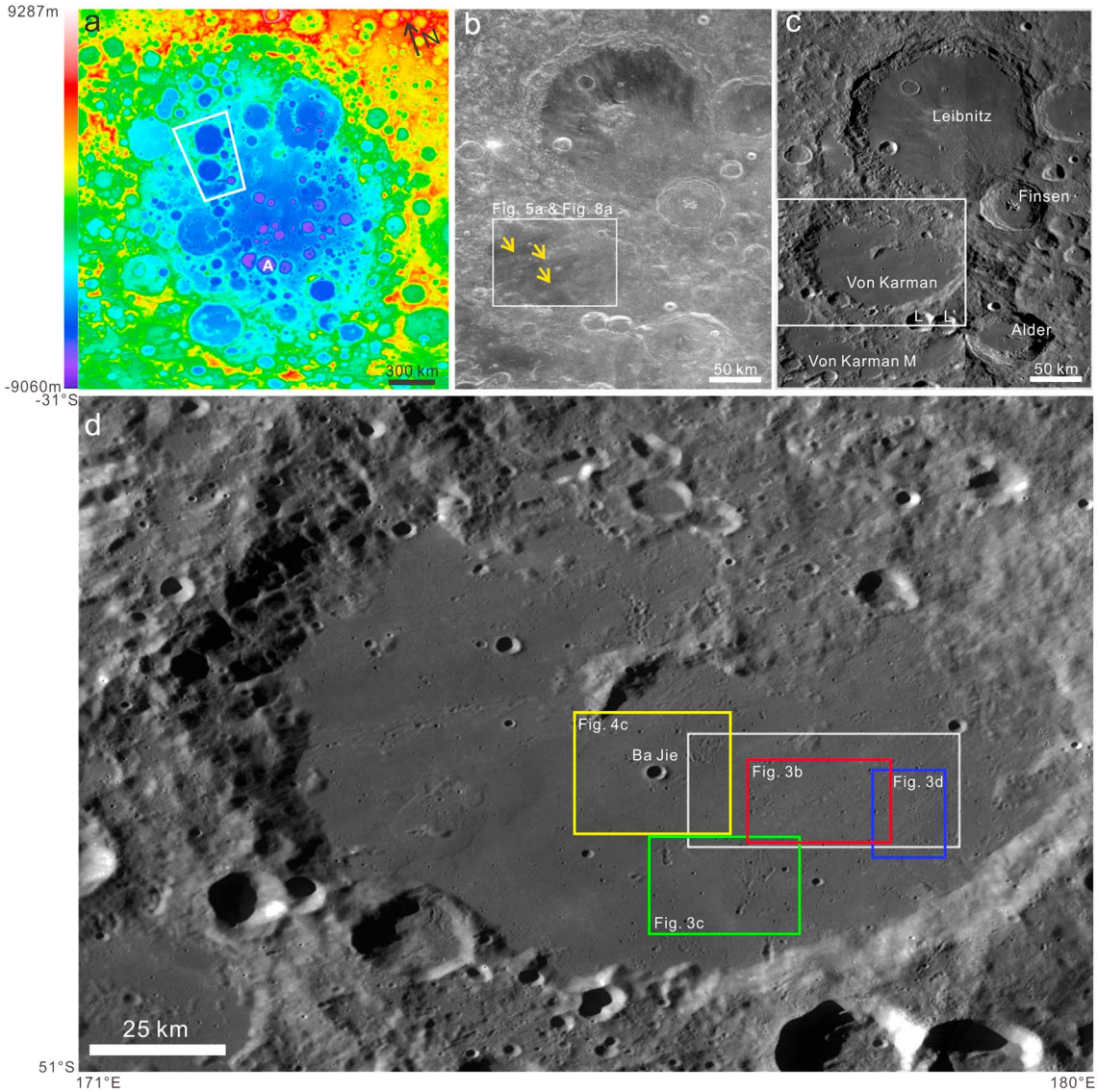


**Figure 1.** (a) Color-coded Lunar Orbiter Laser Altimeter (LOLA) digital elevation model of the South Pole-Aitken Basin (altitude scale on the left). The polygon shows the location of subsets b and c. Letter "A" indicates the location of the Antoniadi crater. (b) Global normalized reflectance (incidence = 30, emission = 0, phase = 30) of the 643 nm Lunar Reconnaissance Orbiter Camera (LROC) Wide-Angle Camera (WAC) mosaic of the Von Kármán area. The rectangle shows the location of Figures 5a and 8a. The yellow arrows indicate the ray materials on the floor of Von Kármán crater, and they are converged to Finsen crater. (c) LROC WAC mosaic of the same area. The white box shows the location of subset d. (d) LRO WAC mosaic of Von Kármán crater. The white box shows the selected landing region, which shows the locations of Figures 2a and 2b, red box in Figure 3a, black boxes in Figures 5c and 5d, 7, and 9a–9d. The red, green, blue and yellow rectangles show the locations of Figures 3b–3d and 4c, respectively. We informally named the unnamed impact crater (diameter $D$ = 3.6 km; central coordinates as 43.3°S 176.1°E) near the landing region as *Ba Jie*, which we use in italics to indicate its informal designation. North is toward the top in subsets b–d.

and Oberbeck (1968) found that relatively fresh concentric craters with diameters less than 250 m could be used to estimate the thickness of the regolith with the equation: thickness = $(k - D_F/D_A) * D_A * \tan(\alpha)/2$, where $D_A$ is the rim-to-rim diameter of a crater, $D_F$ is the diameter of the inner concentric ring, $k$ is an empirically constant, and $\alpha$ is the angle of repose of materials on the surface of the Moon. The angle of repose of lunar regolith ($\alpha$) is 31°, so the corresponding $k$ is 0.86 and the corresponding slope of inner walls of fresh craters is 31° ± 2° (Quaide & Oberbeck, 1968). It is considered more robust to identify concentric craters using images with smaller incidence angle; otherwise, the flat bottomed craters and concentric craters could be misrecognized as normal craters and flat-bottomed craters, respectively (Fa et al., 2014). Thus, we conservatively chose these LROC NAC images with incidence angles less than 55°. Only relatively well-preserved craters with diameters less than 250 m were used to estimate the regolith

thickness (Oberbeck & Quaide, 1967) due to the difficulties in diameter identification and measurements using degraded craters (Soderblom, 1970).

The thickness of ejecta deposits (i.e., the mixture of ejecta and excavated local material) that were transported from craters outside of the landing region are estimated using the empirical scaling laws estimated by Xie and Zhu (2016). Local geological context suggests that the Finsen, Von Kármán L, and Von Kármán L′ craters have contributed most of the ejecta deposits within the proposed landing region (McGetchin et al., 1973; Oberbeck et al., 1975; Petro & Pieters, 2006; Sharpton, 2014). We have a detailed description of the model in section 4.4.

### 2.3. Absolute Model Ages

The absolute model age of the landing region is derived from crater statistics. Since obvious secondary craters (i.e., secondaries) that occur in chains and clusters have almost covered the entire landing region (see section 3.2), we employed two independent methods to estimate the model age. (1) The mare surface on the floor of Von Kármán was interpreted to be emplaced by one episode of basaltic volcanism based on the uniform reflectance spectral characteristics (Yingst & Head, 1999). Therefore, the model age for the mare surface is derived via craters that are substantially larger than the largest obvious secondaries (diameter $D > \sim 2$ km; see section 3.1) on the LROC WAC mosaic. (2) There are a few subareas, including two within the proposed landing region of CE-4, where craters larger than ~300–400 m are not heavily modified by obvious secondaries. The model ages for these subareas are derived by studying the size-frequency distributions of craters larger than 300–400 m in diameter using Kaguya TC mosaics. During analysis of the crater statistics, the CraterTools toolbox in ArcMap was employed to collect the craters by fitting circles based on three points on the crater rims. The crater chronology and production functions proposed by Neukum et al. (2001) were used to derive the model ages based on the Poisson Possibility analyses method advocated by Michael et al. (2016).

### 2.4. Compositional Aspects

In order to distinguish geological units of different composition, age, or texture, a RGB composite mosaic of MI data was built (R = 750 nm/415 nm, G = 950 nm/750 nm, B = 415 nm/750 nm (e.g., Huang et al., 2011; Weitz & Head, 1999). Observed variations in this RGB composite that mimic the Clementine false color ratio are commonly due to variations of the titanium and iron contents and the maturity of the surface materials (Pieters et al., 1993). We marked locations representative of different spectral units in the MI RGB composite. The mineralogy of these locations was derived from spectroscopic data from Chandrayaan-1 $M^3$ instrument (Pieters et al., 2009). $M^3$ is a visible to near-infrared hyperspectral imager, with 85 spectral channels spanning from 430 to 3,000 nm. The data used in this study are archived in the Planetary Data System (PDS, version 1 of Level 2), radiometrically corrected (Green et al., 2011), geometrically corrected (Boardman et al., 2011), thermally corrected (Clark et al., 2011), and photometrically corrected (Besse et al., 2013). The optical period used in this study is the OP2C2, with a resolution of 280 m/pixel. We selected this optical period because it covers the entire landing site region. The continuum of the spectra was removed with the algorithm developed by Martinot et al. (2018), and a suite of band parameters were calculated. The continuum is modeled as linear segments connected to the original $M^3$ spectrum in points called tie points, defined in fixed intervals. The algorithm maximized the 1 and 2 μm absorption band areas and automatically extracted the continuum. After continuum removal, a suite of spectral parameters is calculated (e.g., band center position, band area, and band depth) and exported as maps.

## 3. Results

### 3.1. Surface Morphology and Terrain Characteristics

The selected landing region is located on the mare units within Von Kármán crater. The average elevation of this area is about −5926 m, with a standard deviation of 20.4 m. The elevation ranges over about 321 m. The highest geological feature in the region is the mound located near the north boundary (Figure 2a). The proposed landing region is generally flat at a scale length of 59 m, as nearly 99% of the area has a slope less than 15°, and the slopes of about 94% of the area are less than 5° at a 59 m scale length (Figure 2b). Local steep slopes (>15°) are mostly associated with craters larger than ~1 km diameter (Figure 2b). The northeastern and southwestern portions of the landing area are lower in elevation compared with the northwestern

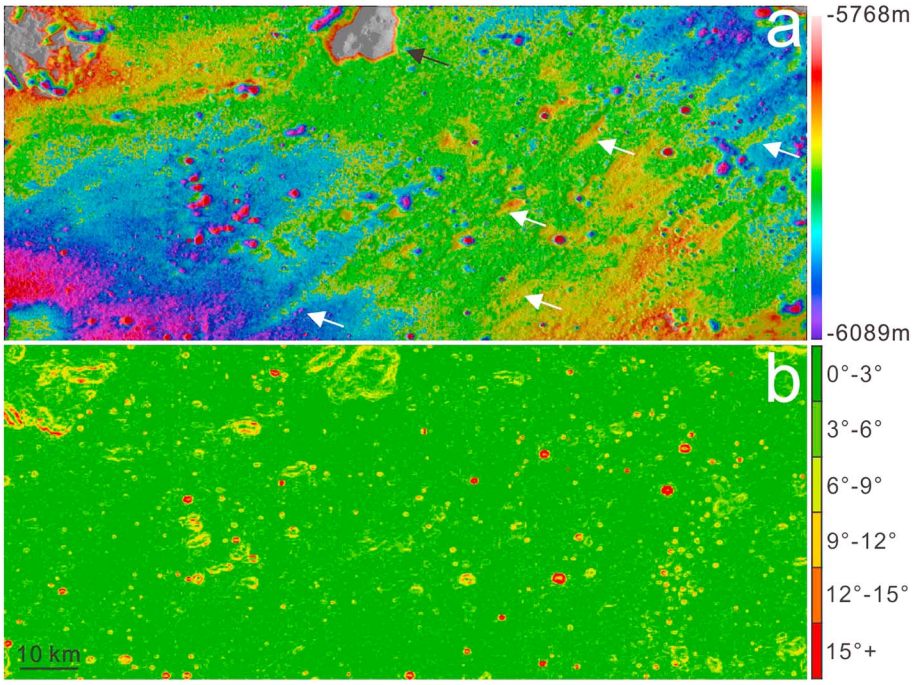


**Figure 2.** (a) Colorized SLDEM topography overlain in transparency over the TC morning mosaic of the landing region. The black arrow points to the mound with the highest altitude in this region. The white arrows indicate NE-SW linear features with elevated topography. (b) Slope map of the landing region calculated with a baseline of 59 m. The location of (a) and (b) is indicated in Figure 1d.

and southeastern portions (Figure 2a). NE-SW linear features with elevated topography are visible across the landing region (Figure 2) and correspond to the ejecta deposits and secondary craters that originated from the Finsen crater (Figure 1b).

Obvious secondary craters are widespread within the entire landing region (Figure 3a). With irregular planar morphology, secondaries are recognized by their spatial occurrences in chains and/or clusters that exhibit herringbone-shaped morphology. Secondaries within a given chain and cluster have similar preservation states and their elevated crater rims all point in the same direction. Based on the preferential spatial orientation of secondaries within the landing region (Figures 1d and 3), we have identified at least four sets of various-sized secondary craters that have different preservation states. The NE-SW trending secondary craters (Figure 3a) are larger than 500 m in diameter, and they converge toward the Finsen crater (Figures 1b and 3a). These secondaries are heavily degraded because their rims now occur as subparallel ridges (Figure 3b) and the original shallow cavity has been gradually filled by mass wasting and subsequent ejecta deposition. The second set of secondaries generally trend north to south and are larger than 1 km in diameter. The secondaries overlap those formed by Finsen and have a better preservation state (Figures 3c and S1). The steepened crater walls are located at the southern part of the secondaries, suggesting that the source crater is located to the south of Von Kármán. The minimum diameter of the parent crater should be at least 20 km considering that the maximum ratio between continuous secondaries and primaries is ~5% on terrestrial planets (Melosh, 1989) and that distant secondaries are much smaller than those on continuous secondaries facies (Xiao, 2016). Tracing southward along a great ellipse circle in ArcMap, we noticed that the Antoniadi crater ($D$ = 138 km; central coordinates as 69.3°S, 186.9°E) is the most likely source crater that fulfills the above criteria (Figure S1). Judging by the same criteria, the freshest secondaries within the proposed landing region are the east-northeast and south-southwest trending secondaries that are located on top of the secondaries formed by Finsen and Antoniadi. These secondaries (e.g., Figure 3d) are much smaller, and they are ~250–500 m in diameter (Figure 3d). Tracing along the secondaries, we find that the Von Kármán L and Von Kármán L′ craters to the south of the landing region are the possible source craters (Figure S2).

Notably, we have identified extensive sinuous ridges within the landing region, which are different from wrinkle ridges (e.g., Binder, 1982) and degraded secondary crater chains (e.g., Lucchitta, 1977) on the Moon. The

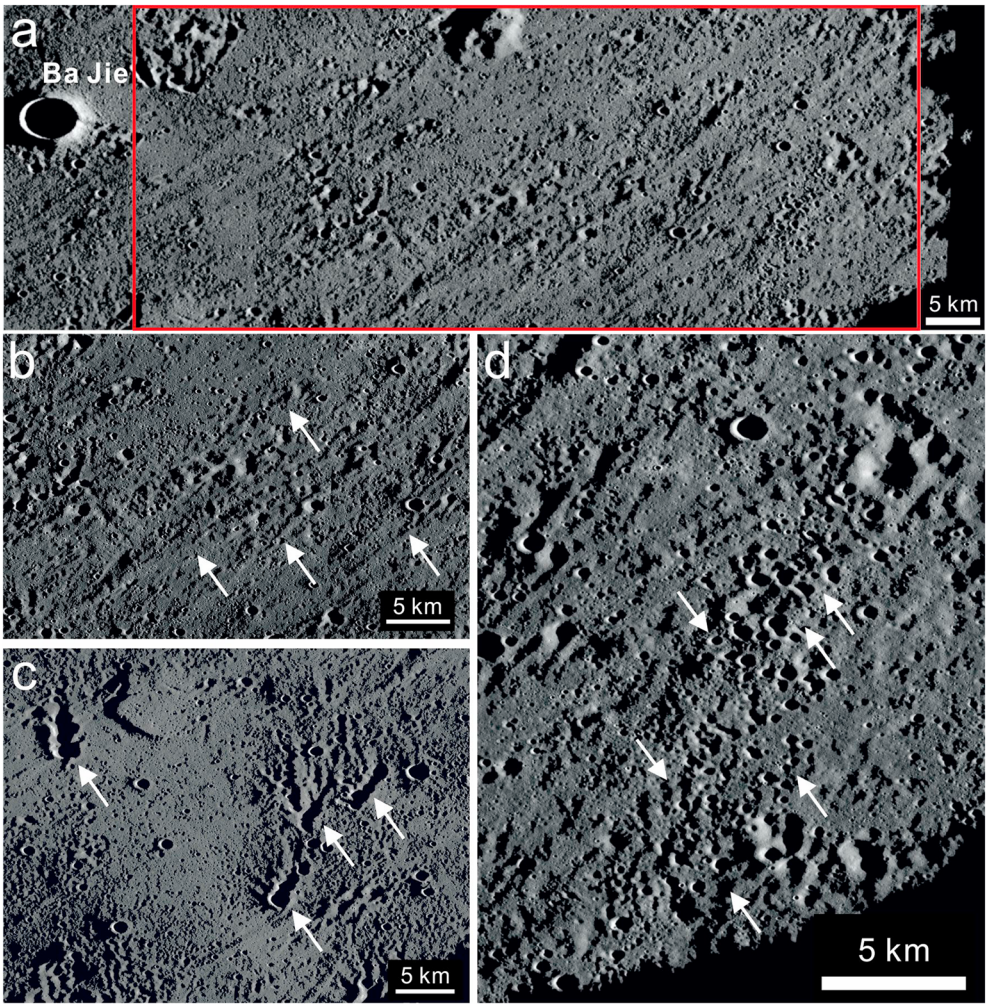


**Figure 3.** (a) TC morning mosaic shows secondary craters occurrence all over the landing region (indicated by the red box). The red box is the same location of the white box in Figure 1d. (b) NE-SW trending linear features formed by Finsen, which are interpreted as highly degraded secondary craters with diameters >500 m. (c) N-S trending secondary craters ($D > 1$ km) overlapping the previous NE-SW trending linear features formed by Finsen. The source crater is most likely Antoniadi crater. (d) NE-SW relatively fresh secondary craters superposing the NE-SW trending linear features. The source craters are most likely the Von Kármán L and Von Kármán L′ craters. North is up in all the panels. The locations of (b)–(d) are indicated in Figure 1d.

ridges are asymmetric in shape and extend in a sinusoidal-like shape (Figure 4a): the widths of the ridges are tens of meters. Sinuous troughs are formed between the ridges (Figure 4b), and both the troughs and ridges are spatially associated with *Ba Jie* crater, which is to the west of the landing region (Figure 4c).

### 3.2. Compositional Diversity

Variations in composition are identified in the reflectance spectra of the proposed landing area (Figure 5). Spectrally, the entire region is dominated by pyroxene signatures (Figures 5b, 5d, and 5e). Pyroxene reflectance spectra are characterized by the presence of diagnostic, broad absorption bands located around 1 and 2 μm, shifting toward longer wavelengths with increasing iron or calcium content (e.g., Klima et al., 2007). The 1 and 2 μm absorption band center positions, displayed on the parameter maps, show that the mare itself is rather homogenous (Figure 5b). Minor variations of the 1 and 2 μm absorption band center positions of pyroxene spectra are observed within impact crater ejecta located on the mare floor, suggesting variations in chemistry with depth (Figure 5b). On the MI color composite (Figure 5d), relatively fresh small craters (diameter ~66 to 324 m; Figure 6a) show blue-toned ejecta (e.g., site 1 in Figure 5d) and higher albedo in the MI 750 nm reflectance data (Figure 5c). Their reflectance spectra are consistent with that of

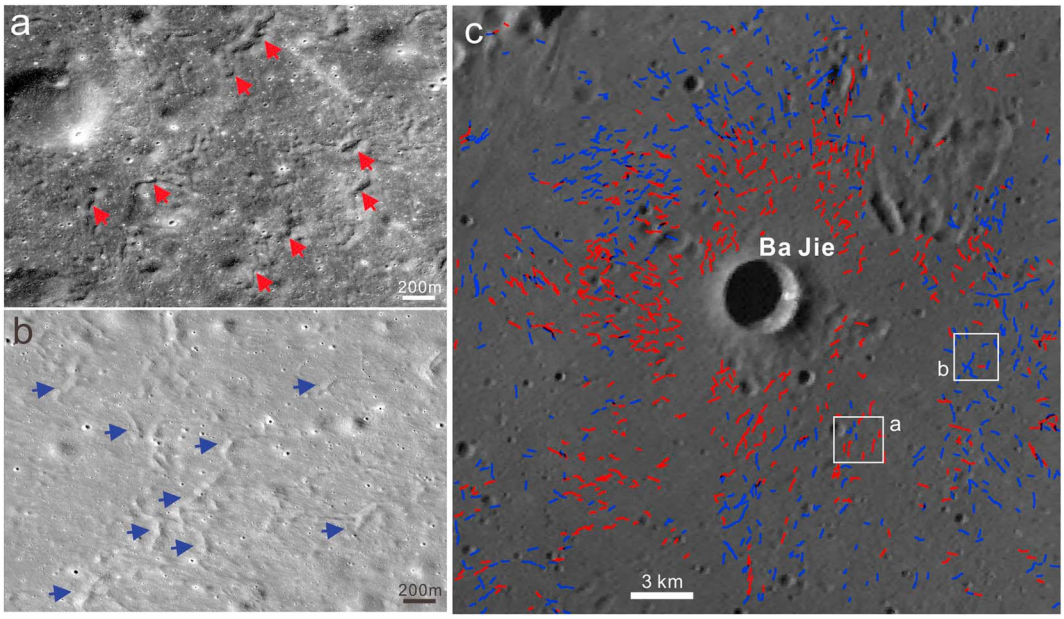


**Figure 4.** (a) LRO NAC image (M1100060445RE) of a region west of the landing region. The red arrows indicate the position of asymmetric sinuous ridges. (b) LRO NAC image (M1183658592RE) of an area in the western part of the landing region. The blue arrows indicate the position of sinuous troughs. (c) The spatial relationships between sinuous ridges and sinuous troughs observed in the vicinity *Ba Jie* crater. The red lines indicate sinuous ridges, and the blue lines indicate sinuous troughs. North is toward the top in all the panels.

Low-Calcium Pyroxene (LCP)-bearing material (Figure 5e). The orange-toned ejecta (e.g., site 2 in Figure 5d) are related to larger craters (diameter 252–950 m; Figure 6b), with spectra consistent with Higher-Calcium Pyroxene (HCP)-bearing materials (Figure 5e). The spectra of the ejecta of *Ba Jie* crater are similar to the spectra of the orange-toned ejecta (sites 4, 5, 6, and 7 in Figure 5d). The ejecta on the rim of *Ba Jie* crater presents HCP signatures, but with larger spectral contrast (site 5 in Figure 5d). The mare itself (site 3 in Figure 5d) has a spectral signature consistent with these HCP-rich materials with weaker absorption bands.

### 3.3. Regolith Thickness

We analyzed relatively fresh concentric impact craters using LROC NAC images with incidence angle less than 55° to estimate the regolith thickness using the method of Quaide and Oberbeck (1968). These images have solar angles greater than 35°, which are larger than the repose angle of the regolith (31°). Therefore, we can clearly determine the morphology of the impact craters with these NAC images (Fa et al., 2014). The estimated thickness of the regolith in this area varies from ~2.5 to 7.5 m (Figure 7). It appears that the regolith in the northeastern portion of the region is thicker than that of the southwestern portion, which is consistent with a larger contribution of ejecta deposits (Figure 10), as well as a strong gardening effect of secondary crater chains (Figure 2a) formed as a result of the Finsen crater-forming event.

### 3.4. Stratigraphic Ages of the Landing Area

Obvious secondary crater chains have dominated the entire mare unit on the floor of Von Kármán (Figure 3a). Most of the secondaries are less than 2 km in diameter (section 3.2). Therefore, we studied the size-frequency distribution of craters larger than 2 km in diameter to estimate the model age of the mare unit. The absolute model age derived by probability analyses (Michael et al., 2016) is 3.6 (+0.09, −0.2) Ga, which falls in the Imbrian period. This result is consistent with the recent geological mapping (Yingst et al., 2017), and crater statistics (Haruyama et al., 2009). We also selected three subregions on the mare units that have been less affected by large secondary craters in order to verify the model age. Figure 8a shows the locations of the counting areas. The surface morphology of the subregions shows that craters larger than ~300–400 m are not obvious secondary craters (e.g., Figures 8c, 8e, and 8g), and model ages derived from the crater counts are identical with those estimated from craters larger than 2 km in diameter.

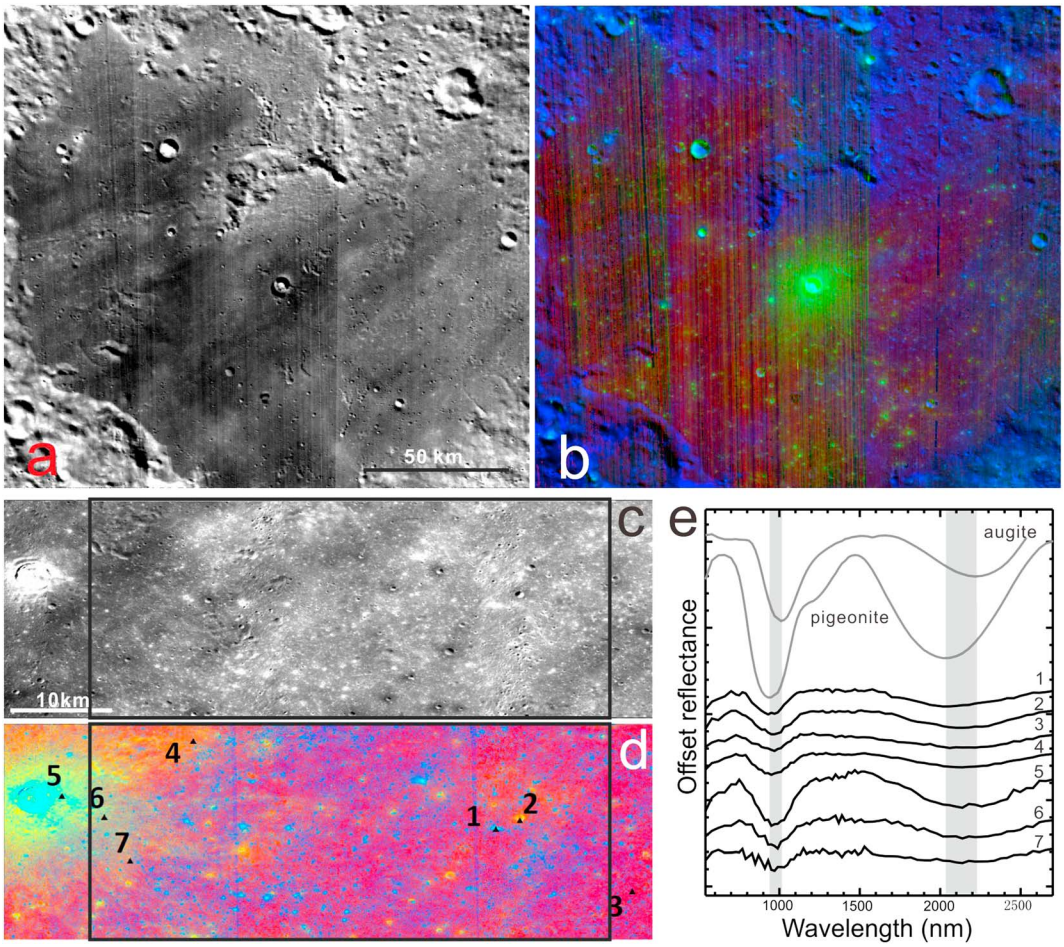


**Figure 5.** (a) $M^3$ 750 nm reflectance mosaic of Von Kármán crater (stretch: 0.044–0.082). High albedo linear features oriented WSW-ENE are visible on the crater floor, and they can be traced back to Finsen crater in Figure 1b. The location of this subset and (b) is indicated in Figure 1b. (b) $M^3$ color composite of Von Kármán crater (same region as a). R = 2 μm band center (2,000–2,500); G = 2 μm band depth (0.04–0.17); B = reflectance at 1580 nm (0.085–0.15). Stretch values are indicated in brackets. LCP-bearing material appears in light blue, and HCP-bearing material appears green. Spectral parameters were calculated using the method described in Martinot et al. (2018). (c) MI 750 nm reflectance mosaic of the landing area. Relatively high albedo features are mostly associated with ejecta deposits of small fresh craters, and impact rays from the Finsen crater, whereas low albedo features are mostly associated with mare basalts and ejecta deposits of large craters. The landing area is indicated as a black rectangle, which is indicated in Figure 1d. (d) RGB composite of MI data. R: 750 nm/415 nm (1.797–1.925), G: 950 nm/750 nm (0.877–1.034), B: 415 nm/750 nm (0.515–0.564). Stretch values are indicated in brackets. The landing area is indicated as a black rectangle, which is indicated in Figure 1d. (e) Continuum-removed $M^3$ spectra of locations (1 to 7) in Figure 5d. Each spectrum corresponds to a single pixel. Spectra were processed with the method described in Martinot et al. (2018). A pigeonite (LCP) and an augite (HCP) spectrum from the RELAB database are displayed above the observed spectra for comparison (respective RELAB-ID: DL-CMP-008 and AG-TJM-010). The shaded areas represent the diversity of values of the 1 and 2 μm bands.

## 4. Discussion

### 4.1. Context of CE-4 Mission

CE-4 is scheduled to launch in 2018 and will be the first lunar farside in situ exploration mission. The CE-4 mission will be carried out in two phases. First, a relay satellite with two microsatellites will be launched by a CZ-4C rocket from Xichang, China. The relay satellite will be sent to the Earth-Moon Lagrange Point 2. A Dutch-made low-frequency radio spectrometer (0.1–80 MHz) is carried by the relay satellite to perform space physics measurements. In addition, the relay satellite will carry several laser reflectors for assisting orbital determination. This mission will also include two microsatellites that will orbit the Moon, and they will be equipped with very-long-baseline interferometry instruments to conduct radio science experiments. One

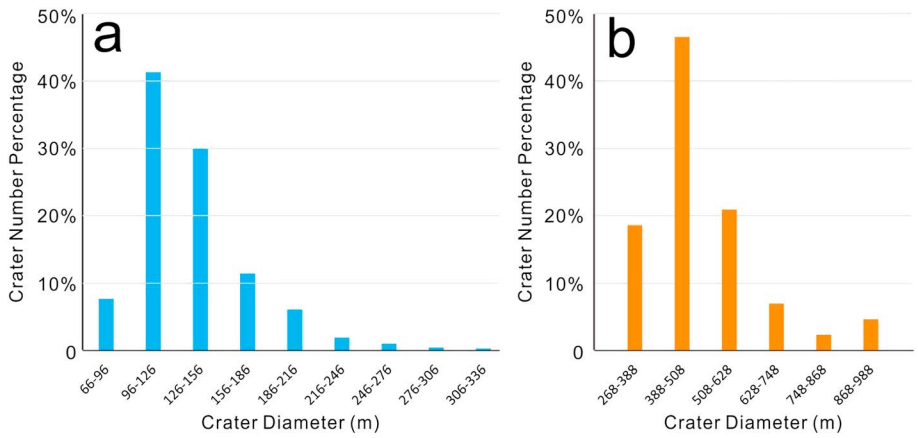


**Figure 6.** Diameter distribution of craters with (a) low-Ca pyroxene bearing ejecta (blue) and (b) high-Ca pyroxene bearing ejecta (orange) within the landing region (see Figure 5d).

of the microsatellites will have a visible wavelength microcamera contributed from Saudi Arabia. Six months after the launch, the second part of the CE-4 mission, which is composed of a lander and a rover, will be launched by a CZ-3B rocket launched from Xichang, China. Since both the lander and the rover were designed as a backup for the Chang'E-3 (CE-3) mission, some of the science payloads on CE-4 are similar to those on CE-3 (Jia et al., 2018), which include a landing camera, a terrain camera, a panorama camera on the lander and a visible/near infrared imaging spectrometer (He et al., 2014), and two ground penetrating radars (Fang et al., 2014) on the rover. Additional instruments on the lander (Jia et al., 2018) include (1) a low-frequency radio spectrometer (0.1–40 MHz) to perform joint space physics observations with the low-frequency radio spectrometer on the relay satellite, (2) a German lunar neutron and radiation dose detector to explore the farside surface radioactive environment, and (3) a lunar microecosystem for astrobiology experiments and public outreach. A new instrument on the rover (Jia et al., 2018) is the Swedish neutral atom detector designed to study the interaction between the solar wind and lunar surface materials. However, the CE-4 will not be equipped with the alpha particle X-ray spectrometer that was previously used by CE-3 to detect elemental abundances within surface material (Jia et al., 2018; Wu et al., 2017). Still the lander and rover together should be able to perform imaging, spectral, radar, and low-frequency radio spectral measurements.

### 4.2. Geological Features

Several features of interest have been identified within the landing region, including farside mare basalts, sinuous linear features, and ejecta rays. Nonnearside mare basalts will be investigated in situ for the first time at Von Kármán and may bring new clues about the farside and SPA volcanism. Spectral data show HCP

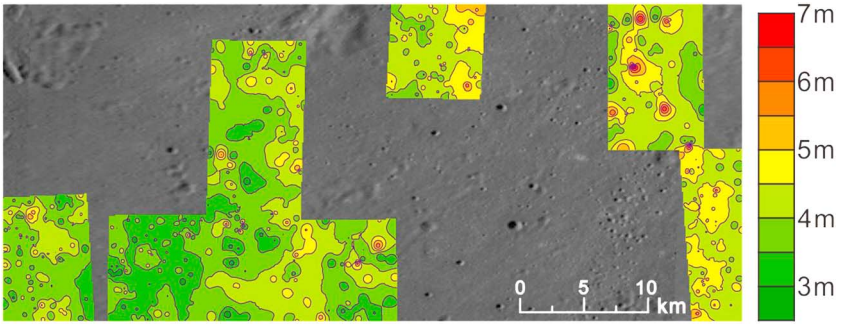


**Figure 7.** Estimated thickness contour of regolith in the landing region based on available LROC NAC images with incidence angle inferior to 55°. The background image is WAC mosaic, and the location is indicated in Figure 1d. The IDs of NAC images used are M143453659RE, M143453659LE, M143460468RE, M143460468LE, M156434145RE, M156434145LE, M189435642RE, M189435642LE, M1133052548RE, M1133052548LE, M1145979809RE, M1145979809LE, and M1163658519LE.

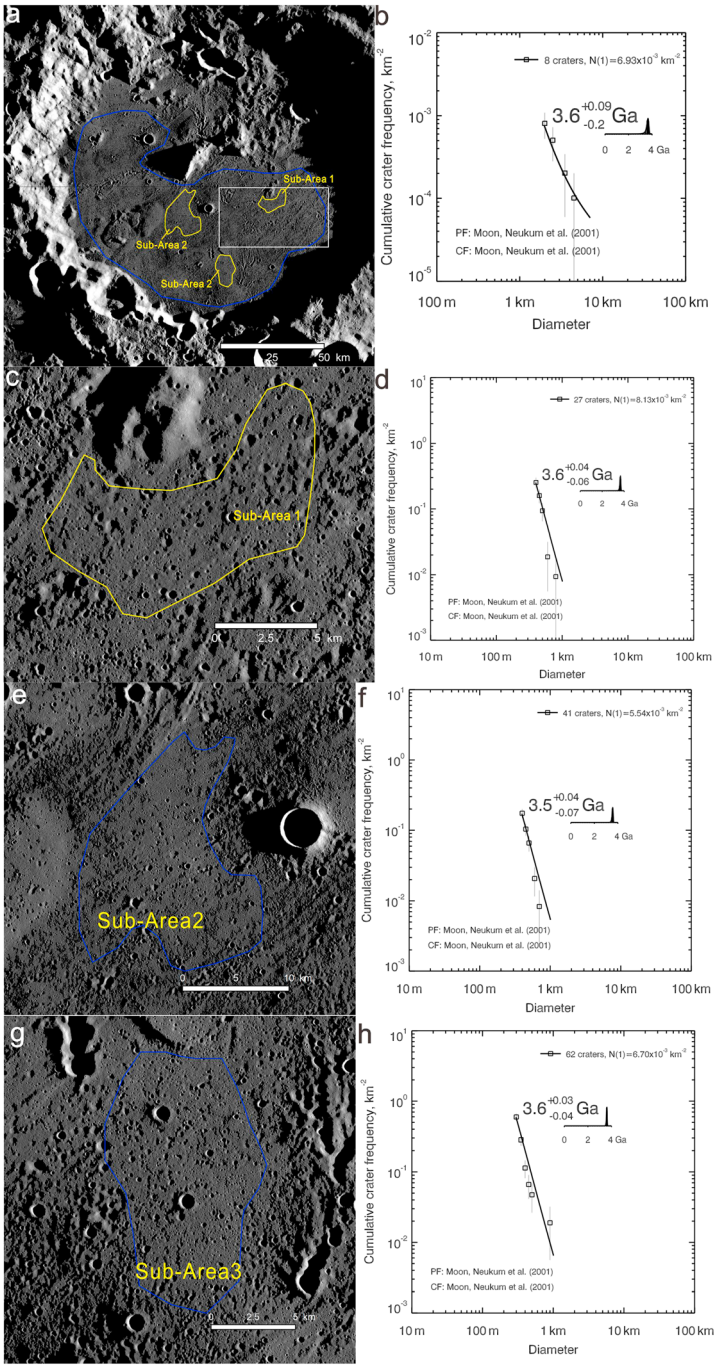


**Figure 8.** Absolute model ages derived from crater statistics for the mare unit located within the floor of Von Kármán crater. (a) Counting areas on the crater floor based on Kaguya TC mosaic. The mare units on the crater floor were classified as a single geological unit based on recent geological mapping (Yingst et al., 2017). The blue area shows the counting area where only craters larger than 2 km in diameter are used in deriving the model age. The locations of the three subareas are shown in yellow polygons. These regions were selected as they are less affected by obvious secondaries in comparison to the rest of the crater floor. (b) Model age for the mare unit derived from probability analysis (Michael et al., 2016). (c) Detailed surface morphology of the subarea 1 shown in Kaguya TC mosaic. This area is located within the selected landing area, where the population of obvious secondary craters is smaller. Degraded secondary craters within this subarea are less than 400 m in diameter. (d) Model age for the subarea 1 on the mare surface derived from probability analysis (Michael et al., 2016). (e) Context of subarea 2 shown by Kaguya TC mosaic and the location of the counting area (blue polygon). (f) Model ages derived for the crater population in subarea 2. (g) Context of subarea 3 shown by Kaguya TC mosaic and the counting area (blue polygon). (h) Model ages derived for the crater population in subarea 3. North is to the top in (a), (c), (e), and (g).

signatures associated with the mare unit, which is consistent with most lunar mare (e.g., Staid et al., 2011). However, in contrast to the CE-3 landing site, olivine has not yet been detected at Von Kármán (Ling et al., 2015; Zhang et al., 2015), which suggests that the farside mare might be of slightly different composition. The mare unit is homogeneous and likely to represent a single eruptive episode during the lunar peak volcanic period that occurred in the Late Imbrian (3.80–3.20 Ga; e.g., Yingst & Head, 1999). A single eruptive episode was one in which the mechanism of emplacement did not significantly vary over the period of activity, meaning that the rock unit left in place should share generally similar morphological and compositional characteristics, making it a viable geologic unit.

Sinuous linear features, ridges and troughs, have been identified in the vicinity of *Ba Jie* crater. They are distinct from lunar wrinkle ridges, but their origin remains controversial. For example, Oberbeck (1975) proposed these to be ejecta deposits typical of small craters in which the ejecta is emplaced at relatively low velocity, and Atwood-Stone et al. (2016) suggested that these structures are likely the results of Kelvin-Helmholtz instabilities within the ejecta flows. The key information to understand their formation mechanism is the subsurface structure of these features, that is, the depth and structural disturbance of the ejecta deposits of the *Ba Jie* crater, and whether or not fractures deeper than *Ba Jie*'s ejecta exist. The ground penetrating radars onboard CE-4 could reveal the subsurface structure of these linear features and provide clues to their possible formation mechanism.

The secondary craters produced by the Finsen crater-forming event, and associated with relatively high albedo linear features, are heavily degraded but also of interest (Figures 1b and 3). Hawke et al. (2004) proposed four different mechanisms to explain the formation of impact rays: (1) immature primary ejecta emplacement, (2) secondary craters immature local material deposition, (3) the action of debris surges downrange of secondary clusters, and (4) immature interior. Reflectance spectra for the landing region show that the rays formed by Finsen appear to have distinct composition compared with the buried mare basalts (Figure 5b), indicating that the rays are composed of primary ejecta deposits. With the aid of the CE-4 cameras and radar system, the thickness and spatial distribution of impact ejecta from the Finsen crater could be more well constrained. This would be the first in situ constraint for the subsurface structure of compositional rays, which will serve as an observational basis for understanding the efficiency of material transport by impact cratering on the Moon.

### 4.3. Stratigraphy of the Landing Region

Impact craters are probes of local stratigraphy (Melosh, 1989). Variations of reflectance spectra of crater ejecta deposits indicate vertical variations in composition/mineralogy in the landing area (section 3.3). We used the geometric relationship between the diameter of impact craters and the depth from which the ejecta was excavated to reconstruct the regional stratigraphy (Figure 9). The maximum depth of excavation is approximately 1/10 of the transient crater diameter, which equals to 0.84 times final crater rim-to-rim diameter for simple craters (Melosh, 1989). Therefore, we used this relationship for the diameter measured on the image to calculate the excavation depth of each of the simple craters located upon the mare unit. Note that most of the small craters less than 2 km in diameter are probably secondary craters; thus, they have smaller excavation depths than similar-sized primary craters (McEwen & Bierhaus, 2006; Oberbeck, 1975), indicating that the calculated excavation depths are the upper bound for the actual values.

The regolith constitutes the uppermost layer of the reconstructed stratigraphic column (A in Figure 9), with a thickness of ~2.5 to 7.5 m (the regolith in the northeastern part is thicker than in the southwestern part in the landing region; Figure 7). The main uncertainties in the regolith thickness estimates come from LROC NAC images with the necessary illumination geometry (incidence angle less than 55°), the determination of rim-to-rim diameter of craters, and the limitations of the estimation method (Quaide & Oberbeck, 1968).

Beneath the regolith is the Finsen LCP-bearing ejecta layer (B in Figure 9; which might be discontinuous or variable in thickness). Represented in blue tones in the MI color composite (Figure 5d), this layer is excavated by craters ~66 to 336 m in diameter (Figure 6a). The majority of these craters is 96 to 156 m in diameter (Figure 6a), suggesting that the LCP-bearing material is at least ~8 to 13 m deep.

The HCP-bearing layer (D + E + F in Figure 9) is exposed in the orange-toned ejecta in the MI color composite (Figure 5d) of larger craters with diameters ranging from 268 to 988 m (Figure 6b) as well as *Ba Jie* crater. The majority of orange toned ejecta craters fall in the 388 to 628 m range in diameter (Figure 6b), indicating that

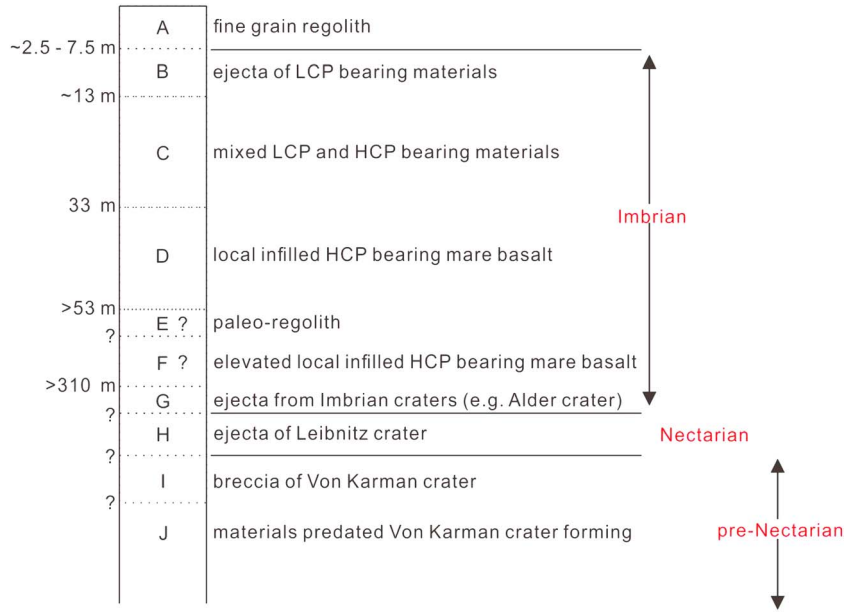


**Figure 9.** Proposed stratigraphy of the landing region. The thickness of the layers is not to scale.

the HCP-bearing materials (D) are at least ~33 to 53 m deep. *Ba Jie* crater is ~3.7 km in diameter, suggesting that local minimal depth of the HCP-bearing materials (and hence mare unit) is greater than 310 m. The spectrum extracted from the site 5 of *Ba Jie* crater's ejecta has a deeper absorption band than the spectra of sites 6 and 7 (Figure 5e). This absorption band depth difference could indicate that the material of site 5 is slightly distinct compared to material of sites 6 and 7, possibly more enriched in HCP or with a different grain size or texture (or less mature). Alternatively, the ejecta could be thicker at site 5 and less mixed with the underlying likely space-weathered layer, resulting in a more intense signature. Spectral variations within the ejecta of *Ba Jie* crater (Figures 5d and 5e) could hint at a subtle vertical compositional difference in the layer of HCP-bearing materials. The material located at site 5 (layer F) are from deeper portions of the preimpact stratigraphy than the material located at sites 6 and 7, due to the fact that the deeper-seated material tends to be ejected closer to the crater rim (Stöffler et al., 1975). Therefore, there is probably a layer of enriched HCP-bearing material (F) under the HCP-bearing-material layer, and could imply a possible paleo-regolith layer (E) between layers D and F if there were at least two episodes of basalt emplacement. The paleo-regolith thickness (if such a layer exists) could be studied with the radar instrument onboard the CE-4 rover, similarly to the detections made at the CE-3 landing site (Xiao et al., 2015). It appears reasonable to speculate that there could be somewhere in the stratigraphy a layer of mixed LCP and HCP-bearing material (C) due to collision of these two types of materials. However, we are not able to constrain the thickness of this mixed layer. The main uncertainties of the reconstructed stratigraphy come from ejecta of unidentified impact craters, mixing of ejecta of local materials, and products of uncertain geological events between stratigraphic layers.

We propose a stratigraphic column with several layers beneath the HCP-bearing-material layer/mare unit based on the regional setting and previous geological maps (Wilhelms et al., 1979; Yingst et al., 2017). However, the thickness of these layers cannot be constrained using available data and previous mapping results. We expect a layer G made of ejected material from Imbrian-aged craters (e.g., Alder) resurfacing HCP-bearing basalts. Layer B to G were formed during the Imbrian epoch. Ejecta of Leibnitz crater (H) occurred as the layer beneath, and this impact event occurred in Nectarian. Then there should be a layer (I) of breccia from Von Kármán crater forming event lying above the target materials (J) of Von Kármán crater. Layer I and J are of pre-Nectarian age (Figure 9), likely to be part of the SPA basin Mg-Pyroxene Annulus (Moriarty & Pieters, 2018).

The two ground penetrating radars onboard the CE-4 rover will be able to reveal the subsurface structure of the landing area and test the stratigraphy predicted in this study. In a manner similar to the CE-3 Yutu rover,

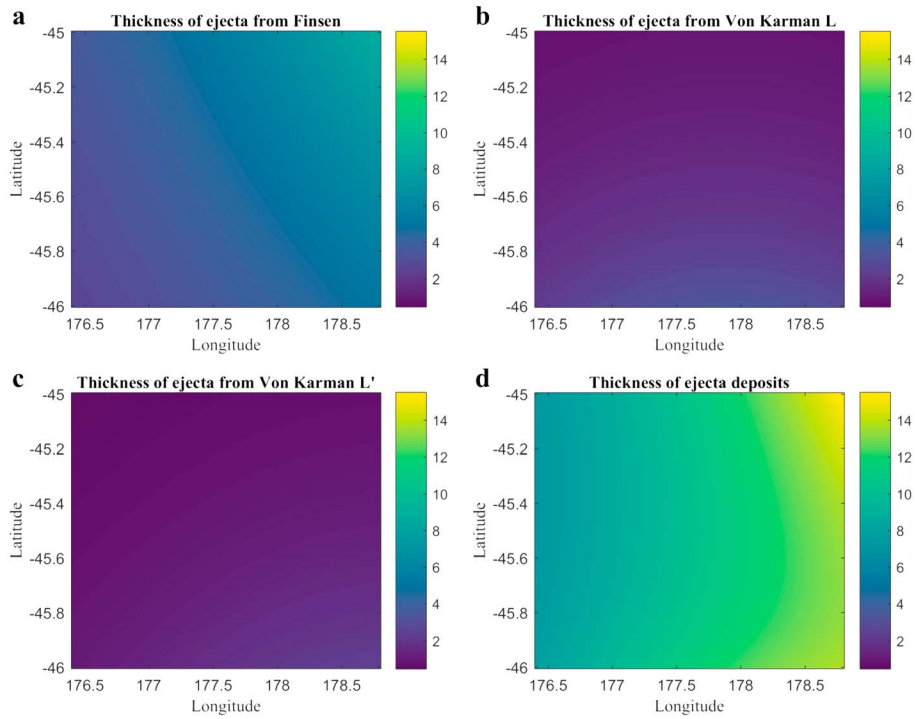


**Figure 10.** The thickness of ejecta from (a) Finsen crater, (b) Von Kármán L crater, and (c) Von Kármán L′ crater. (d) Thickness of all ejecta deposits consisting of excavated local material and accumulated ejecta from Finsen, Von Kármán L, and Von Kármán L′. The locations of (a)–(d) are labeled in Figure 1d.

the radar system of the CE-4 rover has two frequency channels with different penetrating depths and vertical resolutions: Channel 1 has a frequency of 40–80 MHz, whereas Channel 2 has a frequency of 250–750 MHz (Jia et al., 2018). The radar system on the CE-3 mission demonstrated that the Channel 2 radar could detect details of the subsurface structures up to a depth of ~12 m, and the Channel 1 radar could reveal subsurface structures up to ~400 m (Xiao et al., 2015). Therefore, the ground penetrating radars Channel 1 can detect layers A, B, C, D, E, and F, and it could detect layer G, H, I, and J depending on their thickness. Channel 2 could detect detailed structures within layers A and B, and the upper portion of the layer C.

### 4.4. The Origin of the LCP Bearing Materials

The LCP-bearing materials have relatively higher albedo compared to the relatively lower albedo mare basalts in the landing region. Regional geological context suggests that the LCP-bearing materials are part of the ejecta of the Finsen crater forming event (section 3.1). Besides Finsen crater, we have surveyed the nearby regions for younger craters that might have contributed ejecta over the landing region. Von Kármán L and Von Kármán L′ adjacent to the landing region are the two large craters that are younger than the mare units, and they have inevitably launched ejecta into the landing region. We estimate the thickness of ejecta deposits formed by the impact of ejecta from Finsen, Von Kármán L, and Von Kármán L′ craters. First, we estimate the ejecta thickness distribution. Then, the thickness of local material excavated by the impact of ejecta is derived from empirical equation. Finally, the ejecta deposit thickness is the sum of ejecta from other craters and local material. Assuming a power law distribution of ejecta with slope of $-3$ (McGetchin et al., 1973) and using the scaling relationship between ejecta thickness at final crater rim crest and final crater radius given by Sharpton (2014), we estimate the ejecta thickness distribution by using this relationship $T = 3.95R^{0.399}(r/R)^{-3}$, where $r$ is the distance from crater center in meters and $R$ is the final crater radius (all in meters). Therefore, the amount of ejecta contributed from Finsen (Figure 10a; diameter $D$ = 73 km) is the largest among the three craters, followed by Von Kármán L (Figure 10b; diameter $D$ = 29 km) and Von Kármán L′ (Figure 10c; diameter $D$ = 29 km). Assuming the incident angle of ejecta was 75°, Oberbeck et al. (1975) established an empirical model that can estimate the excavation efficiency ($\mu$) of crater ejecta for given thickness of ejecta and the distance from crater center based on the analysis of Copernicus secondary craters

(i.e., $\mu = 4.5 \times 10^{-5} r^{0.87}$, all in meters). However, recent works (e.g., Petro & Pieters, 2006; Xie & Zhu, 2016) suggested that the authors may have overestimated the excavation efficiency. Here we adopt half of excavation efficiency of Oberbeck et al. (1975) (i.e., $\mu = 2.25 \times 10^{-5} r^{0.87}$) according to the result of Petro and Pieters (2006). The thickness of local material excavated by the ejecta from either Von Kármán L or Von Kármán L′ is predicted to be smaller than 1 m, whereas the thickness of Finsen ejecta is larger than 2.5 m (Figure 10a). In addition, Finsen crater is older than both Von Kármán L and Von Kármán L′ (Wilhelms et al., 1979; Yingst et al., 2017). Therefore, the ejecta from Von Kármán L or Von Kármán L′ is expected to rework the ejecta deposits formed by Finsen crater ejecta. The thickness of ejecta deposits including the excavated local material and the total accumulated ejecta is predicted to vary from about 7.2 to 15.5 m (Figure 10d), which is consistent with the depth of LCP bearing materials discussed previously. This is independent evidence that the LCP-bearing materials were likely from Finsen crater, Von Kármán L, and Von Kármán L′.

LCP-bearing materials are pervasive across the SPA basin, including the central peak of Finsen crater (Moriarty et al., 2013; Moriarty & Pieters, 2018; Pieters et al., 2001). However, the origin of the LCP bearing materials is still under debate. The LCP-bearing material could correspond to exposed KREEP-related Mg-suite rocks (Pieters et al., 1997; Klima et al., 2011) or the differentiated upper layer of the hypothesized SPA melt sheet (Nakamura et al., 2009; Uemoto et al., 2017). Alternatively, the LCP-bearing materials could come from a LCP-dominated lunar upper mantle (Melosh et al., 2017; Moriarty & Pieters, 2018).

The hypotheses can be evaluated using geological context, but it is challenging to use orbital remote sensing data to pin down the origin of the LCP bearing materials due to lack of detailed geochemical data. The definitive way to establish the origin of the LCP-bearing materials is by sample return (e.g., Jolliff et al., 2010), and the current payloads onboard the CE-4 mission are not designed to reveal element distribution for surface materials. However, we point out that the penetrating radar onboard the CE-4 rover can test and help verify the stratigraphy of the landing area, which might be used to indirectly infer the composition (e.g., by backward modeling for the dielectric constant) and provide additional clues about the origin of the LCP-bearing materials. These LCP-bearing materials could help to better constrain the history of the SPA region (Moriarty & Pieters, 2018) and might represent high priority targets for future sample return missions, for example, Chang'E-6.

## 5. Conclusions

The Chinese CE-4 lunar mission will be the first in situ exploration to explore the surface of the Moon and study its environment on the farside. The selected landing area is located in the southern portion of the Von Kármán crater, on the top of the infilling mare unit, and within the SPA basin (Figure 1). We characterized the terrain and geological characteristics of the landing region using multisource remote sensing data sets. The main conclusions are as follows:

1. The landing region (45°S–46°S, 176.4°E–178.8°E) is generally flat at a length scale of 59 m and located within a rather homogenous mare unit.
2. The absolute model age of the mare unit within Von Kármán crater is 3.6 Ga (+0.09, −0.2), based on multiple crater size-frequency distribution measurements.
3. Secondary craters have almost covered the entire landing area. The oldest secondary craters (NE-SW direction) look degraded and converge to Finsen crater. N-S direction secondary craters are superposing on them, and they are converging to Antoniadi crater. The youngest secondary craters are NE-SW, and they are likely from Von Kármán L and Von Kármán L′.
4. The thickness of the regolith is estimated to be ~2.5 to 7.5 m in the landing area.
5. Extensive sinuous ridges and sinuous troughs are identified in the landing area. They are related to *Ba Jie* crater spatially, but the origin is controversial. The ground penetrating radar onboard CE-4 rover will reveal the subsurface structure and provide clues to the origin of these linear features.
6. Spectral variations among the ejecta of craters of various sizes reveal the subsurface structures. Along with the estimated thickness of the regolith, crater size-frequency distribution absolute model age, and previously geological mapping results, we proposed a stratigraphic profile of the landing area that can be tested with CE-4 ground penetrating radar data.
7. LCP-bearing material, probably excavated from the nearby Finsen crater from a depth <7 km, are widespread in the landing region and could bring more clues about SPA history.

8. The detailed stratigraphy and the diversity of farside geologic units sampled by impact craters in the region (in both the vertical and lateral sense) and delivered to the landing and traverse area to form secondary craters ensure that the Von Kármán landing site will be an excellent candidate for the first sample return mission to the lunar farside by Chang'E-6. Soils in the Von Kármán regolith are very likely to contain samples of farside lunar maria, a diversity of farside highland rock types, and samples of the SPA basin Mg-Rich Annulus (impact melt and possible mantle of the SPA basin). The Change'E-4 mission and surface traverses will provide the surface and three-dimensional stratigraphic information necessary to help refine the lateral and vertical stratigraphy to ensure optimal sample return.

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## References

Atwood-Stone, C., Bray, V. J., & McEwen, A. S. (2016). A new study of crater concentric ridges on the Moon. *Icarus*, *273*, 196–204. https://doi.org/10.1016/j.icarus.2016.03.012

Barker, M., Mazarico, E., Neumann, G., Zuber, M., Haruyama, J., & Smith, D. (2016). A new lunar digital elevation model from the Lunar Orbiter Laser Altimeter and SELENE Terrain Camera. *Icarus*, *273*, 346–355. https://doi.org/10.1016/j.icarus.2015.07.039

Besse, S., Sunshine, J., Staid, M., Boardman, J., Pieters, C., Guasqui, P., et al. (2013). A visible and near-infrared photometric correction for Moon Mineralogy Mapper ($M^3$). *Icarus*, *222*(1), 229–242. https://doi.org/10.1016/j.icarus.2012.10.036

Binder, A. B. (1982). Post-Imbrian global lunar tectonism: Evidence for an initially totally molten Moon. *The Moon and the Planets*, *26*(2), 117–133. https://doi.org/10.1007/BF00929277

Boardman, J. W., Pieters, C., Green, R., Lundeen, S., Varanasi, P., Nettles, J., et al. (2011). Measuring moonlight: An overview of the spatial properties, lunar coverage, selenolocation, and related Level 1B products of the Moon Mineralogy Mapper. *Journal of Geophysical Research*, *116*, E00G14. https://doi.org/10.1029/2010JE003730

Clark, R. N., Pieters, C. M., Green, R. O., Boardman, J., & Petro, N. E. (2011). Thermal removal from near-infrared imaging spectroscopy data of the Moon. *Journal of Geophysical Research*, *116*, E00G16. https://doi.org/10.1029/2010JE003751

Fa, W., Liu, T., Zhu, M. H., & Haruyama, J. (2014). Regolith thickness over Sinus Iridum: Results from morphology and size-frequency distribution of small impact craters. *Journal of Geophysical Research: Planets*, *119*, 1914. https://doi.org/10.1002/2013JE004604–1935

Fang, G.-Y., Zhou, B., Ji, Y.-C., Zhang, Q.-Y., Shen, S.-X., Li, Y.-X., et al. (2014). Lunar penetrating radar onboard the Chang'e-3 mission. *Research in Astronomy and Astrophysics*, *14*(12), 1607–1622. https://doi.org/10.1088/1674-4527/14/12/009

Garrick-Bethell, I., & Zuber, M. T. (2009). Elliptical structure of the lunar South Pole-Aitken basin. *Icarus*, *204*(2), 399–408. https://doi.org/10.1016/j.icarus.2009.05.032

Green, R., Pieters, C., Mouroulis, P., Eastwood, M., Boardman, J., Glavich, T., et al. (2011). The Moon Mineralogy Mapper (M3) imaging spectrometer for lunar science: Instrument description, calibration, on-orbit measurements, science data calibration and on-orbit validation. *Journal of Geophysical Research*, *116*, E00G19. https://doi.org/10.1029/2011JE003797

Haruyama, J., Ohtake, M., Matsunaga, T., Morota, T., Honda, C., Yokota, Y., et al. (2009). Long-lived volcanism on the lunar farside revealed by SELENE Terrain Camera. *Science*, *323*(5916), 905–908. https://doi.org/10.1126/science.1163382

Hawke, B. R., Blewett, D. T., Lucey, P. G., Smith, G. A., Bell, J. F., Campbell, B. A., & Robinson, M. S. (2004). The origin of lunar crater rays. *Icarus*, *170*(1), 1–16. https://doi.org/10.1016/j.icarus.2004.02.013

He, Z.-P., Wang, B.-Y., Lü, G., Li, C.-L., Yuan, L.-Y., Xu, R., et al. (2014). Operating principles and detection characteristics of the Visible and Near-Infrared Imaging Spectrometer in the Chang'e-3. *Research in Astronomy and Astrophysics*, *14*(12), 1567–1577. https://doi.org/10.1088/1674-4527/14/12/006

Head, J. W., Murchie, S., Mustard, J. F., Pieters, C. M., Neukum, G., McEwen, A., et al. (1993). Lunar impact basins: New data for the western limb and far side (Orientale and South Pole-Aitken basins) from the first Galileo flyby. *Journal of Geophysical Research*, *98*(E9), 17,149–17,181. https://doi.org/10.1029/93JE01278

Huang, J., Xiao, L., He, X., Qiao, L., Zhao, J., & Li, H. (2011). Geological characteristics and model ages of Marius Hills on the Moon. *Journal of Earth Science*, *22*(5), 601–609. https://doi.org/10.1007/s12583-011-0211-8

Jia, Y. Z., Zou, Y. L., Xue, C. B., Ping, J. S., Yan, J., & Ning, Y. M. (2018). Scientific objectives and payloads of Chang'E-4 Missionormalsize [in Chinese]. *Chinese Journal of Space Science*, *38*(1), 118–130.

Jolliff, B. L., Shearer, C. K., Papanastassiou, D. A., Alkalai, L., & Team, M. (2010). MOONRISE: South Pole-Aitken Basin sample return mission for solar system science. In Annual Meeting of the Lunar Exploration Analysis Group (Vol. 1595, p. 31).

Kato, M., Sasaki, S., & Takizawa, Y. (2010). The Kaguya mission overview. *Space Science Reviews*, *154*(1–4), 3–19. https://doi.org/10.1007/s11214-010-9678-3

Klima, R. L., Pieters, C. M., Boardman, J. W., Green, R. O., Head, J. W., Isaacson, P. J., et al. (2011). New insights into lunar petrology: Distribution and composition of prominent low-Ca pyroxene exposures as observed by the Moon Mineralogy Mapper ($M^3$). *Journal of Geophysical Research*, *116*, E00G06. https://doi.org/10.1029/2010JE003719

Klima, R. L., Pieters, C. M., & Dyar, M. D. (2007). Spectroscopy of synthetic Mg-Fe pyroxenes I: Spin-allowed and spin-forbidden crystal field bands in the visible and near-infrared. *Meteoritics & Planetary Science*, *42*(2), 235–253.

Ling, Z., Jolliff, B. L., Wang, A., Li, C., Liu, J., Zhang, J., et al. (2015). Correlated compositional and mineralogical investigations at the Chang' e-3 landing site. *Nature Communications*, *6*(1), 8880. https://doi.org/10.1038/ncomms9880

Losiak, A., Wilhelms, D., Byrne, C., Thaisen, K., Weider, S., Kohout, T., et al. (2009). A new lunar impact crater database. Paper presented at the Lunar and Planetary Science Conference.

Lucchitta, B. K. (1977). Crater clusters and light mantle at the Apollo 17 site: A result of secondary impact from Tycho. *Icarus*, *30*(1), 80–96. https://doi.org/10.1016/0019-1035(77)90123-3

Martinot, M., Besse, S., Flahaut, J., Quantin-Nataf, C., Lozac'h, L., & Westrenen, W. V. (2018). Mineralogical diversity and geology of Humboldt crater derived using Moon Mineralogy Mapper data. *Journal of Geophysical Research: Planets*, *123*, 612–629. https://doi.org/10.1002/2017JE005435

McEwen, A. S., & Bierhaus, E. B. (2006). The importance of secondary cratering to age constraints on planetary surfaces. *Annual Review of Earth and Planetary Sciences*, *34*(1), 535–567. https://doi.org/10.1146/annurev.earth.34.031405.125018

McGetchin, T. R., Settle, M., & Head, J. (1973). Radial thickness variation in impact crater ejecta: Implications for lunar basin deposits. *Earth and Planetary Science Letters*, *20*(2), 226–236. https://doi.org/10.1016/0012-821X(73)90162-3

Melosh, H. J. (1989). *Impact cratering: A geologic process*. Research supported by NASA. New York, Oxford Univ. Press (*Oxford Monographs on Geology and Geophysics*, No. 11), 253 p., 11.

Melosh, H. J., Kendall, J., Horgan, B., Johnson, B., Bowling, T., Lucey, P., & Taylor, G. (2017). South Pole–Aitken basin ejecta reveal the Moon's upper mantle. *Geology*, *45*(12), 1063–1066. https://doi.org/10.1130/G39375.1

Michael, G. G., Kneissl, T., & Neesemann, A. (2016). Planetary surface dating from crater size-frequency distribution measurements: Poisson timing analysis. *Icarus*, *277*, 279–285. https://doi.org/10.1016/j.icarus.2016.05.019

Moriarty, D. P., & Pieters, C. M. (2018). The character of south pole - Aitken Basin: Patterns of surface and sub-surface composition. *Journal of Geophysical Research: Planets*, *123*, 729–747. https://doi.org/10.1002/2017JE005364

Moriarty, D. P., Pieters, C. M., & Isaacson, P. J. (2013). Compositional heterogeneity of central peaks within the South Pole-Aitken Basin. *Journal of Geophysical Research: Planets*, *118*, 2310–2322. https://doi.org/10.1002/2013JE004376

Morrison, D. A. (1998). Did a thick South Pole-Aitken Basin melt sheet differentiate to form cumulates? Lunar and Planetary Science Conference (Vol. 29).

Nakamura, R., Matsunaga, T., Ogawa, Y., Yamamoto, S., Hiroi, T., Saiki, K., et al. (2009). Ultramafic impact melt sheet beneath the South Pole–Aitken basin on the Moon. *Geophysical Research Letters*, *36*, L22202. https://doi.org/10.1029/2009GL040765

National Research Council (2007). The scientific context for exploration of the Moon. National Academies Press.

Neukum, G., Ivanov, B. A., & Hartmann, W. K. (2001). Cratering Records in the Inner Solar System in Relation to the Lunar Reference System. *Space Science Reviews*, *12*, 55–86. https://doi.org/10.1007/978-94-017-1035-0_3

Oberbeck, V. R. (1975). The role of ballistic erosion and sedimentation in lunar stratigraphy. *Reviews of Geophysics*, *13*(2), 337–362. https://doi.org/10.1029/RG013i002p00337

Oberbeck, V. R., Hörz, F., Morrison, R., Quaide, W., & Gault, D. (1975). On the origin of the lunar smooth-plains. *The Moon*, *12*(1), 19–54. https://doi.org/10.1007/BF02626332

Oberbeck, V. R., & Quaide, W. L. (1967). Estimated thickness of a fragmental surface layer of Oceanus Procellarum. *Journal of Geophysical Research*, *72*(18), 4697–4704. https://doi.org/10.1029/JZ072i018p04697

Ohtake, M., Haruyama, J., Matsunaga, T., Yokota, Y., Morota, T., & Honda, C. (2008). Performance and scientific objectives of the SELENE (KAGUYA) Multiband Imager. *Earth, Planets and Space*, *60*(4), 257–264. https://doi.org/10.1186/BF03352789

Ohtake, M., Uemoto, K., Yokota, Y., Morota, T., Yamamoto, S., Nakamura, R., et al. (2014). Geologic structure generated by large-impact basin formation observed at the South Pole-Aitken basin on the Moon. *Geophysical Research Letters*, *41*, 2738–2745. https://doi.org/10.1002/2014GL059478

Pasckert, J. H., Hiesinger, H., & van der Bogert, C. H. (2018). Lunar farside volcanism in and around the South Pole–Aitken basin. *Icarus*, *299*, 538–562. https://doi.org/10.1016/j.icarus.2017.07.023

Petro, N. E., & Pieters, C. M. (2006). Modeling the provenance of the Apollo 16 regolith. *Journal of Geophysical Research*, *111*, E09005. https://doi.org/10.1029/2005JE002559

Pieters, C., Head, J., Gaddis, L., Jolliff, B., & Duke, M. (2001). Rock types of South Pole-Aitken basin and extent of basaltic volcanism. *Journal of Geophysical Research*, *106*(E11), 28,001–28,022. https://doi.org/10.1029/2000JE001414

Pieters, C. M., Boardman, J., Buratti, B., Chatterjee, A., Clark, R., Glavich, T., et al. (2009). The Moon Mineralogy Mapper ($M^3$) on Chandrayaan-1. *Current Science*, 500–505.

Pieters, C. M., Head, J., Sunshine, J., Fischer, E., Murchie, S., Belton, M., et al. (1993). Crustal diversity of the Moon: Compositional analyses of Galileo solid state imaging data. *Journal of Geophysical Research*, *98*(E9), 17,127–17,148. https://doi.org/10.1029/93JE01221

Pieters, C. M., Tompkins, S., Head, J. W., & Hess, P. C. (1997). Mineralogy of the mafic anomaly in the South Pole-Aitken Basin: Implications for excavation of the lunar mantle. *Geophysical Research Letters*, *24*(15), 1903–1906. https://doi.org/10.1029/97GL01718

Potter, R. W. K., Collins, G. S., Kiefer, W. S., McGovern, P. J., & Kring, D. A. (2012). Constraining the size of the South Pole-Aitken basin impact. *Icarus*, *220*(2), 730–743. https://doi.org/10.1016/j.icarus. 2012.05.032

Quaide, W. L., & Oberbeck, V. R. (1968). Thickness determinations of the lunar surface layer from lunar impact craters. *Journal of Geophysical Research*, *73*(16), 5247–5270. https://doi.org/10.1029/JB073i016p05247

Robinson, M. S., Brylow, S. M., Tschimmel, M., Humm, D., Lawrence, S. J., Thomas, P. C., et al. (2010). Lunar Reconnaissance Orbiter Camera (LROC) instrument overview. *Space Science Reviews*, *150*(1–4), 81–124. https://doi.org/10.1007/s11214-010-9634-2

Sharpton, V. L. (2014). Outcrops on lunar crater rims: Implications for rim construction mechanisms, ejecta volumes and excavation depths. *Journal of Geophysical Research: Planets*, *119*, 154–168. https://doi.org/10.1002/2013JE004523

Smith, D. E., Zuber, M. T., Neumann, G. A., Lemoine, F. G., Mazarico, E., Torrence, M. H., et al. (2010). Initial observations from the lunar orbiter laser altimeter (LOLA). *Geophysical Research Letters*, *37*, L18204. https://doi.org/10.1029/2010GL043751

Soderblom, L. A. (1970). A model for small-impact erosion applied to the lunar surface. *Journal of Geophysical Research*, *75*(14), 2655–2661. https://doi.org/10.1029/JB075i014p02655

Spudis, P. D., Gillis, J. J., & Reisse, R. A. (1994). Ancient multiring basins on the Moon revealed by Clementine laser altimetry. *Science*, *266*(5192), 1848–1851. https://doi.org/10.1126/science.266.5192.1848

Staid, M. I., Pieters, C. M., Besse, S., Boardman, J., Dhingra, D., Green, R., et al. (2011). The mineralogy of late stage lunar volcanism as observed by the Moon Mineralogy Mapper on Chandrayaan-1. *Journal of Geophysical Research*, *116*, E00G10. https://doi.org/10.1029/2010JE003735

Stöffler, D., Gault, D., Wedekind, J., & Polkowski, G. (1975). Experimental hypervelocity impact into quartz sand: Distribution and shock metamorphism of ejecta. *Journal of Geophysical Research*, *80*(29), 4062–4077. https://doi.org/10.1029/JB080i029p04062

Stuart-Alexander, D. E. (1978). *Geologic map of the central far side of the Moon*. Washington, DC: US Geological Survey.

Uemoto, K., Ohtake, M., Haruyama, J., Matsunaga, T., Yamamoto, S., Nakamura, R., et al. (2017). Evidence of impact melt sheet differentiation of the lunar South Pole-Aitken basin. *Journal of Geophysical Research: Planets*, *122*, 1672–1686. https://doi.org/10.1002/2016JE005209

Vaughan, W. M., & Head, J. W. (2014). Impact melt differentiation in the South Pole-Aitken basin: Some observations and speculations. *Planetary and Space Science*, *91*, 101–106. https://doi.org/10.1016/j.pss.2013.11.010

Weitz, C. M., & Head, J. W. (1999). Spectral properties of the Marius Hills volcanic complex and implications for the formation of lunar domes and cones. *Journal of Geophysical Research*, *104*(E8), 18,933–18,956. https://doi.org/10.1029/1998JE000630

Wilhelms, D. E., Howard, K. A., & Wilshire, H. G. (1979). Geologic map of the south side of the Moon.

Wilhelms, D. E., John, F., & Trask, N. J. (1987). The geologic history of the Moon.

Wu, W. R., Wang, Q., Tang, Y. H., Yu, G. B., Liu, J. Z., Zhang, W., et al. (2017). Design of Chang'E-4 lunar farside soft-landing mission (in Chinese). *Journal of Deep Space Exploration*, *4*(2), 111–117.

Xiao, L., Zhu, P., Fang, G., Xiao, Z., Zou, Y., Zhao, J., et al. (2015). A young multilayered terrane of the northern Mare Imbrium revealed by Chang'E-3 mission. *Science*, *347*(6227), 1226–1229. https://doi.org/10.1126/science.1259866

Xiao, Z. (2016). Size-frequency distribution of different secondary crater populations: 1. Equilibrium caused by secondary impacts. *Journal of Geophysical Research, Planets*, *121*, 2404–2425. https://doi.org/10.1002/2016JE005139

Xie, M., & Zhu, M.-H. (2016). Estimates of primary ejecta and local material for the Orientale basin: Implications for the formation and ballistic sedimentation of multi-ring basins. *Earth and Planetary Science Letters*, *440*, 71–80. https://doi.org/10.1016/j.epsl.2016.02.012

Yingst, R., Chuang, F., Berman, D., & Mest, S. (2017). Geologic Mapping of the Planck Quadrangle of the Moon (LQ-29). Paper presented at the Lunar and Planetary Science Conference.

Yingst, R. A., & Head, J. W. (1997). Volumes of lunar lava ponds in South Pole-Aitken and Orientale basins: Implications for eruption conditions, transport mechanisms, and magma source regions. *Journal of Geophysical Research*, *102*(E5), 10,909–10,931. https://doi.org/10.1029/97JE00717

Yingst, R. A., & Head, J. W. (1999). Geology of mare deposits in South Pole-Aitken basin as seen by Clementine UV/VIS data. *Journal of Geophysical Research*, *104*(E8), 18,957–18,979. https://doi.org/10.1029/1999JE900016

Zhang, H., Yang, Y., Yuan, Y., Jin, W., Lucey, P. G., Zhu, M. H., et al. (2015). In situ optical measurements of Chang'E-3 landing site in Mare Imbrium: 1. Mineral abundances inferred from spectral reflectance. *Geophysical Research Letters*, *42*, 6945–6950. https://doi.org/10.1002/2015GL065273