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Key Points:

- We obtain a direct measurement of density of impact craters ≥1 km ($N(1)$ value) of the Chang'e-5 mare unit as $(1.696 \pm 0.221) \times 10^{-3}$ km^{-2}
- The Chang'e-5 mare basalts are estimated as ~1.3–2.7 Ga old in various lunar chronologies, younger than all collected Apollo/Luna basalts
- Our $N(1)$ value can be combined with radio-isotopic ages of Chang'e-5 samples for a recalibration of lunar crater chronology

Supporting Information:

Supporting Information may be found in the online version of this article.

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Cratering Records in the Chang'e-5 Mare Unit: Filling the "Age Gap" of the Lunar Crater Chronology and Preparation for Its Recalibration

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Abstract The Moon is the cornerstone for dating planetary surfaces as it is the only planetary body that has been sampled multiple times from multiple places. The major deficiencies of the lunar crater chronology function are the somewhat limited number of calibration points and data gaps, especially in the ~1–3 Ga segment. China's Chang'e-5 mission recently returned samples from a young nearside mare, whose age is estimated to be in that age gap, providing a long-awaited opportunity for recalibrating the lunar chronology. Here, we report a direct density measurement of impact craters ≥1 km in diameter of Chang'e-5 mare unit, as $(1.696 \pm 0.221) \times 10^{-3}$ km^{-2}. The Chang'e-5 mare deposits are estimated as ~1.3–2.7 Ga old in various lunar chronologies, younger than all collected Apollo/Luna basalts. Accurate radio-isotopic ages of Chang'e-5 samples can be combined with our crater density measurement for a recalibration of lunar chronology.

Plain Language Summary Measuring the size and number of surface impact craters is the primary technique for dating lunar and planetary surfaces remotely. This technique relies on calibration points provided by sample return missions. The Earth's Moon is the only extraterrestrial body for which samples have been collected from multiple locations, enabling the calibration of cratering rates in the inner solar system and dating surfaces not only on the Moon, but also on Mercury, Venus, and Mars. Drawbacks of this technique are the somewhat limited number of calibration points and data gaps in the ~1–3 billion years segment. The basalt samples recently returned by China's Chang'e-5 mission likely lie in such gaps and provide an opportunity to recalibrate lunar crater chronology. In this work, we measure directly the density of impact craters ≥1 km on the basalt unit across the Chang'e-5 sampling site. From our measurements, the Chang'e-5 basaltic deposits are estimated as ~1.3–2.7 billion years old, younger than all lunar basalts previously returned by Apollo and Luna missions. Our results can be combined with the accurate ages of Chang'e-5 samples measured in Earth laboratory for a recalibration of lunar impact flux and improvement of the crater counting dating technique.

1. The Lunar Crater Chronology: The Cornerstone for Dating Planetary Surfaces in the Inner Solar System

Impact crater size-frequency distribution (SFD) analysis is the most known tool to date lunar and planetary surface remotely. The principle of cratering record as a chronometer is twofold: (a) the accumulation of impact craters of a specified size on a given surface is temporally cumulative and (b) the crater density has been correlated with radio-isotopic ages of rocks from the same surface unit. This crater density-age correlation is a crater chronology function. The Moon remains the only extraterrestrial world for which samples have been collected from multiple well-known locations, enabling the calibration of the lunar crater chronology. Through theoretical extrapolations, the lunar crater chronology is translated to Mercury, Venus, and Mars. Therefore, the Moon serves as the "Rosetta Stone" for dating planetary surface remotely (e.g., Fassett, 2016; Stöffler et al., 2006).

Uncertainties and complexities, however, persist in the lunar crater chronology function. A major part of these uncertainties comes from the limited number ($n = \sim 10$) of calibration points (crater density-age data pairs). Significant segments of the lunar chronology function are not constrained by sample data, and are thus purely interpolated. In particular, no returned samples tied to a specific surface terrain have ages of ∼1–3 Ga. As a consequence, various crater chronologies would give very different ages from the same surface crater density value in this age range, with age disparities up to ∼1 Ga (Robbins, 2014). Newly returned lunar samples from this "age gap" are much needed (e.g., Draper et al., 2021; van der Bogert & Hiesinger, 2020).

In December 2020, China's Chang'e-5 mission successfully returned lunar samples from a young mare in the northeastern Oceanus Procellarum. Crater SFD analyses suggest that the mare unit across the Chang'e-5 landing site is ∼1–2 Ga old (e.g., Hiesinger et al., 2003; Qian, Xiao, Wang, et al., 2021), much younger than all current lunar basalt samples and among the youngest surface maria on the Moon (Qiao et al., 2021), showing its significant scientific potential for characterizing the late-stage lunar volcanism. More importantly, this age lies right in the age gap of the existing calibration points of lunar crater chronology. Laboratory high-precision radio-isotopic dating results of the Chang'e-5 samples will be invaluable in recalibrating the lunar crater chronology, which is also the cornerstone for dating planetary surfaces in the inner solar system.

The establishment of a new control point of the lunar chronology requires accurate measurements of both sample ages and the size frequency of impact craters superposed on the surface geological units represented by the returned samples. It turns out that both procedures suffer from complications and uncertainties. For instance, it is very likely that multiple different ages can be measured from a same sample or different samples from the Chang'e-5 sample collections. Determining which data directly date the age of the geological unit is challenging and may take years or even decades of analyses (e.g., Stöffler et al., 2006).

In this contribution, we focus on the lunar surface cratering record part of a recalibration effort of lunar chronology function. We employ the latest high-resolution imaging and spectroscopic data sets to (a) define the extent of geological units represented by the Chang'e-5 samples, and then (b) measure directly the density of impact craters ≥1 km in diameter (the $N(1)$ value) superposed on the Chang'e-5 mare unit (see analysis data and methods in Text S1 of Supporting Information S1). We then discuss the constrains on the age of Chang'e-5 mare units from our updated crater SFD result for various lunar chronologies and the implications for the recalibration of lunar chronology. Our accurate crater population measurement can be combined with the forthcoming radio-isotopic dating results of Chang'e-5 samples and allows a redefinition of lunar crater chronology.

2. Results

A spectrally homogeneous mare unit with a surface area of 34,797 km^2 is defined surrounding the Chang'e-5 sampling site (Figure 1). The east boundary is based on the mare-highland contact delineated by Nelson et al. (2014). The south and west boundaries are roughly consistent with that of the Em4 unit in Qian, Xiao, Head, et al. (2021), though with some minor variations. Two small patches surrounding Mons Hua, while included in the P58 mare of Hiesinger et al. (2003) and Em4 mare of Qian, Xiao, Head, et al. (2021), are not incorporated here, as their colors in spectral color ratio map are closer to maria in Sinus Roris in the north. We also exclude a relatively extensive mare near to Mons Rümker that was incorporated in the P58 mare, consistent with the definition of Qian, Xiao, Head, et al. (2021).

In the mare unit surrounding the Chang'e-5 landing site, 59 superposed impact craters ≥1 km in diameter are identified (Figure 2). Of them, 41 craters are 1–1.5 km in diameter, 13 are 1.5–2 km, 4 are 2–5 km, and only one is >5 km. Thirteen circle depressions are excluded as they are interpreted as preexisting partially resurfaced impact craters, per their unusual geomorphologies, including very subtle topographic relief and flooding/embaying by younger lava flows (Figure S2 in Supporting Information S1). The raw crater population data are presented in a reverse cumulative SFD plot (Figure 2b) without any binning to retain as much information as possible. The crater SFD on the Chang'e-5 mare has a cumulative slope of −2.7, suggesting that craters ≥1 km are not in equilibrium (e.g., Gault, 1970; Xiao & Werner, 2015). A relative or R-plot is also presented using a bin size of the fourth-root-2 (Figure 2c). We also perform a "Z-statistic" test and find that

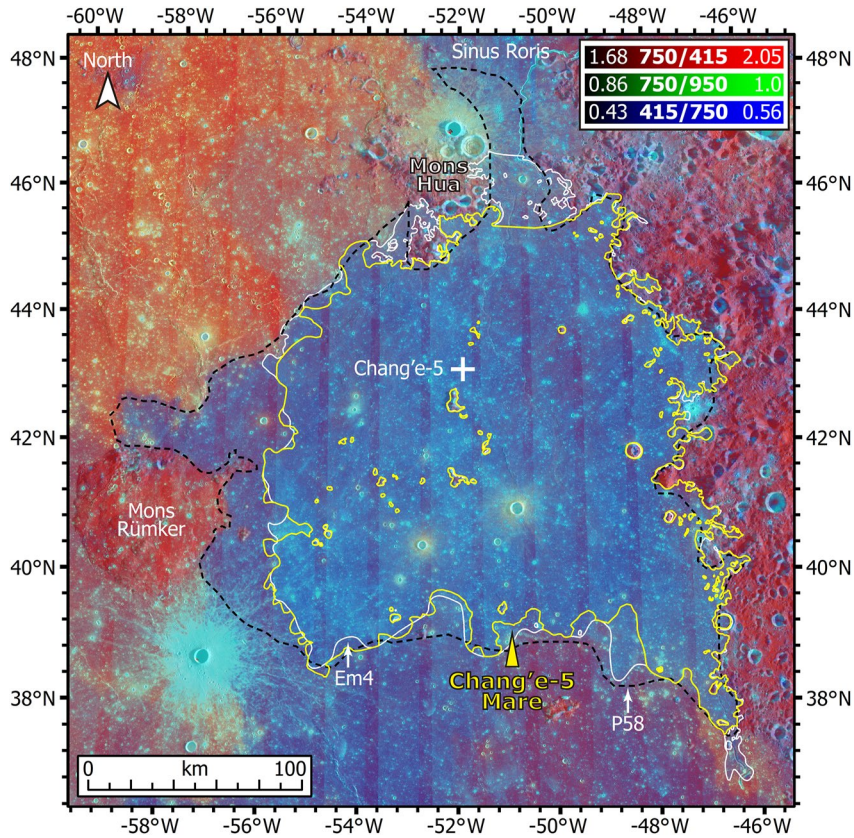


Figure 1. The definition of mare unit (yellow polygons) surrounding the Chang'e-5 landing site (white cross) using a Kaguya MI color ratio composite map. The P58 (Hiesinger et al., 2003) and Em4 (Qian, Xiao, Head, et al., 2021) units by are outlined by dashed black and white polygons, respectively. The background map is the LROC WAC mosaic. All maps are projected into a Mollweide equal-area projection, with a central meridian of 51.8°W.

kilometer-scale craters on the Chang'e-5 mare are spatially random (Text S2 in Supporting Information S1). From the surface area of the Chang'e-5 mare unit and the crater population analyzed above, we obtain a direct calculation of the $N(1)$ value $(1.696 \pm 0.221) \times 10^{-3}$ km^{-2}. In addition, eight craters are observed to be surrounded by obvious clusters of smaller secondaries (Figure S5 in Supporting Information S1). Excluding these probable secondaries and the neighboring secondary fields (Figure S6 in Supporting Information S1) would result in a smaller $N(1)$ value of $(1.504 \pm 0.211) \times 10^{-3}$ km^{-2}. Whereas, we find that these craters are much larger than their adjacent clusters of secondaries and some are characterized by well-developed and symmetrical ejecta blankets. These observations argue against a secondary origin for them. We have included them as primary superposed craters in the following analyses.

A routine procedure when analyzing crater populations is fitting the crater SFD data with crater production functions, most commonly those of Neukum et al. (NPF), Hartmann (HPF), and Marchi et al. (MPF) (Hartmann, 2005; Marchi et al., 2009; Neukum et al., 2001). We fit the crater population of the Chang'e-5 mare to the NPF, HPF, and MPF, and derive $N(1)$ values of $(1.789 \pm 0.223) \times 10^{-3}$, $(1.777 \pm 0.223) \times 10^{-3}$, and $(1.726 \pm 0.225) \times 10^{-3}$ km^{-2}, respectively (Table 1).

3. Discussion

3.1. Crater SFD Analysis Results: Comparison With Previous Studies

There have been multiple crater population studies related to the Chang'e-5 mare unit defined in this work (Figure 1; Hiesinger et al., 2003; Morota et al., 2011; Robbins, 2019), especially after the selection of the Chang'e-5 landing area in northern Oceanus Procellarum (e.g., Jia et al., 2020; Qian et al., 2018). Among these previous studies, three have released their crater database publicly (Qian et al., 2018; Robbins, 2019;

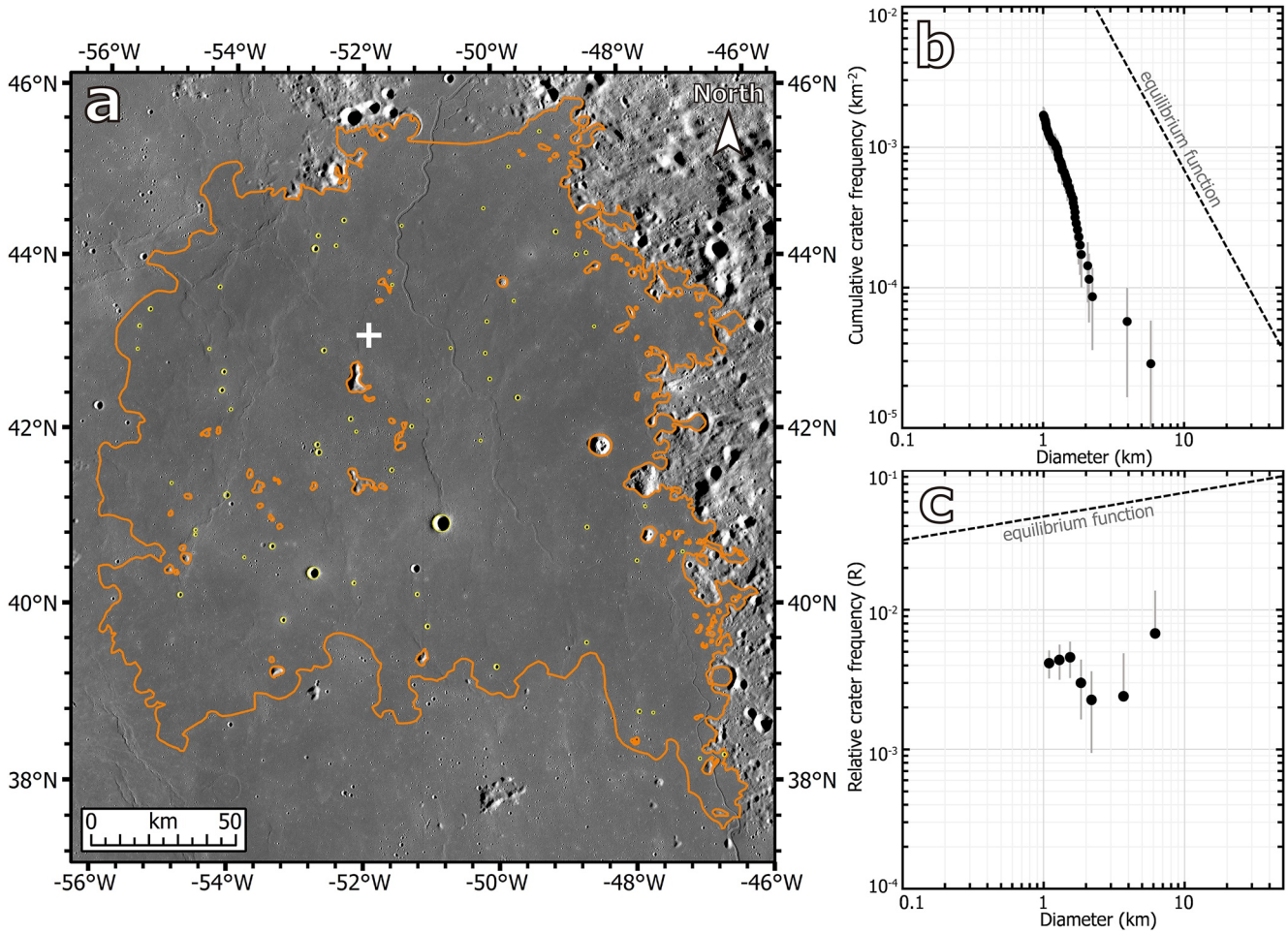


Figure 2. Crater size-frequency distribution (SFD) measurements for the mare unit (orange polygon) surrounding the Chang'e-5 landing site (white cross): (a) spatial distribution of craters ≥1 km in diameter (yellow circles) and the (b) cumulative and (c) relative (*R*) size-frequency distribution plots. The dashed lines are the lunar equilibrium function from Hartmann (1984).

Wu et al., 2018), while others reported mainly the final crater SFD results (e.g., *N*(1) values). We have compared each crater in our catalog with that of the three studies, and found that our measurements are consistent with previous works (Text S3 in Supporting Information S1), with disparities well within the typical investigator-to-investigator differences (Robbins et al., 2014).

The *N*(1) results, however, diverge a lot among different studies (Table 1). Among these derived *N*(1) values, Qian et al. (2018) reported the smallest values, close to Hiesinger et al. (2003) from old Lunar Orbiter image data, while Qian, Xiao, Head, et al. (2021) and Qian, Xiao, Wang, et al. (2021) updated their results later to around 1.3×10^{-3} km^{-2}. Xu et al. (2021) obtained an almost identical *N*(1) value with Wu et al. (2018), and these two studies both measured craters on LROC NAC images for smaller count areas. Morota et al. (2011) got *N*(1) values around 1.6×10^{-3} km^{-2} for the P58 unit. Jia et al. (2020) calculated a greater *N*(1) value of 1.74×10^{-3} km^{-2} for the Em4 unit. Our directly measured *N*(1) value is greater than most previous studies, while slightly smaller than that of Jia et al. (2020). Besides, Giguere et al. (2021) also conducted a crater SFD analysis for the Chang'e-5 region. From their ~3.0 Ga age result, an *N*(1) value around of 2.6×10^{-3} km^{-2} can be projected under the Neukum et al. (2001) chronology, also larger than our value.

The exact reason for the range of *N*(1) values determined from a certain lunar surface unit among different studies, with a span by a factor of ~2.5, is not well known and likely a combination of the variations in the sizes and locations of the crater population working area (e.g., Hiesinger et al., 2003), image data, and procedures of crater counting and analysis (e.g., Giguere et al., 2021). Notwithstanding these disparities, this work provides a direct

Table 1
Summary Data of Crater SFD Results From the Chang'e-5 Mare Unit, and Comparison With Different Count Areas From Previous Studies

	$N(1)$ (10^{-3} km^{-2})	Crater counting area (km^2)	Crater counting images	Crater diameter for $N(1)$ calculation	# of craters for $N(1)$ calculation	$N(1)$ calculation production function
This work	1.696 (±0.221)	34,797	Kaguya TC (10 m/pixel)	≥1 km	59	Direct measurement
	1.789 (±0.223)					Neukum et al. (2001)
	1.777 (±0.223)					Hartmann (2005)
	(1.726 (±0.225)					Marchi et al. (2009)
Hiesinger et al. (2003)	1.11 (+0.17/−0.21)	2,551	Lunar Orbiter (60 m/pixel)	—	—	Neukum and Ivanov (1994)
Morota et al. (2011)	1.60 (±0.10)	2801.2	Kaguya TC	≥250 m (?)	—	Neukum (1983)
	1.55 (±0.09)					Ivanov et al. (2001)
Qian et al. (2018)	1.02	—	Kaguya TC	≥200 m	1,580	Neukum et al. (2001)
Wu et al. (2018)	1.24	5,607	LROC NAC (~1 m/pixel)	≥500 m	77	Neukum et al. (2001)
Jia et al. (2020)	1.74	17,074	LROC NAC	≥200 m	6,455	Neukum et al. (2001)
Qian, Xiao, Head, et al. (2021)	1.28	29,600	Kaguya TC	≥~200 m	3,268	Neukum et al. (2001)
Qian, Xiao, Wang, et al. (2021)	1.34	99.4	LROC NAC	160–2,000 m	101	Neukum et al. (2001)
	1.27					Neukum (1983)
Xu et al. (2021)	1.25	2,361	LROC NAC	≥~150 m	313	Neukum et al. (2001)

measurement of the $N(1)$ value of the mare unit surrounding the Chang'e-5 site. This value is model-independent and free of the uncertainties inherent in any crater production function, which is likely one of the major reasons that previous studies had different $N(1)$ values. Moreover, the determination of lunar crater production function is still in intense debate and possibly varies with time (e.g., Marchi et al., 2009; Strom et al., 2005. In this sense, our directly measured $N(1)$ value, $(1.696 \pm 0.221) \times 10^{-3}$ km^{-2}, is relatively more reliable than previous results.

3.2. Constraint on the Age of Mare Basalts Returned by Chang'e-5 Mission

While it is a fundamental consensus that the continued accumulation of lunar impact craters cause larger spatial densities of craters of a given size (e.g., the $N(1)$ value) on older surfaces (relative ages), converting the crater SFD into absolute ages relies on the lunar crater chronology and suffers from many uncertainties and complexities. Due to many limitations, especially the limited number of calibration points, a number of solutions have been proposed for the lunar crater chronology, and the discrepancies among these models remains appreciable (Figure 3). While the chronology curve by Neukum et al. (2001), which is based on crater measurements on over half century-old Apollo orbital photographs, is utilized by most studies (e.g., Jia et al., 2020; Qian, Xiao, Wang, et al., 2021) and confirmed by recent LROC data studies (Iqbal et al., 2019, 2020), a number of new lunar chronologies have also been established (Le Feuvre & Wieczorek, 2011; Marchi et al., 2009; Robbins, 2014). A certain crater SFD measurement would project various absolute ages with meaningful divergences on different lunar chronology curves (Figure 3). In addition, given the very shallow slope on the middle segment (~1–3 Ga) of all these lunar chronology curves, a small variation in the crater SFD would project an appreciable age difference, let alone the range of crater SFD measurements of Chang'e-5 mare reported previously (Table 1).

What is the chronological characteristic of the Chang'e-5 mare deposits derived from our updated estimation of impact crater SFD? We plot our directly measured $N(1)$ value as a horizontal line in the $N(1)$-age coordinate system and see how it intersected with the multiple lunar crater chronology curves (Figure 3). We find that the derived ages vary from ~1.3 to ~2.7 Ga, and can be categorized into three groups: the Robbins (2014) and Marchi et al. (2009) chronologies infer the youngest ages around 1.3–1.4 Ga, the Neukum et al. (2001) and Le Feuvre and Wieczorek (2011) chronologies report ages around 2.0–2.1 Ga, and the Hartmann et al. (2007) chronology derives the oldest age of ~2.7 Ga. We expect that the radio-isotopic ages of the Chang'e-5 basalt samples are very likely in the range between 1.3 and 2.7 Ga. These ages all lie in

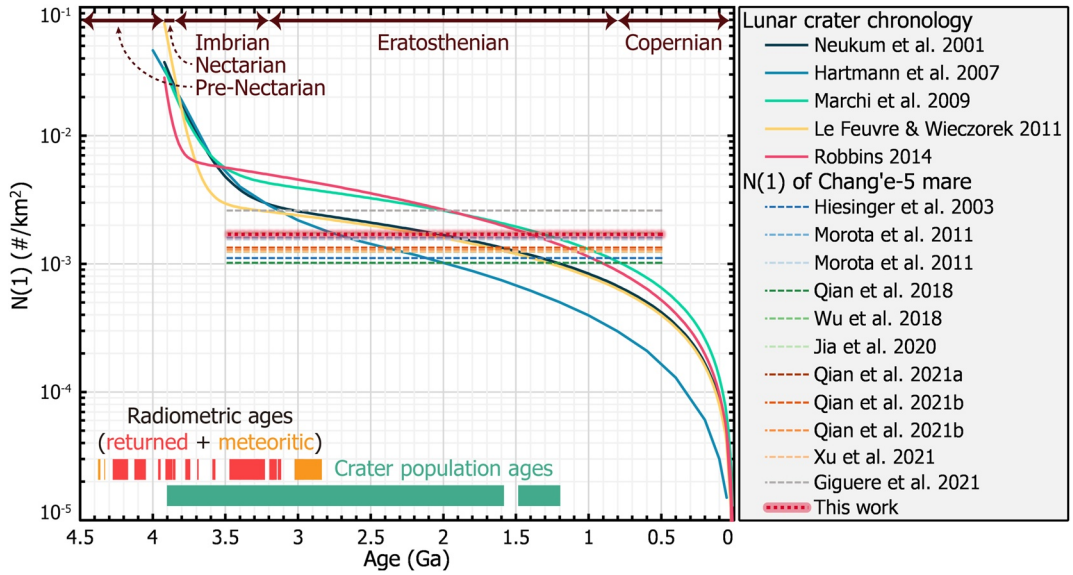


Figure 3. The crater population ages of Chang'e-5 mare basalt determined from various lunar chronology curves (solid lines). The *N*(1) values reported by this and previous works are plotted as horizontal dotted lines of red and other colors, respectively. Radio-isotopic ages of returned and meteoritic lunar basalts (from Tartèse et al. [2019]) and crater population ages of mare units (Qiao et al., 2020) are shown at the bottom. Lunar chronostratigraphic system is shown at the top (Stöffler & Ryder, 2001).

the Eratosthenian period and obviously postdate the peak phase of mare volcanism ca. 3.3–3.8 Ga ago (e.g., Qiao et al., 2020). The basalts returned by the Chang'e-5 mission will provide a remarkable opportunity for an in-depth insight into the late-stage lunar volcanism. More importantly, these ages are younger than all lunar basalts previously returned by the Apollo and Luna missions (as young as ~3.1 Ga; Snape et al., 2018), and lies in the age gap of calibration points of the lunar chronology function (~0.8–3.1 Ga). The Chang'e-5 basalts will provide long-awaited data for recalibrating the lunar crater chronology function.

3.3. Implications for the Recalibration of Lunar Crater Chronology Function

The establishment of the lunar crater chronology model or a specific calibration point is at least a two-part job between crater densities of lunar surface units and radio-isotopic ages of returned samples measured in Earth laboratory, and it requires multidisciplinary collaboration. Either part, however, faces many inherent difficulties and appreciable disparities among different researchers. The radio-isotopic dating analysis of lunar samples itself is very complicated on multiple levels (e.g., Stöffler & Ryder, 2001; Tartèse et al., 2019). More challenging is correlating a radio-isotopically measured age with a specific geological unit on the lunar surface. Even for the relatively straightforward case of a volcanic mare basalt rock, relating a tiny sample to an areally very extensive (usually over 1,000 km^2) surface unit is not necessarily easy. Analysis experiences of Apollo/Luna samples found that a considerable range of radio-isotopic ages are often obtained from samples collected at a certain site, and it is challenging to determine which age best represents that of the surface unit (Stöffler & Ryder, 2001). It is no surprise that the age of a certain surface sampling site will be under debate for years or decades. The situation may be similar with the Chang'e-5 samples, albeit some preliminary radio-isotopic ages around 2.0 Ga have been recently reported (Che et al., 2021; Li et al., 2021).

One of the major drawbacks of existing lunar crater chronologies is the limited number of calibration points and apparent data gaps, especially in the ~1–3 Ga segment. Luckily, the age of the basalt samples collected by Chang'e-5, ranging between 1.3 and 2.7 Ga from crater measurements, lies right in that age gap. Incorporating the Chang'e-5 calibration point would be vital in narrowing down the uncertainties of lunar chronology model. While the ages of Chang'e-5 samples are still being analyzed, some implications can be achieved based on assumption studies. These practices can be quickly applied to the actual sample radio-isotopic dating results once available.

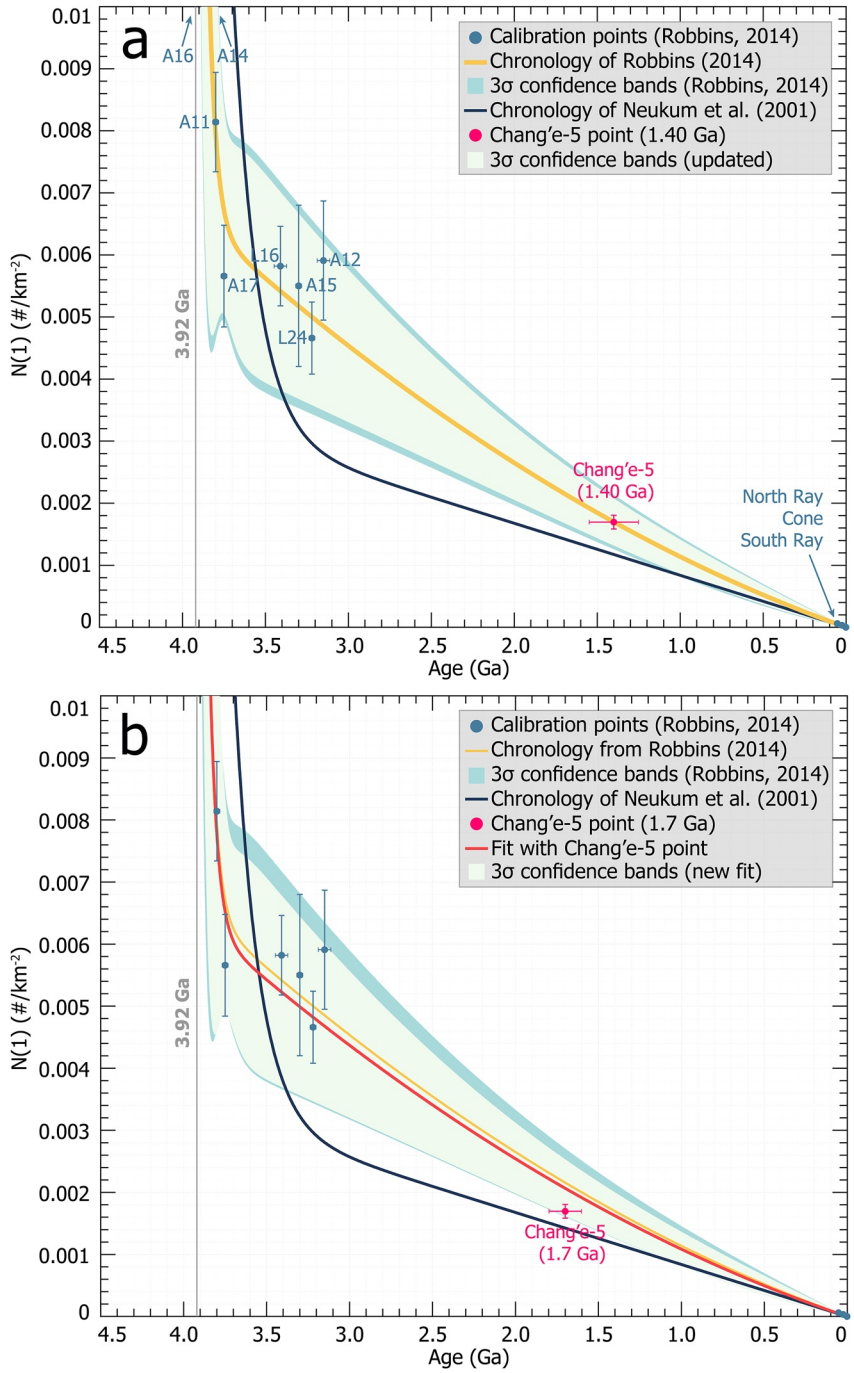


Figure 4. Assumption analyses on the refinement of lunar chronology function by incorporating the Chang'e-5 calibration point. (a) In one scenario, the age of Chang'e-5 samples (1.40 ± 0.15 Ga) is assumed to be close to that from the Robbins (2014) chronology. (b) In another scenario, the sample age is assumed to deviate from previously established lunar chronology curves (1.7 ± 0.1 Ga). The data of Apollo (A) and Luna (L) calibration points are from Robbins (2014). The $N(1)$ value of Chang'e-5 site is from this work (Table 1). The 3σ (±99.7%) confidence bands of chronology functions are overlaid.

One scenario, probably very optimistic, is that the sample age and surface crater SFD of Chang'e-5 locate very close to a certain lunar chronology curve, for instance, the Robbins (2014) chronology. In this case, adding a new calibration point in the ~1–3 Ga age gap would elevate the reliability of lunar chronology significantly. In the chronology of Robbins (2014), the ±3σ of crater counting ages ranges up to ~1.1 Ga in this

segment. We incorporate the direct $N(1)$ value of Chang'e-5 site (Table 1) and the 1.40 ± 0.15 Ga age from the Robbins (2014) chronology, and recalculate of the errors (Figure 4a). We find that the $\pm 3\sigma$ of crater population ages can be reduced by ~15% in the ~1–3 Ga segment (Figure S12 in Supporting Information S1), an impressive improvement for crater population dating analysis.

In another scenario, the radio-isotopic age of Chang'e-5 sample deviates from any crater chronology curve; this is probably the more likely case. Under this context, the Chang'e-5 site would provide crucial observational constraints on the ~1–3 Ga segment of lunar chronology function. We assume arbitrarily an age (e.g., 1.7 ± 0.1 Ga) for the Chang'e-5 basalts and fit a new chronology function as: $N(1) = 9.93 \times 10^{-41} \times \{\exp(22.56 \times T) - 1\} + 8.98 \times 10^{-4} \times T + 1.86 \times 10^{-4} \times T^2$ (Figure 4b; see the fitting details in Text S4 of Supporting Information S1). The newly fitted chronology generally goes below the established Robbins (2014) curve, showing that lunar surfaces are estimated to be younger from the new chronology function (Figure S13 in Supporting Information S1). While the new chronology intersects that of Neukum et al. (2001) at ~3.6 Ga, revealing that surfaces previously dated as <3.6 Ga old are younger by up to ~1 Ga (Figure S14 in Supporting Information S1). We address that this new chronology curve is from a simulation study using a discretionarily assumed sample age. The accurate radio-isotopic dating results of Chang'e-5 samples would enable a redefinition of lunar chronology function, especially in the middle part of lunar history.

4. Conclusions

We redelineate the mare unit, with a surface area of 34,797 km^2, represented by the Chang'e-5 returned samples, and measure superposed impact craters ≥1 km in diameter. Overall, 59 superposed impact craters are identified, which derive a direct measurement of $N(1)$ value as $(1.696 \pm 0.221) \times 10^{-3}$ km^{-2}. This value is free of the uncertainties inherent in any crater production function and thus relatively more reliable than previous studies.

From our direct measurement of the crater SFD, the mare basalt across the Chang'e-5 site is estimated as ~1.3–2.7 Ga old in various lunar chronologies, younger than all Apollo and Luna basalt samples. The Chang'e-5 samples will provide a remarkable opportunity for characterizing the late-stage lunar volcanism.

More importantly, the ages of Chang'e-5 basaltic samples very likely lie in the ~1–3 Ga age gap of calibration points of lunar crater chronology, the cornerstone for dating planetary surfaces remotely. We conduct assumption analyses on the refinement of lunar chronology function by incorporating the new calibration point provided by Chang'e-5. Our practice can be quickly applied to the actual radio-isotopic dating results of Chang'e-5 samples once available. This would provide a key constraint on the impact flux and geological evolution of the middle part of lunar history.

Data Availability Statement

Kaguya maps are archived at https://darts.isas.jaxa.jp/planet/pdap/selene. LROC images are available at https://pds-geosciences.wustl.edu/missions/lro/default.htm. The crater measurement data are accessible https://zenodo.org/record/5513730

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