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Article

Surface Ages in the Vicinity of the Chang'e-6 Landing Site

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Abstract: The samples from lunar farside have great significance for the study of the Moon, and even the solar system. Chang'e-6 landed successfully on the southern mare of the Apollo basin and returned ~2 kg samples from lunar farside. To provide a better understanding for the background of the returned samples, we conducted detailed crater size-frequency distribution (CSFD) measurements in the Chang'e-6 landing region, the southern mare of the Apollo basin. The southern mare is divided into western mare (W region) and eastern mare (E region), and then subdivided into five sub-units (W1, W2, W3, W4, W5) and three units (E1, E2, E3), respectively, according to the elevation, Ti and Fe abundances. Within the W2 and W5 region, more detailed sub-units were divided. The results show that the southern mare generally have two epochs, one of the Imbrian period and the other of the Eratosthenian period. The basalt eruption lasted for ~1.7 Ga, from 3.28 Ga of the eastern mare to 1.54 Ga of the western mare. W region is younger than E region, while the three units of E region has an age of ~3.2 Ga. The ages of the western mare basalts range from 2.98 Ga to 1.54 Ga, lasting for 1.4 Ga. It's worth noting that the age of the basalt at the Chang'e-6 sampling site is ~1.68 Ga, indicating the samples returned may include components with this very young age.

Keywords: Chang'e-6; CSFD measurements; absolute model age; Apollo basin

1. Introduction

Chang'e-6 is the first mission to sample from the lunar farside, which is designed to land on the southern mare of Apollo Basin, northeastern of the South Pole-Aitken (SPA) Basin (Figure 1) [18,51]. Chang'e-6 successfully landed on the lunar farside (153.978° W, 41.625°S) and returned ~2 kg (1935.3 g) samples, both scooped samples and a drilling core, on June 25th, 2024 [22]. The samples returned by Chang'e-6 have significant scientific values since they are the first samples returned from the lunar farside and also the first samples from the South Pole-Aitken (SPA) Basin. These samples may contribute to solving significant problems such as the genesis of the lunar dichotomy, volcanic activities and thermal history of the lunar farside and the formation time and process of the SPA basin [33,37,50]. Except for the local basalts, Chang'e-6 may return exotic materials outside the mare, including from Chaffee S crater [18,50]. Similar to the Chang'e-5 landing site, Chang'e-6 landing site consists of moderate-Ti basalts (4-6 wt.%) [37].

Determining the surface age of a region is a main part to understand the geologic history of a planet. In general, there are three ways to obtain the surface age: 1) the radioisotope age of the lunar

samples and meteorites. 2) the absolute model age by crater size-frequency distribution (CSFD) measurement. 3) the absolute age estimated by degradation of simple craters morphology.

Crater morphology is an indicator of the surface age. A huge amount of impactors impact on the lunar surface during its history. A fresh crater on the lunar surface is a relatively regular circle with obvious ejecta rays. As impactors continuously hit on the lunar surface, ejecta cover the other impact craters and the craters may overlap each other. Therefore, the impact crater morphology is changed. The crater rim is ruined and the inner part of the crater is filled by impact ejecta and the regular circle shape may be destroyed by the crater overlapping. Space weathering contributes to the disappearance of ejecta rays. The changing process of the crater morphology is called degradation. Boyce and Dial [3] and Craddock and Howard [5] estimated the surface age by the degradation of simple craters. This method assumes a consistent erosion rate across the lunar surface. However, the erosion rates are different in different regions and for different crater sizes because of the complex geology on the lunar surface. The incidence angle of image illumination may also affect the final results. Therefore, the absolute age derived by degradation has lots of uncertainties.

The radioisotope ages obtained from the meteorites or samples returned from lunar surface provide the most accurate results. Li et al. [21] concluded that the Chang'e-5 returned basalt has an age of 2030 ± 4 Ma by in-situ Secondary Ion Mass Spectrometry (SIMS) Pb-Pb analysis, which has extended the known duration of lunar volcanism by more than 800 million years. By analyzing the ^{40}Ar - ^{39}Ar of the impact-melting clasts in the meteorites, Cohen et al. [4] obtained ages of different rocks ranging from 2.43 Ga~ 4.12 Ga, deepening our understanding about crystallization sequence of lunar rocks. However, lunar samples and meteorites are precious and difficult to obtain and special minerals are required for the geochronology analysis. In addition, lunar meteorites may be contaminated on Earth, causing errors for the results of the isotope isochron dating analysis. It's hard to relate a meteorite age to a surface location since it's hard to determine where the meteorite originated. CSFD measurements is one of the best choices to determine surface ages since the lunar samples are limited.

Understanding the ages of the mare basalt is the first step to make further analysis for the returned samples by Chang'e-6. Previous studies have dated the southern mare and obtained different results. According to the 1:5000,000 scale geological map of the Apollo basin compiled by Ivanov et al. [17], southern mare was classified into Late Imbrian-aged dark plains. Orgel et al. [33] agreed with Ivanov et al. [17] and classified the southern mare into Imbrian mare basalt. Haruyama et al. [12] considered the southern mare as a uniform mare unit and derived an age of 2.44 Ga. However, the eastern and western part of the southern mare have different reflectance rates and Ti/Fe abundances, indicating two mare basalt units. Therefore, the results of Haruyama et al. [17] may represent the composite age of the two units. Pasckert et al. [34], Zeng et al. [51] and Qian et al. [37] divided the southern mare into two units (the western and eastern mare basalt). They obtained a similar age of the eastern part (3.45 Ga, [34]; 3.43, [51]; 3.34 Ga, [37]) but different ages of the western mare. Pasckert et al. [34] and Qian et al. [37] believed that the western mare basalt erupted shortly after the eastern mare basalt (3.31 Ga, [34]; 3.07 Ga, [37]). Zeng et al. [51] suggested that the western mare was ~1.0 billion years younger than the eastern mare. Yue et al. [50] obtained an age of 2.50 Ga of the western mare basalt.

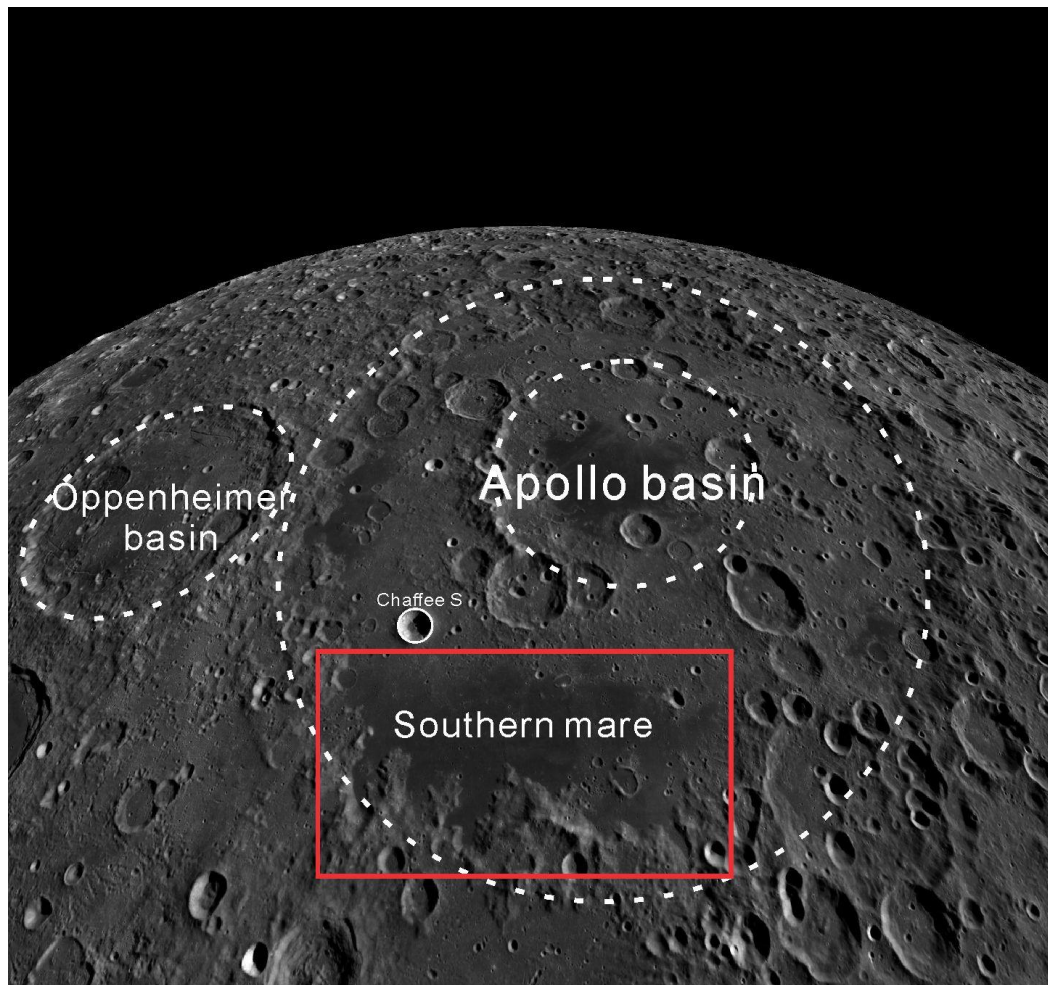


Figure 1. Oblique view of the Apollo basin downloads from QuickMap (<https://quickmap.lroc.asu.edu/>) based on the 100 m/pixel LROC WAC mosaic. The white dashed lines represent the basin rims. The southern mare of the Apollo basin is marked with red rectangle. The crater marked in white solid circle is the Chaffee S crater.

Previous studies failed to reach an agreement on the ages of the western mare basalt. Besides, the variations in compositions may indicate mare basalts of different ages [14,35,43]. We observed the uneven composition of the southern mare, especially western mare basalt, which may result in the different ages. Therefore, detailed crater size-frequency distribution (CSFD) measurements based on the detailed unit-divisions, which may help comprehensively understand the composition differences and ages of the southern mare, are needed.

In this study, we focus on the southern mare of the Apollo basin, the Chang'e-6 landing region, aiming to estimate the absolute model ages of the basalt. Firstly, we classified the basalt into two units according to the TiO_2 content and FeO content. Then, these units are divided into several sub-units using Digital Elevation Model (DEM) map. We counted the craters within each unit using Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) images and analyzed the population to get absolute model ages. Randomness analyses were applied to exclude poor quality data and better constrain the results. Our results may provide a further understanding of the Chang'e-6 landing site and its vicinity, such as the basalt evolution, and then provide a background geologic understanding for the experimental analysis of the Chang'e-6 samples.

2. Data and Methods

2.1. Data

A global mosaic created in June 2013 (https://astrogeology.usgs.gov/search/map/Moon/LRO/LROC_WAC/Lunar_LRO_LROC-WAC_Mosaic_global_100m_June2013) generated from the Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) provides us with global view with a spatial resolution of 100 m/pixel [39,44,46], using for geologic background analysis. A digital elevation model product (SLDEM2015) produced by merging the Lunar Orbiter Laser Altimeter (LOLA) data and Kaguya stereo-derived TC DEMs were used to analyze the topography of the southern mare [2]. The spatial resolution of the DEM product is ~59 m/pixel and the vertical resolution is ~3-4 m. The TiO₂ and FeO abundances were derived from datasets of WAC reflectance mosaic and Kaguya Multiband Imager (MI), respectively [11,40]. The spatial resolution of the TiO₂ abundance map is ~400 m/pixel and that of the FeO abundance map is ~60 m/pixel. The details used to calculate the TiO₂ and FeO contents can be found in Otake et al. [32] and Lemelin et al. [20], respectively.

LROC NAC images with a resolution <3 m were used as a basemap for crater mapping and measurements. Those high-resolution images were download from the PDS Geosciences Node Lunar Orbital Data Explorer website (<https://ode.rsl.wustl.edu/Moon/indexProductSearch.aspx>). The details for generating large area DOM can be found in Di et al. [8].

We use Arcgis to visualize and analyse the data used in this study.

2.2. Crater Size-Frequency Distribution Measurements

Estimating the absolute age of the planet's surface by calculating the crater density is an important technique for planetary geology [1]. The basic assumption of the CSFD measurements is that the impact craters form independently and randomly and that the rate of the crater formation is much less than its destruction rate [14]. Older regions have more craters than the younger regions per unit area. Based on the crater size-frequency distribution and the absolute radioisotope ages from lunar samples, previous studies established quantitative relationships between crater density and the absolute radioisotope ages of the geologic units, which can be used to deduce the absolute model ages of other unsampled units [29,30].

Neukum [29] and Neukum et al. [30] employed a polynomial function to describe the relationship between the crater diameter (D) and cumulative frequency (N_{cum}), that is the production function. The equation is as follows:

$$\log N_{cum} = a_0 + \sum_{k=1}^{11} a_k (\log D)^k$$

where a^k is the fit parameter. The production function is a simple curve on a log N_{cum} vs. log D plot.

Using the integrated LROC NAC images as the basemap, mapping the craters was done on the Arcgis platform. CraterTools toolkit was employed to manually map the craters since it's easy to locate the crater and measure the diameter [19]. A crater can be located with three points on the crater rim. The property list generated by Arcgis records the information about the longitude, the latitude and the diameter of the crater. With those information, fitting the absolute model ages (AMAs) via Poisson timing analysis and randomness analysis with 3000 iterations are carried out with the program Craterstats [24–26]. Production function and chronology function by Neukum [29] were employed. The regions containing secondary craters (crater chains and crater clusters), residual basin floor and wrinkle ridges/orthomorphies and the regions may be affected by the basin rims are excluded. We used the differential pattern to get an absolute model age. With differential pattern, we can better understand the partial resurfacing events.

3. Results

When the counting area is a uniform unit, the absolute model ages derived from the CSFD measurements are reasonable. For the southern mare of the Chang'e-6 landing region, it's obvious that the eastern and western mare have different reflectance rates. According to the elevation, the

titanium and iron abundances, we generally divided the southern mare into two units and more detailed units. Based on the units we divided, we made CSFD measurements and obtained ages for each unit.

3.1. *Mare Units*

The southern mares the largest mare basalt (~9329 km²) of the Apollo basin, locating on the southern part [37]. The southern mare is relatively flat with an average slope <8° [51]. The most obvious topography feature is the wrinkle ridge between the eastern mare basalt and the western part (Figure 2). Besides, another wrinkle ridge can be seen within the western mare basalt. Obvious crater clusters can be seen from WAC mosaic which are oriented north-south or northeast- southwest (Figure 2a). On the north part of the southern mare, some kipukas, the residual of the basin floor, are recognized and excluded from the crater counts.

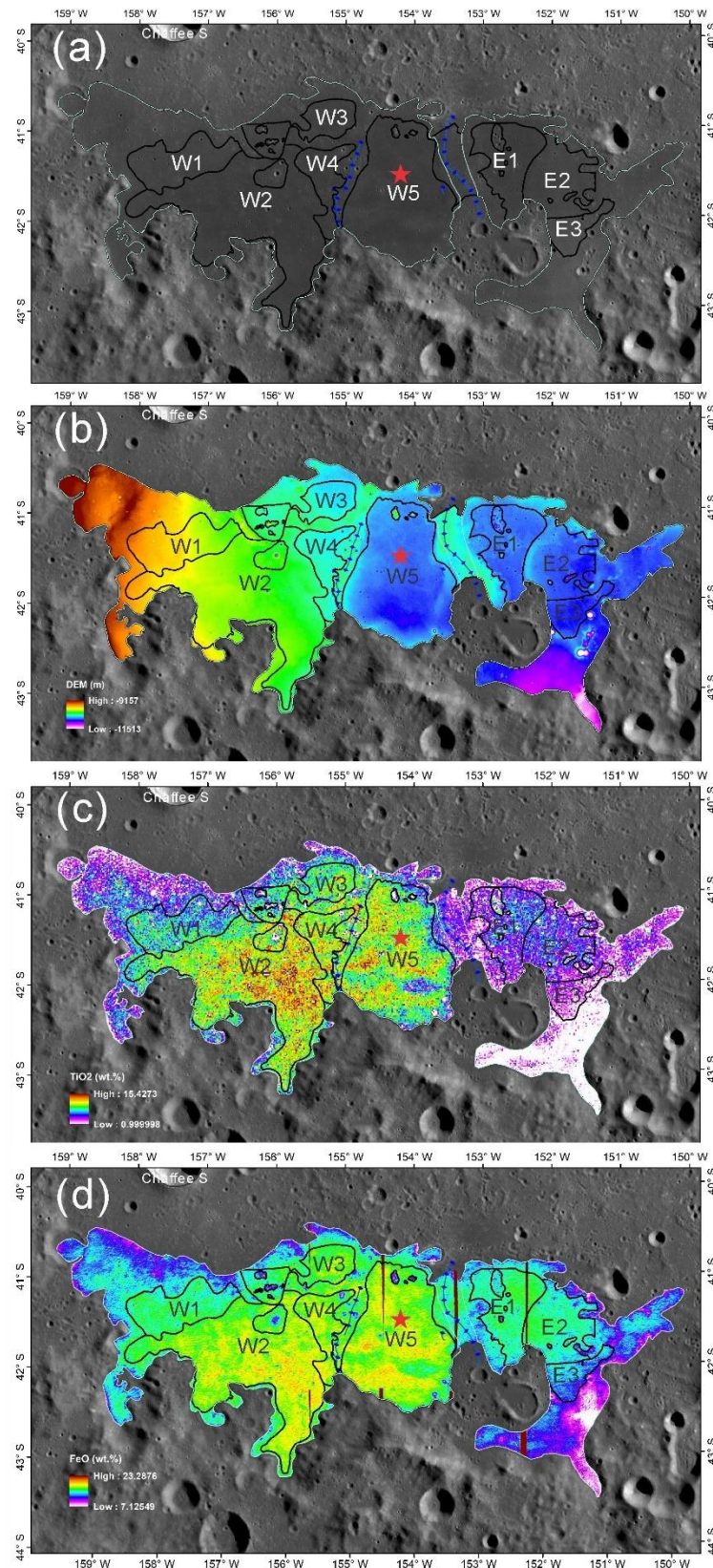


Figure 2. The units of the study region. (a) WAC mosaic. (b) DEM. (c) TiO₂ abundance. (d) FeO abundance. The black lines represent the boundary of each unit. The red star represents the landing site of the Chang'e-6.

The CSFD measurements require a unit of consistent formation age [26]. Therefore, subdivision of the mare basalts according to criteria which may differentiate them, including composition, is of

great significance. Basalts are divided into three different types (high-Ti basalt, low-Ti basalt and very low-Ti basalt according to TiO_2 and FeO abundance. High-Ti basalt has a TiO_2 content over 6 wt.%, and low-Ti basalt ranges from 1 wt.% -6 wt.%, while very low-Ti basalt less than 1 wt.% [28]. TiO_2 and FeO abundances are two important indexes to divide mare basalts. Furthermore, topography may also influence the lava flows, with topographic obstacles potentially blocking later flows. In this study, we used the titanium and iron contents and elevation as three main indicators to divide the mare basalts in the Chang'e-6 landing region, southern mare of the Apollo basin.

Qian et al. [37] divided the southern mare into two units (western mare basalt and eastern mare basalt) since the reflectance rate, Ti and Fe contents are different. There is an obvious and wide wrinkle ridge between eastern mare basalt units (E region) and the western mare basalt unit (W region) (Figure 2b). The eastern mare basalt unit is relatively flat. The difference of the elevation is 1274 m, with a maximum, minimum and average elevation of -10243 m, -11517 m and -10537 m, respectively. E region has a lower abundance of Ti, with an average value of 2.72 wt.%. For the western mare basalt, the elevation gradually decreases from west to east (Figure 2b). The average elevation of the W region is -10248 m. The average Ti content of the W region is 5.38 wt.%, with a maximum and minimum content of 15.4 wt.% and 1.0 wt.%, respectively (Table 1).

To obtain a better understanding of the basalt formation sequence, we further divided the mare basalt units according to elevation, topographic barriers and Ti and Fe contents. As for E region, the boundary of the E1 and E2 is a wrinkle ridge and E2 and E3 are divided by the elevation and Ti, Fe contents. As the E3 is close to the basin rim, where mixing with the materials from the basin rim may occur, the parts close to the basin rim have lower content of titanium and iron. The W region may be affected by the ejecta from Chaffee S crater (Figure 2c,d). The northwestern part of the W region has lower Ti and Fe contents than the eastern part. We then divided the W region into five units (W1, W2, W3, W4 and W5) and E region into 3 units (E1, E2 and E3) (Figure 2). The boundary between W1 and W3 are consistent with the crater ejecta from Chaffee S crater. Some residual basin floor of Apollo basin seems to appear within the boundary of the W2 and W3 unit. W4 and W5 region are separated by a topographic barrier, which appears to be a wrinkle ridge. Table 1 shows the maximum, minimum and average content of Ti and Fe content and elevation of the five units of the W region. Although the unit boundaries are constrained by three indicators, there is still inconsistency within a single sub-unit (W2 and W5). Within W2, the part close to the boundary between W1 and W2 may be slightly affected by the ejecta, causing a lower Ti and Fe content. We then divided the W2 unit according to the relative contents of the Ti and Fe. The W2 unit was then divided into W2_l and W2_h, representing the region that has lower or higher Ti and/or Fe content. The higher Ti/Fe unit may represent the relatively pure local basalt. Therefore, the CSFD results of the W2_h may represent absolute age of the local mare basalt. The situation is more complex within the W5 unit. Obvious reflectance rate anomaly can be seen from WAC image (Figures 2a and 3a). The regions with lower reflectance rate seem like discontinuous ejecta material. They have lower Ti and Fe abundances compared with the dark mare basalt. Similar to the W2 unit, the W5 unit was divided into lower Ti/Fe content region (W5_l) and higher Ti/Fe content regions (W5_h) (Figure 3). By more precise units-divisions, we can better constrain and understand the results.

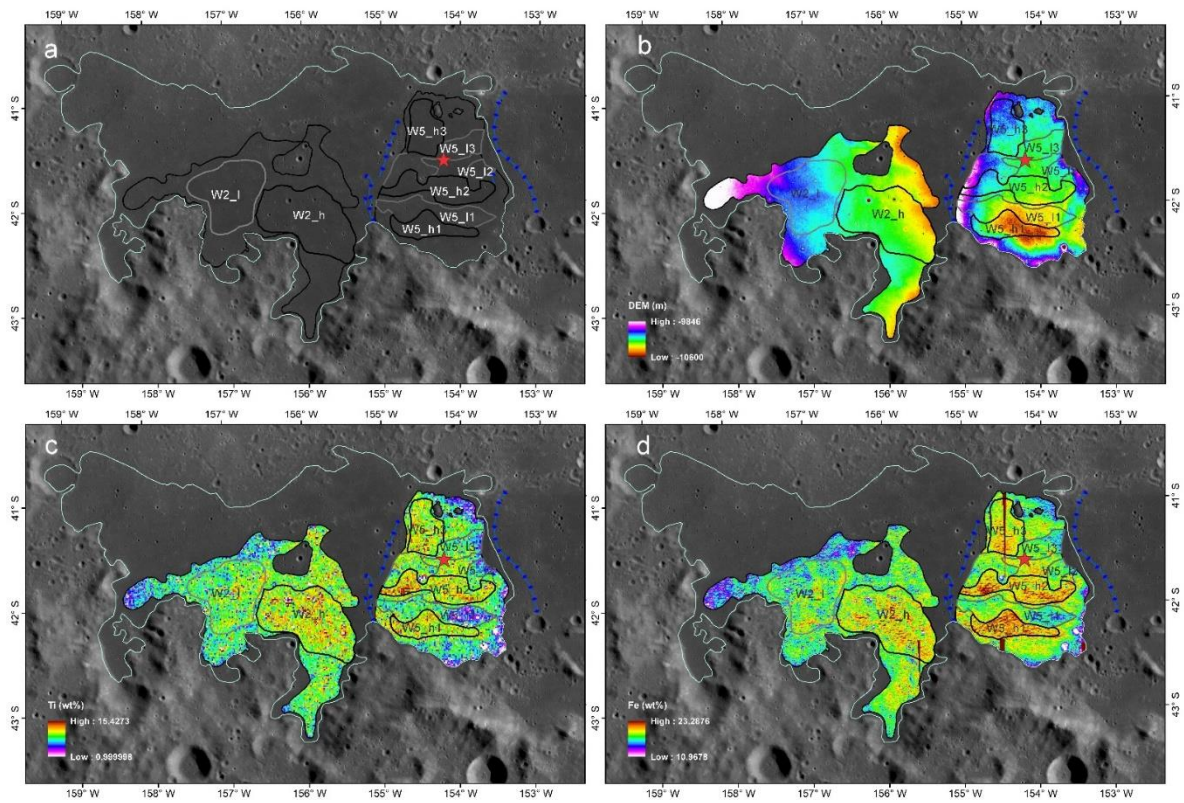


Figure 3. The units division within the W2 and W5 region. a) WAC mosaic. b) digital elevation map. c) Ti abundance. d) Fe abundance. The black solid lines are the boundaries of the mare basalt with higher Ti and Fe contents while the gray solid lines represent the lower Ti/Fe mare basalt. The blue lines with diamonds are wrinkle ridges. The red star represents the Chang’e-6 landing site. The basemap is WAC mosaic with 100 m/pixel.

Table 1. The minimum, maximum and average value of the elevation, Fe and Ti abundances of different units.

units	elevation (m)			Ti (wt.%)			Fe (wt.%)		
	average	min	max	average	min	max	average	min	max
E	-10538	-11517	-10243	2.72	1.00	8.83	15.28	7.13	21.94
E1	-10515	-10814	-10418	3.65	1.00	8.07	16.70	12.02	21.94
E2	-10553	-10766	-10463	3.65	1.00	7.95	16.37	10.63	21.94
E3	-10248	-10989	-9122	2.60	1.00	6.37	15.17	11.41	18.81
W	-10505	-10723	-10429	5.38	1.00	15.43	17.19	9.10	23.29
W1	-10077	-10444	-9853	4.80	1.00	10.72	16.66	10.83	19.94
W2	-10206	-10600	-9383	6.58	1.00	15.43	18.17	10.97	23.29
W3	-10372	-10850	-10237	5.41	1.00	10.10	17.19	12.57	21.94
W4	-10379	-10738	-10308	6.47	1.00	10.81	17.99	10.16	20.72
W5	-10504	-10989	-10333	5.91	1.00	10.66	18.04	10.02	21.94
sub-units	elevation (m)			Ti (wt.%)			Fe (wt.%)		
	average	min	max	average	min	max	average	min	max
W2_h	-10252	-10600	-10136	7.20	1.00	15.43	18.12	12.12	20.79
W2_l	-10164	-10351	-9846	6.56	1.00	10.70	18.67	11.61	23.29
W5_h1	-10552	-10643	-10457	6.75	1.00	10.57	18.82	15.07	20.74

W5_h2	-10511	-10641	-10349	6.88	1.00	9.70	18.63	13.26	20.95
W5_h3	-10485	-10610	-10428	6.63	1.00	10.35	18.59	14.99	21.94
W5_l1	-10528	-10685	-10365	5.21	1.00	9.76	17.61	14.30	20.04
W5_l2	-10498	-10558	-10424	5.33	2.31	7.84	17.74	14.71	19.53
W5_l3	-10489	-10659	-10384	5.83	1.00	8.99	17.69	10.34	21.94

3.2. CSFD Results

Chang'e-6 landed on the southern mare of the Apollo basin and returned ~2 kg samples from lunar farside for the first time [50]. The ages play a crucial role in understanding the geologic background of the landing site. Based on the units divided by several factors (elevation, topographic barriers, Ti and Fe contents), we conduct CSFD measurements with these units to better constrain the absolute model ages. Areas with obvious secondary craters, residual basin floors and wrinkle ridges are excluded. It is obvious that the southern mare has at least two epochs of mare basalt (Figure 2). The E region of the southern mare is older than the W region. The E region has very low-Ti basalt while the W region has low-high Ti mare basalt. We counted the craters in each sub-units of the E and W region and made Poisson timing analysis and randomness analysis for them. The results are shown in Figure 4.

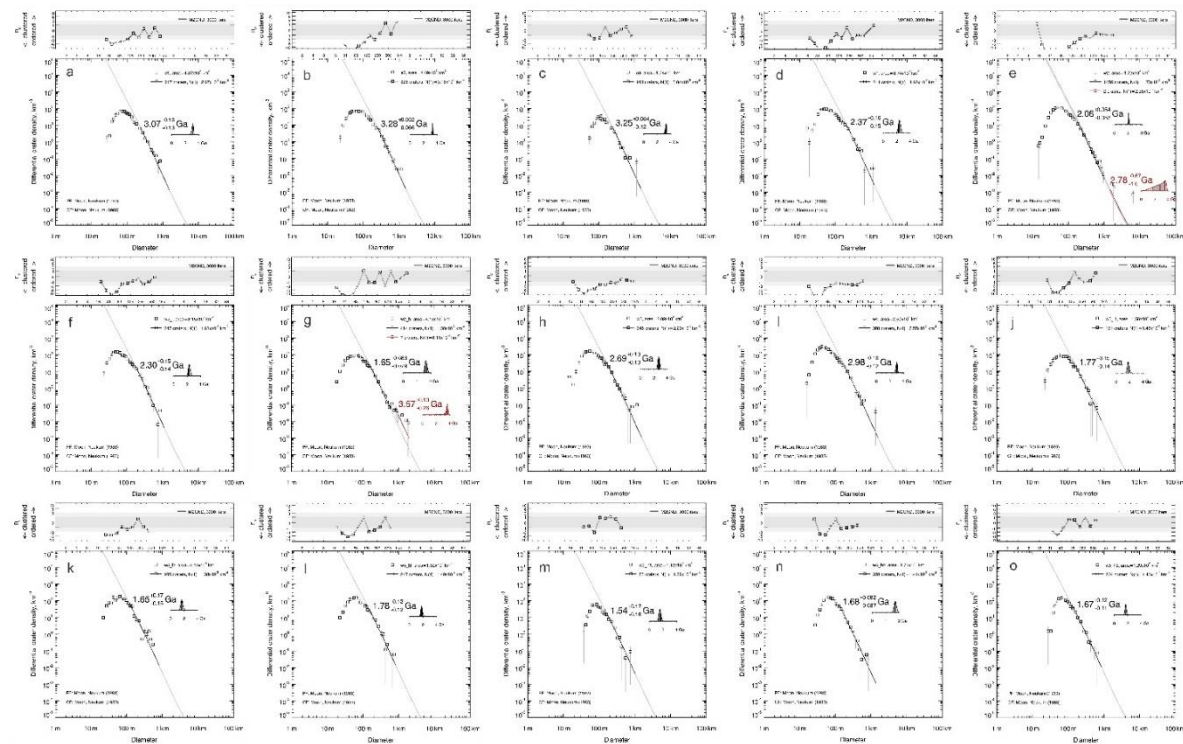


Figure 4. The results of CSFD and randomness analysis of the different units. (a-c) the ages of units of E region. (d, e, h, i) The ages of the W1-W4 units. (f, g) The ages of the W2_l and W2_h unit. (j-l) The ages of the W5_l1, W5_l2 and W5_l3 unit. (m-o) The ages of the W5_h1, W5_h2 and W5_h3 unit.

As for E region, the sub-units are of Imbrian period, with similar ages of ~3.2 Ga (E1 of $3.07^{+0.16}_{-0.13}$ Ga, E2 of $3.28^{+0.052}_{-0.066}$ Ga, and E3 of $3.25^{+0.084}_{-0.12}$ Ga. W region has a complex age assemblage with an age range of ~0.9 Ga, the oldest model age of $3.57^{+0.10}_{-0.26}$ Ga and a youngest age of $1.54^{+0.17}_{-0.16}$ Ga. W1, W3 and W4 has an age of $2.37^{+0.16}_{-0.15}$ Ga, $2.68^{+0.13}_{-0.13}$ Ga, $2.98^{+0.10}_{-0.12}$ Ga (Figure 4). The W2 has two absolute model ages. One is $2.06^{+0.054}_{-0.053}$ Ga and the other is $2.78^{+0.67}_{-0.10}$ Ga. When the lava flow is too thin to cover the older craters, a second older age of the underlying layer can be obtained in the crater counts [14]. That means the older age indicates another epoch/lava flow. The W2 region was divided into W2_h and W2_l since W2_h has higher Fe and Ti abundances from Figure 2c,d. W2_h has a

relatively younger age of $1.54^{+0.17}_{-0.16}$ Ga and an older age of $3.57^{+0.10}_{-0.26}$ Ga which may indicate two mare basalt epochs. We used the younger age as the age of the W2_h unit. The older age may indicate the underlying mare basalt. W2_l is $2.30^{+0.15}_{-0.14}$ Ga. The W5 unit is different. Since W5 region has reflectance rate anomaly and Ti/Fe abundance difference, it was divided into 3 relatively higher Ti/Fe mare basalt units (W5_h) and 3 lower Ti/Fe basalt units (W5_l) (Figure 3). For the relatively higher Ti/Fe mare basalt units, we obtained an age of ~ 1.68 Ga (Figure 6). The three W5_h units are quite consistent with each other. For three W5_l units, W5_l1 has an age of $1.77^{+0.15}_{-0.14}$ Ga, W5_l2 of $1.65^{+0.17}_{-0.15}$ Ga, and W5_l3 of $1.78^{+0.12}_{-0.12}$ Ga. They are all of the Eratothernian period.

The results are shown in Table 2, Figures 4 and 5. The E region has an age of ~ 3.2 Ga, of the late Imbrian period, while the W region is the Eratothernian period. The ages of the W region show a wide range, indicating that the mare basalt evolution is complex. The W4 region has the oldest age of W region, ~ 3.0 Ga. The W5 region has the youngest absolute model ages of ~ 1.6 - 1.7 Ga. Generally speaking, the units with lower Ti/Fe abundances are older than the units with higher Ti/Fe abundances (Figure 5).

Table 2. The results of the CSFD measurements of different units.

units	sub-units	age (Ga)	N(1) ($\times 10^{-3}$)	diameter range
E1		$3.07^{+0.16}_{-0.13}$	2.67	(240m, 1.5km)
E2		$3.28^{+0.052}_{-0.066}$	3.16	(250m, 1.5km)
E3		$3.25^{+0.084}_{-0.12}$	3.04	(240m, 1.5km)
W1		$2.37^{+0.16}_{-0.15}$	1.98	(210m, 1.2km)
W2		$2.06^{+0.054}_{-0.053}$	1.73	(180m, 1.0km)
		$2.78^{+0.67}_{-1.0}$	2.35	(1.5km, 5 km)
		$1.65^{+0.083}_{-0.079}$	1.38	(160m, 600m)
	W2_h	$3.57^{+0.10}_{-0.26}$	6.11	(800m, 1.9km)
		$2.30^{+0.15}_{-0.14}$	1.93	(190m, 1.1km)
W3		$2.68^{+0.13}_{-0.13}$	2.25	(160m, 940m)
W4		$2.98^{+0.10}_{-0.12}$	2.55	(185m, 1.55km)
W5	W5_h1	$1.54^{+0.17}_{-0.16}$	1.29	(170m, 1.0km)
	W5_h2	$1.68^{+0.092}_{-0.087}$	1.41	(130m, 1.35km)
	W5_h3	$1.67^{+0.12}_{-0.11}$	1.40	(140m, 850m)
	W5_l1	$1.77^{+0.15}_{-0.14}$	1.48	(165m, 650m)
	W5_l2	$1.65^{+0.17}_{-0.15}$	1.38	(120m, 800m)
	W5_l3	$1.78^{+0.12}_{-0.12}$	1.49	(150m, 800m)

4. Discussion

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

4.1. Evolution of the Southern Mare Basalts

The duration of the lunar volcanism reflects the thermal states inside the moon and has been an open question for many years [13]. By investigating the ages of the mare basalts on the lunar nearside, Hiesinger et al. [14] found that lunar volcanism might start at ~ 3.9 - 4.0 Ga and cease at ~ 1.5 - 2.0 Ga. The samples returned from Apollo missions have proved a peak of the volcanic activities at ~ 3.6 - 3.9 Ga [31,42]. Guo et al. [10] suggested that the Paleolunar isian era (4.22 - 3.16 Ga, including Aitkenian,

Nectarian and Imbrian) was dominated by both endogenic and exogenic processes. During the Paleolunar isian era, large impacts generated impact basins such as the SPA basin and the Apollo Basin, and the moon was active enough to generate large-scale mare basalt. After the Paleolunar isian era, exogenic processes dominated the morphology of the lunar surface (Neolunar isian era) and the volcanic activities decreased significantly. During the Eratosthenian period (3.16-0.8 Ga), only small-scale mare basalts erupted [12,15,34,37]. The samples returned from Chang'e-5 have an age of ~2.0 Ga [21], indicating that the Moon was still volcanically active at around 2.0 Ga.

The SPA basin is the oldest, largest and deepest impact basin on the Moon, which may excavate materials from the lower lunar crust and even the upper mantle [9,14,23,33,41,47,48]. Outside the melt pool, the ejecta of the SPA basin can be as thick as 30 km [27]. After then, a giant impact impacts on the northeastern part of the SPA basin, removed the SPA ejecta and formed the largest basin within SPA basin, the Apollo basin [14,17,23,36]. Both the SPA impact and the Apollo basin thinned the lunar crust. Wiczorek et al. [49] modeled the crust thickness of the Moon by GRAIL data and found the Apollo basin has the thinnest crust thickness within the SPA basin, <5 km. Fractures are the paths for basalt eruption and it's easier to form on the thin crust than on the thick one. Six mare basalts have been identified within the Apollo basin [37]. The fractures formed by the impacts may be the transportation paths of the mare basalts.

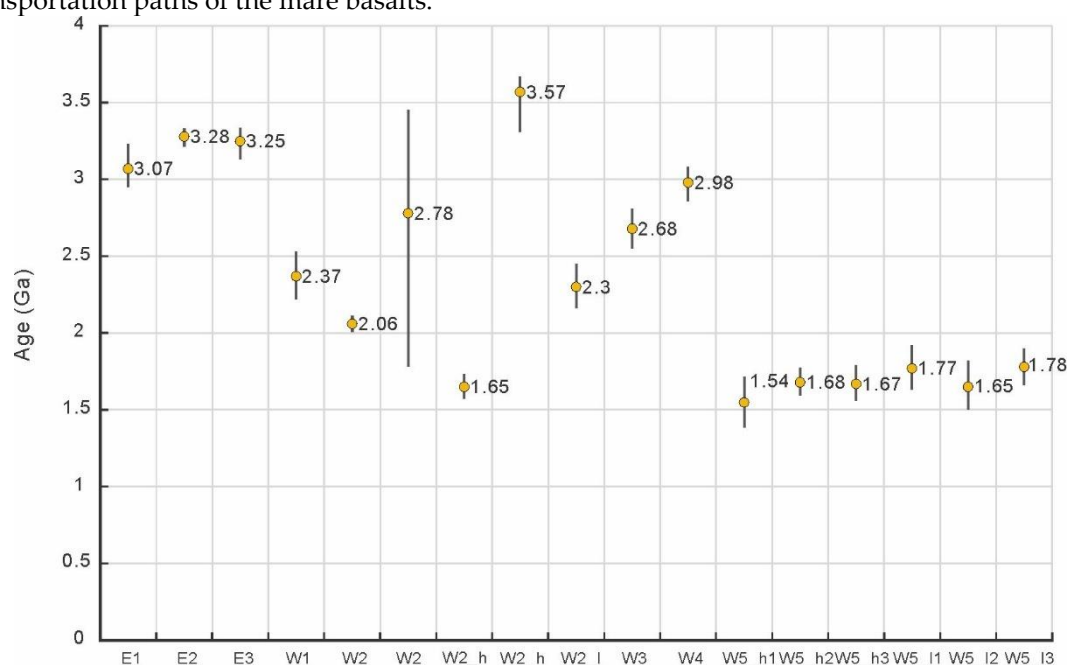


Figure 5. The age diagram of different units.

The southern mare occurs in the south of the Apollo basin, between the inner ring and outer ring (Figure 1). The lunar volcanism of the southern mare was active for at least 1.6 Ga and showed a pattern of multiple eruptions. The southern mare can be divided into two units (eastern mare basalt and western mare basalt) by reflectance, Ti and Fe abundances [37,51]. The eastern part of the southern mare, with lower reflectance rate and Ti and Fe abundances (average Ti abundance: 2.72 wt.%, average Fe abundance: 15.28 wt.%), is older than the western part (Figure 2c,d). The eastern part (E region) is of the Imbrian period (~3.2 Ga) and has low-Ti mare basalt while the western part (W region) is of the Eratosthenian period (3.0-1.6 Ga) and has high-low mare basalts (Figures 2 and 5). The Imbrian-aged low-Ti mare basalt erupted at ~3.2 Ga and covered the eastern part, and formed a wrinkle ridge, which has become the topographic barrier to prevent the western mare basalts (Figure 6). It's possible to have older lava flows under the surface layer. An age of 3.57 Ga was obtained within W2 region, indicating the Imbrian-aged low-Ti lava may extend to the west (Figure 6). The ~3.2 Ga eruptive epoch may created more paths for other basalt lavas. The basalt eruptions are more complicated in the W region. Shortly after the Imbrian-aged low-Ti mare basalt eruption, the earliest Eratosthenian-aged (~2.98 Ga) high-Ti mare basalt (W4) erupted on the middle of the W

region and opened the prelude to the eruption of basalts in the W region (Table 1). The W4 high-Ti lava flow contracted and formed a wrinkle ridge (Figure 6). Immediately after the eruption of the W4 high-Ti mare basalt (average Ti abundance of 6.47 wt.%), another low-Ti mare basalt (W3) erupted at ~ 2.68 Ga and the difference of the Ti abundance is ~ 1.00 wt.%. Another low-Ti mare basalt (W1 and W2) erupted on the northeastern of the W region and flowed to the east. The volume of the eruption was not large and only a thin layer of low-Ti basalt covered on the Apollo basin floor (Qian et al., 2024). It's worth noting that the W1 and W2 low-Ti basalt is close to the Chaffee S crater, indicating that the basalt may be contaminated or covered by the ejecta from Chaffee S crater. We divided the W2 region into W2_l and W2_h units and found that the W2_h unit is younger than the W2_l unit, suggesting another lava flow erupted at ~ 1.65 Ga.

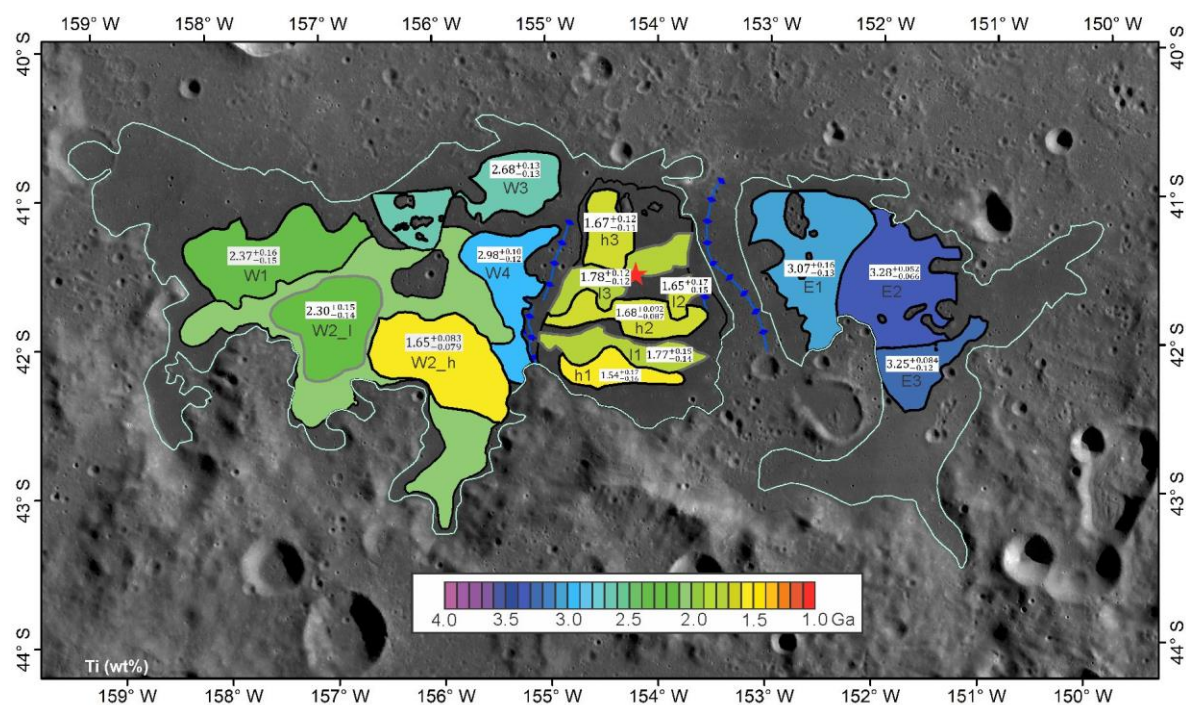


Figure 6. Absolute model ages of different units. The red star represents the Chang'e-6 landing site.

The volcanic activity of the southern mare ceased at around 1.6 Ga. The mare basalt of the W5 unit – where Chang'e 6 landed – has the youngest basalt ages. The W5 region was divided into W5_h (high-Ti mare basalt) and W5_l units (low-Ti mare basalt) (Table 1). All these units have a similar age of ~ 1.70 Ga although the W5_l units seem to be a bit older than the W5_h units (Figure 5), indicating that the high-Ti mare basalt may derive from the low-Ti basalt.

4.2. The Genesis of the Low-Ti Mare Basalt of the W5 Region

Within the W5 region, both high-Ti mare basalts and basalts with low Ti signature can be observed. The low-Ti basalts of the W5 region appear as strip, in an E-W distribution (Figure 3). It looks like the ejecta from some craters, but it can also be the original mare basalt. Orgel et al. [33] made a detailed geologic map of the southern mare and classified the low-Ti region as the Pre-Nectarian/Nectarian hummocky basin material unit, which represented the residual impact melt of basin formation. However, the low-Ti belts have no obvious elevated elevation, unlike those in the northern part of the western mare basalt unit. The basin residuals appear at the northern part of the southern mare are isolated. Next to the eastern mare basalt, the basin residuals seem to have more craters. However, those low-Ti belts don't have those characteristics.

As for the genesis of the low-Ti basalts, we proposed three possible explanations: 1) The ejecta belt. The high-Ti basalt might be covered by a discontinuous ejecta and then appeared like low-Ti basalt from spectral images. The distribution pattern and the higher reflectance rate are the evidence.

When making crater counts, Zeng et al. [51] and Yue et al. [50] excluded those areas. However, no such ejecta has been found in other places of the W region although they are older than the W5 unit. 2) Original low-Ti basalts. Our results show that the W5_l and W5_h units have similar age and W5_l units were even older than the W5_h units, indicating that the ejecta covered the W5_l units shortly after the high-Ti basalt formed or the W5_l units are original low-Ti basalt which have different magma sources with high-Ti basalt. Due to the cooling of the Moon, the volume of the basalt lavas reduced and only small-scaled lava flows could form. The eruption of previous lava flows formed fractures, the transportation paths for the basalt of the W5 region. The lava flow from different magma sources erupted and formed the low-Ti and high-Ti mare basalts. 3) Magnetic swirl. Swirls are sinuous, high-reflectance markings co-located with crustal magnetic anomalies [7]. The magnetic anomaly can influence the spectral features by affecting space weathering. Therefore, it can influence the compositions of the material on the top surface. The wrinkle ridges are the topographic barrier to prevent the lava flow. From the distribution pattern, the W5_l units are sinuous similar to magnetic swirls. However, the resolution of the instruments to detect the magnetic anomalies cannot detect the high-reflectance belt on the W5 region (~28 km) [45]. The samples returned by Chang'e-6 may solve the question.

In this study, we suggested that the low-Ti belts are original low-Ti mare basalts. The eruptions of the other lavas may produce fractures, which are the transportation panels for younger basalt eruptions. Therefore, small amount of Eratosthenian basalt lavas are proved by the returned samples of Chang'e-5, a young volcanic eruption of ~2.0 Ga [21].

Further investigations and analysis, especially the sample analysis, are necessary to test these hypotheses.

5. Conclusions

We conducted detailed CSFD measurements on the southern mare to better understand the surroundings of the Chang'e-6 landing site. The southern mare of the Apollo basin has a long and continuously active volcanic history (~1.6 Ga), from 3.28 Ga to 1.54 Ga. Two main basalt epochs are identified, one of the Imbrian period and the other of the Eratosthenian period. The first episode of the low-Ti mare basalt happened on the Imbrian period (3.0-3.2 Ga), on the eastern part. The W region has experienced enduring basalt eruptions, from 2.98 Ga to 1.65 Ga. The low-Ti basalts on the northwestern part of the W region may be affected by the Chaffee S crater. The high-Ti basalts generally have a younger age, ~1.65 Ga, mainly distributed within the W2 and W5 region. The basalts of the W5 region have an age of ~1.7 Ga. The basalt of the Chang'e-6 landing site has an age of ~1.68 Ga, which means that the samples returned may include components with this very young age.

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Data Availability Statement: Optical image data from LROC WAC and DEM data from LROC & SELENE used in this study can be downloaded from the website of the United States Geological Survey at https://astrogeology.usgs.gov/search/map/Moon/LRO/LROC_WAC/Lunar_LRO_LROC-WAC_Mosaic_global_100m_June2013 and https://astrogeology.usgs.gov/search/map/Moon/LRO/LROC_DEM/Lunar_LRO_LROC-DEM_Mosaic_global_100m_June2013, respectively. LROC NAC images with a resolution <3 m were download from the PDS Geosciences Node Lunar Orbital Data Explorer website (<https://ode.rsl.wustl.edu/Moon/indexProductSearch.aspx>).

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