CHAPTER 9

The Chang'e-5 mission

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Chapter Outlines

9.1 Mission overview

The Chang'e-5 mission (CE-5) is the last step of the three-step Chinese Lunar Exploration Program (CLEP), designed to orbit, land, and return samples from the Moon (Zheng et al., 2008). The Chang'e-1 and Chang'e-2 missions successfully launched and orbited the Moon in October 2007 and October 2010, respectively, beginning China's lunar and space explorations and achieving the goal for Step 1. Chang'e-3 and Chang'e-4 missions achieved the goal for Step 2, by accomplishing successful soft landing and robotic rover explorations. Chang'e-3 landed in Mare Imbrium (northern hemisphere) in December 2013, and placed the Yutu rover on the Moon 37 years after the last robotic visit (Luna 24). In January 2019, Chang'e-4 landed on the farside of the Moon in Von Kármán Crater within the South Pole-Aitken Basin. At the time of writing (January 2021), Chang'e-4 and its rover Yutu-2 are still carrying on scientific observations and have just passed its 600-m milestone. The Chang'e-5 and Chang'e-6 missions, belonging to Step 3, aim at collecting lunar samples and bringing them back to the Earth >40 years after the Apollo and Luna missions. Since 2017, the launch date of the Chang'e-5 mission was postponed two times due to launch vehicle issues, and it finally launched in November 2020.

The China National Space Administration (CNSA) has set several ambitious engineering and scientific goals for the Chang'e-5 mission (Pei et al., 2015).

The main engineering objectives of the Chang'e-5 mission are: (1) to improve China's space capabilities by developing key technologies such as narrow window

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multi-orbit binding launch, automatic lunar sampling and packaging, lunar sample storage, lunar surface takeoff, lunar orbit rendezvous and docking, Moon-Earth transfer, high-speed re-entry into the Earth's atmosphere, and multi-target high-precision measurement and control; (2) to realize China's first automatic sample return from an extraterrestrial body; (3) to optimize China's lunar exploration engineering system, form a high-level talent team of scientists and engineers and construct solid technology foundations for future crewed lunar missions and deep space explorations.

The main scientific objectives of the Chang'e-5 missions are: (1) to characterize the geological backgrounds of the landing site, (2) to study lunar samples *in-situ*, and connect *in-situ* data with laboratory analyses of the returned samples; and (3) to deepen the understanding of the formation and evolutionary history of the Moon by comprehensive studies of the returned samples, including geophysical and geochemical characterizations.

The Chang'e-5 spacecraft is composed of an orbiter, a lander, an ascender, and a returning capsule. It launched on November 24, 2020 from the Wenchang Satellite Launch Center, Hainan Island, and landed on the Moon on December 1, 2020 at 43.1°N, 51.8°W in Northern Oceanus Procellarum. Chang'e-5 has collected 1731 g of lunar samples, including ~1 m of drilling core, and returned to the Earth on December 17, 2020. The Chang'e-5 landing site is ~170 km ENE of Mons Rümker, and is characterized by some of the youngest mare basalts on the Moon (Qian et al., 2021a, 2021b). The scientific package of Chang'e-5 includes a Landing Camera, a Panoramic Camera, a Lunar Mineralogical Spectrometer and a Lunar Regolith Penetrating Radar in order to assist sampling operations and landing site investigations (Pei et al., 2015).

The mission profile of the Chang'e-5 mission, from launch to orbit transfer, lunar surface sampling, lunar surface takeoff, and back to the Earth, is shown in Fig. 9.1.

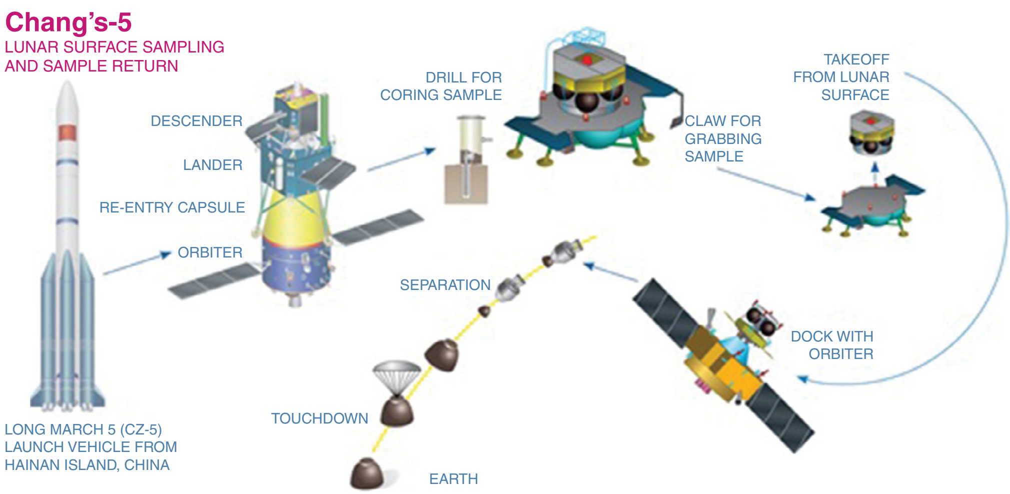

Fig. 9.1 An overview of the Chang'e-5 mission *(Xiao, 2018)*.

9.2 Sampling and science operations

9.2.1 Landing site

The pre-selected CE-5 landing region (41°−45°N, 49°−69°W) is located in Northern Oceanus Procellarum, in the northwest nearside of the Moon (Fig. 9.2). Northern Oceanus Procellarum is within the Procellarum KREEP Terrain (PKT; Jolliff et al., 2000), westward of Mare Imbrium, characterized by elevated heat-producing elements (Prettyman et al., 2006), extended volcanism (Hiesinger et al., 2011), and thin crust (Wieczorek et al., 2013). This region was selected as it has some of the youngest lunar mare basalts (Hiesinger et al., 2003, 2011; Liu et al., 2021; Qian et al., 2018, 2021a). Sampling these young mare basalts could profoundly improve our knowledge of lunar impact history and late thermal history (Qian et al., 2018, 2021a), and may solve some of the fundamental scientific questions raised recently (National Research Council, 2007).

Chang'e-5 landed within the Rümker region. It has an area of ~53,000 km^2 and is named after Mons Rümker, the most prominent feature in this area. It is a generally smooth mare plain (Fig. 9.2), covered by widespread mare basalts (Fig. 9.2 & Fig. 9.3). The mean slope of the mare surface is 1.1° with a baseline length of 354 m; only 10% of the surface, corresponding to impact features, has a slope larger than 2°. The mean elevation of the region is ~2145 m and wrinkle ridges could raise the mare surface about 100–200 m locally. The western part of the CE-5 landing region is ~200–300 m higher than the eastern part.

The landing site region includes a large number of volcanic features, such as a volcanic complex (Mons Rümker), a silicious dome (NW Mairan Dome), and a sinuous rille (Rima Sharp). Mons Rümker is one of the three largest volcanic complexes on

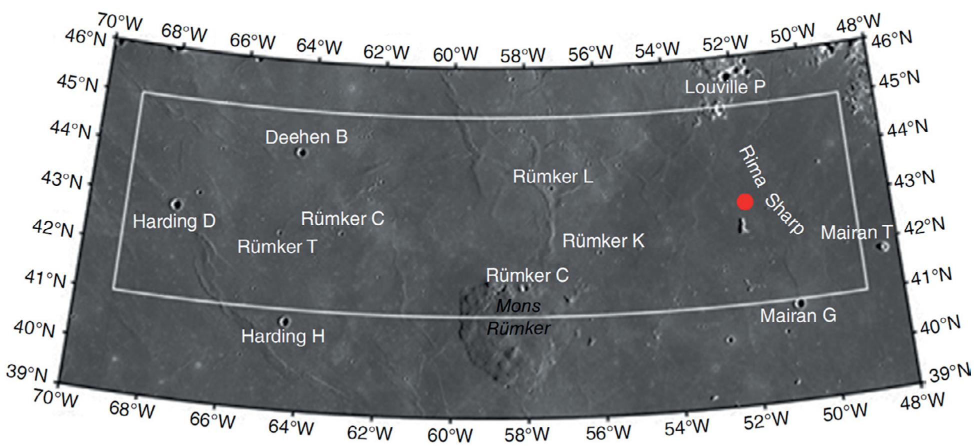

Fig. 9.2 ***Chang'e-5 landing region (white box) in Northern Oceanus Procellarum.*** The red point represents the CE-5 landing site.

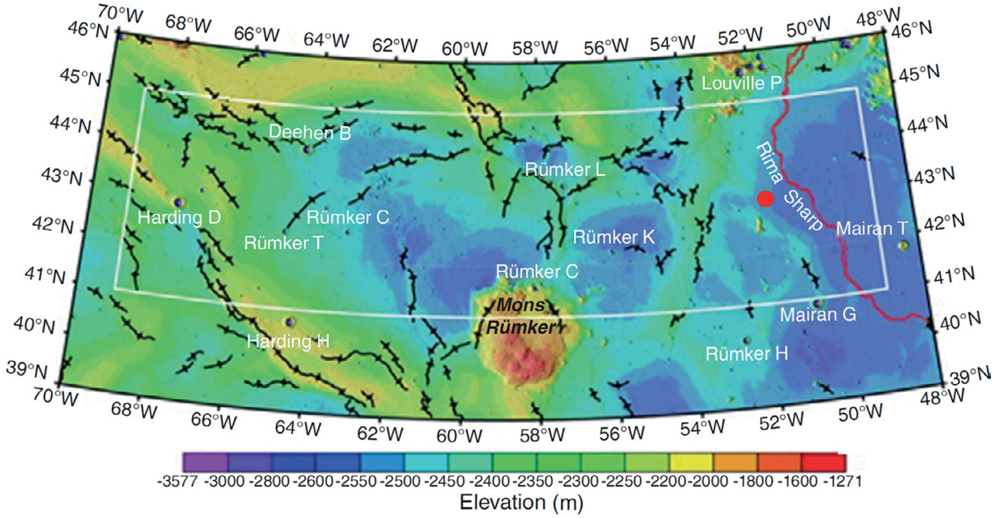

Fig. 9.3 ***Topography map of the Chang'e-5 landing region (white box).*** Black lines denote wrinkle ridges. Red lines denote Rima Sharp. The red point represents the CE-5 landing site.

the Moon (Fig. 9.2) (Head and Gifford, 1980). It is an almost circular feature, with a diameter of ~70 km and the highest point is ~1300 m above the mare surface. Because Mons Rümker formed before the surrounding mare basalts, its original size maybe even larger. Zhao et al. (2017) studied the geology and evolution history of Mons Rümker in detail. They identified 22 independent domes on the Rümker plateau and classified them into shallow domes (**ld**, Fig. 9.4) and steep-sided domes (**sd**, Fig. 9.4), representing different eruption stages. In addition, Zhao et al. (2017) divided the Rümker plateau

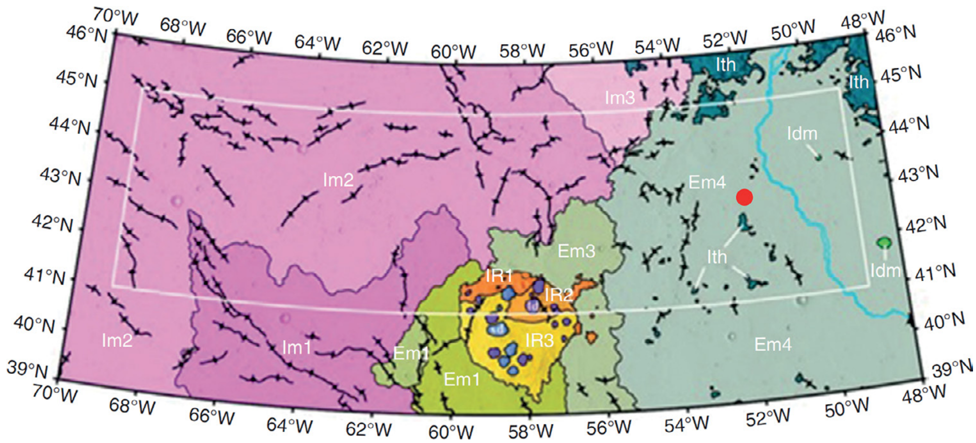

Fig. 9.4 ***Geological map of Chang'e-5 landing region (white box).*** Blue lines indicate the Rima Sharp. Ith indicates highland materials. Idm indicates silica-rich Mairan domes. IR1, IR2, and IR3 indicate Rümker plateau units. Im1, Im2, Im3, Em1, Em2, Em3, and Em4 are Imbrian-aged and Eratosthenian-aged basaltic mare units, respectively. The red point represents the CE-5 landing site.

into three units, i.e., **IR1**, **IR2**, **IR3** (Fig. 9.4). Their ages are estimated by crater size-frequency distribution to be 3.71 Ga, 3.58 Ga, and 3.51 Ga, respectively.

Rima Sharp (red line in Fig. 9.3, blue line in Fig. 9.4) is located in the east of the CE-5 landing region. It was described as the longest lunar sinuous rille (Hurwitz et al., 2013). It has a length of ~566 km, an average width of ~840 m, an average depth of ~76 m, and a regional slope of –0.008°. Because lunar sinuous rilles are formed by thermal and mechanical erosion of lava flows (Head and Wilson, 2017; Williams et al., 2000), some of the lavas that carved the rille channel may have been emplaced and distributed in the area nearby the rille and have been sampled by CE-5 (Qian et al., 2021a).

Highland material remnants (**Ith**, Fig. 9.4) are scattered in the eastern part of the landing region. They have a hilly to hummocky appearance with various shapes, and are up to 500 m higher than the mare surface. Some of them are thought to be possible ring materials of the Imbrium Basin embayed by mare lavas (Wilhelms and McCauley, 1971).

Mare basalts are the dominant materials in the CE-5 landing region. Wrinkle ridges (black lines, Fig. 9.4) develop on the mare surface across the entire area. They have three preferred orientations, i.e., NW, NNW, NE. In the western part of the landing region, wrinkle ridges range up to 6 km in width and 110 km in length and are 200 m higher than the surrounding mare. The eastern part wrinkle ridges are much smaller.

The mare basalts and the scientific significance of the younger ones have been studied in detail by Qian et al. (2018, 2021a). They found that the CE-5 landing region has two types of mare basalts, distributed in the western and eastern part of the landing region, respectively (and thus named western maria and eastern maria). The western maria have a very-low-Ti to low-Ti composition (TiO_2 content lower than 5 wt%) and low FeO content (15.8 wt% on average); the eastern maria have higher TiO_2 contents (4.7 wt% on average) and FeO content (6.7 wt %, mean content) than the western maria, excluding areas contaminated by low-Ti crater ejecta materials (Qian et al., 2021b). Both western maria and eastern maria spectra are characterized by high-Ca pyroxenes, with absorption features at <1000 nm and >2000 nm (Qian et al., 2020). However, the eastern maria pyroxenes are probably richer in iron or calcium, because of the shorter absorption Band II center (2200 nm against 2300 nm). By combining elemental composition, mineralogy, and geomorphology, Qian et al. (2018) divided the mare basalts in the region into six units. Their geologic ages are estimated by crater size-frequency distribution measurements, which are 3.42 Ga, 3.39 Ga, 3.16 Ga, 2.30 Ga, 1.51 Ga, 1.21 Ga and then labeled as **Im1**, **Im2**, **Im3**, **Em1**, **Em2**, **Em3**, **Em4** (Fig. 9.4) respectively, according to their formation sequence. Therefore, it is clear that the differences in the western maria and eastern maria are caused by two stages of volcanic activities, each with different compositions, occurred in the Imbrian Period (older than 3 Ga) and in the Eratosthenian Period (younger than 3 Ga), respectively.

The Eratosthenian-aged mare basalts are among the youngest mare basalts on the Moon. These young basalts have never been sampled by Apollo or Luna sample return missions, and thus the returned Chang'e-5 samples will provide enormous potentials for solving some basic lunar scientific questions. Qian et al. (2021a) has summarized the 27 fundamental questions that may be answered by the returned CE-5 samples, including questions about chronology, petrogenesis, regional setting, geodynamic & thermal evolution, and regolith formation (Tab. 1 in Qian et al. 2021a), especially calibrating the lunar chronology function, constraining the lunar dynamo status, unraveling the deep mantle properties and assessing the Procellarum KREEP Terrain structures and significance.

In summary, the CE-5 landing region experienced the following geological events, from older to younger:

1. The Imbrium impact occurred at ~3.92 Ga ago (Snape et al., 2016) and generated a complex multiring system, forming the Ith unit in the area.
2. Basaltic activities were active from 3.71 to 3.51 Ga on the Rümker plateau and formed plateau basaltic units IR1 (3.71 Ga), IR2 (3.58 Ga), and IR3 (3.51 Ga).
3. The most extensive phase of basaltic volcanism occurred in the Late Imbrian Period, forming very low-Ti to low-Ti mare basalts (Im1, 3.42 Ga; Im2, 3.39 Ga; Im3, 3.16 Ga) in the western maria.
4. The extended phase of mare volcanism started at ~2.30 Ga and ceased at ~1.21 Ga, and formed four mare units (Em1, 2.30 Ga; Em2, 2.13 Ga; Em3, 1.51 Ga; Em4, 1.21 Ga). The youngest mare eruption formed the Em4 mare basalts, with higher Ti contents.

9.2.2 Sampling technologies

Chang'e-5 has collected lunar samples by using two methods, i.e., collecting subsurface samples using a drill, and collecting surface samples using a scooping device.

The drill is developed by Beijing Spacecrafts (Pang et al., 2012). It is composed of a drilling mechanism, a loading device, and a coring system. The drill stem has an internal and an external drilling pipe. During drilling operations, the external pipe rotates, while the internal drilling pipe is static to the lunar regolith. The internal drilling pipe is designed as a thin-walled hollow pipe to better preserve the original stratigraphic layers of the lunar regolith. The external pipe is a hollow pipe with helical blades to discharge drilling chips and dissipate heat. The coring mechanism uses a soft sampling bag technique to take and store samples. First, the soft sampling tube bag is installed on the inner wall of the internal pipe. The sampling bag then surrounds lunar regolith when it enters the hollow pipe. Then, the sampling bag is extracted and convolved into the primarily package device for drilling samples, and finally transfered to the sealing capsule on the top of the ascender. The goal is to penetrate and recover ~2 m of lunar regolith in the nominal sequence and Chang'e-5 has collected a ~1 m core by drilling finally.

The scooping device (Surface Sampling System) is developed by Hong Kong Polytechnic University. It consists of four joints, two samplers, and a close-range camera. Following landing and prior to sampling operations, camera images from the Sampling Monitoring Cameras, Panoramic Cameras, Far-range Camera, and Close-range Camera have been used to establish a sampling plan. Then, the robotic arm has scooped the surface regolith and rock fragments using two samplers with the help of camera images. Collected samples have then been placed into the primary package device for surface samples on the top of the lander. The scooping device has conducted 12 times of samplings, and ~1.5 kg samples have been gathered around the lander. Then, the primary package device closed and the samples have been transported to the sealing capsule on the top of the ascender.

In summary, CE-5 conducted the following sampling workflow during the mission operations Fig. 9.5:

1. Unlock the drilling system and scooping system after landing.
2. The drilling system conducted drilling and coring. Samples were then separated and transferred to the primary package device for drilling samples. Finally, the samples were transported to the sealing capsule.
3. The robotic sampling arm conducted surface sampling. Samples were then transferred to the primary package device for surface samples on top of the lander, where it underwent primary packaging. Finally, the robotic sampling arm transported the primary package device to the sealing capsule on the top of the ascender.
4. The sealing capsule was then sealed. The package consisted of both of the drilling samples and the surface samples, which remained separately.

9.2.3 *In-situ* exploration

The Chang'e-5 mission has two key scientific payloads onboard its lander, i.e., the Lunar Mineralogical Spectrometer (LMS) and the Lunar Regolith Penetrating Radar (LRPR).

The Lunar Mineralogical Spectrometer was designed to obtain in-situ visible and ultra-violet spectra of the lunar surface both before and after sampling operations. The acquired spectra would be helpful to understand the mineralogical composition of the CE-5 landing site, especially hydrated minerals, providing information on water-rock interaction and lunar volatiles.

LMS employs acousto-optic tunable filters (AOTFs). An aluminum plate and an Infragold plate are used for calibrating the VIS/NIR and IR spectra, respectively. The visible spectrometer can acquire images of the drilling and sampling sites. The measuring capabilities of LMS are listed below (Li et al., 2015; Cai et al., 2019).

1. Spectral range: 480 ~3200 nm, covered by a VIS/NIR and an IR module. The VIS/NIR module is composed of visible (480 ~950 nm) and near-infrared (900 ~1450 nm) spectrometers, and the IR module is composed of short-infrared (1400 ~2450 nm) and middle-infrared (2400 ~3200 nm) spectrometers.

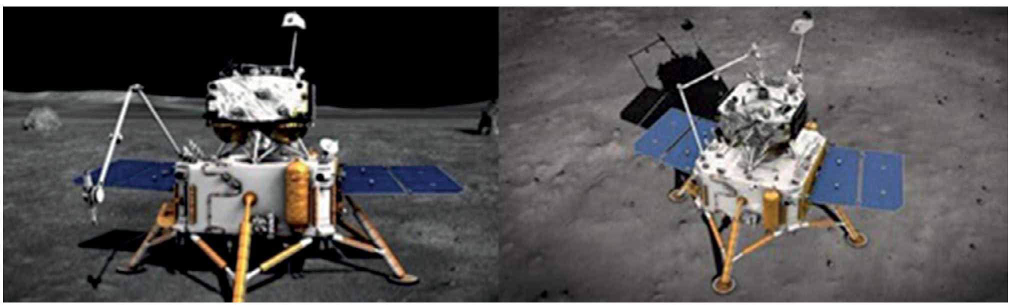

Fig. 9.5 Chang'e-5 samples the lunar surface with a robotic arm (artistic impression).

2. Spectral resolution: 3 ~25 nm
3. Detection range: 2 ~5 m
4. Field of view (FOV): 4.24°×4.24°

The Lunar Regolith Penetrating Radar was used to detect and analyze lunar regolith structure and thickness at the landing site, supporting drilling and sampling operations, and further stratigraphic analysis (Qian et al., 2021b).

LRPR is an ultra-wideband array-based ground penetrating radar (Feng et al., 2019;Y. Li et al., 2019; Xiao et al., 2019). It is composed of a high-frequency antenna array, cables, and an electronics box. The antenna array consists of 12 bow-tie antennas with a working frequency range of 1 ~3 GHz; these are asymmetrically mounted around the drill (90 cm above the ground). The LRPR works in the time domain and transmits carrier-free pulses with a Full Width at Half Maximum of 200 ps. During its operation, one of the antennas sends a pulse signal into the lunar subsurface and the other antennas receive the echo signals. The 12 antennas work taking turns, providing 132 traces of data recorded in an operation period. Each trace has a time window of 55 ns, with a temporal sampling interval of 18.3 ps. The measuring capabilities of LRPR are listed below:

1. Detection depth: ≥2 m
2. Vertical spatial resolution: ≤5 cm
3. Detection area: sampling site
4. Frequency range: 1~3 GHz

9.3 Landing, recovery and transport procedures

The sample return capsule landed in the desert area of Inner Mongolia, North China, on December 17, 2020, a traditional landing field for China's crewed and robotic space exploration missions. The recovered sample capsule was then packaged and sealed in a transfer box (filled and protected by nitrogen) and transferred to the Lunar Sample Laboratory at Ground Research Application System (GRAS), Beijing, the primary sample storage and curation center.

9.4 Sample storage and analysis

9.4.1 Sample storage and curation

The returned samples are managed by the Lunar Exploration and Space Engineering Center (LESEC), CNSA (China National Space Administration, 2020). LESEC has been entrusted to carry out the management of lunar samples, with main responsibilities including: 1) reviewing standards and operating procedures formulated by the curatorial agencies; 2) establishing an expert committee on lunar samples; 3) reviewing applications for requesting lunar samples; 4) supervising and coordinating the process of unsealing, classification, preparation, documentation, storage, application, distribution, transportation, use, return, dispositioning, management of information, and documentation of results.; 5) publishing dynamic information on lunar samples on a regular basis through data information platform; and 6) implementing the monitoring of science returns and its applications, and preparing and publishing a list of publications and achievements.

Sample prelimary analysis and curation. The primary storage center (GRAS) is responsible for sample classification and cataloging. The general procedure is as follows (Zhang et al., 2020): 1) GRAS would receive the sealed package from the spacecraft system; 2) sample bags would be unsealed. Both scooped and drilled samples would be taken out and cataloged separatly in two unsealed containers inside the unsealed package; 3) drilled samples soft bag would be cut into several sections of 15 cm each, while scooped samples would be put into a squared container and classified into different types; and 4) after classification, the permanent storage samples will be transferred to the permanent storage glove box in the long-term storage room, and the research and backup permanent samples will be transferred to the temporary glove box waiting for further utilization.

Preliminary analysis includes physical properties, mass, grain size of the samples, and etc. GRAS is equipped with balances, microscopes, glove boxes, cryogenic freezer, etc. All the tools that will contact with lunar samples are made of stainless steel, teflon, quartz glass or materials of known composition that do not contaminate the samples and therefore do not affect subsequent scientific analysis. The pure nitrogen pressure in the glove box will be strictly monitored to prevent the lunar samples contamination from the Earth contaminations (Zhang et al., 2020).

Sample storage. Returned samples will be stored in CNSA-designated storage facilities (GRAS). Two storage types are planned: primary storage and remote disaster-tolerant backup storage. The primary storage institution has the responsibilities of (China National Space Administration, 2020): 1) formulating standards and operating procedures related to lunar samples; 2) implementing the unsealing, classification, preparation, documentation, and storage of lunar samples; 3) Implementing the distribution, return and dispositioning of lunar samples in accordance with the procedures; 4) Building and maintaining the lunar sample storage facilities, to make sure that these facilities have the capability to carry out the necessary work; and 5) Establishing a lunar sample curation catalog, thus to secure the information safety of the lunar samples.

The remote backup storage institution has the responsibilities of (China National Space Administration, 2020): 1) participating in the formulation of the standards and operating procedures related to lunar samples; 2) building and maintaining storage facilities; and 3) establishing a lunar sample information catalog to guarantee the security of lunar samples stored.

Allocation of samples for research purposes. Several specific procedures will be applied for allocation of samples for study and analysis (China National Space Administration, 2020). The institution of the applicant is the legal entity responsible for the agreement for sample allocation. At the same time, the legal entity should have safe storage conditions and research capabilities. LESEC shall accept applications all year round and shall conduct evaluations on the applications once every three months. The approved applicant shall sign the "Lunar Sample Loan Agreement" with the LESEC, and the primary curation center shall issue the allocated samples in accordance with the procedures. The sample preparation and distribution shall be completed within 30 working days, and the relevant information shall be returned to LESEC in a timely manner. For the purpose of research, the sample allocation period will not be generally longer than 1 year. If the sample allocation apply for an extension, an agreement will need to be renewed, the renewal period will be no longer than 6 months, and the application for renewal shall be submitted to the engineering center at least 30 days in advance. Due to the preciousness and uniqueness of the samples, the allocated research samples shall be used sparingly. For destructive experiments, it will be necessary to carefully design a plan to reduce the consumption of samples and document a detailed demonstration and explanation in the sample allocation research plan. For public outreach or education purposes, the sample allocation period will be generally no longer than 2 months. If the sample agreement shall be renewed, the renewal will be no longer than 1 month, and the application for renewal shall be submitted to the LESEC at least 15 days in advance.

The person requesting allocation of a sample (the borrower) will have to maintain a record of the entire process on the samples, and video recording will be requested to ensure the traceability of the use of destructive and consumable samples. The borrowing institution shall accept inspection of facilities by the LESEC and shall not provide the samples to a third party for use. If the borrower violate the provisions of the allocation agreement, the LESEC may terminate the loan and require the immediate return of the sample. When the period of normal use expires, the records and remaining samples of the user shall be returned to the primary curation center. If there are no remaining samples, a complete video record of sample usage shall be provided.

9.4.2 International collaboration

The management and utilization of lunar samples will comply with relevant international conventions. CNSA supports joint science-based research work and promotes the international sharing of scientific results. CNSA is responsible for signing the relevant international cooperation agreements.

The LESEC undertakes and organizes the joint research, exchange, display and allocation of lunar samples, and encourages foreign research institutions and domestic research institutions and universities to set up research teams for joint researches.

9.5 Conclusions

The Chang'e-5 mission is the China's first attempt to collect samples from an extraterrestrial body, as well as the first attempt to collect lunar samples since Luna 24 in 1976, after nearly a half century. Chang'e-5 has landed in Northern Oceanus Procellarum on December 1, 2020, far from previous landing sites and having distinct geological backgrounds and especially young mare basalts. The returned samples could be used to calibrate lunar chronology function by dating the young basalts, trace the lunar magmatic history and disclose the potential genetic link between young volcanism and the PKT terrains, using state-of-art technologies (Qian et al., 2021a). At the same time, China welcomes science teams from all around the world to jointly work to study the new returned samples with Chinese scientists and to promote lunar science toward a big step after Apollo and Luna era.

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