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Innovative developments in lunar and planetary science promoted by China's lunar exploration

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Abstract As the only natural satellite of the earth, the Moon has always been the first choice for human exploration of the solar system. China's lunar exploration project (Chang'e project) was launched in 2004. At present, it has created a perfect end to the three phases of "orbiting, landing and returning". A series of remarkable research achievements have been made on the basic issues of current lunar scientific research, such as the Earth-Moon space environment, lunar surface material, morphology, geological structure, lunar subsurface and internal structure, and the origin and evolution of the Moon, further deepening the human understanding of the Moon. This paper briefly reviews the development process of China's lunar exploration project, summarizes the main research results and scientific understanding, and finally prospects to the future development of China's lunar and planetary exploration.

Keywords Lunar exploration, Lunar science, Chang'e project, Scientific achievements, Future prospects

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1. Introduction

As the only natural satellite of the Earth and the nearest celestial body, the Moon is the first target for the human to move toward the vast universe. Human exploration of the solar system often begins with lunar exploration. Up to now, more than 110 lunar probes have been successfully launched. Among them, the United States has achieved 6 manned lunar landings and obtained a total of 382 kg lunar samples. A series of breakthroughs have been made in major issues of lunar science, which has greatly promoted scientific innovation and technological breakthroughs, led to the progress of high technology and spawned the establishment of a large number of new industrial groups, and advanced economic development and the prosperity of civilization (Liu et al., 2013). Currently, comprehensive scientific exploration and resource exploitation of the Moon have become the inevitable trend and competitive hotspot of the world's space activities, which will certainly better enhance human scientific knowledge, expand human living space, and serve the sustainable development of human society (Pei et al., 2020).

Chinese scientists and technicians have always wished to explore the Moon and move towards deep space, with the scientific pursuit and the dream of a powerful country. The development of artificial earth satellites and the successful implementation of manned space projects have enabled China to timely carry out deep space exploration, of which lunar exploration is the main activity. In 1993, China embarked on a comprehensive program of scientific objectives and engineering realization for lunar exploration. Over the course of this decade-long endeavor, an idea was proposed to divide China's lunar exploration into three phases, namely

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the unmanned lunar exploration, the manned lunar exploration, and the construction of a lunar base to develop and utilize the Moon. The first phase, i.e., unmanned lunar exploration, is divided into “orbiting, landing and returning”, specifically including the “orbiting” lunar exploration project, to achieve a global, integrated and comprehensive exploration of the Moon; the “landing” exploration project, to achieve a soft landing on the Moon, *in-situ* exploration and inspection survey on the lunar surface; and the last exploration project to achieve automatic sampling of lunar samples and safe return to the Earth (Ouyang, 2005).

Up to now, China has successfully completed the “orbiting”, “landing”, and “returning” phases of the unmanned lunar exploration project, obtaining a large amount of scientific exploration data, and providing valuable first-hand basic information for scientific research. China’s lunar scientific exploration has been transformed from investigative and follow-up research to independent research and free exploration, resulting in fruitful research results (Li et al., 2020). As of April 2022, more than 800 scientific papers related to or using Chang’e data have been published according to the statistics of the Web of Science, covering all areas specified in the scientific objectives of the first phase of China’s lunar exploration project.

This paper will review the development process of China’s lunar exploration project and focus on summarizing the research progress and scientific understanding on three fundamental lunar science issues, including the lunar surface environment and the Earth-Moon space environment, the lunar subsurface structure and internal structure, and the origin and evolution of the Moon, as well as their contribution to the development of lunar and planetary science.

2. The development of China’s lunar exploration project

2.1 Scientific proof

In 1989, the United States’ plan to return to the Moon caused a strong response in China. In 1994, under the leadership of astrochemist Ouyang Ziyuan and space exploration expert Chu Guibai, China’s first complete “Necessity and Feasibility Study Report of China’s Lunar Exploration” was completed. In 1998, with the support of the National High-tech R&D Program of China (863 Program), experts from the Institute of Geochemistry, Chinese Academy of Sciences, the Center for Space Science and Applied Research, Chinese Academy of Sciences, and other units jointly completed the “Research on the Development Strategy and Long-term Planning of China’s Lunar Exploration”, which proposed a general plan for the development of China’s lunar exploration. With Ouyang Ziyuan as the chief scientist, a research report on “Scientific Objectives and Payload Configuration of China’s First Lunar Resource Exploration Satellite” was completed, which proposed the idea of “orbiting, landing and returning” lunar exploration that was widely accepted as a national development strategy and became the design input for the lunar exploration project. In November 2000, the white paper “China’s Space” officially announced the “pre-research on deep space exploration based on lunar exploration” as one of the goals of China’s space development in the near future. In 2001, the Chinese Academy of Sciences launched the “Research on Key Science and Technology of Lunar Exploration” with Ouyang Ziyuan as the chief scientist, and completed the scientific demonstration of the first phase of the lunar exploration project in China and the pre-study of the scientific objectives and payloads of the subsequent second and third phases of the project. In December 2002, under the leadership of Sun Jiadong, a comprehensive project demonstration of the first phase of the lunar exploration project was carried out with the scientific objectives as the starting point, involving satellites, launch vehicles, measurement and control, launch sites and ground applications. The demonstration provides a detailed and comprehensive analysis of the overall scheme and key technologies, and formed the overall implementation plan of the lunar exploration project. In April 2003, the key technology research of the lunar exploration project was carried out. In January 2004, the first phase of China’s lunar exploration project, that is, the “lunar orbiting exploration project” (code name “Chang’e project”) was formally established, and China’s lunar exploration project officially entered the implementation phase. (Liu et al., 2013; Ouyang and Li, 2015).

2.2 Lunar orbiting exploration

China’s lunar orbiting exploration includes two missions of Chang’e-1 and Chang’e-2. The scientific objectives are to obtain three-dimensional images of the lunar surface, analyze the distribution characteristics of the main element content and material types on the lunar surface, detect the properties of lunar regolith, and detect the Earth-Moon space environment, configured with eight and seven scientific payloads respectively (seen in Table 1).

Chang’e-1 probe was launched at Xichang Satellite Launch Center on October 24, 2007, becoming China’s first lunar probe. On November 20, 2007, the CCD (Charge-coupled Device) stereo camera was successfully switched, marking the beginning of China’s extraterrestrial scientific exploration. Chang’e-1 flew in orbit for a total of 494 days, completing all the scheduled scientific exploration missions and space technology test missions. On March 1, 2009, it successfully completing its historical mission by impacting into the area of Mare Fecunditatis on the nearside of the Moon under control.

Table 1 Scientific objectives and scientific payloads of China's lunar exploration project

Missions	Scientific objectives	Scientific payloads
Chang'e-1	(1) obtaining 3D images of the lunar surface (2) mineralogy and chemical composition investigation of lunar surface (3) characteristics investigation of lunar soil, estimation of the thickness of lunar soil and the amount of helium-3 resources (4) Earth-Moon space environment exploration	CCD stereo camera, laser altimeter, Interference Imaging Spectrometer, X-ray spectrometer, γ-ray spectrometer, High-energy particle detector, Microwave radiometer, Solar Wind Ion Detector A total of 8 payloads
Chang'e-2	(1) obtaining 3D image of the lunar surface with a resolution better than 10 m (2) composition investigation of lunar material (3) characteristics investigation of lunar soil (4) Earth-Moon and near-Moon space environment exploration	CCD stereo camera, laser altimeter, X-ray spectrometer, γ-ray spectrometer, High-energy particle detector, Microwave radiometer, Solar Wind Ion Detector A total of 7 payloads
Chang'e-3	(1) investigation of the morphological features and geological structures of the landing area (2) integrated *in-situ* analysis of mineral and chemical composition of the landing area (3) exploration of the Earth-Moon space environment and lunar-based astronomical observations	Lander: Landing camera, Terrain Camera, Moon-based ultraviolet telescope, Extreme ultraviolet camera Rover: Panoramic Camera, Visible and Near-infrared Spectrometer, Lunar Penetrating Radar, Active Particle Induced X-ray Spectrometer A total of 8 payloads
Chang'e-4	(1) low-frequency radio astronomical observation on the lunar surface; (2) the topographic and the mineralogical composition investigation on the lunar far side; (3) shallow structure investigation on the lunar far side of roving area; (4) research on neutron radiation dose and neutral atoms on the farside of the Moon	Lander: Landing camera, Terrain Camera, Lunar Lander Neutrons & Dosimetry, Low-Frequency Radio Spectrometer, Rover: Panoramic Camera, Lunar Penetrating Radar, Visible and Near-infrared Imaging Spectrometer, Advanced Small Analyzer for Neutrals A total of 8 payloads
Chang'e-5	(1) *In-situ* investigation and analysis of the landing area. Detection of the regional topography of the landing site, investigation of its geological background, acquisition of on-situ analysis data related to lunar samples, and association of on-situ detection data with laboratory analysis data (2) Lunar sample analysis and research. Systematic and long-term laboratory studies of lunar samples, analysis of lunar soil structure, physical properties, and material composition, deepening the study of lunar genesis and evolutionary history	Landing camera, Panoramic camera, Lunar Mineralogical Spectrometer, Lunar Regolith Penetrating Radar A total of 4 payloads

The Chang'e-2 probe, a backup satellite of Chang'e-1, was launched on Oct. 1, 2010, and completed the scheduled lunar scientific exploration missions and technical tests during more than seven months of scientific exploration around the Moon. In June 2011, Chang'e-2 flew out of lunar orbit to the second Lagrange point (L2 point), 1.5 million kilometers away, and carried out 235 days of space environment exploration. In June 2012, Chang'e-2 flew away from the L2 point again and encountered the asteroid 4179 Toutatis at a distance of 7.06 million kms from Earth on December 13, 2012, achieving the first close flyby of this asteroid (Huang et al., 2013; Zou et al., 2014; Zhu et al., 2014; Jiang et al., 2015). Subsequently, Chang'e-2 becomes a small artificial object orbiting the Sun, and will re-enter the Earth's proximity orbit around 2029.

2.3 Lunar soft landing exploration

China's lunar landing exploration is an exploration mission targeting lunar scientific *in-situ* and roving exploration on the lunar surface, including two missions of Chang'e-3 and Chang'e-4, which are equipped with 8 and 9 scientific payloads, respectively (seen in Table 1). The Chang'e-3 probe (including lander and rover, namely "Yutu" lunar rover) was launched from Xichang on December 2, 2013, and successfully landed in the northwestern part of Mare Imbrium at 19.51°W, 44.12°N on December 14, realizing the first soft landing of China on an extraterrestrial body. After landing, the Yutu rover and the lander respectively carried out scientific exploration of the lunar surface, *in-situ* investigated the lunar surface morphology, geological structure and subsurface structure, analyzed the chemical and mineral composition of the lunar surface materials, carried out the monitoring of the Earth's plasma layer and lunar-based optical astronomical observation, and achieved significant innovative results in "lunar measurement, earth observation and sky survey".

The Chang'e-4 probe was launched in Xichang on December 8, 2018, and successfully landed in the Von Kármán crater on the lunar farside on January 3, 2019. For the first time in the world, Chang'e-4 achieved continuous and reliable relay communication between the farside of the Moon and the Earth, autonomous obstacle avoidance and high-precision landing on the complex and rugged terrain of the farside of the Moon (Wu et al., 2020), pioneering the history of soft landing and scientific exploration on the farside of the

Moon for humans. As of April 8, 2022, Chang'e-4 lander and Yutu-2 lunar rover have completed 41 lunar days of exploration work, spent 1192 Earth days on the farside of the Moon. The Yutu-2 rover has traveled about 1142 m, obtaining a large amount of scientific data. The landing site of Chang'e-4 is located in the South Pole-Aitken (SPA) basin on the lunar farside, which has unique advantages in deep lunar material detection and low-frequency radio astronomical observation, and has achieved original scientific results (Li et al., 2019a).

2.4 Lunar sample returning

The mission of the third phase of China's lunar exploration project is to launch Chang'e-5 and Chang'e-6 probes, achieve the lunar sample returning. The scientific objectives of lunar sample returning include two independent but interlinked tasks, namely, *in-situ* investigation and analysis of the landing area, and analysis and research of lunar samples in the laboratory, in which the landing site area topography, geological background detection and *in-situ* analysis of lunar surface materials can obtain *in-situ* analysis data related to lunar samples, thus providing a basis for establishing the correlation between *in-situ* detection data and laboratory analysis data. Chang'e-5 was equipped with 4 scientific payloads (seen in Table 1) to complete the geological background detection and analysis of the lunar surface sampling sites.

The Chang'e-5 probe was launched in Wenchang, Hainan on Nov. 4, 2020, and landed on Dec. 1 in the pre-selected landing area in the northeastern part of Oceanus Procellarume on the lunar nearside. On Dec. 17, the Chang'e-5 returner carried the sample back to the ground successfully, collecting 1731 g lunar samples. Chang'e-6 is expected to be launched in 2024 and will realize the collection and return of samples on the back of the Moon for the first time.

It can be seen that the scientific objectives of the three phases of China's lunar exploration project, namely "orbiting, landing and returning", are closely focused on the lunar scientific issues such as the lunar surface environment and the Earth-Moon space environment, the internal structure of the Moon, the origin and evolution of the Moon, and so on. The successful implementation of the lunar exploration project demonstrates China's ability to carry out scientific exploration of the Moon and will make important contributions to promoting the in-depth understanding of the Moon.

3. Lunar surface environment and Earth-Moon space environment

3.1 Lunar topography and geological structure

The surface morphology and geological structure of the Moon have always been an indispensable and important part for lunar exploration. Based on the image data and topographic data of the lunar surface, the identification and division of the lunar surface geographical units, basic tectonic and geological units, the measurement and analysis of the shape, size, distribution and density of the craters can be carried out. These data are the basic information for human to understand the evolution history of the lunar surface and the internal structure of the Moon. Abundant image data have been acquired by China's lunar exploration project during the lunar orbiting and *in-situ* exploration, and various types of global and regional lunar image maps and topographic datasets have been developed (Li et al., 2010, 2012, 2014a; Li, 2013), which accurately portray the lunar surface topographic features, geographic units and geological formations. The global lunar topographic dataset (CE-2TMap2015; Figure 1), developed based on the photogrammetry using 384 orbital image strips acquired by the Chang'e-2 two-linear CCD stereo camera from October 24 and May 20, 2010, covers three different resolution types of 7, 20, and 50 m, and achieves a seamless mosaic and high-precision positioning over the whole lunar range (Li et al., 2018b; Ren et al., 2019). The 7 m resolution lunar global Digital Orthophoto map (DOM) and topography data remains the highest spatial resolution lunar global digital product in the world, and is the basic data for studying the lunar topography, geology, tectonics and volcanism history.

Based on the CE-2TMap2015 dataset, a number of scientific researches related to lunar surface topography and geological structures have been carried out. For example, 39 domes were identified in the Cauchy region, among which 11 new domes not yet included in the current database were discovered, enhancing the understanding of lunar volcanism (Liu et al., 2019b); The topography, geomorphology, geology and lunar dust of the Chang'e-3 landing site and its surrounding area are comprehensively analyzed. The regional topographic features and geological characteristics of the landing site are studied, and the scientific criteria and strategies for landing area selection were validated and formed (Li et al., 2014b).

The high-precision topographic data obtained by Chang'e project also plays an important role in lunar mapping, topographic research and engineering applications. Based on the CE-2TMap2015 dataset and landing camera images, the precise positioning of Chang'e-3 and Chang'e-4 landing sites was realized, and the accuracy reached the existing international advanced level. The precise positioning of Chang'e-3 landing site was used to establish a northernmost high-precision lunar surface absolute control point on the lunar surface, effectively expanding the spatial range of the current lunar surface control network (Figure 2). The control area increased from about 1.23 million km^2 to about 1.5 million km^2 (an increase of 22%. Liu et al., 2014; Wang et

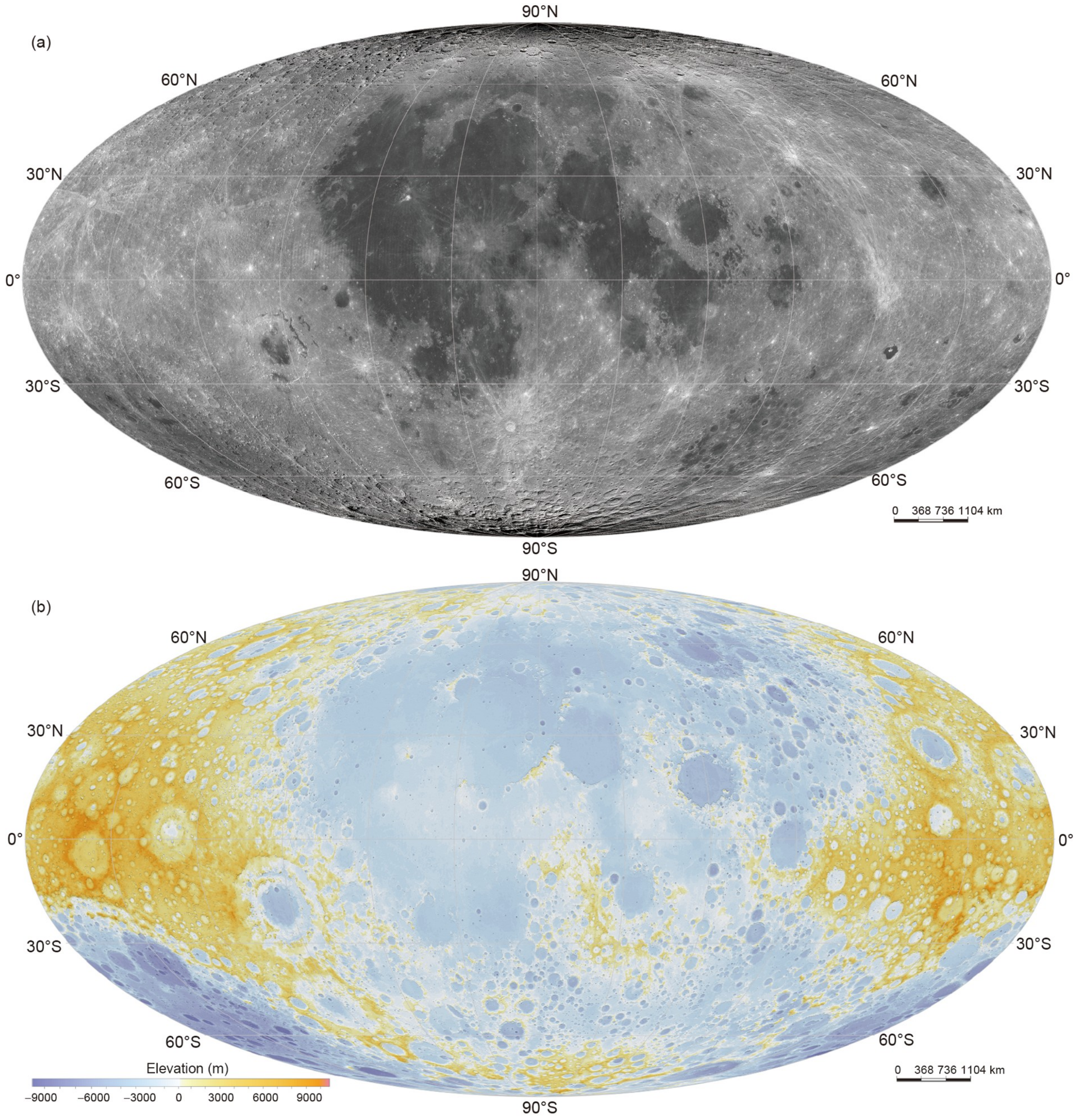


Figure 1 The orthophoto images (a) and topographic data (b) of Chang'e-2 covering the whole Moon with a resolution of 7 m (Li et al., 2018b; Ren et al., 2019).

al., 2014). The powered descent of Chang'e-4 probe on the lunar farside and the precise positioning of the landing site are mainly depended on the CE-2TMap2015 dataset too. Using the images obtained by the landing camera and the CE-2TMap2015 dataset, the autonomous navigation landing process of Chang'e-4 such as coarse obstacle avoidance, fine obstacle avoidance and hovering obstacle avoidance, was reconstructed detailed (Figure 3a–3c). Since the ground observation equipment is not visible to the lunar farside, it is impossible to perform the direct radio measurement. On the other side, the telemetry data of the probe are also very limited. These factors bring great difficulties to the descent trajectory reconstruction of the probe and accurate positioning of the landing site. The accurate location of the Chang'e-4 probe on the lunar farside was finally achieved by photogrammetry (Figure 3d and 3e), which provides background information and position reference for the scientific exploration of Chang'e-4 lander and Yutu-2 lunar rover, and becomes the first mapping control point on the lunar farside (Liu et al., 2019a).

3.2 Lunar surface composition

Lunar surface material is the most direct object to study the

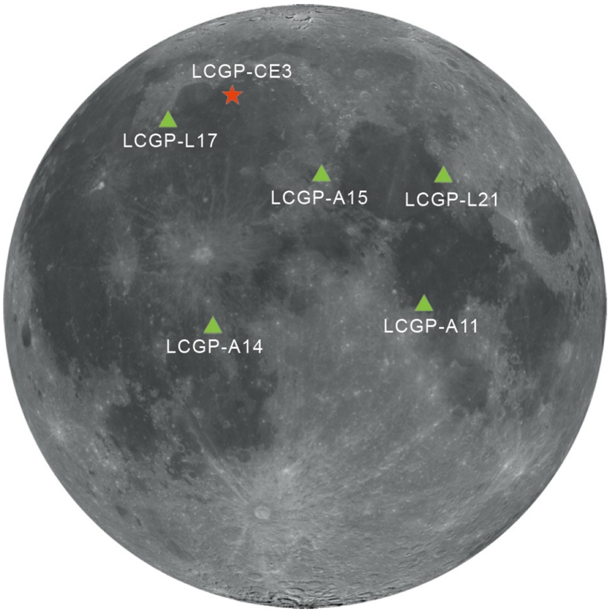


Figure 2 An absolute control point on the lunar surface using Chang'e-3 landing site (Wang et al., 2014).

formation and evolutionary history of the Moon. Obtaining the chemical composition of lunar surface materials, as well as mineral composition, rock types and their distribution patterns is the most basic work of lunar science.

Remote sensing is an important means to obtain the global scale composition lunar surface. The Chang'e-1 Interference Imaging Spectrometer acquired 706 orbits of effective data, and high-resolution distribution maps of six major elements on the lunar surface were obtained, including Fe, Ti, Mg, Al, Ca, and Si, as well as the Mg# (Figure 4; Wu, 2012), among which, the global distribution map of Mg# is the first result completed internationally, which can be widely used to determine the crustal heterogeneity of lunar highlands, search for high-alumina (HA) basalts, and assess the average elemental abundance of the stratigraphy and the whole moon, helping to further understand the origin and evolution of the Moon. The results show that the average elemental abundance in the lunar highlands is in the order of SiO_2>Al_2O_3>CaO>MgO>FeO>TiO_2, while for the lunar mare, the order is SiO_2>FeO>Al_2O_3>CaO>MgO>TiO_2. The Chang'e-1 γ-ray spectrometer acquired 1103 orbits of detection data, analyzed and mapped the global lunar distribution of U, K, and TH and other elements with a resolution of 150 km ×150 km (Zou et al., 2011), which is of great significance for studying the distribution of KREEP materials on a global scale, especially in large basin regions, and understanding the history of lunar impact and volcanism. According to the observation data of Chang'e-2 γ-ray spectrometer, a new distribution map of K element on the whole Moon was further obtained (Figure 5). The distribution map shows that the global average abundance of K element is 620±615 ppm (1 ppm=1 $\mu g\ g^{-1}$) with the upper limit of 3240 ppm, which is in general agreement with Lunar Prospector (LP), Kaguya and Chang'e-1 measurements. At the same time, it is pointed out that the abundance of K element is relatively high in the Mare Crisium and Mare Orientale (Zhu et al., 2013).

Lunar surface *in-situ* detection can expand and improve the global-scale research results in terms of detection accuracy and research depth, which promote the high integration of global knowledge and local precise understanding, and realize the sublimation of scientific and rational understanding. The comprehensive research of the Active Particle-induced X-ray Spectrometer (APXS) and Visible and Near-infrared Imaging Spectrometer (VNIS) data on Chang'e-3 Yutu rover has obtained the chemical composition and mineralogical information of lunar soil and rocks in the landing site and found that the rocks near "GuangHanGong" are a new type of mare basalt containing relatively abundant olivine and ilmenite, making the Chang'e-3 landing site is a new calibration site for lunar remote sensing research (Figure 6; Ling et al., 2015). The Chang'e-4 Visible and Near-infrared Imaging Spectrometer (VNIS) realized the *in-situ* spectral detection of the lunar farside for the first time (Li et al., 2019a; Gou et al., 2019; Huang et al., 2020; Lin et al., 2020). Among them, the reflectance spectra in the 0.4–2.4 μm band obtained by the VNIS of Chang'e-4 rover were used to find a combination of low-calcite pyroxene and olivine at the landing site, which may represent deeper material originating from the lower lunar crust or even the lunar mantle (Figure 7; Li et al., 2019a). These "unexpected" discoveries have updated our understanding of the composition, distribution, and volcanism of the Moon.

The Laboratory analysis and research on Chang'e-5 samples have further quantitatively measured the material composition of the lunar soil and can serve for the understanding of lunar chronology. A large amount of comprehensive analysis and research on the basic characterization of Chang'e-5 lunar samples have been carried out (Li et al., 2022; Zhang et al., 2022; Guo et al., 2022; Gu et al., 2022; Mo et al., 2022), which greatly promoted the development of sample processing and analysis techniques in China. The preliminary results found that the mineral composition of Chang'e-5 lunar soil is mainly plagioclase, pyroxene, olivine, titanite and glassy substances, among which plagioclase is characterized by high calcium content of peperite, pyroxene is mainly common pyroxene, followed by variable pyroxene and almost no plagioclase; olivine is mainly iron peridotite, and the content of glassy substances is low (relative to Apollo lunar samples), only about 20%. Chemically, the Chang'e-5 lunar samples exhibit low SiO_2 and alkaline element contents, moderate TiO_2 and Al_2O_3, and high FeO contents, while K, U, Th, and REE contents are all lower than those of KREEP material, representing a potentially young, "new" type of differentiated lunar sea basalts (Figure 8; Li et al., 2022).

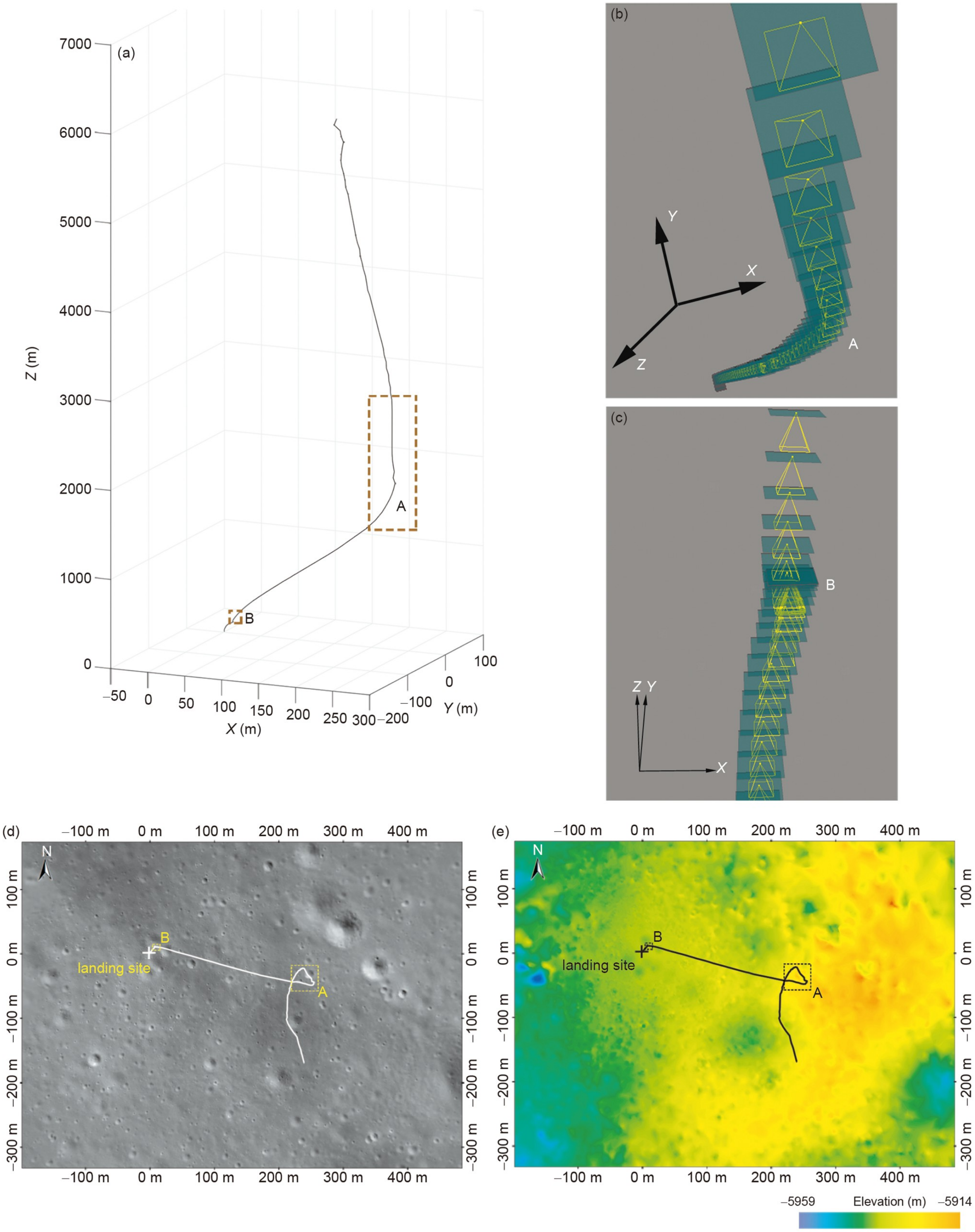


Figure 3 The powered descent trajectory of Chang'e-4 lander and the positioning results (Liu et al., 2019a). (a) The Chang'e-4 descent trajectory from the altitude of 6000 m to the lunar surface; (b) and (c) are zoomed images of the descent trajectories of A and B, respectively. The green box represents the position of the Landing camera (LCAM) focal plane, and the yellow cone represents the field of view of the LCAM. The solid white line in (d) is the projection of the descent trajectory on the LCAM DOM. The solid black line in (e) is the projection of the descent trajectory on the LCAM DEM.

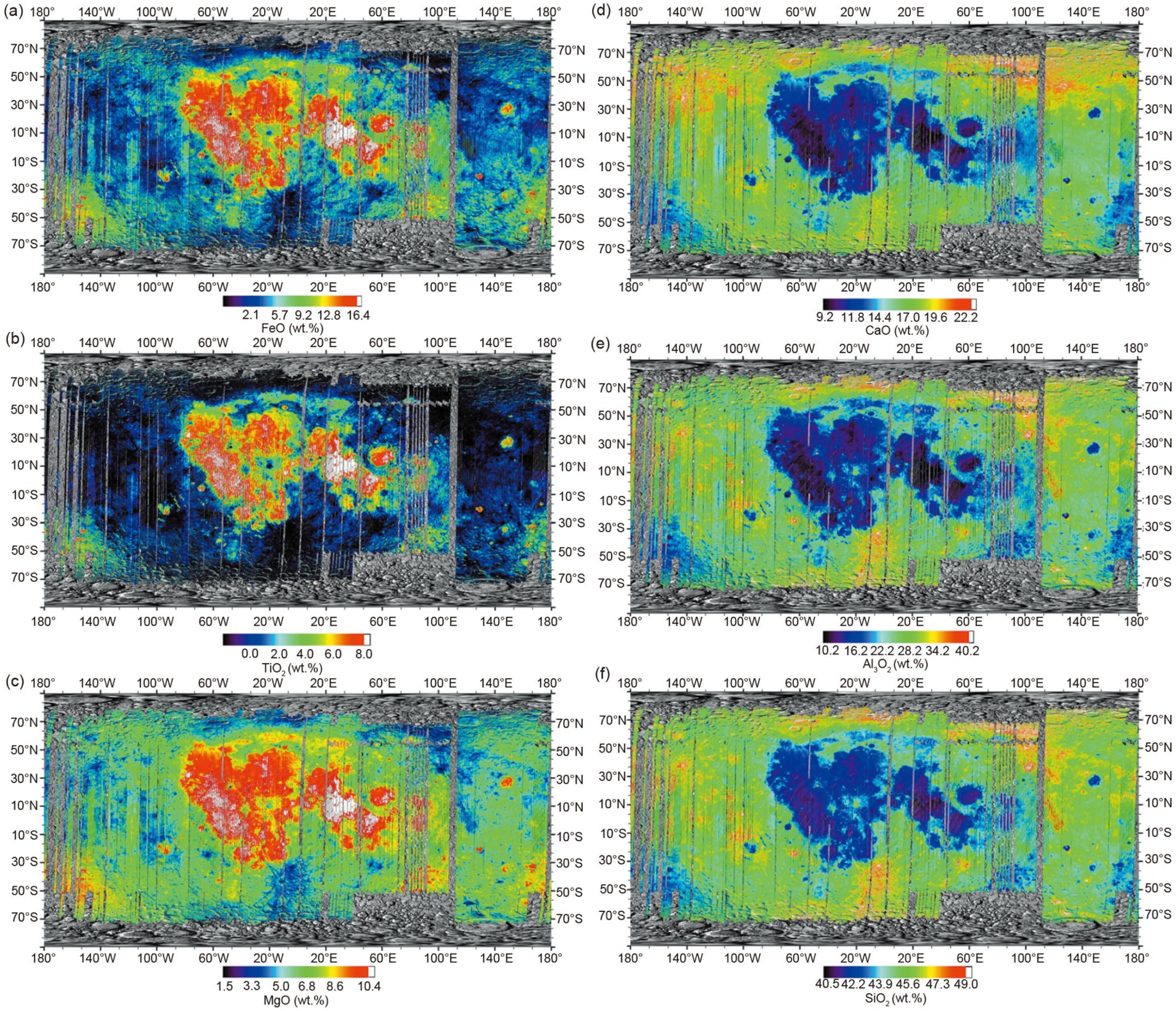


Figure 4 Equidistant cylindrical maps of 6 major elemental abundances (Wu, 2012).

3.3 Microwave properties of lunar soil

Lunar soil can record the radiation history of the Sun through its interaction with the solar wind, which provides a convenient way to study the exposure age of lunar material, the evolution of solar activity, and the influence of the Sun on the Earth's climate change. The study of lunar soil is also helpful to understand the material composition of the whole Moon, even the distribution of rock types. The distribution of craters, and the thickness and maturity of lunar soil can provide a basis for the studies such as lunar material exposure age and impact dating. The thickness data of lunar soil can be obtained by microwave radiation technology, which provides information for further study of the lunar material composition. Chang'e-1 was equipped with a microwave radiometer to measure the natural microwave radiation on the lunar surface. By measuring brightness temperature (TB) data at different frequencies, the distribution and properties of lunar soil were analyzed. Chang'e-1 microwave radiometer has obtained 1690 orbit detection data, including microwave radiation data of the whole Moon in four frequency bands of 3.0, 7.8, 19.35 and 37.0 GHz, with a spatial resolution of several tens of kilometers. It is the first time to study the "microwave moon" in the world, and the distribution and thickness change of the lunar regolith layer on the surface of the whole moon were obtained (Figure 9), while the distribution and total amount of helium-3 resources in the lunar soil were estimated (Zheng et al., 2012). From the microwave brightness temperature distribution map, the main geological units on the Moon such as highlands, mare,

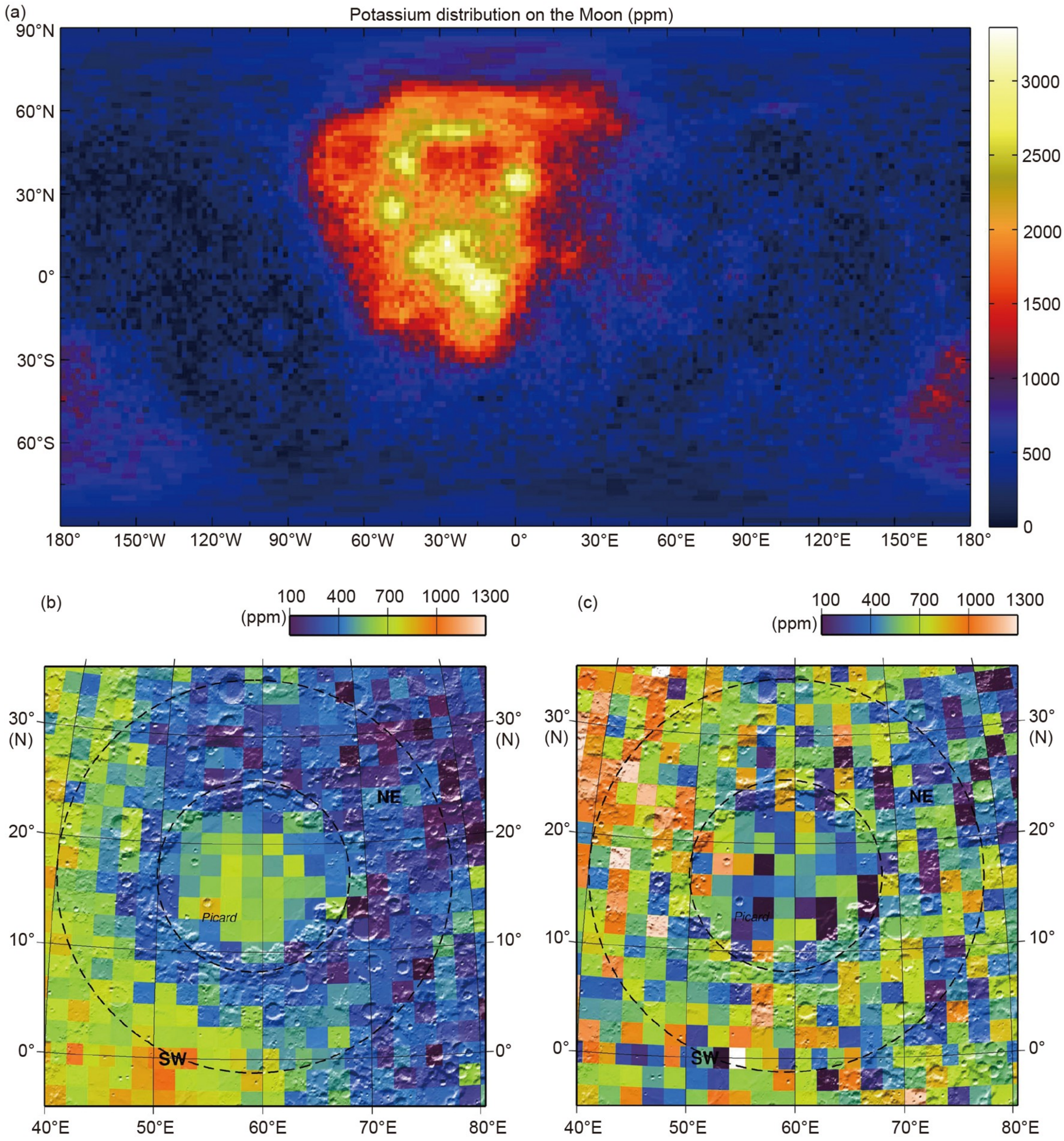


Figure 5 The global K abundance (unit: ppm) of the Moon from CE-2 GRS measurements (a), and the K distributions of the 550-km-diameter Crisium Basin from CE-2 GRS (b) and LP GRS (c) (Zhu et al., 2013).

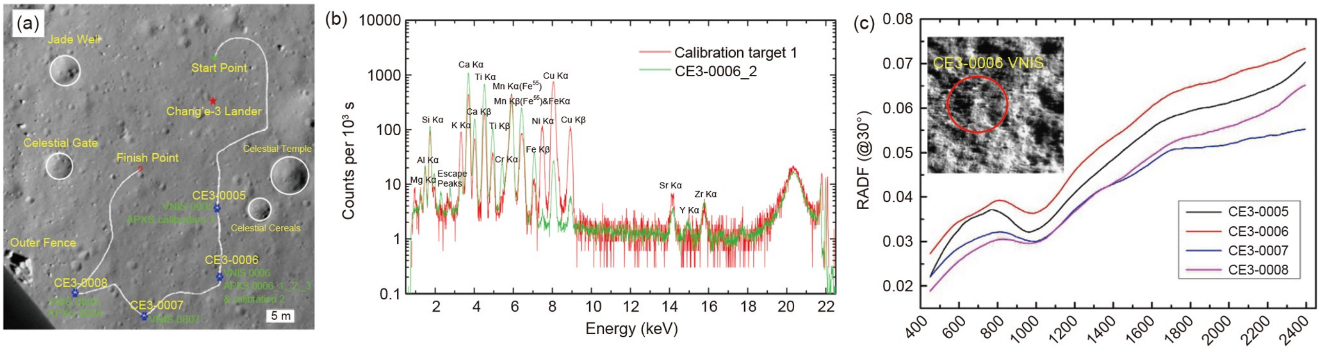


Figure 6 The traverse map of Yutu rover on the lunar surface and *in-situ* detection data of material composition (Ling et al., 2015). (a) The traverse map of the Yutu rover and the locations of APXS and VNIS measurements; (b) APXS spectrum CE3-0006_2 overlain on the calibration spectrum. (c) Combined VNIS spectra (450–2,400 nm) from sites 0005, 0006, 0007 and 0008. The inset image is from site CE3-0006 of the VNIS (450–950 nm) image mode at 750 nm.

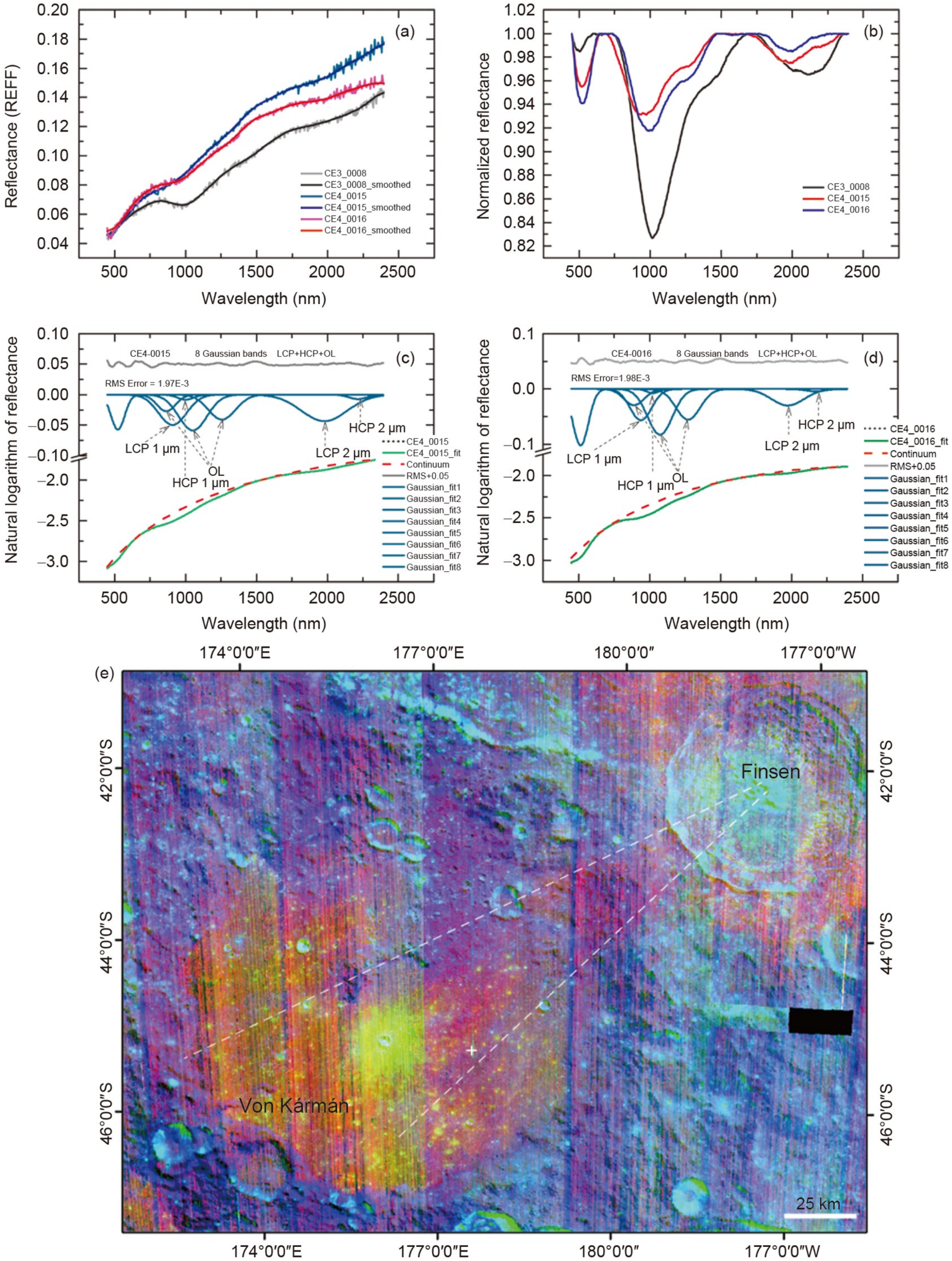


Figure 7 Spectral detection results of Chang'e-4 landing area (Li et al., 2019a). (a) Reflectance (REFF) spectra were obtained by Chang'e-4 VNIS (CE4_0015 and CE_0016) and the Chang'e-3 VNIS detection point (CE3_0008). (b) Continuum-removed spectra of (a). (c) and (d) MGM-fitting results for CE4_0015 and CE4_0016 using endmember LCP, HCP and olivine. (e) Distribution of Finsen ejecta in the Von Kármán crater (M^3 colour composite)

and large craters can be clearly distinguished, indicating that there is a significant correlation between the distribution of lunar brightness temperature and the distribution of material components, and is affected by topography. The mare is mainly distributed with basalt, with a relatively high brightness temperature, while the highlands is distributed with plagioclase, with a relatively low brightness temperature.

In-situ exploration provides a better opportunity for the study of lunar soil maturity. Based on the topographic data collected by the Yutu-2 rover, the effect of the interaction between the rover wheels and lunar soil was studied. The

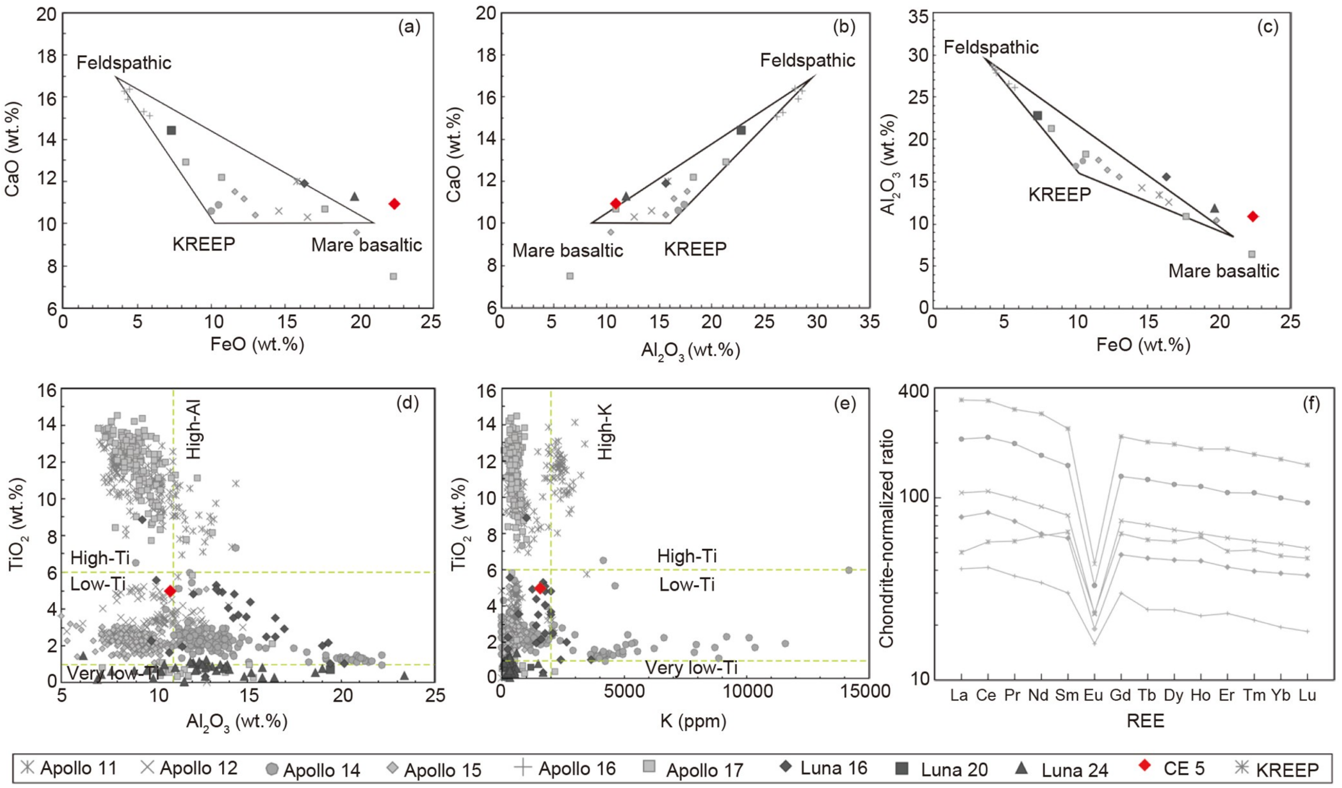


Figure 8 The chemical composition of Chang'e-5 lunar soils compared with Apollo and Luna collections (Li et al., 2022). (a)–(c) Elemental variations of Al_2O_3, CaO and FeO; (d), (e) TiO_2, Al_2O_3 and K classification scheme of mare basalts; (f) chondrite-normalized concentrations of rare-earth element (REE) in lunar soils as a function of an REE atom.

results can reflect the difference in the strength of lunar soil in the landing area of Chang'e-4 and Chang'e-3, which may indicate a great relationship with morphology and spatial weathering (Tang et al., 2020). The Chang'e-4 landing site is located in the area within the Von Kármán crater, which is covered by ejecta from nearby craters and has a high degree of lunar soil maturity.

Laboratory samples analysis, especially the comprehensive study of petro-mineralogical characteristics and whole-rock chemical composition of samples from different layers of lunar soil, is expected to obtain a new understanding of the formation and evolution of lunar soil. Studies of Chang'e-5 lunar samples (Li et al., 2022; Zhang et al., 2022; Guo et al., 2022; Gu et al., 2022; Mo et al., 2022; Xi et al., 2022) indicate that 95% by weight of particles in Chang'e-5 lunar soil are distributed in the range of 4.84–432.27 μm (mean 49.80 μm), showing a high degree of maturity. The stacked density of Chang'e-5 lunar sample is only about 1.2389 g cm^{-3}, but the true density can reach 3.1952 g cm^{-3} and the specific surface area is 0.56 m^2 g^{-1}, indicating that the lunar soil sample is very loose.

3.4 Moon-Earth space environment

Chang'e-1 and Chang'e-2 probes were both equipped with a high-energy particle detector and solar wind ion detector for the detection of the Moon-Earth and near-Moon space environments. The Chang'e-1 solar wind ion detector detected the acceleration of particles at the day-night interface between the lunar poles (Wang et al., 2010), which revealed the physical process of solar wind plasma on the lunar surface and its interaction with the Moon. the spectral data obtained by the Chang'e-2 solar wind ion detector on four lunar orbits identified a region of decreased proton density and increased temperature in the near lunar plasma environment, indicating that there may be a micro-magnetic layer in the peri-lunar space with magnetic field anomalies that can effectively shield and heat the incident solar wind protons (Figure 10; Wang et al., 2012). This discovery provides a new important reference for the study of the lunar space environment as well as the lunar evolution.

The Chang'e-3 extreme ultraviolet camera has conducted a full-scale and long-term monitoring of the 30.4 nm radiation generated by the Earth's plasma layer, fully observed the overall range of the Earth's plasma and its variation characteristics, and obtained the three-dimensional image of the Earth's plasma layer (Feng et al., 2014). In addition, observations revealed that under the influence of magnetosphere substorms, the boundary of the Earth's plasmasphere would bulge, which revealed the influence of solar activity

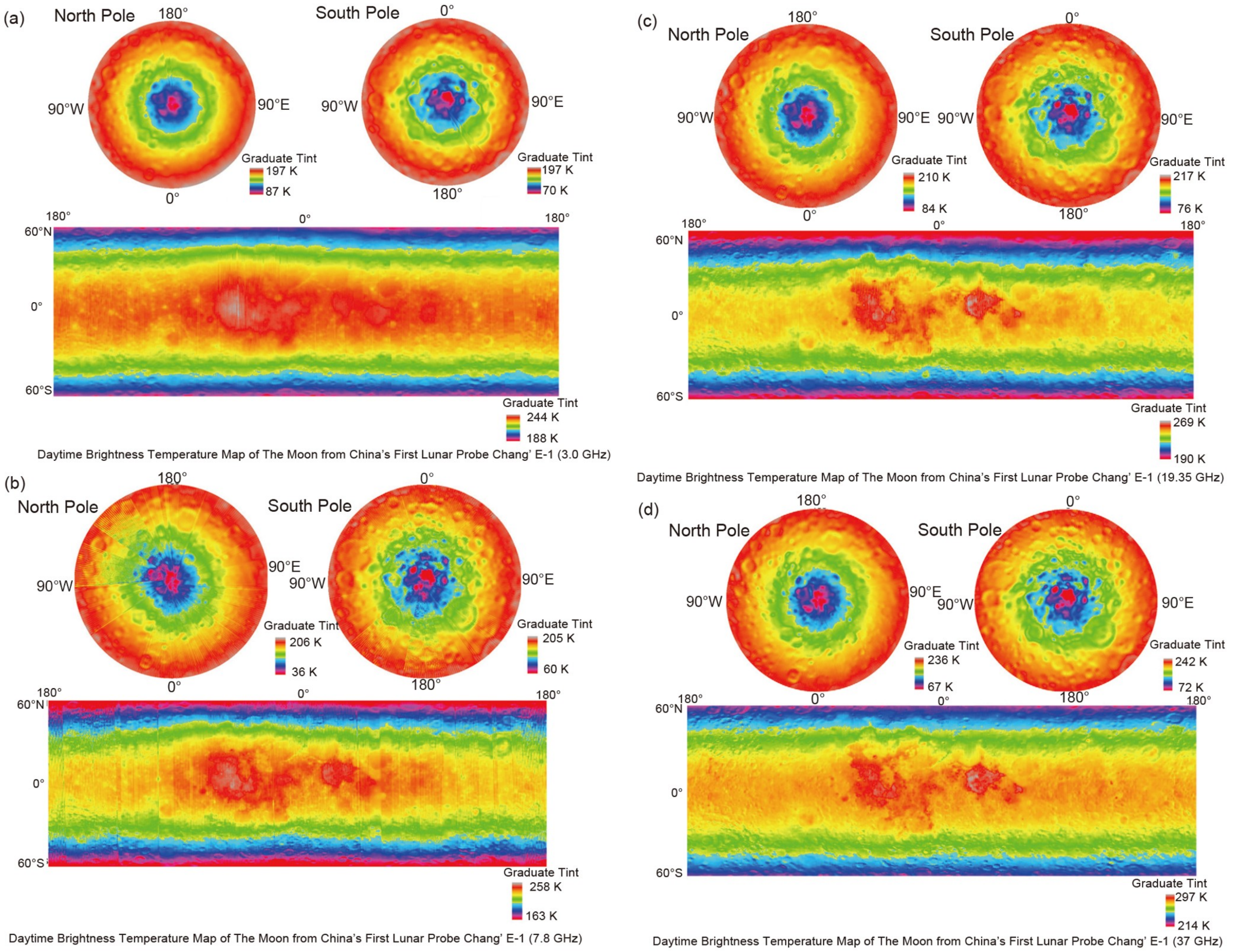


Figure 9 Daytime (noon) brightness temperature images of the Moon for the four channels at 3.0, 7.8, 19.35, 37.0 GHz respectively (Zheng et al., 2012).

on the Earth's space environment, and confirmed the scale of the Earth's plasma layer and its inverse correlation with the intensity of geomagnetic activity. A new view is proposed that the spatial structure of the plasma layer is constrained and controlled by the Earth's magnetic and electric fields (Figure 11; He et al., 2016).

The Chang'e-4 mission has experimentally carried out the detection and research of the particle radiation environment on the lunar farside. The Lunar Lander Neutrons & Dosimetry observed strong radiation on the lunar farside (Zhang S Y et al., 2020), and Advanced Small Analyzer for Neutrals found that the flux of neutral atoms below 0.1Esw (the solar wind ion energy) was significantly higher than the results of previous remote sensing observations (Zhang A B et al., 2020), which provided an important support for the studies of the interaction between the solar wind and the lunar surface, and promoted the evaluation and protection design of the lunar radiation hazard.

The Chang'e-3 Moon-based ultraviolet telescope has carried out long-term optical variation monitoring on eight occultation binaries and the RR variable star in Lyrae (Li et al., 2015), and obtained the latest value of the upper limit of hydroxyl (water) density in the lunar exosphere. It was found that the lowest upper limit of hydroxyl (water) density in the lunar exosphere is 10^4 cm^{-3}, which is the lowest upper limit value of hydroxyl density in the lunar exosphere obtained so far (Wang et al., 2015). It was of great significance for the study of the content of lunar material water, escape, and near-moon space environment.

4 Subsurface structure and internal structure of the Moon

The exploration of the lunar internal structure not only provides a clearly understand the state, structure and composition of the Moon, but also provides the most reliable and direct evidence for understanding the origin and evolutionary

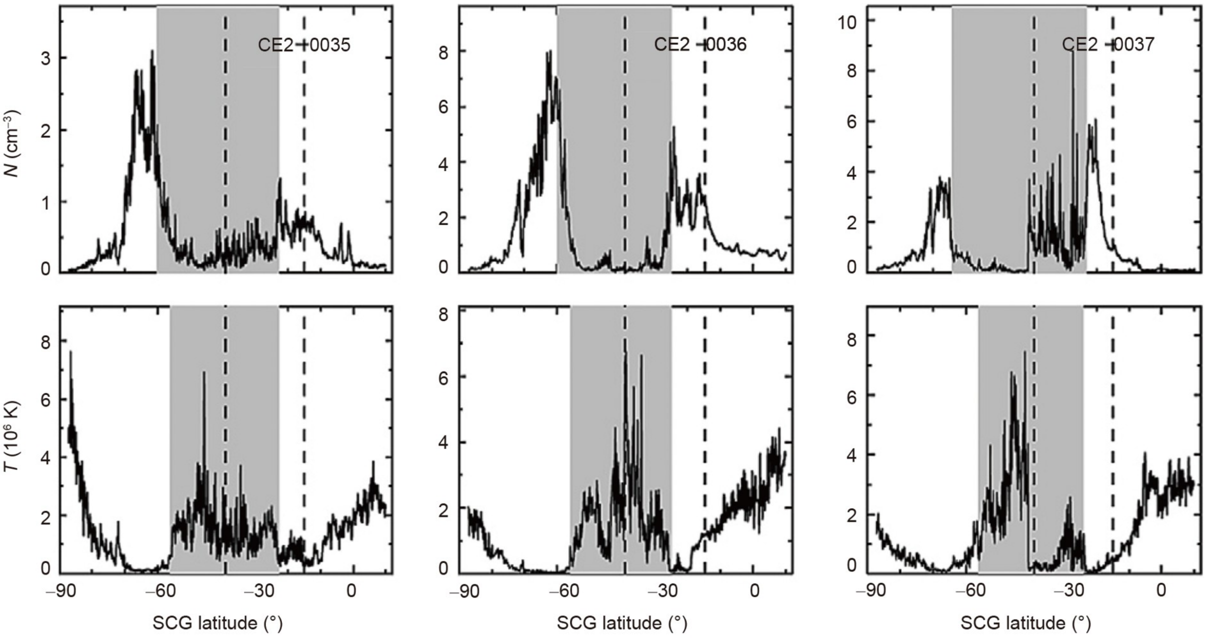


Figure 10 The existence of the lunar surface micromagnetosphere confirmed using scientific data from the Chang'e-2 satellite solar wind ion detector (SWID) (Wang et al., 2012). The profiles of proton density (upper panels) and temperature (lower panels) as a function of Selenocentric Geographic (SCG) latitude obtained from several Chang'e-2 lunar orbits near the proton cavity. The shadowed regions show apparent decrement in proton density and enhancement in proton temperature.

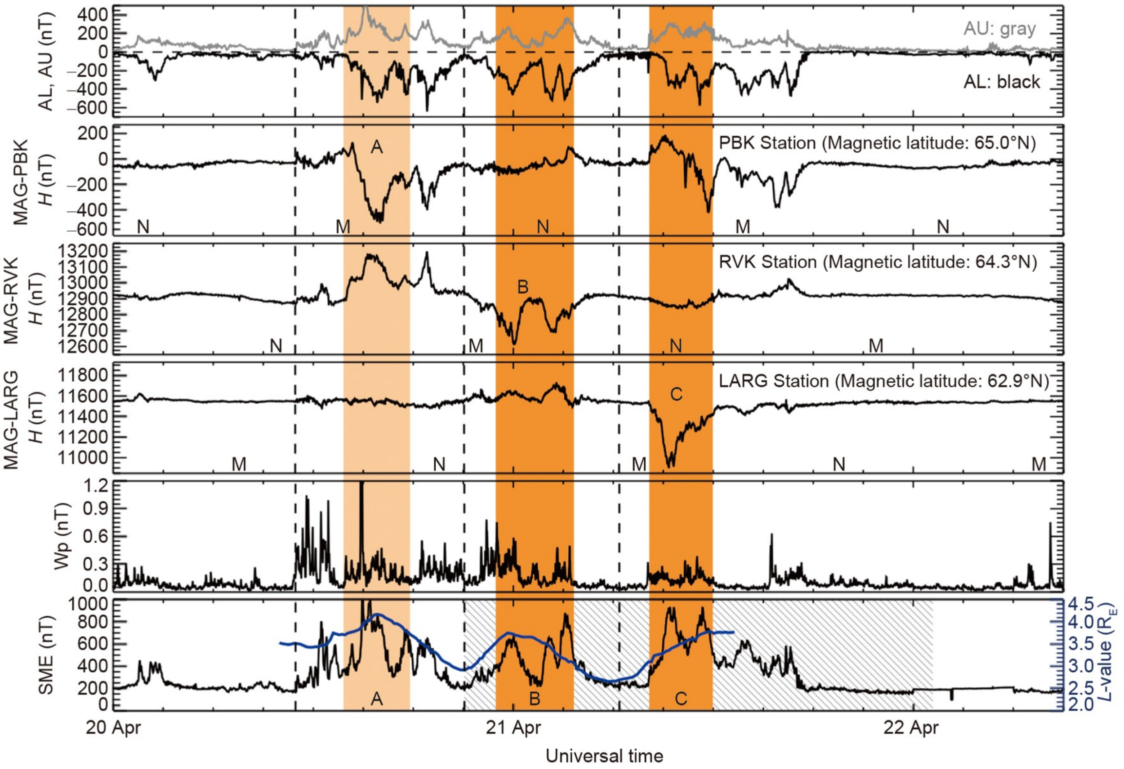


Figure 11 Comparison of the midnight transit times of the three bulges with various substorm observations (He et al., 2016).

history of the Moon. China's lunar exploration project was equipped with lunar penetrating radar to obtain the structural information of the lunar subsurface. Combined with orbit tracking data of the orbiter and detection data at home and abroad, the distribution of the lunar gravity field and the inversion of the lunar interior structure were studied (Yan et al., 2011).

The Chang'e-3 mission used radar echo sounding to detect the lunar subsurface shallow structure and lunar regolith thickness in the landing area, and established techniques and methods for identifying subsurface lunar structures (Su et al., 2014; Fa et al., 2015; Li et al., 2018a). Based on the lunar penetrating radar data of the Yutu rover, it was found that the subsurface of the Chang'e-3 landing site has an obviously stratified structure, with as many as nine strata in a depth range of more than 400 m (Xiao et al., 2015). On the lunar farside, the lunar penetrating radar of Yutu-2 rover has obtained clearer imaging results. High-frequency radar (500 MHz) data showed that the subsurface of the Chang'e-4 rover route was mainly composed of low-loss, loose lunar soil and rocks. Three different subsurface stratigraphic units were identified, and it was found that the depth of the lunar mare basalt in this area should be greater than 42 m (Figure 12; Li et al., 2020). Based on low-frequency radar (60 MHz) data, stratified structures such as deep spars and basalts at a depth of about 500 m in the landing area were also obtained (Zhang et al., 2021).

The lunar regolith penetrating radar, installed at the bottom of the Chang'e-5 lander, is the first antenna-array radar deployed for the investigation of an extraterrestrial body. The radar imaging results unveiled a hyperfine structure for the top 2.5-m-thick lunar regolith with an unprecedented high resolution of 5 cm. The analysis results showed that the subsurface layer of the lunar soil at the sampling site is mainly composed of tiny lunar soil particles and unevenly distributed rock fragments. The depth of the disturbed lunar soil layers "seen" by the radar was generally consistent with the analysis results of other telemetry data and the lunar drilling samples, which also verified the correctness of the interpretation method for lunar regolith penetrating radar data (Figure 13; Su et al., 2022).

5. Contribution of Chang'e-5 lunar samples to the study of the origin and evolution of the Moon

Studies of Apollo and Luna lunar samples suggest that the youngest lunar samples are older than 3.1 Ga. Even if some lunar meteorites have a basalt crystallization age of about 2.8 Ga, it is generally believed that the Moon stopped volcanic geological activity about 3.0 Ga ago. Chang'e-5 has chosen to sample the northeastern part of Oceanus Procellarume at higher latitude. Geological background analysis suggests that the Chang'e-5 sampling site may have collected younger basalt material with less contamination by ejecta.

After the return of Chang'e-5 lunar sample to the Earth, the results of the basic characterization indicated that it was a differentiated, atypical KREEP-type basalt component (Li et al., 2022; Zhang et al., 2022), impact dating and preliminary age analysis indicated that its formation age might be less than 2 Ga (Che et al., 2021). Isotope analysis of Pb-Pb fur-

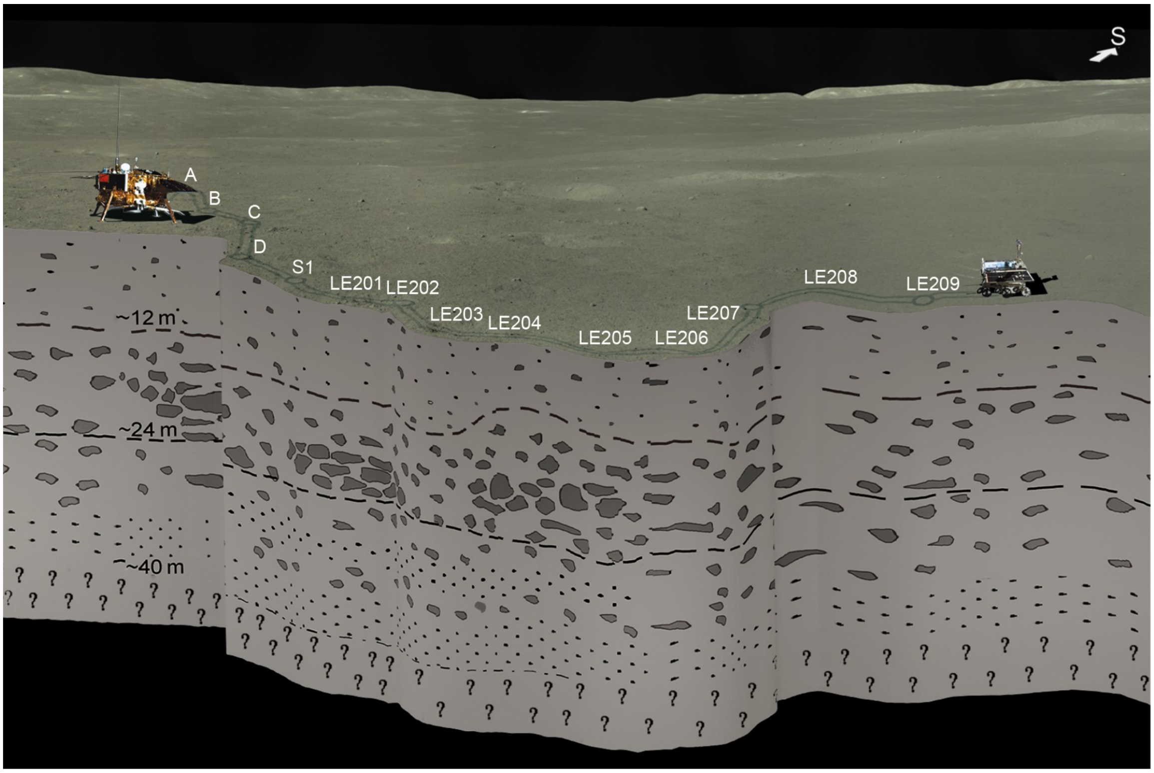


Figure 12 The first high-resolution image of the lunar ejecta sequence at a depth of ~40 m underground (Li et al., 2020).

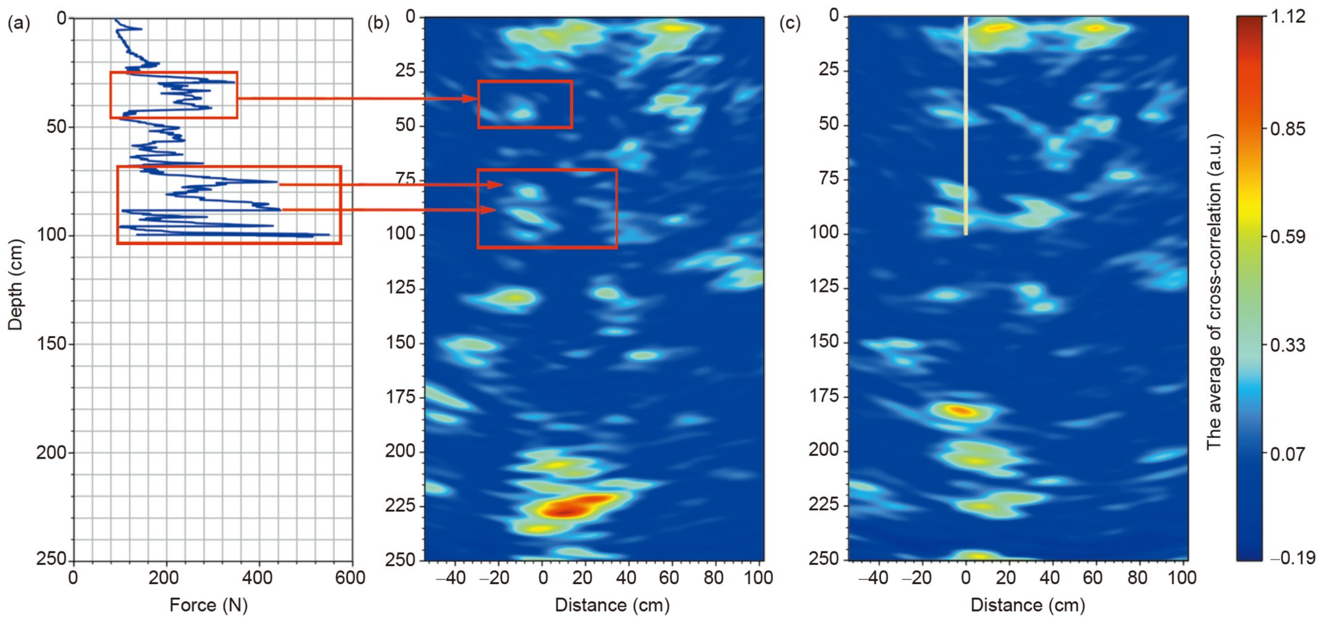


Figure 13 Chang'e-5 Lunar Regolith Penetrating Radar (LRPR) observations at the drill-sampling site (Su et al., 2022). (a) Variation of the drill bit force along the depths. (b) LRPR radar image before drilling after applying sample time calibration, bandpass filtering, time-delay calibration, background removal, spherical and exponential compensation (SEC) gain, and improved cross correlation. (c) Radar image after drilling with the same processing method as that used in (b).

ther precisely limited the crystallization age of basaltic clasts in Chang'e-5 samples to 2030±4 Ma (Li Q L et al., 2021), confirming that Chang'e-5 basalts are about 800 Ma younger than all lunar samples, proving that volcanism still existed on the Moon at least 2 Ga ago, which greatly prolonged the "geological life" of the Moon, and changed the traditional understanding that the lunar magma ceased geological activity 3 Ga ago. *In situ* U-Pb isotopic analysis of phosphate and silicate minerals in Chang'e-5 lunar soil samples qualified its initial Pb composition, deduced a low U/Pb ratio in the source region, and indicated that the basaltic source region does not contain KREEP components (Figure 14; Li Q L et al., 2021). With its significantly younger age and the significantly different types and components, this precious and unusual lunar sample from Chang'e-5 has changed the human perception of lunar evolution and opened a new era of lunar science research.

The results of the approximately 2.0 Ga crystallization age of Chang'e-5 samples updated the Neukum model, a widely used impact chronology model, and provided a key anchor for the statistical dating curve of craters (Figure 15; Yue et al., 2022). The updated model may yield more reliable impact ages with important implications for the chronology and impact history of the inner solar system.

The research results of China's lunar exploration project, especially those of Chang'e-5 samples, have made important contributions to solving the fundamental lunar science issue of the origin and evolution of the Moon, providing a number of new understandings on the historical issues of lunar evolution such as the formation and evolution of lunar soil and solar activity records, lunar surface impact events, lunar volcanism history, and the formation and evolution of the lunar crust.

The results of remote sensing detection speculate that young volcanism (<2.8 Ga) on the Moon may be mainly distributed on the KREEP terrane of Oceanus Procellarum. A popular hypothesis is that the KREEP components, which are rich in radioactive elements U, Th, K, etc., provides the heat source for the continued lunar volcanism. Mineralogical and Sr-Nd isotopic studies of the Chang'e-5 lunar basaltic rock debris show that basalt was not involved in KREEP material during its formation, and the high rare-earth element content results from the low proportion of melting and a high degree of fractional crystallization during magma formation. The characteristics of the Chang'e-5 samples indicate the mainstream hypothesis that the magma source region should be rich in radiogenic heat-producing elements is excluded in the late lunar magmatic processes (Figure 16; Tian et al., 2021).

The water content of the Moon and its distribution are the most important constraints for revealing major lunar geological events such as the origin of the Moon, fractional crystallization of magma ocean, and the duration of lunar volcanism. At present, there is still great controversy about the content, distribution characteristics, time variation and the source of lunar water (OH/H_2O). The analysis of water content and hydrogen isotope of melt inclusions in apatite and ilmenite of Chang'e-5 clasts show that the genesis of Chang'e-5 sample, the youngest basalt, is not due to its water-rich lunar mantle source region. Instead, the water

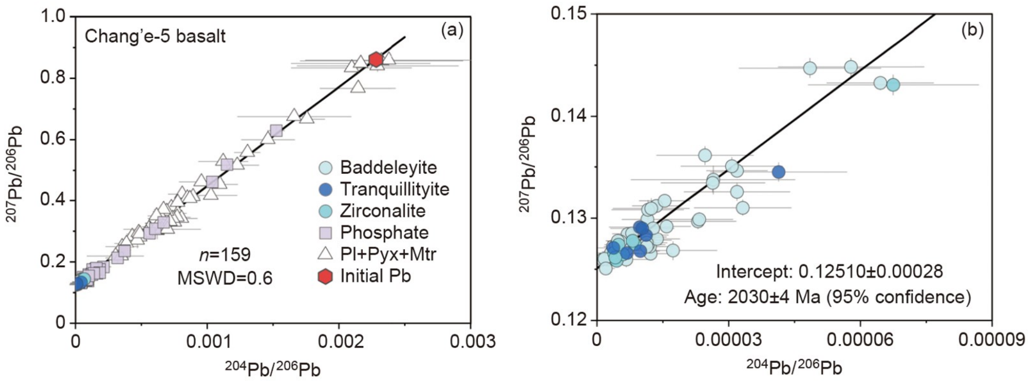


Figure 14 Pb-Pb isochron for the Chang'e-5 basalts (Li Q L et al., 2021). (a) The integrated Pb-Pb isochron. (b) The enlarged lowest part of the isochron in a highlighting the measurements of Zr-bearing minerals.

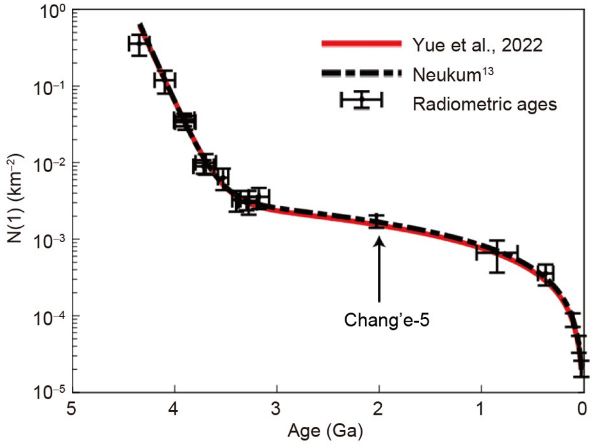


Figure 15 The new lunar chronology model (solid red line) based on Chang'e-5 lunar samples (Yue et al., 2022).

content of the subducting mantle source region of the Oceanus Procellarum shows a decreasing trend with time, probably because the continuous volcanism in this region has been extracting water from the mantle source region (Hu et al., 2021). In contrast, an obvious absorption characteristics of hydroxyl water at 2.85 μm was found in the lunar surface by Chang'e-5 *in-situ* spectral detection data (Lin et al., 2022; Liu et al., 2022). Mineralogical analysis of the lunar samples confirmed that the source of this hydroxyl water was mainly (at least) hydroxyapatite in the lunar samples, rather than solar wind, indicating the presence of endogenous water in Chang'e-5 lunar sample (Liu et al., 2022). The role of water in the formation and crystallization of late basaltic magma should have been present.

The lunar magma ocean model shows that the mineral composition and spatial distribution of the lunar surface are all determined by early global-scale divergent events and magmatism. Therefore, it is an important way to understand the evolution history of the Moon by determining the elements in different regions and confirming the content of the main minerals on the lunar surface. The results of lunar mare basalt near the Chang'e-3 landing site "GuangHanGong" provide new information on the mechanisms of lunar late-stage volcanism and magma evolution (Ling et al., 2015). The lunar penetrating radar even identified three stages of volcanic eruptions in the Chang'e-3 landing area, leading to the idea that large-scale volcanism may still be present in 2.5 Ga (Zhang et al., 2015). Combining the lunar surface material composition data from the interference imaging spectrometer of Chang'e-1, the Multispectral Imager of Japanese Kaguya, the Mineral Mapper of Indian Chandrayaan-1, and the thermal infrared radiometer of U.S. LRO, the magnesium index, Ferromagnesium mineral content, rock type distribution, the age and geological significance of the lunar mare basalt in the Chang'e-3 landing area were studied in depth from the perspective of lunar remote sensing, and new understandings were generated.

The *in-situ* spectroscopy data obtained in the Chang'e-4 landing area provides the most possible direct evidence for answering the questions of the material composition of the lunar mantle, crust, and core, and how they affect the formation and evolution of the Moon. The results of *in-situ* spectroscopic detection on the lunar farside show that the lander and the rover are located on the impact spatter of the Von Kamen crater basalt "plain". For the first time, material compositions that may represent the deep part of the Moon have been discovered on the farside of the Moon, possibly revealing the material composition of the lunar mantle and provide new constraints for studying the depth, cooling rate and other characteristics of the early lunar magma ocean. It also provides new constraints and useful information for future lunar sample return missions in China (Li et al., 2019a).

6. Future research prospects

By the end of 2020, the Chang'e-5 mission has completed the lunar surface sampling and return. China's lunar exploration

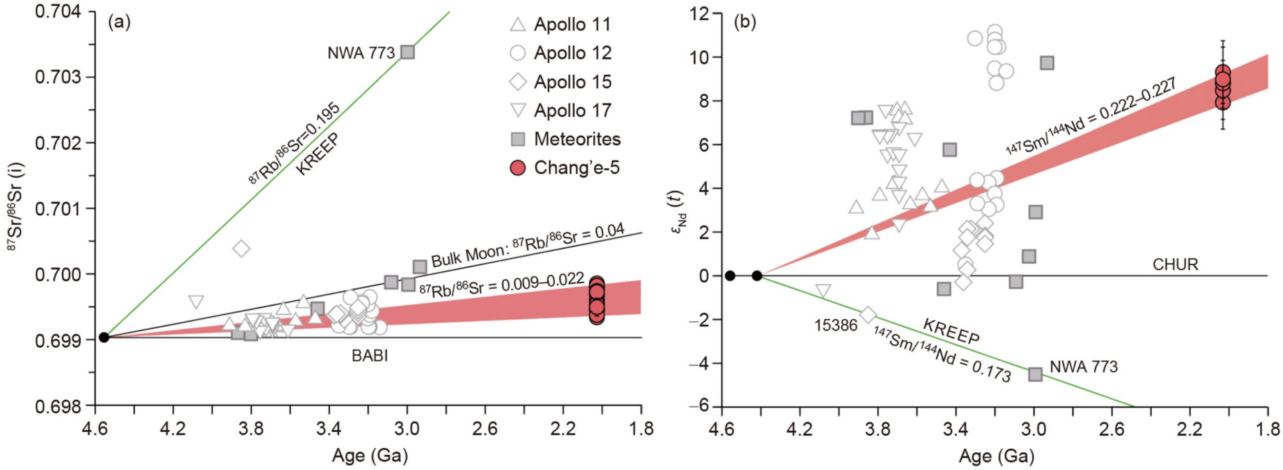
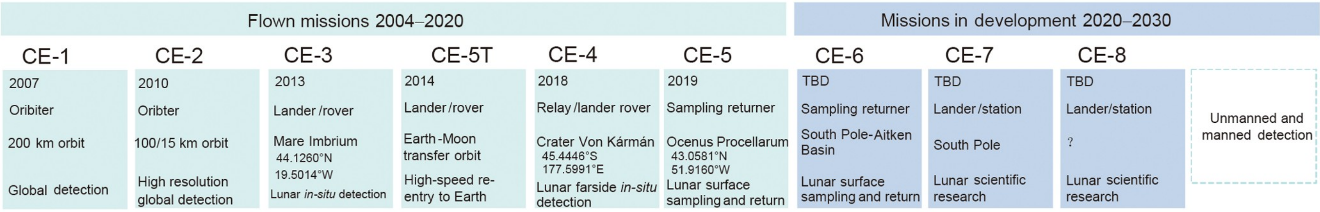


Figure 16 Rb-Sr and Sm-Nd isotopic evolution of lunar materials (Tian et al., 2021). (a) ^{87}Rb/^{86}Sr ratios of Chang'e-5 basalt source regions; (b) the ^{147}Sm/^{144}Nd ratios of the basalt source regions.

project has achieved the success of all five consecutive missions starting from Chang'e-1, completed the three-step goals of "orbiting, landing and returning", gradually established the standard specifications and knowledge system for lunar exploration. A series of highly regarded scientific research have expanded and enriched human understanding of the Moon. The development of China's lunar and planetary science has been greatly and actively promoted, and a number of planetary science talents have been trained, forming the research ecology of lunar and planetary science.

In 2005, during the demonstration of China's lunar exploration project, Ouyang Ziyuan and other experts summarized 14 major issues in the current lunar science research (Ouyang, 2005; Li et al., 2019b). The National Research Council of the United States proposed 8 key scientific issues for lunar exploration in the "Scientific Context for the Exploration of the Moon" (NRC, 2007) report. On this basis, the Lunar Exploration and Analysis Organization of the Lunar and Planetary Institute released the "Advancing Science of the Moon" report (LEAG, 2017), which updated and improved 11 core scientific concepts for lunar exploration, as well as research recommendations for these 11 scientific concepts. In 2019, ESA proposed 7 priority lunar science activities for the next decade (ESA, 2019). Focusing on these scientific issues, China's Lunar Exploration Project has made Chinese contributions to the research on the lunar surface environment and the Earth-Moon space environment, the lunar subsurface structure and internal structure, and the origin and evolution of the Moon, promoting the innovative development of lunar and planetary science. Representative research results mainly include: (1) A large number of basic lunar data have been obtained, such as the highest spatial resolution digital terrain product of the whole Moon in the international arena and the first control point on the lunar farside; the global lunar microwave radiation brightness temperature data (3.0, 7.8, 19.35 and 37.0 GHz four frequency bands) measured by passive microwave remote sensing technology for the first time in the world, which pioneering the research of "lunar microwave". The distribution and thickness variation of the lunar regolith layer on the surface of the whole moon have been obtained, and the distribution and total resources of helium 3, the raw material for nuclear fusion, in lunar regolith have been estimated; The distribution of iron, titanium, magnesium, aluminum, calcium, silicon, uranium, thorium and potassium on the surface of the whole Moon and the distribution of main minerals were systematically carried out, and the distribution maps of various elements and the main minerals on the whole Moon were compiled. (2) It is the first time to realize the full-scale monitoring of the lunar plasmasphere layer and the lunar-based optical astronomical observation. In particular, it has pioneered the scientific research on the farside of the Moon, discovered the preliminary evidence of the mantle-source material on the farside of the Moon, revealed the shallow underground structure of the farside of the Moon, and obtained the original scientific results such as the radiation environment characteristics of the particles on the farside of the Moon. It has updated the understanding of the composition, distribution, volcanism and space environment of the Moon. (3) The study of Chang'e-5 lunar samples has provided several new understandings of the history of late lunar magmatism and opened a new era of lunar scientific research.

After the completion of the "three steps", the goal of China's lunar exploration will gradually change from developing lunar exploration capabilities to "the deepening of lunar science research and comprehensive utilization of resources" (Pei et al., 2020). In the future, the focus of China's lunar exploration will gradually shift from mastering technology to scientific exploration and resource investigation and utilization. The traction effect of scientific objectives will become more and more prominent. The landing area



Flown missions 2004–2020						Missions in development 2020–2030			
CE-1	CE-2	CE-3	CE-5T	CE-4	CE-5	CE-6	CE-7	CE-8	
2007	2010	2013	2014	2018	2019	TBD	TBD	TBD	Unmanned and manned detection
Oribiter	Oribter	Lander /rover	Lander/rover	Relay /lander rover	Sampling returner	Sampling returner	Lander/station	Lander/station	
200 km orbit	100/15 km orbit	Mare Imbrium 44.1260°N 19.5014°W	Earth-Moon transfer orbit	Crater Von Kármán 45.4446°S 177.5991°E	Ocenus Procellarum 43.0581°N 51.9160°W	South Pole-Aitken Basin	South Pole	?	
Global detection	High resolution global detection	Lunar *in-situ* detection	High-speed re-entry to Earth	Lunar farside *in-situ* detection	Lunar surface sampling and return	Lunar surface sampling and return	Lunar scientific research	Lunar scientific research	

Figure 17 China's lunar exploration development strategy (Li et al., 2019b).

tends to choose the deepest and oldest lunar basin, the South Pole-Aitken Basin, and the resource-rich lunar South Pole region, which is expected to make further breakthroughs in key lunar science issues, such as the "old" and "new" problems in the evolutionary history of the Moon, the mystery of the Moon's water ice, the composition of the Moon's internal material, the structure and formation process of the internal circles, etc.

Lunar and planetary science is the frontier of science and technology today, and lunar exploration will remain an important field of deep space exploration and a growth point for scientific research. The United States has launched a new manned lunar landing program, the Artemis Program, which plans to carry out normalized Earth-Moon presence and scientific exploration, and focuses on manned landing and scientific investigation on Mars. According to the plan of the fourth phase of China's lunar exploration project, a series of lunar scientific exploration will be carried out from 2020 to 2030, including comprehensive lunar research, lunar-based observation and experimental research, and *in-situ* utilization experiments of lunar resources. It is planned to build a lunar scientific research station with comprehensive functions of scientific exploration, scientific research experiments, and technical verification of resource utilization (Figure 17; Li et al., 2019b). China's lunar exploration will enter a rapid development stage, and scientific researches on the Moon will also enter a new phase of applied research, which will greatly promote the development of lunar science and comparative planetary science. At the same time, it will be helpful to cultivate a world-class team of planetary science talents, and promote China from a major aerospace country to a powerful aerospace country.

References

Che X C, Nemchin A, Liu D Y, Long T, Wang C, Norman M D, Joy K H, Tartese R, Head J, Jolliff B, Snape J F, Crow C, Benedix G, Jourdan F, Yang Z Q, Yang C, Liu J H, Xie S W, Bao Z M, Fan R L, Li D P, Li Z S, Webb S G. 2021. Age and composition of young basalts on the Moon, measured from samples returned by Chang'E-5. Science, 374: 887–890

ESA. 2019. ESA Strategy for Science at the Moon. https://exploration.esa.int/web/moon/-/61371-esa-strategy-for-science-at-the-moon. Accessed: 8 October 2019

Fa W Z, Zhu M H, Liu T T, Plescia J B. 2015. Regolith stratigraphy at the Chang'E-3 landing site as seen by lunar penetrating radar. Geophys Res Lett, 42: 10,179–10,187

Feng J Q, Liu J J, He F, Yan W, Ren X, Tan X, He L P, Chen B, Zuo W, Wen W B, Su Y, Zou Y L, Li C L. 2014. Data processing and initial results from the CE-3 Extreme Ultraviolet Camera. Res Astron Astrophys, 14: 1664–1673

Gou S, Di K C, Yue Z Y, Liu Z Q, He Z P, Xu R, Lin H L, Liu B, Peng M, Wan W H, Wang Y X, Liu J Z. 2019. Lunar deep materials observed by Chang'E-4 rover. Earth Planet Sci Lett, 528: 115829

Gu L X, Chen Y J, Xu Y C, Tang X, Lin Y T, Noguchi T, Li J H. 2022. Space weathering of the Chang'e-5 lunar sample from a mid-high latitude region on the Moon. Geophys Res Lett, 49: e97875

Guo Z, Li C, Li Y, Wen Y Y, Tai K R, Li X Y, Liu J Z, Ouyang Z Y. 2022. Nanophase iron particles derived from fayalitic olivine decomposition in Chang'E-5 lunar soil: Implications for thermal effects during impacts. Geophys Res Lett, 49: e2021GL097323

He H, Shen C, Wang H N, Zhang X X, Chen B, Yan J, Zou Y L, Jorgensen A M, He F, Yan Y, Zhu X S, Huang Y, Xu R L. 2016. Response of plasmaspheric configuration to substorms revealed by Chang'e 3. Sci Rep, 6: 32362

Hu S, He H C, Ji J L, Lin Y T, Hui H J, Anand M, Tartèse R, Yan Y H, Hao J L, Li R Y, Gu L X, Guo Q, He H Y, Ouyang Z Y. 2021. A dry lunar mantle reservoir for young mare basalts of Chang'e-5. Nature, 600: 49–53

Huang J, Xiao Z Y, Xiao L, Horgan B, Hu X Y, Lucey P, Xiao X, Zhao S Y, Qian Y Q, Zhang H, Li C L, Xu R, He Z P, Yang J F, Xue B, He Q, Zhong J, Lin H Y, Huang C N, Xie J F. 2020. Diverse rock types detected in the lunar South Pole-Aitken Basin by the Chang'E-4 lunar mission. Geology, 48: 723–727

Huang J C, Ji J H, Ye P J, Wang X L, Yan J, Meng L Z, Wang S, Li C L, Li Y, Qiao D, Zhao W, Zhao Y H, Zhang T X, Liu P, Jiang Y, Rao W, Li S, Huang C N, Ip W H, Hu S C, Zhu M H, Yu L L, Zou Y L, Tang X L, Li J Y, Zhao H B, Huang H, Jiang X J, Bai J M. 2013. The ginger-shaped asteroid 4179 Toutatis: New observations from a successful flyby of Chang'e-2. Sci Rep, 3: 3411

Jiang Y, Ji J H, Huang J H, Marchi S, Li Y, Ip W H. 2015. Boulders on asteroid Toutatis as observed by Chang'e-2. Sci Rep, 5: 16029

Li C L, Ren X, Liu J J, Zou X D, Mu L L, Wang J Y, Shu R, Zou Y L, Zhang H B, Lü C, Liu J Z, Zuo W, Su Y, Wen W B, Bian W, Wang M, Xu C, Kong D Q, Wang X Q, Wang F, Geng L, Zhang Z B, Zheng L, Zhu X Y, Li J D, Ouyang Z Y. 2010. Laser altimetry data of Chang'E-1 and the global lunar DEM model. Sci China Earth Sci, 53: 1582–1593

Li C L, Liu J J, Mu L L, Zuo W, Ren X, Zhang H B, Liu J Z, Su Y, Wen W B, Wang X Q, Zhang Z B, Zou X D. 2012. Chang'e-2 High-Resolution Lunar Image Atlas (in Chinese). Beijing: SinoMaps Press

Li C L. 2013. Photogrammetric processing and lunar global topographic map form the Chang'E-1 3 line-array CCD data (in Chinese). Acta Geod Cartogr Sin, 42; 853–860

Li C L, Liu J J, Mu L L, Ren X, Zuo W, Zeng X G, Liu Y X, Zhang H B, Su Y, Wen W B, Wang F F, Wang W R, Yan W, Gao X Y, Zhang X X, Li L, Zou X D, Yang Y M. 2014a. Chang'e-2 High-Resolution Sinus Iridum Landform Atlas (in Chinese). Beijing: SinoMaps Press

Li C L, Mu L L, Zou X D, Liu J J, Ren X, Zeng X G, Yang Y M, Zhang Z B, Liu Y X, Zuo W, Li H. 2014b. Analysis of the geomorphology surrounding the Chang'e-3 landing site. Res Astron Astrophys, 14: 1514–1529

Li C L, Liu J J, Ren X, Zuo W, Tan X, Wen W B, Li H, Mu L L, Su Y, Zhang H B, Yan J, Ouyang Z Y. 2015. The Chang'e 3 mission overview. Space Sci Rev, 190: 85–101

Li C L, Xing S G, Lauro S E, Su Y, Dai S, Feng J Q, Cosciotti B, Paolo F D, Mattei E, Xiao Y, Ding C Y, Pettinelli E. 2018a. Pitfalls in GPR data interpretation: False reflectors detected in lunar radar cross sections by Chang'e-3. IEEE Trans Geosci Remote Sens, 56: 1325–1335

Li C L, Liu J J, Ren X, Yan W, Zuo W, Mu L L, Zhang H B, Su Y, Wen W B, Tan X, Zhang X X, Wang W R, Fu Q, Geng L, Zhang G L, Zhao B C, Yang J F, Ouyang, Z Y. 2018b. Lunar global high-precision terrain reconstruction based on Chang'e-2 stereo images (in Chinese). Geomati Inform Sci Wuhan Univ, 43: 485-495

Li C L, Liu D W, Liu B, Ren X, Liu J J, He Z P, Zuo W, Zeng X G, Xu R, Tan X, Zhang X X, Chen W L, Shu R, Wen W B, Su Y, Zhang H B, Ouyang Z Y. 2019a. Chang'E-4 initial spectroscopic identification of lunar far-side mantle-derived materials. Nature, 569: 378–382

Li C L, Wang C, Wei Y, Lin Y T. 2019b. China's present and future lunar exploration program. Science, 365: 238–239

Li C L, Su Y, Pettinelli E, Xing S G, Ding C Y, Liu J J, Ren X, Lauro S, Soldovieri F, Zeng X G, Gao X Y, Chen W L, Dai S, Liu D W, Zhang G L, Zuo W, Wen W B, Zhang Z B, Zhang X X, Zhang H B. 2020. The Moon's farside shallow subsurface structure unveiled by Chang'E-4 Lunar Penetrating Radar. Sci Adv, 6: eaay6898

Li C L, Liu J J, Zuo W, Su Y, Ouyang Z Y. 2021. Progress of China's lunar exploration (2011–2020) (in Chinese). Chin J Space Sci, 41: 68–75

Li C L, Hu H, Yang M F, Pei Z Y, Zhou Q, Ren X, Liu B, Liu D W, Zeng X G, Zhang G L, Zhang H B, Liu J J, Wang Q, Deng X J, Xiao C J, Yao Y G, Xue D S, Zuo W, Su Y, Wen W B, Ouyang Z Y. 2022. Characteristics of the lunar samples returned by the Chang'E-5 mission. Natl Sci Rev, 9: nwab188

Li Q L, Zhou Q, Liu Y, Xiao Z, Lin Y, Li J H, Ma H X, Tang G Q, Guo S, Tang X, Yuan J Y, Li J, Wu F Y, Ouyang Z, Li C, Li X H. 2021. Two-billion-year-old volcanism on the Moon from Chang'e-5 basalts. Nature, 600: 54–58

Lin H, Li S, Xu R, Liu Y, Wu X, Yang W, Wei Y, Lin Y T, He Z P, Hui H J, He H Y, Hu S, Zhang C, Li C L, Lv G, Yuan L Y, Zou Y L, Wang C. 2022. *In situ* detection of water on the Moon by the Chang'E-5 lander. Sci Adv, 8: eabl9174

Lin H L, He Z P, Yang W, Lin Y T, Xu R, Zhang C, Zhu M H, Chang R, Zhang J H, Li C L, Gou S, Wei Y, Hu S, Xue C B, Yang J F, Zhong J, Fu X H, Wan W X, Zou Y L. 2020. Olivine-norite rock detected by the lunar rover Yutu-2 likely crystallized from the SPA-impact melt pool. Natl Sci Rev, 7: 913–920

Ling Z C, Jolliff B L, Wang A L, Li C L, Liu J Z, Zhang J, Li B, Sun L Z, Chen J, Xiao L, Liu J J, Ren X, Peng W X, Wang H Y, Cui X Z, He Z P, Wang J Y. 2015. Correlated compositional and mineralogical investigations at the Chang'e-3 landing site. Nat Commun, 6: 8880

Liu J J, Yan W, Li C L, Tan X, Ren X, Mu L L. 2014. Reconstructing the landing trajectory of the CE-3 lunar probe by using images from the landing camera. Res Astron Astrophys, 14: 1530–1542

Liu J J, Ren X, Yan W, Li C L, Zhang H, Jia Y, Zeng X G, Chen W L, Gao X Y, Liu D W, Tan X, Zhang X X, Ni T, Zhang H B, Zuo W, Su Y, Wen W B. 2019a. Descent trajectory reconstruction and landing site positioning of Chang'E-4 on the lunar farside. Nat Commun, 10: 4229

Liu J J, Li C L, Wang W R, Zeng X G, Mu L L, Yang Y M. 2019b. Extraction of lunar domes from Chang'E-2 data with new method. Icarus, 321: 29–33

Liu J J, Liu B, Ren X, Li C L, Shu R, Guo L, Yu S Z, Zhou Q, Liu D W, Zeng X G, Gao X Y, Zhang G L, Yan W, Zhang H B, Jia L H, Jin S F, Xu C H, Deng X J, Xie J F, Yang J F, Huang C N, Zuo W, Su Y, Wen W B, Ouyang Z Y. 2022. Evidence of water on the lunar surface from Chang'E-5 *in-situ* spectra and returned samples. Nat Commun, 13: 3119

Liu J Z, Ouyang Z Y, Li C L, Zou Y L. 2013. China national moon exploration progress (2001–2010) (in Chinese). Bul Miner Petrol Geochem, 32: 544-551

Lunar Exploration Analysis Group (LEAG). 2017. Advancing Science of the Moon: Report of the Specific Action Team. Houston, TX, USA

Mo B, Guo Z, Li Y, Zhu D, Zeng X J, Li X Y, Liu J Z, Wu Y X. 2022. *In situ* investigation of the valence states of iron-bearing phases in Chang'E-5 lunar soil using FIB, AES, and TEM-EELS techniques. AtSpectrosc, 43: 53–59

National Research Council (NRC). 2017. Scientific Context for the Exploration of the Moon. Washington: National Academies Press

Ouyang Z Y. 2005. Introduction of Lunar Science (in Chinese). Beijing: China Astronautic Publishing House

Ouyang Z Y, Li C L. 2015. The Special Study on the Scientific Objectives of Chang'E-1 Lunar Exploration (in Chinese). Beijing: Science Press

Pei Z, Liu J, Wang Q, Kang Y, Zou Y, Zhang H, Zhang Y, He H, Wang Q, Yang R, Wang W, Ma J. 2020. Overview of lunar exploration and International Lunar Research Station (in Chinese). Chin Sci Bull, 65: 2577–2586

Ren X, Liu J J, Li C L, Li H H, Yan W, Wang F F, Wang W R, Zhang X X, Gao X Y, Chen W L. 2019. A global adjustment method for photogrammetric processing of Chang'E-2 stereo images. IEEE Trans Geosci Remote Sens, 57: 6832–6843

Su Y, Fang G Y, Feng J Q, Xing S G, Ji Y C, Zhou B, Gao Y Z, Li H, Dai S, Xiao Y, Li C L. 2014. Data processing and initial results of Chang'e-3 lunar penetrating radar. Res Astron Astrophys, 14: 1623–1632

Su Y, Wang R G, Deng X J, Zhang Z Y, Zhou J F, Xiao Z Y, Ding C Y, Li Y X, Dai S, Ren X, Zeng X G, Gao X Y, Liu J J, Liu D W, Liu B, Zhou B, Fang G Y, Li C L. 2022. Hyperfine structure of regolith unveiled by Chang'E-5 lunar regolith penetrating radar. IEEE Trans Geosci Remote Sens, 60: 1–14

Tang Z C, Liu J J, Wang X, Ren X, Chen W L, Yan W, Zhang X X, Tan X, Zeng X G, Liu D W, Zhang H B, Wen W B, Zuo W, Su Y, Yang J F, Li C L. 2020. Physical and mechanical characteristics of lunar soil at the Chang'E-4 landing site. Geophys Res Lett, 47: e89499

Tian H C, Wang H, Chen Y, Yang W, Zhou Q, Zhang C, Lin H L, Huang C, Wu S T, Jia L H, Xu L, Zhang D, Li X G, Chang R, Yang Y H, Xie L W, Zhang D P, Zhang G L, Yang S H, Wu F Y. 2021. Non-KREEP origin for Chang'e-5 basalts in the Procellarum KREEP Terrane. Nature, 600: 59–63

Wang F F, Liu J J, Li C L, Ren X, Mu L L, Yan W, Wang W R, Xiao J T, Tan X, Zhang X X, Zou X D, Gao X Y. 2014. A new lunar absolute control point: established by images from the landing camera on Chang'e-3. Res Astron Astrophys, 14: 1543–1556

Wang J, Wu C, Qiu Y L, Meng X M, Cai H B, Cao L, Deng J S, Han X H, Wei J Y. 2015. An unprecedented constraint on water content in the sunlit lunar exosphere seen by Lunar-based Ultraviolet Telescope of Chang'e-3 mission. Planet Space Sci, 109-110: 123–128

Wang X D, Bian W, Wang J S, Liu J J, Zou Y L, Zhang H B, Lü C, Liu J Z, Zuo W, Su Y, Wen W B, Wang M, Ouyang Z Y, Li C L. 2010. Acceleration of scattered solar wind protons at the polar terminator of the Moon: Results from Chang'E-1/SWIDs. Geophys Res Lett, 37: L07203

Wang X Q, Cui J, Wang X D, Liu J J, Zhang H B, Zuo W, Su Y, Wen W B, Rème H, Dandouras I, Aoustin C, Wang M, Tan X, Shen J, Wang F, Fu Q, Li C L, Ouyang Z Y. 2012. The Solar Wind interactions with Lunar Magnetic Anomalies: A case study of the Chang'E-2 plasma data near the Serenitatis antipode. Adv Space Res, 50: 1600–1606

Wu W R, Yu D Y, Wang C, Liu J Z, Tang Y H, Zhang H, Zhang Z. 2020. Technological breakthrough and scientific achievement of Chang'e-4 project (in Chinese). Sci Sin-Inf, 50: 1783–1797

Wu Y Z. 2012. Major elements and Mg# of the Moon: Results from Chang'E-1 interference imaging spectrometer (IIM) data. Geochim Cosmochim Acta, 93: 214–234

Xi J X, Ma L Y, Xian H Y, Wang G F, Xing J Q, Wei J M, Zhu J X, He H P. 2022. *In situ* micro-XRD methods for identifying glass and minerals in extraterrestrial samples. AtSpectrosc, 43: 19–27

Xiao L, Zhu P M, Fang G Y, Xiao Z Y, Zou Y L, Zhao J N, Zhao N, Yuan Y F, Qiao L, Zhang X P, Zhang H, Wang J, Huang J, Huang Q, He Q, Zhou B, Ji Y C, Ouyang Z Y, Shen S X, Li Y X, Gao Y Z. 2015. A Young multilayered terrane of the northern Mare Imbrium revealed by Chang'E-3 Mission. Science, 347: 1226–1229

Yan J G, Koji M, Ping J S, Sander G, Liu J Z, Li J L, Tang G S, Li F. 2011. Optimization on lunar gravity field model using Chang'E-1 orbital tracking data (in Chinese). Sci Sin-Phys Mech Astron, 41: 870–878

Yue Z Y, Di K C, Wan W H, Liu Z Q, Gou S, Liu B, Peng M, Wang Y X, Jia M N, Liu J Z, Ouyang Z Y. 2022. Updated lunar cratering chronology model with the radiometric age of Chang'e-5 samples. Nat Astron, 6: 541–545

Zhang A B, Wieser M, Wang C, Barabash S, Wang W J, Wang X D, Zou Y L, Li L, Cao J B, Kalla L, Dai L, Svenssno J, Kong L G, Oja M, Liu B, Alatalo V, Zhang Y T, Takonen J, Liu W L. 2020. Emission of energetic neutral atoms measured on the lunar surface by Chang'E-4. Planet Space Sci, 189: 104970

Zhang H, Zhang X, Zhang G, Dong K Q, Deng X G, Gao X S, Yang Y D, Xiao Y, Bai X, Liang K X, Liu Y W, Ma W B, Zhao S F, Zhang C, Zhang X J, Song J, Yao W, Chen H, Wang W H, Zou Z G, yang M F. 2022. Size, morphology, and composition of lunar samples returned by Chang'E-5 mission. Sci China-Phys Mech Astron, 65: 229511

Zhang J H, Zhou B, Lin Y T, Zhu M H, Song H J, Dong Z H, Gao Y Z, Di K C, Yang W, Lin H Y, Yang J F, Liu E H, Wang L, Lin Y, Li C, Yue Z Y, Yao Z X, Ouyang Z Y. 2021. Lunar regolith and substructure at Chang'E-4 landing site in South Pole-Aitken basin. Nat Astron, 5: 25–30

Zhang J H, Yang W, Hu S, Lin Y T, Fang G Y, Li C L, Peng W X, Zhu S Y, He Z P, Zhou B, Lin H Y, Yang J F, Liu E H, Xu Y C, Wang J Y, Yao Z X, Zou Y L, Yan J, Ouyang Z Y. 2015. Volcanic history of the Imbrium basin: A close-up view from the lunar rover Yutu. Proc Natl Acad Sci USA, 112: 5342–5347

Zhang S Y, Wimmer-schweingruber R F, Yu J, Wang C, Fu Q, Zou Y L, Sun Y Q, Wang C Q, Hou D H, Bottcher S I, Burmeister S, Seimetz L, Schuster B, Knierim V, Shen G H, Yuan B, Lohf H, Guo J N, Xu Z G, Forstner J L F V, Kulkarni S R, Xu H T, Li J, Zhang Z, Zhang H, Berfer T, Zhang B Q, Chen Y S, Geng H, Quan Z D. 2020. First measurements of the radiation dose on the lunar surface. Sci Adv, 6: EAAZ1334

Zheng Y C, Tsang K T, Chan K L, Zou Y L, Zhang F, Ouyang Z Y. 2012. First microwave map of the Moon with Chang'E-1 data: The role of local time in global imaging. Icarus, 219: 194–210

Zhu M H, Chang J, Ma T, Ip W H, Fa W Z, Wu J, Cai M S, Gong Y Z, Hu Y M, Xu A A, Tang Z S. 2013. Potassium map from Chang'E-2 constraints the impact of crisium and orientale basin on the moon. Sci Rep, 3: 1611

Zhu M H, Fa W Z, Ip W H, Huang J C, Liu T T, Meng L Z, Yan J, Xu A A, Tang Z S, Wang X L, Qiao D. 2014. Morphology of asteroid (4179) Toutatis as imaged by Chang'E-2 spacecraft. Geophys Res Lett, 41: 328–333

Zou X D, Li C L, Liu J J, Wang W R, Li H, Ping J S. 2014. The preliminary analysis of the 4179 Toutatis snapshots of the Chang'E-2 flyby. Icarus, 229: 348–354

Zou Y L, Zhang L Y, Liu J Z, Mu L L, Ren X, Zhang G L, Chang J, Yan J, Zhang N, Zhang H B, Lu C, Liu J J, Zuo W, Su Y, Wen W B, Bian W, Wang M X C, Li C L, Ouyang Z Y. 2011. Data analysis of Chang'E-1 gamma-ray spectrometer and global distribution of U, K, and Th elemental abundances. Acta Geol Sin-Engl Ed, 85: 1299–1309

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