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Review

Return to the Moon: New perspectives on lunar exploration

Yangting Lin [a], Wei Yang [a], Hui Zhang [a], Hejiu Hui [b], Sen Hu [a], Long Xiao [c], Jianzhong Liu [d], Zhiyong Xiao [e], Zongyu Yue [a], Jinhai Zhang [a], Yang Liu [f], Jing Yang [d], Honglei Lin [a], Aicheng Zhang [b], Dijun Guo [f], Sheng Gou [a], Lin Xu [f], Yuyang He [a], Xianguo Zhang [f], Liping Qin [g], Zongcheng Ling [h], Xiongyao Li [d], Aimin Du [a], Huaiyu He [a], Peng Zhang [i], Jinbin Cao [j], Xianhua Li [a,*]

[a] Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[b] State Key Laboratory for Mineral Deposits Research and School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China
[c] State Key Laboratory of Geological Processes and Mineral Resources, School of Earth Sciences, China University of Geosciences, Wuhan 430074, China
[d] Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China
[e] Planetary Environmental and Astrobiological Research Laboratory, School of Atmospheric Sciences, Sun Yat-sen University, Zhuhai 519082, China
[f] National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China
[g] Deep Space Exploration Laboratory / CAS Key Laboratory of Crust-Mantle Materials and Environments, University of Science and Technology of China, Hefei 230026, China
[h] Shandong Key Laboratory of Optical Astronomy and Solar-Terrestrial Environment, Institute of Space Sciences, Shandong University, Weihai 264209, China
[i] Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences, Beijing 100094, China
[j] School of Space and Environment, Beihang University, Beijing 100191, China

A R T I C L E I N F O

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A B S T R A C T

Lunar exploration is deemed crucial for uncovering the origins of the Earth-Moon system and is the first step for advancing humanity's exploration of deep space. Over the past decade, the Chinese Lunar Exploration Program (CLEP), also known as the Chang'e (CE) Project, has achieved remarkable milestones. It has successfully developed and demonstrated the engineering capability required to reach and return from the lunar surface. Notably, the CE Project has made historic firsts with the landing and on-site exploration of the far side of the Moon, along with the collection of the youngest volcanic samples from the Procellarum KREEP Terrane. These achievements have significantly enhanced our understanding of lunar evolution. Building on this success, China has proposed an ambitious crewed lunar exploration strategy, aiming to return to the Moon for scientific exploration and utilization. This plan encompasses two primary phases: the first crewed lunar landing and exploration, followed by a thousand-kilometer scale scientific expedition to construct a geological cross-section across the lunar surface. Recognizing the limitations of current lunar exploration efforts and China's engineering and technical capabilities, this paper explores the benefits of crewed lunar exploration while leveraging synergies with robotic exploration. The study refines fundamental lunar scientific questions that could lead to significant breakthroughs, considering the respective engineering and technological requirements. This research lays a crucial foundation for defining the objectives of future lunar exploration, emphasizing the importance of crewed missions and offering insights into potential advancements in lunar science.

1. Introduction

The Moon plays a pivotal role in our understanding of the formation and early evolution of our planet. The Moon appears to have largely ceased its endogenic activities to become what might be considered a "dead" planet at an early stage. However, this very characteristic makes it an invaluable resource for comprehending the evolution of Earth's habitable environment. The Moon serves as a pristine archive, preserving a detailed history of the Earth-Moon system, including crucial processes like asteroid impacts and exposure to solar radiation. Serving as a unique vantage point, the Moon offers an unparalleled platform for long-term monitoring of Earth's macroscopic phenomena and enables continuous, comprehensive observation of the universe. Additionally, it serves as a crucial outpost and launching point for human exploration into

* Corresponding author.
E-mail address: lixh@gig.ac.cn (X. Li).

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deep space. The Moon has emerged as a focal point and frontier for deep space exploration, ushering in a new era where both scientific investigation and space utilization are of equal significance.

The success of a series of increasingly complex Chang'e (CE) missions [1], characterized by the "orbiting, landing, and returning" of lunar probes, has positioned China alongside the United States and the Soviet Union as the third nation capable of returning samples from the lunar surface. Among the five missions executed, CE-4 landed on the far side of the Moon and conducted a thorough survey within the largest lunar basin, known as the South Pole-Aitken (SPA) Basin. CE-5, on the other hand, collected samples from an area on the Moon containing the youngest lunar basalts. The analysis of these samples has greatly enhanced our understanding of the Moon's magmatic history [2]. Currently, China is advancing into Phase IV of the CE project, which involves launching CE-6, 7, and 8 probes. The objectives of these missions include retrieving samples from the far side of the Moon [3] and directly detecting water ice in the permanent shadow regions at the Southern Pole [4]. Concurrently, China is planning for crewed lunar exploration before 2030 and considering the establishment of International Lunar Research Station (ILRS). Crewed lunar exploration offers significant advantages in sample collection and instrument deployment compared to robotic lunar exploration. The six Apollo crewed missions, for instance, collected a total of 382 kg of samples and covered exploration distances of approximately 30 km on the Moon's surface. The National Aeronautics and Space Administration (NASA) of the United States has announced the Artemis crewed lunar exploration, element of the Moon to Mars Architecture. This initiative aims to undertake human landings on the Moon's South Pole region around 2027, with the strategic objective of returning 20–80 kg of samples from both the polar region and the SPA Basin.

The designated landing site for China's first crewed lunar exploration mission will be positioned between the north and south latitudes of 20 degrees on the lunar near side. The region is located within the Procellarum KREEP (an acronym for the incompatible K, Rare-Earth Elements, and P) Terrane (PKT). Notably, it shares striking similarities with the landing sites of the six crewed Apollo missions. However, within the constraints of engineering capabilities, the challenge lies in uncovering new findings and expanding the current understanding of lunar science. In addition, it is anticipated that China's forthcoming crewed lunar exploration will be capable of achieving ultra-long distance traverses for thousands of kilometers on the surface of the Moon. Leveraging this engineering and technological breakthrough to spearhead innovative scientific research and achieve unprecedented advancements in lunar science presents both a challenge and an opportunity for China's crewed lunar exploration. This study examines the current state, developing trend, and prevailing obstacles of lunar exploration and research. It identifies key scientific questions regarding the Moon that can effectively capitalize on the advantages of crewed missions while concurrently addressing their engineering prerequisites. Additionally, the study puts forth inventive ideas and recommendations for future crewed lunar exploration and research initiatives.

2. Current state of lunar exploration and research

2.1. Lunar exploration history

The Moon is the earliest and most extensively explored destination in space exploration. Over 130 lunar probes have been launched to date, marking a rich history of lunar exploration. This exploration journey can be broadly divided into three distinct phases: the robotic Luna and crewed Apollo landing missions, the era of high-resolution orbiting surveys, and the contemporary resurgence of lunar exploration with a focus on returning to the Moon.

Phase 1: This Phase primarily encompassed the robotic Luna missions by the Soviet Union (1959–1976) and the crewed Apollo missions by the United States (1961–1972). The Luna missions successfully executed three robotic sample returns (Luna 16, 20, and 24), resulting in the retrieval of approximately 0.321 kg of lunar soil. These samples were drilled from the Fecunditatis Basin (L16), the Crisium Basin (L24), and the Eastern Limb highlands (L20). Meanwhile, the Apollo project achieved the historic milestone of landing humans on the Moon [5], and returning a total lunar sample weight of 382 kg (including 3.05 m of continuous drilling cores from lunar soil, various types of basalts, impact breccias, abyssal rocks, and highland anorthosite). Concurrently, the Apollo missions provided comprehensive data on fundamental physical parameters and the internal structure of the Moon by deploying a diverse array of physical sensors and scientific instruments [6]. The successful execution of the Apollo project, along with subsequent research on the Apollo lunar samples, laid the groundwork for understanding the formation and evolution of the Moon [7–11]. This significant achievement highlighted the substantial scientific output and societal impact derived from crewed lunar exploration.

Phase 2: High-resolution orbiting probes (1994–2020). NASA led the way with a series of high-resolution lunar orbiters, such as Clementine (1994), Lunar Prospector (1998), Lunar Reconnaissance Orbiter (2009), Gravity Recovery and Interior Laboratory (GRAIL) (2011), and Lunar Atmosphere and Dust Environment Exploration (LADEE) (2013). These missions have provided valuable data on the Moon's global high-resolution topography, morphology, regolith composition, space environment, gravity field, and magnetic field. Besides the United States, China, European Space Agency (ESA), Japan, and India have launched their lunar exploration missions. Japan's Kaguya mission (2007) acquired laser altitude and elemental distribution data for the entire lunar surface. The Moon Mineralogy Mapper (M^3), part of India's Chandrayaan-1 mission (2008), conducted surface exploration using visible to near-infrared spectroscopy. China launched the Chang'e project in 2004. With the successful completion of the three phases of lunar missions—orbiting, landing, and returning—China has mastered crucial technologies for exploring most of the lunar surface and returning samples to Earth. For example, the CE-4 mission achieved a significant milestone by landing on the far side of the Moon, while CE-5 retrieved lunar samples after a 44-year hiatus in sample return missions. This phase highlights the growing interest in lunar exploration, with extensive research underway to prepare for future lunar expeditions.

Phase 3: Return to the Moon. Following the completion of orbiting, landing, and sample returning missions, China has embarked on Phase IV of the Chang'e project. China is actively engaged in discussions regarding the ILRS initiative and crewed lunar exploration missions. Meanwhile, NASA, in collaboration with ESA, Japan, India, and others, is planning crewed Artemis project on basis of the lunar orbit Gateway project, aimed at returning humans to the Moon's surface. This contemporary phase of lunar exploration targets previously unexplored geological units, such as the far side of the Moon and the polar regions. In the meantime, the ILRS will be established to facilitate long-term, sustainable, and continuous lunar exploration efforts. The paradigm of lunar exploration will also be transitioned to an era that scientific research and the practical utilization of the Moon are of equal importance.

2.2. Hypotheses and discrepancies on the formation and the evolution of the Moon

Geological features of the Moon: The lunar surface is characterized by numerous craters and basins of varying sizes. As their diameters increase, the morphology of these features transitions from bowl-shaped to central peaks and eventually to multi-ring basins. Craters larger than 200 km in diameter are typically classified as impact basins. To date, 76 impact basins have been identified [12], with the SPA Basin being particularly noteworthy due to its 2400 km diameter and approximate depth of 12 km. The lunar surface is covered by a fine-grained (<1 mm) regolith layer, ranging from several to tens of meters in depth. The lunar regolith consists of rock and mineral fragments, impact glasses, and other materials. The thickness of the lunar regolith corresponds to the age of the lunar surface on which it has accumulated. Analysis of Apollo regolith drilling cores (2–3 m long) indicates that the composition and grain size of the regolith remain relatively consistent across the depths, except for the uppermost layer (<1 m), where a more pronounced depth-dependent trend is observed [13]. Beneath the regolith lies an irregularly thick debris layer, formed through *in situ* impact fracturing and brecciation or via deposition from material ejected by impact craters.

Lunar rocks include mare basalts, highland anorthosites, and plutonic rocks. Mare basalts are categorized into three groups based on their TiO_2 content: high Ti (>6 weight percent (wt%) TiO_2), low Ti (1 wt%–6 wt% TiO_2), and very-low Ti (<1 wt% TiO_2). Similarly, they can be divided into high Al (>11 wt% Al_2O_3) and low Al (<11 wt% Al_2O_3) groups according to Al_2O_3 content, as well as high K (>1000 parts per million (ppm) K_2O) and low K (<1000 ppm K_2O) groups based on K_2O content. Remote sensing observations have identified lava flows, shield volcanoes or silicic domes, dark pyroclastic deposits, and irregular mare patches that are sporadically distributed. Highland anorthosites may consist of pure plagioclase (An > 96). In the Apollo samples, only a minor presence of plutonic rocks was observed, including magnesian suite (Mg-suite), alkaline suite, and the relatively rare spinel-rich lithology [14]. To date, no felsic rocks or granites of hand-sample size have been found, and only a few rock fragments rich in KREEP have been observed in impact-melt breccias and lunar regolith [15,16].

Based on the distribution of Th and considering the contents of FeO and TiO_2, the Moon can be divided into three geochemical provinces: the PKT on the near side, the Feldspathic Highlands Terrane (FHT) on the far side, and the SPA Basin [17]. The PKT is notable for its significant enrichment of Th element, with levels reaching up to 12 ppm. KREEP-enrichment is primarily concentrated around the Mare Imbrium rim and within the Procellarum Basin. Conversely, the SPA Basin exhibits relatively low Th content (less than 5 ppm), despite its considerable depth of excavation. Notably, there are significant differences in material distribution between the near and far sides of the Moon, showcasing its dichotomy. Additionally, the lunar crust on the near side, where most mare basalts are found [18], is thinner compared to the far side [19]. Although the frequency of impact basins is similar on both sides, those on the near side tend to have larger diameters [20].

Three hypotheses have been proposed to explain the formation and early evolution of the Moon: the Giant Impact [21,22], the Lunar Magma Ocean (LMO) [23], and Late Heavy Bombardment [24]. The Giant Impact hypothesis is supported by significant isotopic similarities between the Moon and Earth, particularly in major and refractory elements like Oxygen (O), Chromium (Cr), Titanium (Ti), and Iron (Fe) [25–30]. These similarities suggest thorough mixing of materials from the proto-Earth with the impacting body Theia [31], the inheritance of lunar material primarily from Earth [32–34], the accretion of both the impactor and Earth in close proximity [35], or multiple asteroid collisions [36]. Regardless of the specific models employed, it is widely accepted that the Moon re-accreted from high-temperature impacts involving melts and gases, such as water vapor and other volatiles. This process led to significant deficits of water and volatiles in the Moon compared to Earth and resulted in associated isotope mass-dependent fractionation in some moderately volatile elements [36–38]. Analyses of plagioclase suggest that the LMO may contain water, and its hydrogen isotope composition could resemble that of the primitive Earth [39,40]. Additionally, gases produced by post-magmatic processes may have formed a transient atmosphere on the lunar surface [41–43]. Hence, there is ongoing debate regarding whether the primitive Moon was "dry" or "wet". [44].

After the giant impact, it is very likely that the nascent Moon was completely submerged in magma, forming what is known as a LMO. The differentiation of this magma ocean resulted in the formation of a mafic silicate mantle and a plagioclase crust. The residual melt trapped between these layers was enriched in KREEP and other large ion incompatible elements, eventually solidifying into primitive urKREEP rock [45]. During the later stages of the LMO, iron-rich cumulates likely accumulated in the upper mantle layer. With their density surpassing that of the lower Mg-rich mantle layer, this led to gravitational instability and the overturn of the lunar mantle [46]. Debates surrounding the magma ocean hypothesis include discussions on the depth of the magma ocean, the influence of water and volatile content on the crystallization process, lateral mantle heterogeneity caused by overturn, potential decoupling of titanite and KREEP, and the timing of lunar mantle differentiation. Zircon, a late-stage product of magmatic evolution, serves as a key indicator of the Moon's complete solidification. The Pb/Pb age of the oldest lunar zircon, found in Apollo 17 impact melt breccia 72,215 and dated by SIMS, is 4.42 billion years (Ga) [47]. However, highlands ferroan anorthosites and Mg-suite rocks have ^{147}Sm-^{143}Nd mineral isochron ages of 4.33–4.37 Ga [48]. Similarly, basaltic fragments in lunar meteorites also exhibit a crystallization age of 4.33–4.37 Ga [49]. These crystallization ages are consistent with the ^{146}Sm–^{142}Nd model age for highlands anorthosites, Mg-suite rocks, and the mare basalt source regions [50].

Isotope dating of Apollo samples and lunar meteorites indicates a peak in the age of impact melt rocks at 3.9–4.0 Ga, with recent studies indicating impact events around 4.2 Ga [51–53]. The Ar-Ar dating of glass beads shows a peak at 3.9 Ga [54,55]. Additionally, the ages of most impact basins are concentrated around the same time frame. The Late Heavy Bombardment hypothesis suggests that while the overall asteroid impact flux to the Earth-Moon system declines exponentially over time, there is an anomalous peak around 3.9 Ga. Orbital dynamic simulations of planetary bodies, including Jupiter and Saturn, propose that their orbital migration contributed to this phenomenon. However, the hypothesis remains unverified due to the lack of ancient samples for asteroid impact flux calibration prior to 4.0 Ga.

Mare basalt flooding and volcanic activities: Lunar impact basins and large impact craters are typically filled with basalt, giving them a distinct low reflectance and dark color. Researchers have tracked the evolution of basalt eruption intensity over time by analyzing crater size-frequency distribution measurements alongside the area and thickness of basaltic units. This analysis revealed a significant eruption phase around 4.0 Ga, followed by a gradual decline to 3.0 Ga [56]. A recent study has shed light on the significance of lunar *syn*-tectonic mare emplacement along reactivated inherited faults, providing valuable insights into basin-scale and structure-involved volcanism [57]. The basaltic formations found in the PKT region are primarily among the youngest [58]. Analysis of CE-5 samples provided a precise crystallization age of 2.03 Ga [59], which extended the known age range of lunar basalt samples by approximately 800 million years [59,60]. This discovery offers new perspectives on the Moon's volcanic history and thermal evolution. In addition, orbital observations have identified numerous small shield volcanoes [61], silicic domes [62], and dark pyroclastic deposits [63]. Analysis of volcanic glass beads from Apollo 15 and 17 samples has revealed higher concentrations of water and volatile substances toward the center [44]. Spectral data analysis also suggests that pyroclastic deposits contain significant amounts of water, with concentrations reaching up to about 300 ppm [64].

Asteroid impact and solar wind radiation: Asteroid impacts, especially those forming large impact basins, are closely tied to the flooding of basaltic material across the lunar surface. This phenomenon significantly affects the Moon's internal structure and volcanic activity, creating wide depressions that allow for the accumulation of basaltic lava. Concurrently, these impacts excavated and scattered lunar material from beneath the surface, leading to extensive redistribution of mass and mixing of surface layers [65]. These phenomena are crucial not only for the formation of lunar soil but also for interpreting data from remote sensing and identifying sources of lunar samples. Furthermore, the density of craters correlates with the frequency of asteroid impacts and other temporal factors. By calibrating the isotopic ages of Apollo samples, researchers established a function that relates crater size and frequency to age [66]. However, the age range of Apollo basalt samples only covers 3–4 Ga, leaving gaps in the calibration curve for older and younger samples. The precise dating of isotopes in samples from the CE-5 mission provided a key "reference point" for the period between 1 to 3 Ga [67].

Particle radiation, especially from the solar wind, is a crucial factor affecting the lunar surface. The interaction of solar wind radiation, along with impacts from meteorites, leads to space weathering, altering the composition and physical properties of lunar regolith. This phenomenon results in the formation of nanophase metallic iron (npFe^0), amorphous layers, helium-infused bubbles, and similar structures on the surface of mineral grains, typically up to 100 nm in size [2,68,69]. Additionally, thin layers (less than 10–20 nm) of vapor phase precipitation often develop on particle surfaces [70]. The lunar surface experiences solar wind irradiation at an average speed of approximately 400–500 km/s. This radiation implants solar matter into lunar regolith particles to depths of approximately 30 nm. By analyzing isotope compositions of key elements implanted in lunar regolith grains, such as H, O, C and N, their isotope compositions of the Sun can be determined [71–73]. In theory, intact lunar regolith drilling core samples can be used as a record of solar radiation history, dating back to nearly the formation of the Moon. These samples retain material emitted from the Sun during different periods.

2.3. The main challenges in lunar exploration strategies

A comprehensive understanding of the Moon relies heavily on orbital remote sensing with high spatial resolution, *in situ* exploration, and sample collection. However, past lunar exploration endeavors have encountered notable limitations stemming from engineering and technological constraints, leading to five key deficiencies: (1) Temporal Limitations: Previous explorations have mainly focused on samples from the "middle age" era, overlooking representation from both "ancient" and "young" periods; (2) Spatial Restrictions: Exploration efforts have primarily targeted the "central part" of the near side of the Moon, disregarding regions such as the "far side" or the "north and south poles"; (3) Depth Limitations: There has been a notable lack of exploration into the "interior", including deep lunar regolith (<3.05 m) and mantle (with only brief seismic data obtained from Apollo missions); (4) Sample Collection Challenges: The collection of samples has largely involved "displaced" materials, resulting in a scarcity of *in situ* samples from pristine rock outcrops; (5) Dispersed Exploration: Explored areas are "scattered", lacking integrated and continuous coverage of traverses and regions, especially at depth through lava flows or across different geological units. To address these deficiencies, future lunar exploration missions must pursue significant technological advancements and innovative strategies. The objective is to enhance lunar exploration capabilities to unprecedented levels, facilitating a more comprehensive understanding of the Moon's history and composition.

3. Key scientific issues and engineering technology prerequisites

This section is dedicated to exploring the existing controversies and research gaps within the current framework of lunar science, considering the five challenges mentioned earlier. It delves into the major scientific issues expected to be tackled through the first crewed mission and the subsequent scientific expedition aimed at constructing a geological cross-section across the lunar surface. Furthermore, it outlines the essential engineering technology requirements necessary to achieve these objectives.

3.1. Constraints on the origin and evolution of the Moon from water and volatiles

The prevailing hypothesis regarding the Moon's formation revolves around a cataclysmic event known as the "Giant Impact Hypothesis". This theory suggests that the Moon originated from a high-energy collision between Earth and a celestial body. Several factors, including the size, composition, velocity, and angle of impact, as well as the subsequent mixing between the impacting body and proto-Earth, and the post-impact accretion are crucial elements of this hypothesis and directly influence the geochemical characteristics of the Moon. Refractory elements and their isotope compositions are particularly significant in assessing the degree of mixing between the impactor and proto-Earth, as well as the geochemical nature of the impactor, and contribution of the impactor to the Moon [27–29,74,75]. During the Giant Impact event, volatiles such as water would have been susceptible to loss due to their high volatility under the extreme temperatures generated. Consequently, lunar rocks exhibit significantly lower volatile abundances compared to Earth. Early investigations of water content in Apollo lunar samples indicated an extremely low presence of water (i.e., in parts per billion level), often referred to as a "bone dry" Moon [76]. These observations align with the traditional Giant Impact model, suggesting that the Moon formed from gas and melt accretion at high temperatures resulting from the impact. However, analyses of water and other volatiles (S, Cl, F, P) in volcanic glass beads from Apollo 15 and 17 lunar samples have unveiled unexpected results. These studies suggest that the primitive magma of these pyroclastic glass beads could contain substantial water content, up to 745 ppm [44], which is 3–4 orders of magnitude higher than previously thought. This significant disparity has sparked a debate surrounding the "dry" versus "wet" Moon hypotheses, which holds pivotal implications for understanding the origin and formation of the Moon. The post-impact Synestia model [31] proposes an alternative scenario where the gas and melt expelled during the giant impact could have created a high-pressure environment conducive to the accretion of water and other volatiles in the hot disk from which the Moon emerged.

The CE-5 mission successfully collected the youngest (2.03 Ga) mare basalt sample to date [59]. Petrogenesis studies, along with lead (Pb), strontium (Sr), and neodymium (Nd) isotopes, have unveiled that this sample underwent a process involving low degree of partial melting of mantle rocks followed by a high degree of fractional crystallization [77]. Investigations into the water content and hydrogen isotopes in melt inclusions and apatites from the CE-5 mare basalts have shown that the water content was measured at 7 ± 3 ppm for the bulk basalt, 283 ± 22 ppm for the parent magma, and 1–5 ppm for the mantle source. These measurements align with the lower limit of the estimates for the water content of the lunar mantle previously reported (3–200 ppm) [78]. Previous studies have shown that: (1) Mantle derived rocks, mare basalts and pyroclastic clasts, provide valuable constraints on the geochemical nature of the lunar mantle, serving as "probes" for mantle composition. However, these samples have undergone multiple stages of degassing during ascent, intrusion, eruption, and outflow processes [79]. This degassing is crucial for refining our understanding of original water and volatile abundance in the lunar mantle. (2) The reported variability in water content within the mantle source area spans over two orders of magnitude, indicating substantial uncertainties. Further verification through comprehensive geological, petrogenesis, and modeling studies is necessary to elucidate the spatiotemporal evolution of water and volatiles in the Moon, including considerations of heterogeneous or homogeneous distribution and long-term degassing patterns of the mantle source.

Specific types of samples are required to address the above scientific questions: (1) Basalts from varying depths acquired during *in situ* examination of a stratigraphic profile from the interior wall of a small, recently formed mare impact crater. These samples would enable investigations into lava degassing processes at different depths throughout the cooling history of the flow. (2) Basalts collected from diverse locations along the flow direction of a single lava during extensive geological cross-section surveys. Such samples would provide insights into degassing mechanisms during the emplacement of lava flows. (3) Volcanic rocks sourced from different time periods within the same lunar basin. These samples could shed light on the temporal evolution of water and volatile components within the mantle source region. For instance, Rima Bode displays distinct phases of at least two mare lava flows (3.3–3.7 Ga) and two pyroclastic deposits (>3.7 Ga) [80]. (4) Comparing mare basalts and pyroclastic deposits, both originating from the lunar mantle but at varying depths and with different geochemical properties, offers an opportunity to examine the spatial distribution of water and volatile components within the mantle source region.

3.2. Lower crust materials and their constraint on lunar magma ocean crystallization

The LMO model suggests that as the LMO solidified approximately 70% of its mass, plagioclase started to precipitate and rise to form a feldspathic crust on the lunar surface. As the differentiation of the LMO progressed, the remaining residual melts (after > 99% solidification) between the lunar crust and mantle resulted in the formation of urKREEP. Therefore, the composition profile originating deep within the lunar crust not only represents a fundamental aspect of the Moon but also serves as essential evidence for validating Moon formation theories, such as the LMO hypothesis.

KREEP is considered to represent the final phase of solidification in the LMO. However, it has yet to be discovered in its pristine igneous rock form. Only a few breccias found in Apollo 12 samples [16,81] and the lunar meteorite Sayh al Uhaymir (SaU) 169 [15,82] exhibit KREEP-like characteristics, with formation ages estimated at approximately 3.92 Ga [15,16]. KREEP basically is identified through its geochemical signature, which varies in concentration within lunar mare basalts and impact melt breccias. Therefore, the identification and collection of pristine KREEP rocks are essential for understanding the Moon's differentiation process and further assessing the LMO crystallization model. The global distribution of Th concentration on the lunar surface, as measured by the Lunar Prospector, is utilized to track the presence of KREEP components. By combining this data with the high magnesium number (the atomic ratio of Mg and Mg+Fe), the Th enrichment resulting from magmatic differentiation can be distinguished, allowing for the identification of potential landing sites where KREEP may have been present.

The Mg-suite, which encompasses olivine-rich and Mg-spinel-rich lithologies, is believed to originate from the lower lunar crust. These rocks are predominantly found at the base of impact basins, within central peaks and ring-shaped mountains of large impact craters, and in ejecta from impact basins and large craters. The Mg-suite rocks are thought to have formed as a result of upwelling magnesium-rich partial melts originating from the deep mantle, as well as KREEP melt percolating through and altering the primordial anorthositic crust during the late-stage mantle overturn process in the LMO crystallization [83,84]. According to this model, the formation of the Mg-suite should have occurred after the formation of highland anorthosites. However, isotopic dating results and the initial ε_{Nd} range of Mg-suite rocks overlap significantly with those of highland anorthosites [85]. Since only a small fraction (<5%) of plutonic rocks have been identified in Apollo lunar samples, the identification and collection of a wider range of plutonic rocks will be a crucial objective for future scientific endeavors utilizing crewed lunar missions.

To address the aforementioned scientific questions, it is necessary to harness the benefits of crewed lunar exploration in sampling various plutonic rock types: (1) Prioritizing sampling efforts in regions exhibiting high Th concentration and high Mg number, such as Lalande, Aristarchus, and Mayer, where pristine KREEP rocks may be present; (2) Employing *in situ* sieving techniques to select a substantial quantity of rock fragments (e.g., 2 kg of grains with a 2 mm grain size, which contains approximately 160,000 pieces of rock fragments), thereby facilitating the collection of more Mg-suite samples; (3) Gathering rocks along a long-distance geological cross section, focusing on locations at or near the central peaks or ring mountains of large impact craters; (4) Collecting ejecta from impact basins and large impact craters.

3.3. Spatiotemporal evolution of volcanism and mantle reservoirs

Volcanic activity is the most important and direct manifestation of the Moon's internal dynamics, showcasing extensive basaltic extrusions, pyroclastic explosions, and a limited number of silicic volcanic cones and domes [61]. The evolutionary trajectory of lunar volcanism serves as a tangible indicator of the Moon's thermal history, with volcanic deposits serving as remnants of partial melting processes within the mantle source. In line with the LMO and overturn hypothesis, a stratified structure with varying mineral compositions across different depths, superimposed by lateral heterogeneity with later dense upper materials sunk beneath early lighter ones [86], would be theoretically yielded. Hence, scrutinizing the composition of volcanic rocks provides critical evidence for validating the LMO hypothesis and understanding the mantle source's material composition.

The analysis of crater size-frequency distribution, along with isotopic dating of returned samples, coupled with the spatial distribution of different basalt types, enables the reconstruction of the evolution of basalt eruption frequency and material compositions throughout lunar history [87]. However, it should be noted that basalts might have experienced varying degrees of differentiation prior to eruption. For instance, CE-5 basalt exhibits a moderate Ti content (5.7 wt%), yet its source area resembles that of low-Ti basalts [77]. Conventionally, high-Ti basalts are believed to originate from a high-Ti mantle source formed by the settling and overturning of Fe-Ti-rich cumulates during the late stages of the LMO [88]. The spatial distribution of high-Ti basalt does not correspond to the distribution of Th content, suggesting that the overturn of the LMO resulted in the separation of KREEP components from Fe-Ti-rich cumulates. However, the limited occurrences of basalt restrict our understanding of their formation mechanisms and differentiation processes. Moreover, there is a lack of effective methods to determine the formation depth of different basalt types, leaving the spatiotemporal evolution of mantle source material largely unexplored. Hence, the systematic collection and return of various types and ages of basalts with known locations are imperative for future lunar explorations.

High-resolution orbiting exploration has discovered a variety of unique special volcanic morphologies, including dark pyroclastic deposits, volcanic domes, and irregular lunar mare patches [48,89,90]. These distinctive volcanic formations likely arise from localized magmatic differentiation, typically confined to small areas. It is essential to investigate whether these materials accurately reflect the composition (including water and other volatile components) of the mantle source region. Furthermore, understanding the formation mechanism behind their configuration and its correlation with basaltic lava flow eruptions in the same vicinity is crucial. Exploring the potential for lunar magmatic differentiation leading to the development of granite is also of interest [90]. Additionally, the formation mechanisms of specific silicate-rich volcanic domes and their implications warrant further investigation [90]. Detailed analysis of factors contributing to the formation of large volcanic rises (e.g., Rümker, Aristarchus, Marius, etc., with diameters ranging from 66 to 560 km) is necessary. Furthermore, given the prolonged duration of eruptions (3.8–1.1 Ga) [91], further exploration is warranted.

To address the aforementioned questions, it is imperative to unravel the spatiotemporal evolution of lunar volcanism, the genesis and differentiation of parent magma, the spatial distribution characteristics, and the evolutionary trajectory of the mantle source region's composition, as well as the thermal history of the Moon. To achieve this, priority should be given to identifying and collecting samples from various volcanic units (Fig. 1): (1) Lunar mare basalts and volcanic pyroclastic deposits from different time periods within the same region, such as Rima Bode; (2) Volcanic rock specimens encompassing lunar mare basalts, irregular mare patches, and high-silica volcanoes across different epochs, through extensive geological surveys; (3) Employing *in situ* grain size sorting of lunar regolith to ensure maximum acquisition of volcanic rocks representing all lunar surface geological units, while adhering to engineering constraints regarding total sample return weight.

3.4. The initiation and cessation of the lunar magnetic field dynamo

The Moon currently lacks a magnetic field similar to Earth's dipole magnetic field. Analysis of paleointensity from Apollo samples suggests the possible presence of a dipole magnetic field between 4.0 to 3.6 Ga [93] and an advecting liquid metallic core. However, all lunar rocks collected thus far are either local boulders or transported blocks, providing no *in situ* orientation information. Consequently, determining the direction of the early Moon's dipole magnetic field poses a significant challenge. Equally crucial is investigating whether the Moon's magnetic field experienced reversals and, if so, what the reversal frequency was. Were these reversals linked to the magnetic field's strength or the onset and cessation time of the lunar dynamo? If a dynamo did operate during the Moon's early history, evidence of the lunar magnetic field may have been preserved in the cooling process of lunar mare basalts.

To address the aforementioned questions, it is imperative to conduct *in situ* examinations of magnetic fields on rock outcrop profiles and directly collect host rock samples. Given the Moon's extensive history of asteroid impacts, its surface is covered by a regolith layer ranging from several meters to tens of meters thick. This layer is typically underlain by an impact debris layer or a disrupted angular breccia layer. The exposed blocks on the lunar surface primarily consist of displaced boulders. Two types of host rock sections on the lunar surface hold potential for investigation: (1) the walls of natural lava pits exposed by meteorite impact, and (2) the walls of newly formed small impact craters. Through a combination of human expertise and collaboration with automated systems, conducting *in situ* examinations and directly sampling these host rock sections can provide valuable insights into a range of critical scientific questions concerning the lunar dynamo.

3.5. The internal structure of the Moon constrained by multiple physical properties

The internal structure of the Moon plays a crucial role in understanding its formation and subsequent evolution. The current understanding is largely based on the LMO hypothesis, supported by experimental petrology and other scientific insights. However, knowledge in this area is limited due to constraints in field exploration. During the Apollo missions, lunar seismometers were deployed, forming a near equilateral triangular network in the PKT. Notable discoveries include: an average crust thickness of about 30 km at the landing site [94]; the detection of shallow (50–200 km) and deep (800–1100 km) seismic sources, the identification of a velocity discontinuity at 500 km depth, and the potential presence of a molten outer core [95]. Nevertheless, numerous questions remain unanswered regarding the geological implications of the 500 km velocity discontinuity, the existence and characteristics of discontinuity surfaces, the mechanisms underlying deep seismic waves, the geophysical structure of the mantle, the dimensions of the Moon's core, and the presence of a solid inner core. Although Apollo missions deployed various instruments such as heat flow probes, magnetometers, gravimeters, and laser retroreflectors, further exploration and data collection are necessary to supplement and enhance understanding of the Moon's internal structure.

Crewed lunar exploration can offer several advantages, particularly in the deployment and operation of geophysical instruments on the lunar surface. Astronauts can establish a cohesive detection network, integrating various geophysical payloads such as gravitational, magnetic, electro-seismic, and thermal instruments. This approach will significantly enhance understanding of the Moon's internal structure and condition. Magnetic field data will contribute to refining comprehension of the Moon's core size. Deploying temperature sensors within the deep drilling core (>3 m) enables accurate measurement of heat flow from the Moon's interior, effectively mitigating the impact of solar heating. This method allows for the precise determination of heat flow and temperature profiles, which is crucial for elucidating the Moon's physical properties and the velocity of lunar seismic waves. Moreover, deploying new laser ranging reflectors facilitates precise measurements of the Earth-Moon distance, offering additional insights into the Moon's internal structure. During extensive geological surveys of the lunar surface, establishing a comprehensive geophysical instrument network covering a broader area becomes feasible. Additionally, integrating lunar seismometers that will be deployed in the south pole during the CE project phase IV and in high-latitude regions during the ILRS missions enables the establishment of a global seismometer network. These advancements hold promise for groundbreaking discoveries in probing the Moon's internal structure.

3.6. Formation of large impact basins and its modification of the Moon

The lunar surface is predominantly characterized by impact basins and craters of various sizes, providing valuable insights into the Moon's impact history and the broader inner Solar System.

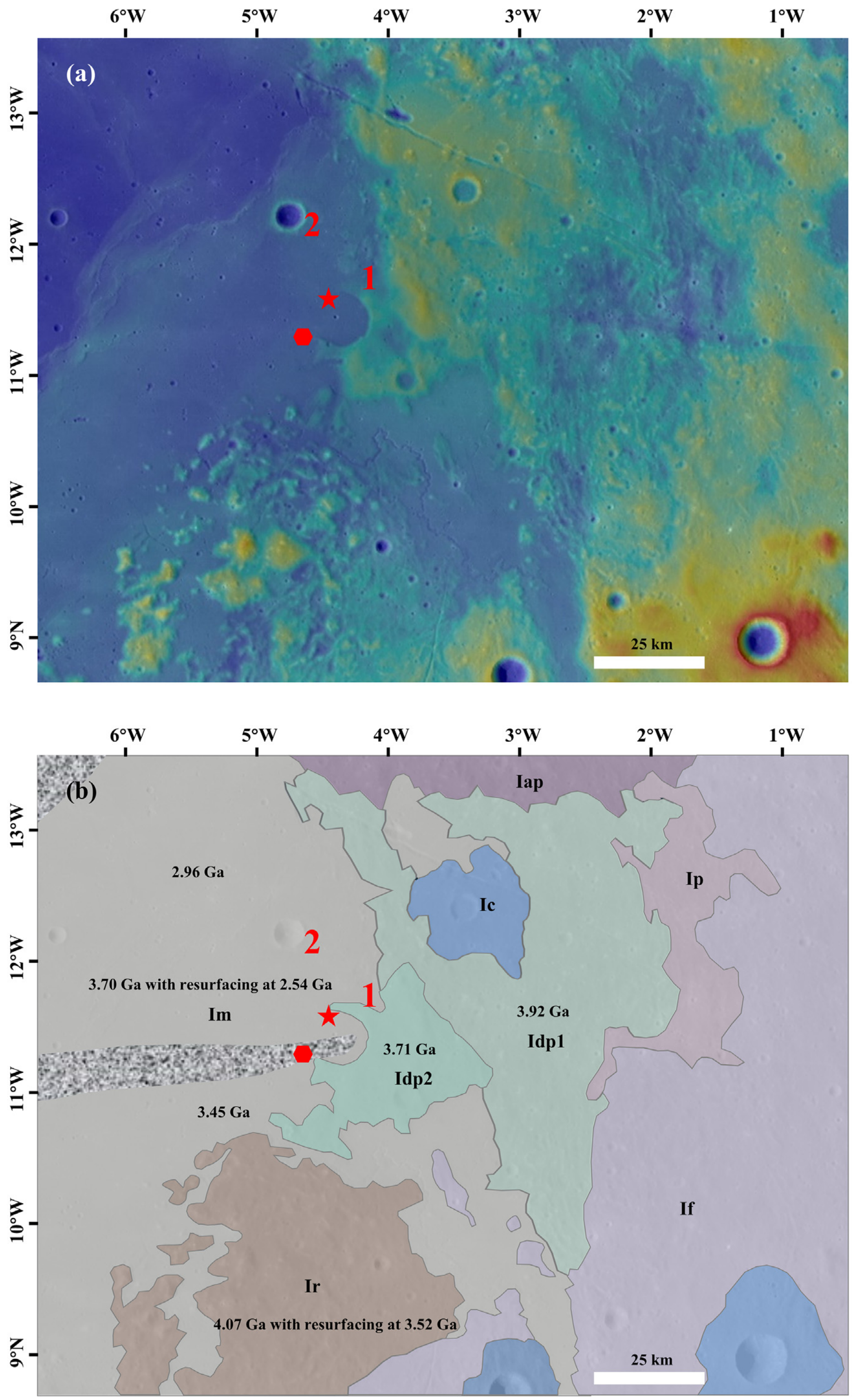

Fig. 1. Context of the Rima Bode. (a) SLDEM (LRO LOLA Digital Elevation Model Coregistered with Selene Data) elevation [92], (b) major geological units [79], alongside suggested surveying and sampling points. The red star indicates the recommended landing site, strategically positioned near basalt and dark pyroclastic deposits. A polygon outlines a promising area for deep drilling, positioned along the Copernicus Crater's ray. Dark pyroclastic samples can be collected at sampling point 1, while ejecta from varying depths can be collected at sampling point 2. Iap: Imbrian Montes Appenin; Ip: Imbrian plain; Ic: Imbrian crater; Im: Imbrian dark mare; Idp: Imbrian dark pyroclastic deposits; If: Imbrian Fra Mauro Formation; Ir: Imbrian rugged and dark pyroclastic deposits.

These features serve as important markers for lunar geological units and offer a chronological reference for lunar stratigraphy. Impact events significantly alter lunar morphology and material composition, with materials ejected from large impact basins scattered across the lunar surface, thus serving as crucial indicators for lunar strata [65]. Precise determination of isotopic ages can establish "golden spike" reference points for lunar stratigraphy. Intense impact events have the potential to excavate and eject deep-seated materials, such as Th-rich bands around the rim of the Imbrium Basin, believed to be KREEP components excavated by the basin-forming event [96]. These processes may expose materials from the lower crust and upper mantle in locations like the Moscoviense

Basin, Crisium Basin, Apollo Basin, and SPA Basin [19]. Simulations indicate that transient craters formed by big impacts can induce extensive mixing and melting of deep-seated lunar materials, affecting depths up to approximately 400 km [97]. In addition, the strong shock waves from impacts may influence antipodal regions and potentially trigger volcanic activity. Notably, lunar basalts are predominantly found filling impact basins and large craters.

The scales of impact basins are immense, with examples like the Imbrium Basin spanning a diameter of 1100 km. Currently, the understanding of the geological structure of impact basins relies primarily on orbital remote sensing observations, which offer insights into morphology, material composition distribution, gravity fields, and other relevant data. However, to date, no comprehensive cross-section surveys or systematic sample collections have been conducted for impact basins. This absence hinders the establishment of a measured three-dimensional structure and composition model, as well as *in situ* verification of orbital remote sensing findings. For example, GRAIL data identified mascons and their distribution [98], but the mechanisms behind their formation and evolution remain unclear. Following the release of impact pressure, central peaks of craters may form due to the rebounding of deep materials, although numerical simulations suggest they could also result from residual impactors [99]. Furthermore, if the Th-rich bands around the rim of the Imbrium Basin originated from excavated deep KREEP material, what is the geological significance of the different Th distribution in the Oceanus Procellarum? Is there any association between the formation of the PKT and the SPA Basin?

All sampling return missions have targeted late-filling basaltic lava surfaces, except for the Apollo 16 mission, which landed on anorthosite highlands. However, none of these missions collected impact melts that crystallized during the formation of the impact basin, which is crucial for obtaining comprehensive information about their occurrence [100]. Additionally, uncertainties surround the radiometric ages of these basins. Furthermore, there is a notable absence of ancient samples for calibrating asteroid impact flux prior to 4 Ga, a critical aspect for evaluating the Late Heavy Bombardment hypothesis. CE-5 mission provided a precise isotopic age that serves as a unique calibration point for lunar crater dating curves spanning between 1 to 3 Ga. Nevertheless, there remain significant challenges in constraining more recent (<1 Ga) asteroid impact fluxes, primarily relying on Ar-Ar isotopic dating of impact ejecta from craters such as Copernicus and Tycho.

To address these scientific questions, it is essential to conduct a comprehensive investigation of representative impact basins. This necessitates the collection of impact melts from large impact basins in accordance with key engineering criteria, which include the following (1) Utilizing a long-distance geological cross-section survey to conduct a thorough geophysical network investigation with extensive spatial mobility. This approach is expected to provide both shallow and deep structural data from large impact basins. Simultaneously, systematic sample collection should be performed along the survey traverse, targeting central peaks, ring mountains, basin margins, and crater ejecta at various distances. (2) Selection of representative impact basins for exploration, prioritizing those with mascons (e.g., Imbrium Basin) or without (e.g., Nubium Basin), as well as the PKT, particularly focusing on the Th-rich and gravity anomaly belts at the rim. (3) Collection of impact melts formed during the formation of significant impact basins, alongside definitive impact ejecta from craters such as Copernicus and Tycho. Accurate determination of the isotopic age of impact events is crucial for establishing "gold spikes" for lunar strata.

3.7. Interaction between solar wind and lunar surface and the formation of swirls

The lunar regolith serves as a historical record of interactions between the lunar surface and its environment, including micrometeorite impacts and solar wind radiation, along with various particles such as high-energy solar particles and cosmic rays. These processes substantially alter the compositional and physical properties of lunar surface materials, thereby impacting the accurate interpretation of remote sensing data. Solar wind particles implanted into the lunar regolith preserve the composition of solar particles at different times. Furthermore, space weathering, influenced by the Moon's electromagnetic field, topography, geomorphology, and regolith composition, further affects the lunar surface. The radiation environment on the lunar surface directly impacts astronaut survival and activities, as well as the long-term sustainability of lunar bases. However, due to the limited depth of the lunar regolith core drilled during the Apollo missions (with the longest core being 3.05 m), only information about space weathering over a specific period was recorded. This limitation persists despite the fact that the thickness of the lunar regolith is approximately 12 m, as determined by penetrating radar onboard CE-4 [101].

In addition to the solar wind, the lunar surface may also be exposed to "Earth Wind". As the Moon orbits Earth, it passes through the Earth's magnetotail approximately 25% of the time. Particles from Earth's ionosphere and upper atmosphere collectively form a particle flow within the magnetosphere, interacting with the solar wind and bombarding the lunar surface, thus generating this phenomenon [102,103]. Theoretical models propose that the ion composition of the Earth Wind (comprising H^+, O^+, NO^+, N^+, O^{2+}, etc.) differs significantly in energy distribution from that of the solar wind. Moreover, this ion composition is subject to variations in Earth's geomagnetic field. Spectral data from the M^3 probe of Chandrayaan-1 identified hematite at high latitudes on the near side of the Moon, believed to be an oxidation product resulting from oxygen ions from the Earth Wind [104]. However, confirming the presence and characterizing the effects of the Earth Wind on the lunar surface remains a formidable scientific challenge. If indeed the Earth Wind exists, questions arise regarding its interaction with lunar regolith and the subsequent alterations to regolith material. Furthermore, how did the Moon's proximity to Earth throughout geological history influence the Earth Wind's radiation? Can we discern the composition of the Earth's Wind from a lunar regolith profile and leverage this information to glean insights into the early Earth's atmosphere and variations in Earth's paleomagnetic field?

Optical imagery reveals intricate, bright structures on certain areas on the lunar surface [105,106], referred to as "lunar swirls". These large white swirls exhibit complex reflectance variations across scales, spanning from a few kilometers to hundreds of kilometers, superimposed on the same lava flows. Despite their conspicuousness, the origins of these phenomena remain enigmatic. Meanwhile, orbital remote sensing has detected magnetic anomalies in similar regions, although fine structural details remain elusive. Given the magnetic field's shielding effect on charged particle radiation, one hypothesis posits that these prominent bright swirls may arise from the deflection and shielding provided by the magnetic anomalies against the solar wind [107]. Another hypothesis suggests that these swirls could stem from grain or compositional fractionation caused by the migration of lunar dust [108]. All of these mechanisms are intricately linked to the interaction between radiation and the lunar surface. The presence of these large bright features presents a prime opportunity to investigate this interaction further. *In situ* exploration spanning these expansive white swirls, coupled with the collection of detailed electromagnetic field structures along survey paths and the comprehensive analysis of radiation particles (including solar wind, solar high-energy particles, potential Earth Wind, and cosmic rays), micrometeorite fluxes, and the physical characteristics of lunar regolith, holds the key to unraveling the mystery surrounding the origins of large bright swirls and magnetic anomalies on the lunar surface. This will also shed light on the mechanism of solar wind-lunar surface interaction and determine the presence of Earth Wind.

A landing exploration is paramount to unraveling the intricate interaction between radiation particles and the lunar surface, shedding light on scientific mysteries such as large bright swirls, magnetic anomalies, and Earth Wind. This comprehensive exploration should focus on three key aspects: (1) electric and magnetic field structures, (2) the radiation environment, and (3) the material composition, the crystal structure of minerals, and the physical properties of the lunar surface. The radiation environment on the lunar surface encompasses the composition, flux, and velocity of injected particles, as well as the composition and flux of secondary particles ejected from the lunar surface. Notably, there are significant disparities in particle composition, flux, velocity, and other factors between the Earth Wind and the solar wind. The designated landing site candidates include: (1) The Reiner Gamma swirl, a conspicuous large bright spot on the lunar surface, which harbors a notable magnetic anomaly and lies within the potential radiation range of Earth Wind. Investigating the concurrent bright and dark stripes on this swirl can unveil the intricate mechanisms governing the interaction between radiation particles and the lunar surface, addressing the aforementioned scientific enigmas. This exploration should prioritize the examination of three-dimensional magnetic field structures with high spatial resolution; the components, fluxes, and energy distributions of various particles such as solar wind, high-energy solar particles, and Earth Wind; grain size and flux of lunar dust, along with their altitude-related variations; neutrons, secondary particles, and gamma rays emitted from the lunar surface; chemical and mineralogical compositions of lunar materials; degrees of space weathering; water content, among other factors. (2) Long-distance lunar geological cross-section survey and long-term monitoring through a network of stations. The primary objective is to investigate the space radiation environment and electromagnetic field of the lunar surface, aiming to discern spatiotemporal variations in radiation particles interacting with the lunar surface. Simultaneously, monitoring stations for the space radiation environment will be established along the extensive lunar geological cross-section. These stations, when integrated with robotic missions, contribute to establishing a comprehensive lunar space environment monitoring network. This network is instrumental in constructing a model of the space radiation environment on the Moon, thereby unveiling the interaction mechanism between radiation particles and celestial bodies' surfaces. The insights gained from this research provide crucial support for the construction and operation of the ILRS.

4. Technological innovation serves as a crucial catalyst for scientific breakthroughs

To address the aforementioned pivotal scientific challenges and establish a novel lunar science system, it is crucial to innovate key technologies and make significant advancements in lunar exploration. This paper outlines several critical technologies relevant to China's two-stage mission plan and scientific objectives for crewed lunar exploration.

4.1. China's first crewed lunar exploration

To optimize the scientific outcomes within the constraints of a crewed lunar mission, two key factors must be considered: The

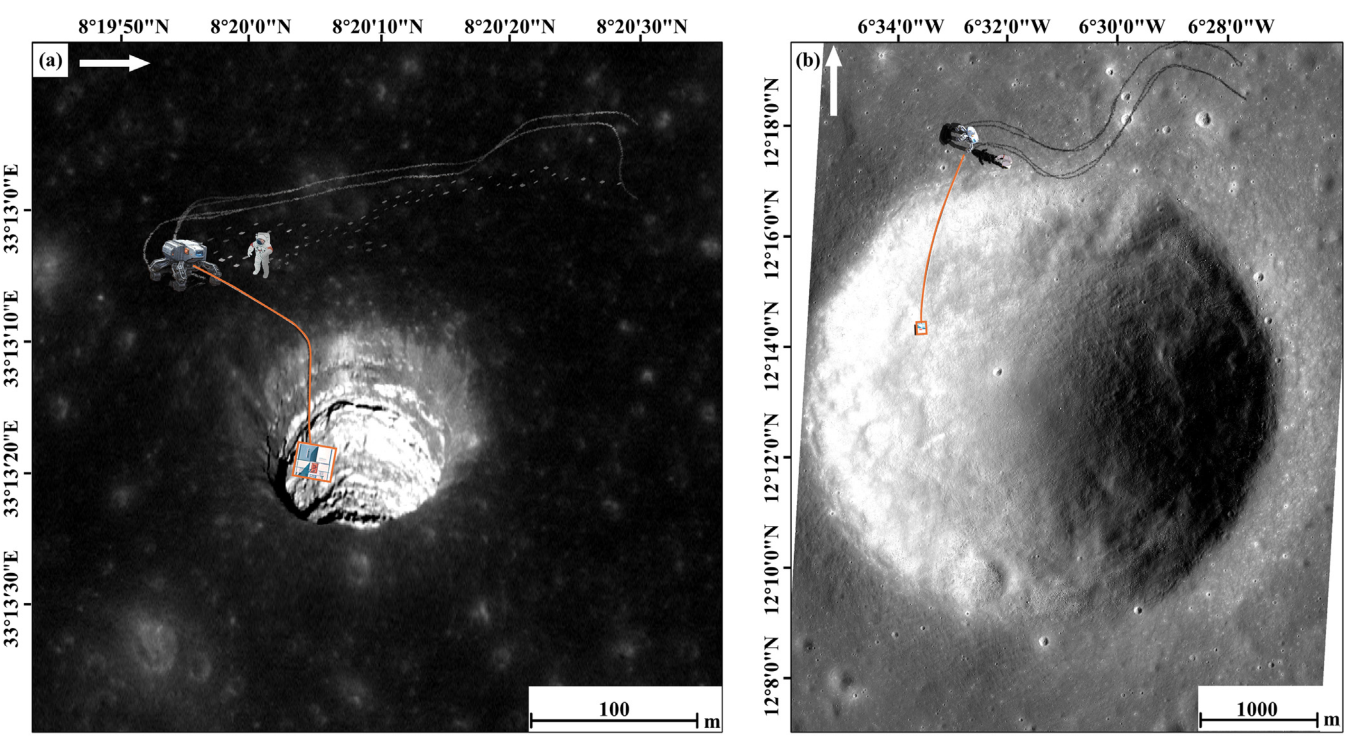

Fig. 2. The pristine rock outcrop exploration scheme for host rock sections that are rare on the lunar surface. (a) Scheme for lava tube skylight (NAC ID: M144395745LE); (b) scheme for impact crater (NAC ID: M1274279516LE) [109]. Astronauts could perform *in situ* measurements along the profiles of the skylight or crater wall using tether-driven instruments.

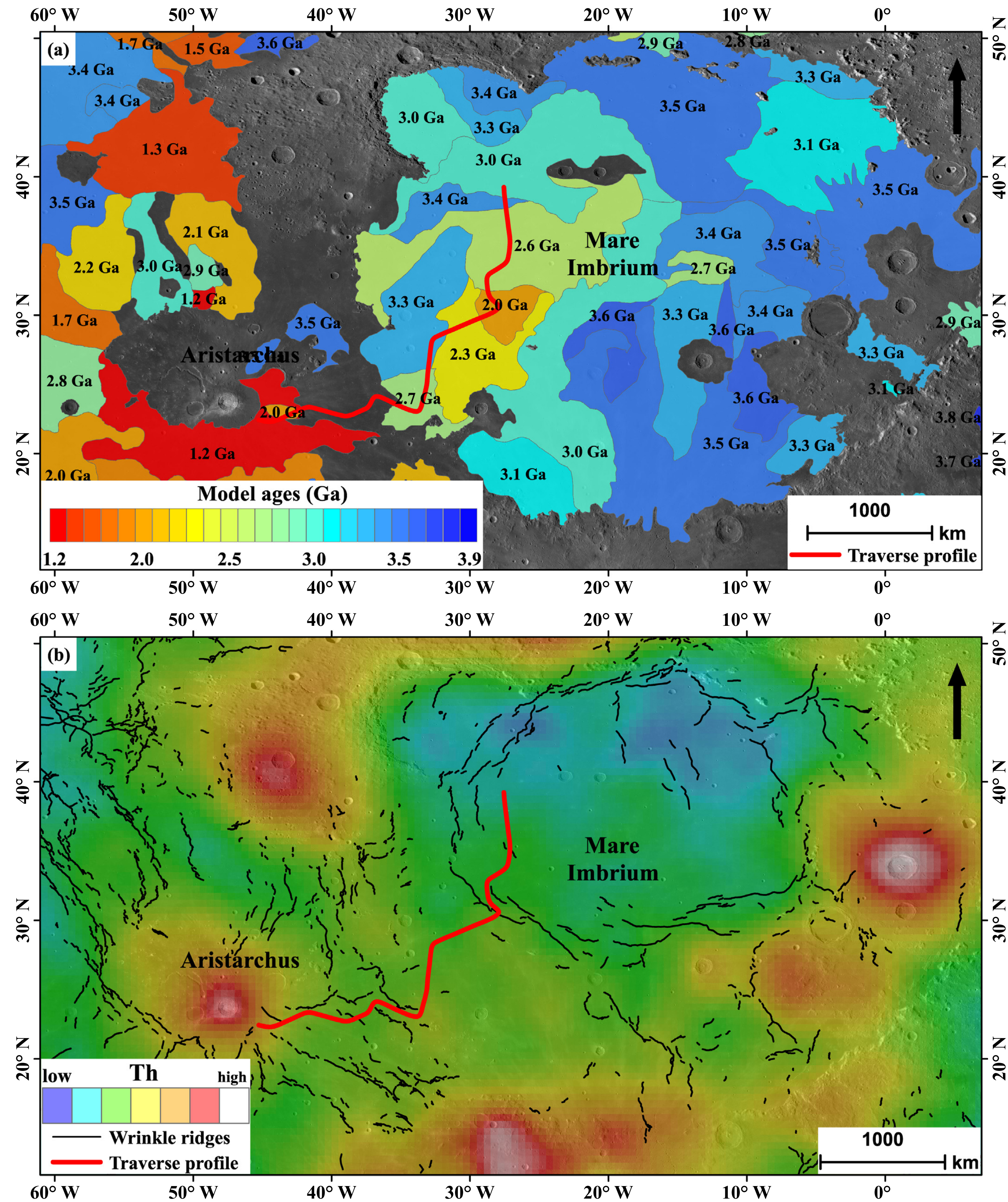

Fig. 3. A candidate traverse profile for a long-distance geological cross-section survey spanning thousands of kilometers on the lunar surface. (a) The traverse profile initiates at the Mare Imbrium, traverses through at least eight basalt units spanning from 1.2 to 3.0 Ga [58] and terminates at the Aristarchus plateau. (b) The traverse profile should avoid craters and scarps [110] and the relief along the route should be less than about 0.5 m. The base map depicts the Th abundance [111].

selection of landing sites and the advancement of exploration capabilities. Optimal landing sites should be chosen in unique geological settings, distinct from those explored in previous missions like Apollo, Luna, and CE-5. These sites should encompass diverse geological units, including areas with multi-stage volcanic activities, volcanic debris, olivine-rich rocks from the lunar deep interior, and rocks containing KREEP components (Fig. 1). Promising locations meeting these criteria include Rima Bode, Lalande, Reiner Gamma, and Aristarchus, among others.

To optimize the advantages of crewed exploration and enhance human–machine integration, significant advancements in key technologies are essential to facilitate the collection of specific types and occurrences of lunar samples. These advancements include (1) Deep drilling technology for lunar regolith cores. Lunar regolith thickness increases with surface age. At the CE-4 landing site, with an age of 3.6 Ga, the lunar regolith thickness is approximately 12 m, as detected by penetrating radar onboard [101]. However, the Apollo mission's drilling core was limited to a maximum length of 3.05 m. Thus, advancements in drilling and mining technologies are imperative. One approach involves deploying a robotic rover to drill and collect deep core samples, which can be retrieved during subsequent crewed missions. This technology should enable the collection of continuous cores spanning the entire thickness of the lunar regolith. Additionally, deploying a heat flow sensor in the drilling hole can mitigate temperature fluctuations on the lunar surface, facilitating reliable and accurate internal heat flow measurements. (2) *In situ* sorting and sampling technology of lunar regolith. Each mission can only land at one location, necessitating the collection of diverse geological samples beyond the immediate vicinity. This not only enhances the scientific value of returned samples but also provides crucial technical support for future *in situ* utilization of lunar resources. Sorting lunar regolith by size and magnetic properties is relatively straightforward. By sieving mm-sized rock fragments, significant quantities of varied samples can be obtained within the weight constraints of the returned samples. Magnetic separation of lunar soil samples can enrich metal particles (primarily asteroid fragments) and titanite. Analysis of asteroid fragments provides insights into the distribution of impactor types on the Moon over time, while titanite represents a potential *in situ* resource. (3) Investigation and sampling of the pristine rock outcrops. Automated probes operated by astronauts can detect critical features *in situ*, such as measuring the three-dimensional magnetic field components. Samples should be collected from the walls of small, fresh impact craters and the walls of lava pit (Fig. 2).

4.2. Lunar expedition

Traditional lunar landing and sampling missions have typically concentrated on exploring the vicinity of the landing site (e.g., Apollo 15–16 were all within a 7 km radius of the Lunar Module). However, these missions have inherent limitations in their ability to investigate complex geological units within a three-dimensional space and to study evolutionary processes such as magmatic activity over time. The development of high-performance lunar mobile laboratory allows ultra-long-distance crossings and autonomous exploration over thousands of kilometers. This mobile laboratory boasts the capability to survey several geological cross-sections of the lunar surface and traverse vast distances. For example, a candidate traverse could span from Mare Imbrium to Aristarchus Plateau, traversing at least eight basalt units (Fig. 3). Moreover, the laboratory can provide essential living conditions for astronauts during multiple crewed missions. This development will mark a significant shift in lunar exploration paradigms and will contribute substantially to the establishment of a comprehensive spatiotemporal evolution model for the Moon.

In addition to its robust obstacle-crossing and autonomous piloting capabilities, the lunar mobile laboratory should also possess autonomous investigation functions. These encompass active seismology, high-resolution and deep-sounding radar, compositional analysis of materials, and surface environmental observation, among others. The laboratory should be equipped for autonomous sampling, sorting, sample preparation, and laboratory analyses. Astronauts will also have the capacity to deploy long baseline geophysical stations. Collaborating with stations established by robotic missions, these stations will form extensive networks covering the expansive lunar surface. This infrastructure will facilitate long-term, continuous monitoring of the lunar internal structure and the spatial environment of the lunar surface.

5. Conclusions

The fundamental understanding of the Moon's formation and evolution was primarily established through extensive study of Apollo samples, shedding light on the profound influence of the Moon's formation process on Earth's early history. Moreover, it revealed insights into the preservation of the history of asteroid impacts and solar radiation on the lunar surface. Since the 1990s, high-resolution orbital remote sensing has provided valuable data on various lunar aspects, including morphology, material composition, and the space environment. These datasets serve as a foundation for contemporary lunar missions, underscoring the significant contrast between the near and far sides of the Moon. Comparative analyses of the global Moon's geological structure and the geochemical characteristics of locally returned samples have raised numerous new scientific questions. There is an urgent need for exploration and sampling in specific key regions. Despite previous missions retrieving lunar samples from only 10 widely separated near side locations, they provided a foundational understanding but insufficient information about major evolutionary events over time and space during the Moon's evolution. Additionally, the analysis of these limited samples does not provide a clear evolutionary path of these significant events. Furthermore, while lunar rocks were collected with a definite sampling strategy during Apollo, they represent only a small sampling in the landing areas, with uncertain insights into their original locations, which could have been delivered from other remote, unidentified sources. This paper systematically assesses the findings from analyses of lunar samples and remote sensing data, with a particular emphasis on analyzing seven significant scientific challenges associated with the constraints of previous sampling return missions. The study proposes specific engineering and technical requirements, along with innovative research ideas. China's crewed lunar exploration poses substantial scientific research challenges that necessitate coordination with robotic lunar exploration tasks to maximize human advantages. This requires technological innovation in key areas to facilitate a transformative shift in lunar exploration paradigms, providing essential engineering and technical support to achieve significant original results in crewed lunar exploration.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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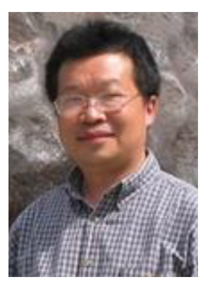
Authors contributions

Yangting Lin and Xianhua Li contributed to the conceptualization and paper writing, and the rest of the authors contributed to the investigation, paper writing, and review.

References

[1] Ouyang Z, Li C, Zou Y, et al. Primary scientific results of Chang'e-1 lunar mission. Sci China Earth Sci 2010;53:1565–81.
[2] Chen Y, Hu S, Li J-H, et al. Chang'e-5 lunar samples shed new light on the Moon. Innovat Geosci 2023;1:100014.
[3] Zeng X, Liu D, Chen Y, et al. Landing site of the Chang'e-6 lunar farside sample return mission from the Apollo basin. Nat Astron 2023;7:1188–97.
[4] Chi W, Jia Y, Xue C, et al. Scientific objectives and payload configuration of the Chang'E-7 mission. Natl Sci Rev 2023;11:nwad329.
[5] Compton WD. Where No Man Has Gone Before: A History of Apollo Lunar Exploration Missions. NASA Technical Report; 1989.
[6] Beattie D A. Taking science to the Moon: Lunar experiments and the apollo program. 2001.
[7] Hiesinger H, Head JW. New Views of lunar geoscience: An introduction and overview. Rev Mineral Geochem 2006;60:1–81.
[8] Canup RM, Righter K, Dauphas N, et al. Origin of the moon. Rev Mineral Geochem 2023;89:53–102.
[9] Gaffney AM, Gross J, Borg LE, et al. Magmatic evolution I: Initial differentiation of the Moon. Rev Mineral Geochem 2023;89:103–45.
[10] Elardo SM, Pieters CM, Dhingra D, et al. The evolution of the lunar crust. Rev Mineral Geochem 2023;89:293–338.
[11] Osinski GR, Melosh HJ, Andrews-Hanna J, et al. Lunar impact features and processes. Rev Mineral Geochem 2023;89:339–71.
[12] Neumann GA, Zuber MT, Wieczorek MA, et al. Lunar impact basins revealed by gravity recovery and interior laboratory measurements. Sci Adv 2015;1: e1500852.
[13] Heiken G, Vaniman D, French BM. Lunar Sourcebook: A User's Guide to the Moon. Houston: Cambridge University Press; 1991. p. 736.
[14] Pieters CM, Besse S, Boardman J, et al. Mg-spinel lithology: A new rock type on the lunar farside. J Geophys Res Planets 2011;116.
[15] Lin Y, Shen W, Liu Y, et al. Very high-K KREEP-rich clasts in the impact melt breccia of the lunar meteorite SaU 169: New constraints on the last residue of the lunar magma ocean. Geochim Cosmochim Acta 2012;85:19–40.
[16] Liu D, Jolliff BL, Zeigler RA, et al. Comparative zircon U-Pb geochronology of impact melt breccias from Apollo 12 and lunar meteorite SaU 169, and implications for the age of the Imbrium impact. Earth Planet Sci Lett 2012;319:277–86.
[17] Jolliff BL, Gillis JJ, Haskin LA, et al. Major lunar crustal terranes: Surface expressions and crust-mantle origins. J Geophys Res 2000;105:4197–216.
[18] Morota T, Ishihara Y, Sasaki S, et al. Lunar mare volcanism: Lateral heterogeneities in volcanic activity and relationship with crustal structure. Geological Society, London, Special Publications 2014:401.
[19] Wieczorek MA, Neumann GA, Nimmo F, et al. The crust of the Moon as seen by GRAIL. Science 2013;339:671–5.
[20] Miljković K, Wieczorek MA, Collins GS, et al. Asymmetric distribution of lunar impact basins caused by variations in target properties. Science 2013;342:724–6.
[21] Stevenson DJ. Origin of the moon— The collision hypothesis. Annnu Rev Earth Planet Sci 1987;15:271–315.
[22] Canup RM, Asphaug E. Origin of the Moon in a giant impact near the end of the Earth's formation. Nature 2001;412:708–12.
[23] Warren PH. The magma ocean concept and lunar evolution. Annnu Rev Earth Planet Sci 1985;13:201–40.
[24] Gomes R, Levison HF, Tsiganis K, et al. Origin of the cataclysmic late heavy bombardment period of the terrestrial planets. Nature 2005;435:466–9.
[25] Wiechert U, Halliday AN, Lee D-C, et al. Oxygen isotopes and the Moon-forming giant impact. Science 2001;294:345–8.
[26] Spicuzza MJ, Day JMD, Taylor LA, et al. Oxygen isotope constraints on the origin and differentiation of the Moon. Earth Planet Sci Lett 2007;253:254–65.
[27] Young ED, Kohl IE, Warren PH, et al. Oxygen isotopic evidence for vigorous mixing during the Moon-forming giant impact. Science 2016;351:493–6.
[28] Lugmair GW, Shukolyukov A. Early solar system timescales according to ^{53}Mn-^{53}Cr systematics. Geochim Cosmochim Acta 1998;62:2863–86.
[29] Zhang J, Dauphas N, Davis AM, et al. The proto-Earth as a significant source of lunar material. Nat Geosci 2012;5:251–5.
[30] Polyakov VB. Equilibrium iron isotope fractionation at core-mantle boundary conditions. Science 2009;323:912–4.
[31] Lock SJ, Stewart ST, Petaev MI, et al. The origin of the Moon within a terrestrial synestia. J Geophys Res Planets 2018;123:910–51.
[32] Canup RM. Forming a Moon with an Earth-like composition via a giant impact. Science 2012;338:1052–5.
[33] Ćuk M, Stewart ST. Making the Moon from a fast-spinning Earth: A giant impact followed by resonant despinning. Science 2012;338:1047–52.
[34] Asphaug E, Agnor CB, Williams Q. Hit-and-run planetary collisions. Nature 2006;439:155–60.
[35] Mastrobuono-Battisti A, Perets HB, Raymond SN. A primordial origin for the compositional similarity between the Earth and the Moon. Nature 2015;520:212–5.
[36] Wang K, Jacobsen SB. Potassium isotopic evidence for a high-energy giant impact origin of the Moon. Nature 2016;538:487–90.
[37] Kato C, Moynier F. Gallium isotopic evidence for extensive volatile loss from the Moon during its formation. Sci Adv 2017;3:e1700571.
[38] Paniello RC, Day JMD, Moynier F. Zinc isotopic evidence for the origin of the Moon. Nature 2012;490:376–9.
[39] Hui H, Peslier AH, Zhang Y, et al. Water in lunar anorthosites and evidence for a wet early Moon. Nat Geosci 2013;6:177–80.
[40] Hui H, Guan Y, Chen Y, et al. A heterogeneous lunar interior for hydrogen isotopes as revealed by the lunar highlands samples. Earth Planet Sci Lett 2017;473:14–23.
[41] Needham DH, Kring DA. Lunar volcanism produced a transient atmosphere around the ancient Moon. Earth Planet Sci Lett 2017;478:175–8.
[42] Hui H, Hess K-U, Zhang Y, et al. Cooling rates of lunar orange glass beads. Earth Planet Sci Lett 2018;503:88–94.
[43] Head JW, Wilson L, Deutsch AN, et al. Volcanically induced transient atmospheres on the Moon: Assessment of duration, significance, and contributions to polar volatile traps. Geophys Res Lett 2020;47: e2020GL089509.
[44] Saal AE, Hauri EH, Cascio ML, et al. Volatile content of lunar volcanic glasses and the presence of water in the Moon's interior. Nature 2008;454:192–5.
[45] Warren P H. The origin of pristine KREEP - Effects of mixing between UrKREEP and the magmas parental to the Mg-rich cumulates. In: Lunar and Planetary Science Conference. Houston, 1988. 233–41.
[46] Elkins-Tanton LT, Van Orman JA, Hager BH, et al. Re-examination of the lunar magma ocean cumulate overturn hypothesis: Melting or mixing is required. Earth Planet Sci Lett 2002;196:239–49.
[47] Nemchin A, Timms N, Pidgeon R, et al. Timing of crystallization of the lunar magma ocean constrained by the oldest zircon. Nat Geosci 2009;2:133–6.
[48] Borg LE, Cassata WS, Wimpenny J, et al. The formation and evolution of the Moon's crust inferred from the Sm-Nd isotopic systematics of highlands rocks. Geochim Cosmochim Acta 2020;290:312–32.
[49] Snape JF, Curran NM, Whitehouse MJ, et al. Ancient volcanism on the Moon: Insights from Pb isotopes in the MIL 13317 and Kalahari 009 lunar meteorites. Earth Planet Sci Lett 2018;502:84–95.
[50] White LF, Černok A, Darling JR, et al. Evidence of extensive lunar crust formation in impact melt sheets 4,330 Myr ago. Nat Astron 2020;4:974–8.
[51] Zhang A-C, Taylor LA, Wang R-C, et al. Thermal history of Apollo 12 granite and KREEP-rich rock: Clues from Pb/Pb ages of zircon in lunar breccia 12013. Geochim Cosmochim Acta 2012;95:1–14.
[52] Fernandes VA, Fritz J, Weiss BP, et al. The bombardment history of the Moon as recorded by ^{40}Ar-^{39}Ar chronology. Meteorit Planet Sci 2013;48:241–69.
[53] Norman MD, Nemchin AAA. 4.2 billion year old impact basin on the Moon: U-Pb dating of zirconolite and apatite in lunar melt rock 67955. Earth Planet Sci Lett 2014;388:387–98.
[54] Cohen BA, Swindle TD, Kring DA. Support for the lunar cataclysm hypothesis from lunar meteorite impact melt ages. Science 2000;290:1754–6.
[55] Culler TS, Becker TA, Muller RA, et al. Lunar impact history from ^{40}Ar/^{39}Ar dating of glass spherules. Science 2000;287:1785–8.
[56] Head JW, Wilson L. Lunar mare volcanism: Stratigraphy, eruption conditions, and the evolution of secondary crusts. Geochim Cosmochim Acta 1992;56:2155–75.
[57] Yue Z, Li H, Zhang N, et al. Lunar evolution analysis based on numerical simulations of typical lunar impact craters. Space Sci Technol 2023;3:0084.
[58] Hiesinger H, Head JW, Wolf U, et al. Ages and stratigraphy of lunar mare basalts: A synthesis. Geol Soc Am Spec Paper 2011;477:1–51.
[59] Li Q-L, Zhou Q, Liu Y, et al. Two billion-year-old volcanism on the Moon from Chang'e-5 basalts. Nature 2021;600:54–8.
[60] Che X, Nemchin A, Liu D, et al. Age and composition of young basalts on the Moon, measured from samples returned by Chang'e-5. Science 2021;374:887–90.
[61] Head JW, Wilson L, Hiesinger H, et al. Lunar mare basaltic volcanism: Volcanic features and emplacement processes. Rev Mineral Geochem 2023;89:453–507.
[62] Jolliff BL, Wiseman SA, Lawrence SJ, et al. Non-mare silicic volcanism on the lunar farside at Compton-Belkovich. Nat Geosci 2011;4:566–71.
[63] Weitz CM, Head Iii JW, Pieters CM. Lunar regional dark mantle deposits: Geologic, multispectral, and modeling studies. J Geophys Res Planets 1998;103:22725–59.
[64] Milliken RE, Li S. Remote detection of widespread indigenous water in lunar pyroclastic deposits. Nat Geosci 2017;10:561–5.
[65] Melosh HJ, Kendall J, Horgan B, et al. South Pole-Aitken Basin ejecta reveal the Moon's upper mantle. Geology 2017;45.
[66] Neukum G, Ivanov BA, Hartmann WK. Cratering records in the inner solar system in relation to the lunar reference system. Space Sci Rev 2001;96:55–86.

[67] Yue Z, Di K, Wan W, et al. Updated lunar cratering chronology model with the radiometric age of Chang'e-5 samples. Nat Astron 2022;6:541–5.
[68] Sasaki S, Nakamura K, Hamabe Y, et al. Production of iron nanoparticles by laser irradiation in a simulation of lunar-like space weathering. Nature 2001;410:555–7.
[69] Gu L, Chen Y, Xu Y, et al. Space weathering of the Chang'e-5 lunar sample from a mid-high latitude region on the Moon. Geophys Res Lett 2022;49: e2022GL097875.
[70] Keller LP, McKay DS. Discovery of vapor deposits in the lunar regolith. Science 1993;261:1305–7.
[71] Hashizume K, Chaussidon M, Marty B, et al. Solar wind record on the Moon: Deciphering presolar from planetary nitrogen. Science 2000;290:1142–5.
[72] Hashizume K, Marty B, Wieler R. Analyses of nitrogen and argon in single lunar grains: Towards a quantification of the asteroidal contribution to planetary surfaces. Earth Planet Sci Lett 2002;202:201–16.
[73] Xu Y, Tian H-C, Zhang C, et al. High abundance of solar wind-derived water in lunar soils from the middle latitude. Proc Natl Acad Sci USA 2022;119: e2214395119.
[74] Akram W, Schönbächler M. Zirconium isotope constraints on the composition of Theia and current Moon-forming theories. Earth Planet Sci Lett 2016;449:302–10.
[75] Schonbachler M, Lee D-C, Rehkamper M, et al. Nb/Zr fractionation on the Moon and the search for extinct ^{92}Nb. Geochim Cosmochim Acta 2005;69:775–85.
[76] Albarede F, Ballhaus C, Blichert-Toft J, et al. Asteroidal impacts and the origin of terrestrial and lunar volatiles. Icarus 2013;222:44–52.
[77] Tian H-C, Wang H, Chen Y, et al. Non-KREEP origin for Chang'e-5 basalts in the Procellarum KREEP Terrane. Nature 2021;600:59–63.
[78] Hu S, He H, Ji J, et al. A dry lunar mantle reservoir for young mare basalts of Chang'e-5. Nature 2021;600:49–53.
[79] Mikolajewski S, Hiesinger H, van der Bogert CH, et al. Geological map of the Rima Bode Region: A possible landing site for future lunar exploration. In: 53rd Lunar and Planetary Science Conference. Texas: The Woodlands; 2022. pp. 1961.
[80] Hiesinger H, van der Bogert CH, Wedler A, et al. The Rima Bode region—Absolute model ages of a candidate future lunar landing site. In 53rd Lunar and Planetary Science Conference. The Woodlands, Texas; 2022. pp. 2169.
[81] Korotev RL, Jolliff BL, Zeigler RA, et al. Apollo 12 revisited. Geochim Cosmochim Acta 2011;75:1540–73.
[82] Gnos E, Hofmann BA, Al-Kathiri A, et al. Pinpointing the source of a lunar meteorite: Implications for the evolution of the moon. Science 2004;305:657–9.
[83] Elardo SM, Draper DS, Shearer CK. Lunar magma ocean crystallization revisited: Bulk composition, early cumulate mineralogy, and the source regions of the highlands Mg-suite. Geochim Cosmochim Acta 2011;75:3024–45.
[84] Nelson WS, Hammer JE, Shea T, et al. Chemical heterogeneities reveal early rapid cooling of Apollo Troctolite 76535. Nat Commun 2021;12:7054.
[85] Borg LE, Connelly JN, Cassata WS, et al. Chronologic implications for slow cooling of troctolite 76535 and temporal relationships between the Mg-suite and the ferroan anorthosite suite. Geochim Cosmochim Acta 2017;201:377–91.
[86] Elkins-Tanton LT, Parmentier EM, Hess PC. Magma ocean fractional crystallization and cumulate overturn in terrestrial planets: Implications for Mars. Meteorit Planet Sci 2003;38:1753–71.
[87] Qian Y, She Z, He Q, et al. Mineralogy and chronology of the young mare volcanism in the Procellarum-KREEP-Terrane. Nat Astron 2023;7:287–97.
[88] Neal CR, Taylor LA. Petrogenesis of mare basalts: A record of lunar volcanism. Geochim Cosmochim Acta 1992;56:2177–211.
[89] Zhao J, Qiao L, Zhang F, et al. Volcanism and deep structures of the Moon. Space Sci Technol 2023;3:0076.
[90] Head JW, Wilson L. Generation, ascent and eruption of magma on the Moon: New insights into source depths, magma supply, intrusions and effusive/explosive eruptions (Part 2: Predicted emplacement processes and observations). Icarus 2017;283:176–223.
[91] Spudis PD, McGovern PJ, Kiefer WS. Large shield volcanoes on the Moon. J Geophys Res Planets 2013;118:1063–81.
[92] Barker MK, Mazarico E, Neumann GA, et al. A new lunar digital elevation model from the lunar orbiter laser altimeter and SELENE terrain camera. Icarus 2016;273:346–55.
[93] Weiss BP, Tikoo SM. The lunar dynamo. Science 2014;346:1246753.
[94] Gagnepain-Beyneix J, Lognonne P, Chenet H, et al. A seismic model of the lunar mantle and constraints on temperature and mineralogy. Phys Earth Planet In 2006;159:140–66.
[95] Garcia RF, Khan A, Drilleau M, et al. Lunar seismology: An update on interior structure models. Space Sci Rev 2019;215:50.
[96] Zhang J, Head JW, Liu J, et al. Lunar Procellarum KREEP Terrane (PKT) stratigraphy and structure with depth: Evidence for significantly decreased Th concentrations and thermal evolution consequences. Remote Sens (Basel) 2023;15:1861.
[97] Hurwitz DM, Kring DA. Differentiation of the South Pole-Aitken Basin impact melt sheet: Implications for lunar exploration. J Geophys Res Planets 2014;119:1110–33.
[98] Melosh HJ, Freed AM, Johnson BC, et al. The origin of lunar Mascon basins. Science 2013;340:1552–5.
[99] Yue Z, Johnson BC, Minton DA, et al. Projectile remnants in central peaks of lunar impact craters. Nature Geosci 2013;6:435–7.
[100] Stoeffler D, Ryder G, Ivanov BA, et al. Cratering History and Lunar Chronology. Rev Miner Geochem 2006;60:519–96.
[101] Zhang J, Zhou B, Lin Y, et al. Lunar regolith and substructure at Chang'e-4 landing site in South Pole-Aitken Basin. Nat Astron 2020;5:25–30.
[102] Ozima M, Yin Q-Z, Podosek FA, et al. Toward understanding early earth evolution: Prescription for approach from terrestrial noble gas and light element records in lunar soils. Proc Natl Acad Sci USA 2008;105:17654–8.
[103] Ozima M, Seki K, Terada N, et al. Terrestrial nitrogen and noble gases in lunar soils. Nature 2005;436:655–9.
[104] Li S, Lucey PG, Fraeman AA, et al. Widespread hematite at high latitudes of the moon. Sci Adv 2020;6:eaba1940.
[105] Hemingway D, Garrick-Bethell I. Magnetic field direction and lunar swirl morphology: Insights from airy and Reiner Gamma. J Geophys Res Planets 2012;117:E10012.
[106] Denevi BW, Robinson MS, Boyd AK, et al. The distribution and extent of lunar swirls. Icarus 2016;273:53–67.
[107] Garrick-Bethell I, Kelley MR. Reiner Gamma: A magnetized elliptical disk on the Moon. Geophys Res Lett 2019;46:5065–74.
[108] Farrell WM, Halekas JS, Horányi M, et al. The dust, atmosphere, and plasma at the Moon. Rev Mineral Geochem 2023;89:563–609.
[109] Robinson MS, Brylow SM, Tschimmel M, et al. Lunar reconnaissance orbiter camera (LROC) instrument overview. Space Sci Rev 2010;150:81–124.
[110] Thompson T J, Robinson M S, Watters T R, et al. Global lunar wrinkle ridge identification and analysis. In: 48th Annual Lunar and Planetary Science Conference. The Woodlands, Texas; 2017.
[111] Lawrence DJ, Feldman WC, Barraclough BL, et al. High resolution measurements of absolute thorium abundances on the lunar surface. Geophys Res Lett 1999;26:2681–4.



Yangting Lin is a professor of Institute of Geology and Geophysics, Chinese Academy of Sciences (CAS) since 2004. He graduated from Zhejiang University in 1982, and received his Ph.D. degree from Institute of Geochemistry, CAS in 1991. He studied meteorites in Guangzhou Institute of Geochemistry, CAS, from 1991 to 2003. Since 2004, he has participated in China's lunar and deep space exploration program. His research interest focuses on meteorites and space exploration.

Xianhua Li is a professor of Institute of Geology and Geophysics, Chinese Academy of Sciences (CAS) since 2005. He graduated from University of Science and Technology of China in 1983, and received his Ph.D. degree from Institute of Geochemistry, CAS in 1988. His research interests include isotope geochronology and geochemistry, igneous geochemistry, precambrian geology and continental evolution, chemical geodynamics, isotopic microanalysis and planetary science.