THE SCIENTIFIC ACHIEVEMENTS BY CHANG'E-4 AND THE NEW LUNAR SAMPLES RETURNED BY CHANG'E-5.
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Introduction: Lunar exploration is the key to understand the formation and evolution of the Moon, to probe the early status of the Earth, and to read the entire asteroid impacting history of the Earth-Moon system. The first stage of China's Lunar Exploration Program consists of three phases, which was planned to explore the Moon by orbiting remote sensing, landing and in situ measurement, and sample returning, in sequence. Chang'e-5 is the first sample return mission of China, which returned new lunar samples after the Apollo and Luna missions finished more than 40 year ago.

The Moon is very heterogeneous, consisting of at least three main geochemical provinces with the Procellarum KREEP Terrane (PKT) on the nearside and the Feldspathic Highlands Terrane (FHT) and the South Pole-Aitken (SPA) Terrane on the farside [1]. However, the farside was not in situ explored. Hence, the second stage of Chang'e program aims at investigating SPA, in order to determine the lunar deep interior's composition and structure. After the successful landing of Chang'e-3 in the northwestern Imbrium basin on 14 December 2013 [2,3], Chang'e-4 was delivered to the farside of the Moon, as the first mission of the fourth stage of Chang'e program.

Chang'e-4 mission: On 3 January 2019, Chang'e-4 landed in Von Kármán crater (186 km in diameter), which is located within the Mg-pyroxene annulus of SPA basin (2500 km in diameter, ~13 km in depth). Although the Von Kármán crater was filled with basalts (dated 3.6 billion years old [4]), the landing site is located on the ejecta radiating from the northeast Finsen crater (72 km in diameter) (Fig. 1).

The payloads, for the geological exploration of the Moon, include a descending camera and a terrain camera onboard the lander, a panoramic camera, a Lunar Penetrating Radar (LPR) and a Visible and Near-Infrared imaging Spectrometer (VNIS) onboard the lunar rover Yutu-2. Up to date, the rover has driven more than 600 m in two years.

The lunar regolith depth and subsurface structure at the landing site. The subsurface structure of the landing site was detected by LPR with two frequency channels A (500 MHz, with a spatial resolution of ~30 cm) and B (60 MHz, with a spatial resolution of a few meters). The high-frequency reflections clearly show a thickness of ~12 m of the boulder-poor regolith and the beneath multi-layers of ejecta down to 40-50 m [5-7]. The low-frequency signals reveal more complicated substructures down to ~450 m [6,8]. Combined with the regional geology, the LPR depth profile was interpreted by the deposits of several ejecta excavated and delivered from the neighboring craters with the interlayers of basalts. The LPR results show robust evidence that the surface materials measured by Yutu-2 were predominated by the crater ejecta mainly from the Finsen crater, instead of the beneath basalts.

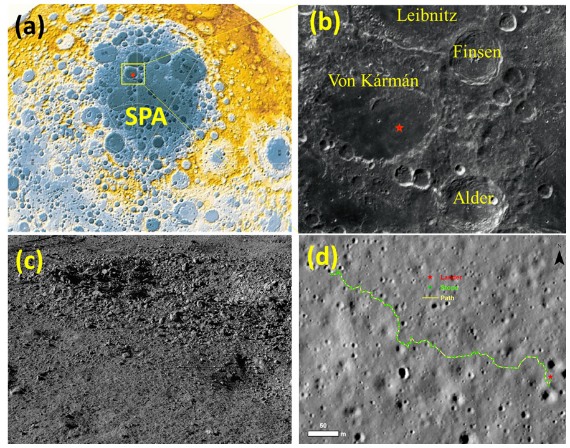

Fig. 1. Landing site of CE-4 (red star), locating in Von Kármán crater (b) in SPA (a). (c) A fragment-filled pits, (d) the rover's track. Images from (http://moon.bao.ac.cn/index_en.jsp).

The lunar deep interior's compositions. The lunar soils along the rover track were in situ measured with VNIS. The spectra reveal significant space weathering, and the maturity index Is/FeO was estimated ~83 [9,10] and OMAT of 0.23-0.25 [11]. The mineral compositions of the soils were determined from the spectra, varying widely with the olivine-contents from 48-55% [12] to 4-10% [9,13-15]. Most of the results are plagioclase-dominant with more low-Ca pyroxene than high-Ca pyroxene, indicative of the lunar deep interior's composition. Rock boulders are very rare in the landing area. This is consistent with the very thick regolith detected by LPR and the old surface age (~3.6 billion years) [4], which is distinct from CE-3 landing site [2]. One of the rock boulders (~20 cm in size) was measured with VNIS, showing deep absorption at 1 and 2 μm bands, which suggests weak space weathering. The estimated composition of the rock is 14±5 % olivine, 38±5 % low-Ca pyroxene and 48±3 % plagioclase [9]. Furthermore, the close-up image (with a spatial resolution of 0.6 mm/pixel) of the rock shows no visible grains, indicative of a fine to mediate-grained texture. This observation argues against a plutonic origin of the rock, instead is consistent with fast crystallization of the magma pool that was produced via formation of SPA basin [9].

Recycling formation of lunar regolith. Beside the typical smooth craters, Yutu-2 has found many meter-sized shallow pits fully covered with fragments (Fig. 1c). VNIS spectra of the fragments reveal similar absorption features of the surrounding regolith, but some high-albedo fragments show a typical peak at ~600 nm, similar to the shock-induced glass and volcanic green glass from Apollo samples [16]. The unique morphology of the fragment-filled pits and the presences of glass suggest a forming mechanism of lunar regolith, via recycling of crashing of rocks and shock-induced melt-conglutination of the regolith by meteorite impacts. The glass-bearing fragments were broken pieces of impact melt-conglutinated regolith breccia that were excavated from pre-existing small craters [16,17].

Implications of Chang'e-4 mission. SPA basin is the key site for the future lunar exploration, because it exposed the deep interior of the Moon. CE-4 mission demonstrates that the floor of SPA basin has been heavily modified by intense asteroid impacts and eruptions of basalts. LPR could be a crucial instrument to probe the surface evolution history and to trace the sources of the surface materials. In addition, the SPA floor may not be the pristine plutonic rocks, but fractional crystallization from the SPA impact magma pool, mixing the lunar crust with the upper mantle.

Chang'e-5 mission: The lunar magmatism mostly ceased before 3 billion years ago, based on the isotope chronology of Apollo samples and the model ages of mare basalts. However, a few regions within the PKT could be as young as 1~1.5 billion years based on the crater counting method [18]. Chang'e-5 was planned to return the unusually young samples from one of these regions (Fig. 2), in order to understand why the magmatism there lasted so late and the unique geochemical features of their mantle reservoirs. The mission was successful, and the sample capsule landed in the Inner Mongolia on December 16, 2020.

Exploration and sampling by Chang'e-5. The lander equipped with cameras, LPR and VNIS, in order to explore the field geology of the landing site. Before and after sampling soil with a shovel, spectra of the lunar regolith were acquired in situ. In addition, the subsurface structure was detected with LPR, and then the drilling of the regolith procedure was conducted. A total mass of 1.73 kg of samples were collected.

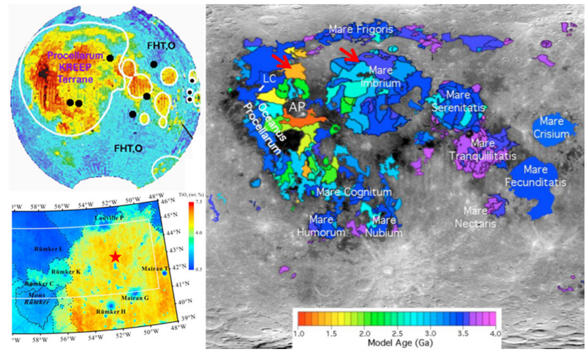

Fig. 2. Landing site of CE-5 (red star) locates in a young region of PKT. Images modified from [1,18,19].

Key questions addressed by Chang'e-5 samples. The new lunar samples are curated in the lunar laboratory, the National Astronomical Observatories, CAS, where they are documented and allocated. The basaltic clasts will be dated, to confirm if they are very young. The isotope chronological data will be used to calibrate the asteroid impacting flux and hence the crater counting method for a period of 3-1 billion years ago. The water and other volatile components (e.g. F, Cl, S, P, C), REE and other trace elements of the basalts and various lithic clasts will be measured, in order to characterize the geochemical features of their mantle reservoirs, and to answer why the magmatic activity last very late in this region. The surface evolution, including asteroid impacting, solar wind implanting and the cosmogenic-ray exposure history will be investigated, based on analysis of the drill core samples.

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