Olivine-norite rock detected by the lunar rover Yutu-2 likely crystallized from the SPA-impact melt pool

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ABSTRACT

Chang’E-4 landed in the South Pole-Aitken (SPA) basin, providing a unique chance to probe the composition of the lunar interior. Its landing site is located on ejecta strips in Von Kármán crater that possibly originate from the neighboring Finsen crater. A surface rock and the lunar regolith at 10 sites along the rover Yutu-2 track were measured by the onboard Visible and Near-Infrared Imaging Spectrometer in the first three lunar days of mission operations. In situ spectra of the regolith have peak band positions at 1 and 2 μm, similar to the spectral data of Finsen ejecta from the Moon Mineralogy Mapper, which confirms that the regolith’s composition of the landing area is mostly similar to that of Finsen ejecta. The rock spectrum shows similar band peak positions, but stronger absorptions, suggesting relatively fresh exposure. The rock may consist of 38.1 ± 5.4% low-Ca pyroxene, 13.9 ± 5.1% olivine and 48.0 ± 3.1% plagioclase, referred to as olivine-norite. The plagioclase-abundant and olivine-poor modal composition of the rock is inconsistent with the origin of the mantle, but representative of the lunar lower crust. Alternatively, the rock crystallized from the impact-derived melt pool formed by the SPA-impact event via mixing the lunar crust and mantle materials. This scenario is consistent with fast-cooling thermal conditions of a shallow melt pool, indicated by the fine to medium-sized texture (≤ 3 mm) of the rock and the SPA-impact melting model [Icarus 2012; 220: 730–43].

Keywords: impact basin, lunar interior composition, visible and near-infrared spectra, lunar rover Yutu-2, Chang’E-4 mission

INTRODUCTION

According to the Lunar Magma Ocean (LMO) hypothesis [1–3], the Moon was, early in its history, covered by global silicate magma up to 800 km thick [4], which crystallized into the modern crust and mantle. Several model compositions of the lunar mantle and crust have been proposed, with the lowermost cumulates dominated by Mg-rich olivine, followed by orthopyroxene (OPX) and finally by Ca pyroxene and plagioclase [5,6]. Furthermore, the lunar-mantle composition may have been modified by the overturn process, with the heavy top mantle materials sinking down due to gravitational instability [7]. In order to constrain the Moon’s formation history, it is critically important to determine the composition of the lunar deep interior. The South Pole-Aitken (SPA) basin is the largest impact basin on the Moon, 2200 km in mean diameter and 13 km in depth [8,9], theoretically opening a window into the lunar lower crust and likely into the upper mantle [10–12]. However, compositional information of the SPA basin has mainly been obtained from orbital remote sensing [13–15] and there have been no in situ measurements of the region before the first landing on the far side of the Moon by Chang’E-4.

On 3 January 2019, the Chinese lunar mission Chang’E-4 (CE-4), the backup of Chang’E-3 (CE-3), landed at 45.457°S, 177.588°E in Von Kármán crater (Fig. 1A), which is within the Mg-Pyroxene Annulus [13] of the SPA basin. Von
Kármán crater has been filled with mare basalt and partially covered by ejecta from nearby impact craters. The landing site is located on ejecta strips radiating from Finsen crater, which lies \( \sim 135 \) km to the northeast (Fig. 1B). The lunar surface at the landing site consists of very homogenous regolith overlain by a few scattered rocks (Fig. 1C). During the first three lunar days of mission operations, the Visible and Near-Infrared Imaging Spectrometer (VNIS) on board the rover Yutu-2 measured nine hyperspectral images of the lunar regolith and one hyperspectral image of a rock boulder along the 163-m rover track (Fig. 1D). These in situ measurements of the lunar regolith and overlying rock reveal the fine-scale composition of the SPA basin at unprecedented spatial resolution, shedding light on the composition of the lunar interior and the LMO crystallization.

**RESULTS**

The radiance spectra measured by VNIS on board Yutu-2 were converted to reflectance via division of the solar irradiance spectrum and then were photometrically corrected using an empirical photometric function (see ‘Materials and methods’). The spectra were smoothed twice with a boxcar average of 17 pixels followed by another boxcar average of...
the SWIR field and the scale bar is 20 mm. at 0.75 μm (C) are the CMOS images of the rock (labeled as 303) and the lunar soil (labeled as 207) RESEARCH ARTICLE Lin et al. 915

Figure 2. (A) VNIS spectra of the rock and lunar regolith measured by Chang‘E-4. The analysis labels are the same as in Fig. 1D. Four other spectra (in gray color) of the basaltic lunar regolith measured by Chang‘E-3 [17] are shown for comparison. (B) and (C) are the CMOS images of the rock (labeled as 303) and the lunar soil (labeled as 207) at 0.75 μm observed by VNIS imaging spectrometer, respectively. The yellow circle is the SWIR field and the scale bar is 20 mm.

The rock analysed by Yutu-2 is >20 cm in size, sitting on the regolith surface. No grains can be unambiguously recognized on the surface, suggesting a fine- or medium-grain-size texture (<3 mm) based on the 0.6-mm/pixel spatial resolution of the image (Fig. 2B). In addition, the rock shows no lithic clasts of lunar-impact breccia (Supplementary Fig. 15), which usually vary in brightness and are embedded in a dark fine-grained matrix. The rock shows deep absorptions at ~1- and ~2-μm bands due to the low degree of space weathering. Hapke radiative transfer modeling [29], which has been validated and applied to lunar samples and meteorites [30,31] (see Supplementary Materials), was used to estimate the modal composition of the rock and our modeling results suggest 38.1 ± 5.4% LCP, 13.9 ± 5.1% olivine and 48.0 ± 3.1% plagioclase in this rock sample. As such, it is referred to as olivine-norite.

DISCUSSION AND CONCLUSION

The spectral features at site A are distinct from those at other sites (Fig. 2A), resulting in different estimated modal mineral compositions and maturity (Table 1). Site A shows the highest agglutinates and L/FeO value, indicating greater maturity than the other sites. Comparison to images acquired by the Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) shows that the surface disturbed by CE-4 descent engines is about 1400 m² (Supplementary Fig. 3), which is in agreement with the relationship between lander mass and blast-zone area constrained by previous missions [32]. Site A, about 11.5 m from the lander, should have been most significantly affected by the rocket exhaust. The higher maturity value at site A is therefore probably caused by deposition of the finest dust particles that were transported from the topmost surface below the lander blown by the rocket exhaust [33].
The regolith at the CE-4 landing site is dominated by plagioclase and pyroxenes with more LCP than HCP (1.8:1) (Table 1), consistently with the findings of a recent study [34]. The estimated modal composition of the lunar regolith is inconsistent with mare basalts (which would contain more pyroxene than plagioclase, with higher HCP than LCP) [35], but suggests its main source was norite [36]. Figure 3 also shows that band positions from in situ spectra of the lunar regolith at the landing site fall within the ranges of Finsen crater materials (the ejecta and crater walls), which are distinct from the underlying mare basalt excavated by Zhinyu crater (Supplementary Fig. 13) and the basaltic regolith on the nearside of the Moon that was analysed by Yutu-1 [17].

Our observations are also supported by topographic features. The landing site is located on NE–SW ejecta strips radiating from Finsen crater (Fig. 4), which superpose the SE–NW dome-like ridge directed towards Alder crater (Fig. 4A). Furthermore, the elevation difference between the landing site and the edge of the SE–NW dome-like ridge was estimated to be ~70 m, suggesting a very thick deposit of ejecta from Finsen crater and probably also from Alder crater. Previous studies also reported that mare basalts were deeply buried by ejecta from nearby craters, with a minimum burial depth of 33 m [37,38]. Hence, the surface materials at the landing site are predominantly ejecta from neighboring craters, with little contribution from the underlying mare basalt.

The rock analysed by Yutu-2 is olivine-norite, not basalt. This is consistent with its setting on the surface of the regolith. Its modal composition is close to that of the regolith, but has higher modal abundances of olivine and LCP. It is possible that the rock was also delivered to its current location from Finsen crater. This is consistent with the similar peak

Table 1. The estimated modal compositions and I_2/FeO values of the lunar regolith measured by the Yutu-2 rover.

| Site | AGG | PYX | HCP | PLG | OL | I_2/FeO | D (m) |
|------|-----|-----|-----|-----|----|---------|-------|
| A    | 57.1 | 11.5 | 3.8 | 15.0 | 1.6 | 97.0    | 11.5  |
| S1   | 55.6 | 14.2 | 5.2 | 13.0 | 1.5 | 78.7    | 20.1  |
| 202  | 55.6 | 14.4 | 5.3 | 13.6 | 1.7 | 85.1    | 29.4  |
| 207  | 56.7 | 12.9 | 4.4 | 14.1 | 1.7 | 89.2    | 51.3  |
| 208  | 56.4 | 12.9 | 5.2 | 12.9 | 1.7 | 86.0    | 54.5  |
| 301  | 55.2 | 13.6 | 4.8 | 14.1 | 1.3 | 76.6    | 71.3  |
| 304  | 55.4 | 13.1 | 4.9 | 13.6 | 0.9 | 76.3    | 68.9  |
| 306  | 56.1 | 13.6 | 4.9 | 13.4 | 1.4 | 86.8    | 85.8  |
| 308  | 55.2 | 14.2 | 5.5 | 12.9 | 1.1 | 74.0    | 98.1  |

AGG, agglutinates; PYX, pyroxene; HCP, augite; PLG, plagioclase; OL, olivine. D is the straight-line distance from the analysis position to the lander.
positions of 1- and 2-μm bands (Fig. 3A). Alternatively, this rock may have been excavated from Alder crater. In this case, it would have been covered by ejecta from Finsen crater and then subsequently excavated from depth. However, this uncertainty makes no difference for constraining the composition of SPA basin, because both Finsen and Alder craters are located within the Mg-Pyroxene Annulus [13] at a similar distance (∼350 km) from the center of SPA basin. Hence, this rock is likely representative of the original bedrock in the Mg-Pyroxene Annulus of SPA basin.

The SPA-impact event excavated the lunar deep interior and exposed lunar lower crust and/or mantle materials [10,12]. The bedrock of SPA basin could be the original plutonic rocks crystallized directly from LMO or may have formed from crystallization of the SPA-impact melt pool. The plagioclase-abundant and olivine-poor modal compositions of the materials measured by Yutu-2 rover are consistent with the origin of the lower crust rather than the mantle. The deep interior origin would also expect coarse-grained textures, typical of plutonic rocks (3 mm or larger) [40,41]. However, the observed fine- to medium-grain-sized texture of the rock suggests a fast-cooling thermal condition, which is consistent with crystallization from the SPA-impact melt pool [10,15,42]. Furthermore, the numerical simulations of impacting suggest that the SPA-scale event could generate a transient cavity with a diameter of 840 km and a melt pond with ∼50-km depth (Fig. 5A) [10,42,43]. The SPA-impact melt would have been a mixture of the lunar crust and upper-mantle materials. Both Finsen and Alder craters are located close to the margin of the melt pond (Fig. 5) [9,10]. Hence, the sources of the regolith and the rock boulder analysed by Yutu-2 are unlikely to be representative of the original lunar lower crust or the mantle as claimed by the previous study [44], but rather are the differentiated rocks from the impact melt pond. It is likely that the Finsen-impact event excavated shallow-layer materials crystallized from the SPA melt pond and delivered them to Von Kármán crater, where they were measured by the rover Yutu-2 (Fig. 5).

In summary, the in situ spectral measurements of the rock and regolith at the Chang’E-4 landing site result in similar estimates for mineral compositions and the rock is likely olivine-norite. These surface materials were delivered mainly from the neighboring Finsen crater, with possible additional contributions from Alder crater, but not from the underlying mare basalts. The fine- to medium-grain-size texture of the rock suggests fast crystallization, probably from the impact melt pond produced via melting the lunar lower crust and mantle materials by the SPA basin-forming event. This scenario is also consistent with the SPA-impact melting models [10]. These observations shed light on the composition of the SPA basin floor and the formation of the SPA basin.

**MATERIALS AND METHODS**

**Data preprocessing**

The VNIS on board the rover Yutu-2 consists of a Complementary Metal-Oxide Semiconductor (CMOS) imager (450–950 nm) with 256×256 pixels and a short-wavelength near-infrared (SWIR) detector (950–2395 nm) with single-pixel [22,45]. VNIS is installed on the front of the rover and measures the lunar surface from a height of ∼1 m above the lunar surface at a 45° emission angle. The SWIR field is centered at pixel 97.5, 127.5 of the CMOS field with a diameter of 107.6 pixels (Supplementary Fig. 1). The spectral-sampling interval of the CMOS and SWIR detectors is 5 nm, and the wavelength and
The rock is much less affected by space weathering than the soil and has typical spectral characteristics. Thus, a more rigorous non-linear model, i.e. a Hapke radiative transfer model [29], was applied to retrieve the mineral abundances of the rock. The endmembers used in this study are high-calcium pyroxene (HCP), low-calcium pyroxene (LCP), olivine (OL) and plagioclase (PLG) (Supplementary Fig. 11 and Supplementary Table 5). More details about the methods are available in Supplementary Materials.

SUPPLEMENTARY DATA
Supplementary data are available at NSR online.

DATA AVAILABILITY
The data reported in this work will be archived at http://moon.bao.ac.cn/searchOrder_dataSearchData.search.

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AUTHOR CONTRIBUTIONS
L.Y.T., Y.W. and L.H.L. designed the research; L.H.L., Y.W. and L.Y.T. performed research; H.Z.P., X.R., L.C.L., L.H.Y., Y.J.F., Z.J. and X.C.B. contributed new reagents/analytic tools; L.H.L., H.Z.P., X.R., L.Y.T., Z.C., Z.J.H., H.S. and C.R. analysed data; L.Y.T., L.H.L., W.Y., Z.M.H., W.W.X., Z.Y.L., L.Y., F.X.H. and G.S. wrote the paper.

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