The regolith properties of the Chang’e-5 landing region and the ground drilling experiments using lunar regolith simulants

Yuqi Qian\textsuperscript{a}, Long Xiao\textsuperscript{a,b,*}, Shen Yin\textsuperscript{c}, Ming Zhang\textsuperscript{c}, Siyuan Zhao\textsuperscript{a}, Yong Pang\textsuperscript{c}, Jiang Wang\textsuperscript{a}, Guoxin Wang\textsuperscript{c}, James W. Head\textsuperscript{d}

\textsuperscript{a}State Key Laboratory of Geological Process and Mineral Resources, and Planetary Science Institute, School of Earth Sciences, China University of Geosciences, Wuhan 430074, China
\textsuperscript{b}Center for Excellence in Comparative Planetology, Chinese Academy of Sciences, Hefei 230026, China
\textsuperscript{c}Beijing Spacecrafts, China Academy of Space Technology, Beijing 10094, China
\textsuperscript{d}Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, USA

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\textbf{ABSTRACT}

The Chang’e-5 (CE-5) mission is China’s first lunar sample return mission. The Rümker region in northern Oceanus Procellarum was selected as the landing area. CE-5 will automatically sample ~ 2 kg of lunar samples from the surface and subsurface. Previous studies focused more on the geological background of the landing region. However, the lunar regolith properties also have a significant influence on the mission, especially drilling, and thus should be studied and constrained. In this research, we analyzed the lunar regolith properties of the CE-5 landing region first using remote sensing measurements. The western maria and eastern maria in the landing region are both covered by very low-Ti to low-Ti basaltic regolith. The western mare regolith, with longer exposure to space weathering, is more mature, finer, and thicker than the eastern mare regolith. CUG-series lunar regolith simulants were then produced based on our analysis (physically and chemically) of the regolith properties of CE-5 landing region and compared to Apollo soils. Finally, the lunar simulants were used to perform ground drilling experiments to support the drilling of the CE-5 mission. In a fixed rotation speed (120 rpm), feed speed (120 mm/min), and total drilling depth (~1 m), 274, 291, and 346 g of lunar simulants were cored on simulants Mixture-1, Mixture-2, and Mixture-3, respectively. Our experiments suggest that it is easier to drill and core finer and looser lunar regolith. In this case, the western mare regolith is easier for drilling than the eastern mare regolith. However, samples from the eastern young maria (Em3, Em4) are scientifically more meaningful. We propose that landing on, and drilling in, a smooth and mature area in unit Em4 should be the highest priority for the CE-5 mission; this can be accomplished by careful landing site selection, precise landing and optimized drilling control.

1. Introduction

In the Apollo and Luna Era, ~382 kg of lunar samples was brought back by the US Apollo Astronauts and the Soviet Union robotic sampling missions (Vaniman et al., 1991). The laboratory studies of the returned samples with modern geochemical techniques have profoundly improved our understandings of the Moon’s composition, interior, formation and evolution history (e.g., Hiesinger and Head, 2006; Jaumann et al., 2012; Taylor, 2014) and provided ground truth for remote sensing interpretations (e.g., Ohtake et al., 2010; Isaacson et al., 2013; Xia et al., 2019).

However, all the available Apollo and Luna samples were collected from a central area of the lunar nearside. Broad areas of the Moon remain unexplored and unsampled. Considering the heterogeneous distribution of the Moon’s geologic terrains (Jolliff et al., 2000), there is a high priority placed on returning samples from different units to advance our scientific knowledge of the Moon. After five successful missions (Chang’e-1 to 4, Chang’e-5 T1), Chang’e-5 and Chang’e-6 plan to return samples from the Rümker region and the south pole of the Moon (Xu et al., 2019), providing opportunities for new samples...
following those returned by the Apollo and Luna missions. The Chang’e-5 mission (CE-5) will automatically sample lunar regolith on the surface by grab sampling, and the subsurface by drilling, in the Rümker region; around 2 kg of lunar materials are planned to be gathered (Xu et al., 2018).

The selected CE-5 landing region (41°45′N, 49°69′W), named the Rümker region, is in northern Oceanus Procellarum in the northwest of the lunar nearside, covering an area of 55,000 km² (Fig. 1). Detailed geological investigations of the area have been conducted recently by different researchers to assess its potential scientific values (Ling et al., 2017; Jolliff et al., 2017; Zhao et al., 2017; Giguere et al., 2018; Qian et al., 2018; Wu et al., 2018; Michael et al., 2019). Dozens of landing sites were proposed from different perspectives (Jolliff et al., 2017; Zhao et al., 2017; Giguere et al., 2018; Qian et al., 2018). Mons Rümker is located at the southern edge of the Rümker region (Fig. 1). It is one of the largest volcanic complexes on the Moon (Head, 1976; Spudis et al., 2013; Head and Wilson, 2017). There are at least two major episodes of basaltic eruptions in the area (Imbrian-aged and Eratosthenian-aged), forming the flat mare plains and Mons Rümker (Hiesinger et al., 2011; Zhao et al., 2017; Qian et al., 2018).

Up to this point, there are only three robotic missions that have successfully retrieved lunar samples (Luna-16, Luna-20, and Luna-24). However, two of them (Luna-16 and Luna-20) encountered drilling problems. Luna-16 penetrated to a depth of 35 cm and stopped when it touched a hard rock or large fragments of hard rock, and only 101 g of samples were collected (Vinogradov, 1971). Luna-20 encountered stiff resistance at 10 cm and operations had to stop three times to avoid overheating (Harvey and Zakutnyaya, 2011). In total, 52 g or 25 cm of samples were collected; the core tube was only partially filled (Ivanov et al., 1973; Vinogradov, 1973). Luna-24 was a more successful sample return mission compared with Luna-16 and Luna-20. Luna-24 landed on the rim of Lev crater (65 m in diameter), which may be a secondary crater of Giordano Bruno (22 km in diameter, ~1300 km northeast of the landing site) (Butler and Morrison, 1977; Robinson et al., 2012; Basilevsky et al., 2013). The mission returned a core of 160 cm in length or 170 g in weight, by percussion-rotary drilling (Barsukov, 1977; Florensky et al., 1977). Four layers (Zone I, II, III, IV) were recognized in the Luna-24 core, which may contain ejecta materials from Fahrenheit Crater (Zone IV, 0.5 m) and Giordano Bruno Crater (Zone I, 0.5–1 m) (Barsukov, 1977; Basilevsky et al., 2013). As indicated by the difficulties met by the Luna-16 and Luna-20 missions, the lunar regolith is sufficiently complex to affect the drilling results and mission outcomes.

The lunar regolith is a several meters thick layer of unconsolidated debris, forming the interface between the Moon and its space environment (Papke and Simon, 1982). It is a mixture of lithic fragments, mineral fragments, breccias, agglutinates, and glasses (Heiken, 1975; McKay et al., 1991). Many properties of lunar regolith, especially geotechnical and thermal properties, have a significant impact on the drilling process (Zhang and Ding, 2017, 2018), which cause challenges in designing robust experiments and drilling mechanism models. Therefore, it is crucial to help constrain the regolith properties of the CE-5 landing region by remote sensing measurements and comparison with Apollo and Luna soils to facilitate drilling designs.

In this study, we analyzed the regolith properties of the CE-5 landing region first, and then produced lunar regolith simulants using terrestrial basalts. Finally, we designed ground drilling experiments on lunar simulants, in order to support the CE-5 mission.

2. Regolith properties

2.1. Regional geological setting

The Rümker region is in northern Oceanus Procellarum, covered by large areas of mare plains (Fig. 2a). Northern Oceanus Procellarum is within the Procellarum-KREEP-Terrain, characterized by elevated incompatible heat producing elements (e.g., U, Th, K; Jolliff et al., 2000; Prettyman et al., 2006), prolonged volcanism (e.g., Staid et al., 2011; Hiesinger et al., 2011; Zhang et al., 2016), and young tectonism (e.g., Lu et al., 2019).

The Rümker region experienced at least two stages of basaltic eruptions. According to Qian et al. (2018), the western maria (west of the CE-5 landing region) is covered by thicker, very low-Ti to low-Ti mare basalts (up to 5 wt%, TiO₂ content). It is divided into three units, i.e., Im1 (3.42 Ga), Im2 (3.39 Ga), and Im3 (3.16 Ga) (Fig. 2b), corresponding to P9 (3.47 Ga) and P10 (3.44 Ga) in Hiesinger et al. (2003, 2011)'s mare stratigraphic map. The eastern maria (east of the CE-5 landing region) is Eratosthenian-aged, much younger than the western maria, with more abundant TiO₂ (4.7 wt%, mean content) and FeO (16.7 wt%, mean content). The eastern maria is divided into Em3 (1.51 Ga) and Em4 (1.21 Ga) (Fig. 2b), corresponding to P58 (1.33 Ga) (Hiesinger et al., 2003, 2011). Wu et al. (2018) also determined the crater size-frequency distribution (CSFD) model age of these geologic units and obtained similar results (Im1, 3.48 Ga; Im2, 3.47 Ga; Em1, 2.03 Ga; Em3, 2.06 Ga; Em4, 1.49 Ga), except that their Em3 unit (2.06 Ga) is much older than Qian et al. (2018)'s (1.51 Ga).

Mons Rümker is a ~1300 m high and ~70 km wide volcanic

Fig. 1. Location of the Chang’e-5 landing region. The basemap is a Lunar Orbiter Laser Altimeter (LOLA) and KAGUYA Terrain Camera (TC) merged hillshade map (Barker et al., 2016). The CE-5 landing region is in the north of Oceanus Procellarum. Mons Rümker is a circular volcanic complex in the southern part of the CE-5 landing region.
complex (Head, 1976; Spudis et al., 2013; Head and Wilson, 2017). Zhao et al. (2017) reported on a detailed geologic analysis of this volcanic complex. They divided it into three basaltic units (IR1, 3.71 Ga; IR2, 3.58 Ga; IR3, 3.51 Ga; Fig. 2b), and identified two categories of volcanic domes (shallow dome, ld; steep-sided dome, sd; Fig. 2b).

In summary, there are at least two episodes of basaltic eruption activities in the area (Qian et al., 2018). The first episode occurred in the Imbrian, forming the basalts in the western maria and Mons Rümker. This episode represents part of the major basaltic eruption phase of the Moon (Hiesinger et al., 2011). The second episode occurred in the Eratosthenian, forming one of the youngest mare basalts on the Moon, in the east of the Rümker region. The existence of the large volcanic complex (Mons Rümker) and the covering of extremely young basaltic units (Em3 and Em4) indicate the extended and unusual volcanic history of the area (Qian et al., 2018).

2.2. Composition

TiO$_2$ and FeO are two crucial oxides in the definition and understanding of a variety of lunar geological issues (Lucey et al., 2000a), such as mineralogy and rock types. The mineralogy of the Moon is relatively simple, dominated by pyroxene, plagioclase feldspar, olivine and ilmenite (Papike et al., 1991). Pyroxene and ilmenite are major carriers of iron and titanium, respectively (Lucey, 2004). Mare basalts are the predominant rock type in the CE-5 landing region (Qian et al., 2018), controlling the composition of overlying lunar regolith. They are usually classified into very low-Ti (<1 wt%), low-Ti (1–6 wt%), and high-Ti basalts (>6 wt%) according to their TiO$_2$ contents (Neal and Taylor, 1992). Therefore, TiO$_2$ and FeO abundance have been investigated in this study.

In this analysis, the Lunar Reconnaissance Orbiter (LRO) Wide Angle Camera (WAC) TiO$_2$ map derived by Sato et al. (2017) was used to estimate the TiO$_2$ abundance of the CE-5 landing region (Fig. 3a). WAC has two ultraviolet bands (320, 360 nm; ~100 m/pixel) and five visible bands (415, 565, 605, 645, and 690 nm; ~100 m/pixel) (Robinson et al., 2010). The TiO$_2$ abundance was calculated based on the linear relationship between the TiO$_2$ contents of the returned samples and the WAC 320/415 nm ratio at the sampling site (Sato et al., 2017). The lower detection limit of this method is 2 wt%; areas with TiO$_2$ abundance lower than 2 wt% are all set as 1 wt% (Sato et al., 2017). The
KAGUYA Multiband Imager (MI) derived FeO weight percent data (Fig. 3b) by Lemelin et al. (2015) was used to analyze the FeO abundance of the CE-5 landing region. MI is a high resolution multiband imaging camera with 5 visible bands (415, 750, 900, 950, and 1000 nm; 20 m/pixel) and 4 near-infrared bands (1000, 1050, 1250, and 1550 nm; 62 m/pixel) (Haruyama et al., 2008; Ohtake et al., 2008). The algorithm used by Lemelin et al. (2015) was derived similarly to that of Lucet et al. (2000a), with calibration against Lunar Soil Characterization Consortium (LSCC) spectra (Pieters et al., 2000; Taylor et al., 2001) and pure anorthosite rocks.

According to the TiO2 and FeO abundance maps (Fig. 3), both the western maria and the eastern maria are dominated by very low-Ti to low-Ti (TiO2 < 6 wt%) basaltic regolith (Table 1). In general, the young eastern Eratosthenian-aged mare basalts and the overlying regolith (Em1, Em2, and Em4) have significantly higher TiO2 content than the western Imbrian-aged mare basalts (Im1, Im2, and Im3). The TiO2 contents of the eastern maria could reach 8 wt% in the center of Em4. The FeO contents of the Rümker region match well with the TiO2 contents. The eastern maria (17.0 wt%, in average) has higher FeO contents than the western maria (15.7 wt%, in average). Ejecta radiating from distant craters (e.g., Pythagoras, Harpalus) is distributed in a NE-SW direction in the eastern maria, producing several anomalous low-Fe rays, representing materials external to the local site.

In addition, other compositional data are provided in the supplementary material for comparison, including: 1) TiO2 and FeO abundance derived from Clementine Ultraviolet Visible Camera (UVVIS) data using Lucet et al. (2000a)’s method (Fig. S1); 2) TiO2 and FeO abundance derived from KAGUYA MI data using Otake et al. (2012)’s method (Fig. S2); 3) TiO2, FeO, MgO, CaO, Al2O3, and Mg# abundance derived from Chang’e-1 Interference Imaging Spectrometer (IIM) data by Wu (2012) (Fig. S3). All datasets correlate well with each other.

Chandrayaan-1 Moon Mineralogy Mapper (M3) hyperspectral data were selected to study the mineralogy of the Rümker region. M3 is an imaging spectrometer with 85 bands ranging from visible to infrared (420–3000 nm) (Pieters et al., 2009). The data used were imaged in the OP2C optical period with a resolution of 280 m/pixel (Boardman et al., 2011). The data are radiometrically, geometrically, thermally, and photometrically corrected (Boardman et al., 2011; Clark et al., 2011; Besse et al., 2013). The spectral continuum was removed following Horgan et al. (2014) and Martinot et al. (2018)’s method, which maximize the 1000 and 2000 nm absorption bands. An IBD (integrated band depth) color composite map (Fig. 3c) was also produced following Mustard et al. (2011) by assigning IBD as red (IBD at 1000 nm), IBD2000 (IBD at 2000 nm) as green and R1580 as blue (reflectance at 1580 nm) (Fig. 3c). The IBD color composite map is sensitive to the mafic minerals (pyroxene and olivine) because of their absorption features at 1000 and 2000 nm (Mustard et al., 2011).

According to the IBD color composite map of the CE-5 landing region, the western maria (Im1, Im2) are yellowish to bluish-green due to a 1000 nm absorption and a strong 2000 nm absorption. Em3 (purple) and Em4 (purplish-green) display different colors in the color composite map, indicating that Em3 has a weaker 2000 nm absorption than Em4.

Blue hue occurs in the northeast of Mons Rümker, northeast of Im2 and east of Em4 as rays, probably related to the highland materials.

The mean spectra and mean continuum-removed spectra of 12 circular areas (15 km in diameter) of the CE-5 landing region were computed (Fig. 4a and b, respectively). The spectra extracted from the Rümker region are all characterized by diagnostic mafic mineral (pyroxene) absorption features at 1000 nm and 2000 nm (e.g., Adams, 1974). The western Imbrian-aged maria (Im1, Im2, and Im3) have a larger absorption depth at both 1000 nm and 2000 nm than the eastern Eratosthenian-aged maria (Em3, and Em4). However, the absorption features of Eratosthenian-aged Em1 unit is similar to the Imbrian-aged maria, indicating a similar mineral composition. The Band II absorption of the western maria is located at 2200 nm, and the eastern maria show a 2300 nm absorption, both of which are high-Ca pyroxene signals, but the eastern maria are probably richer in iron or calcium (Cloutis and Gaffey, 1991; Klima et al., 2007). Olivine has a broad and asymmetric 1000 nm absorption feature, but is easily masked by pyroxenes (e.g., Singer, 1981). According to Staid and Pieters (2001), Staid et al. (2011) and Zhang et al. (2016), olivine is abundant in the young titanium-rich mare basalts in the Procellarum-KREEP-Terrain, including the Em4 unit in the CE-5 landing region. Staid and Pieters (2001) and Zhang et al. (2016) concentrate on the investigation of fresh craters, whose spectra are more distinctive than ours (average mare). In this case, although we did not detect the olivine absorption features directly, we believe that olivine exists across the area, especially in the eastern young mare basalts (Em4).

In addition, mineral abundance maps produced by Lemelin et al. (2015, 2019) are shown in the supplementary material, which includes olivine (OLV), clinopyroxene (CPX), orthopyroxene (OPX), and plagioclase (PLG) (Fig. S4). The mineral abundances are measured by comparing the topographically corrected KAGUYA MI spectra with the lookup table spectra computed from the Hapke radiative transfer model (Lemelin et al., 2015, 2019). PLG is the most abundant mineral in the area; and CPX is the most abundant mafic mineral. There is more CPX and less OPX in the eastern maria than the western maria. However, we think Lemelin et al. (2015, 2019)’s calculation can only offer a first order estimation of the CE-5 landing region, because their algorithm is designed for highland regions, excluding ilmenite, which is more abundant in the mare regions, especially the young Em4 unit. Ilmenite mapping is needed for further analysis, such as Lemelin et al. (2013), based on MI or M3 data.

In summary, both the western and eastern maria are dominated by very low-Ti to low-Ti basaltic regolith with high-Ca pyroxenes and probably olivines. The eastern maria is richer in TiO2, FeO and its pyroxenes are richer in iron or calcium.

2.3. Regolith thickness

The initial measurement of regolith thickness in the CE-5 landing region was made by Yue et al. (2019) through an improved crater morphology method. The crater morphology method is based on the transition of simple, flat-bottomed, central mound, and concentric craters and variations in regolith thickness (e.g., Oberbeck and Quaide, 1967; Quaide and Oberbeck, 1968; Bart et al., 2011; Bart, 2014). Because the flat-bottomed and central mound craters are probably also formed from clustered impacts with low velocity (Kumar et al., 2011), Yue et al. (2019) only included concentric craters in their calculation (958 in total). In this study, we reproduced the regolith thickness map based on the Yue et al. (2019)’s crater measuring data of concentric craters (supplementary material of that paper), and also applied the natural neighbor interpolation technique as they do. However, we use a smaller cell size in interpolation to better reflect local variations of lunar regolith. The lunar regolith map produced is shown in Fig. 5. In addition, the regolith thickness map produced by Fa and Jin (2010) using Chang’e-1 multi-channel microwave radiometer (IIM) data is shown for comparison in supplementary material Fig. S5.

Table 1

<table>
<thead>
<tr>
<th>Unit</th>
<th>TiO2 (%)</th>
<th>FeO (%)</th>
<th>OLV (%)</th>
<th>CPX (%)</th>
<th>OPX (%)</th>
<th>PLG (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Em4</td>
<td>5.9</td>
<td>17.0</td>
<td>13</td>
<td>31</td>
<td>15</td>
<td>41</td>
</tr>
<tr>
<td>Em3</td>
<td>4.4</td>
<td>15.9</td>
<td>14</td>
<td>27</td>
<td>13</td>
<td>46</td>
</tr>
<tr>
<td>Em1</td>
<td>3.9</td>
<td>17.5</td>
<td>12</td>
<td>29</td>
<td>20</td>
<td>38</td>
</tr>
<tr>
<td>Im3</td>
<td>1.7</td>
<td>14.7</td>
<td>11</td>
<td>25</td>
<td>17</td>
<td>47</td>
</tr>
<tr>
<td>Im2</td>
<td>1.5</td>
<td>15.7</td>
<td>14</td>
<td>23</td>
<td>20</td>
<td>43</td>
</tr>
<tr>
<td>Im1</td>
<td>3.1</td>
<td>16.4</td>
<td>12</td>
<td>27</td>
<td>20</td>
<td>41</td>
</tr>
</tbody>
</table>

Data from:

a Sato et al. (2017).
b Lemelin et al. (2015, 2019).
The regolith thickness of the CE-5 landing region ranges from 1 to 18 m with a mean value of 7.9 m, matching well with the geologic boundaries by Qian et al. (2018). Most of the Rümker region has a regolith thicker than 2 m (> 99.9%), and ~95.4% of the lunar regolith is thicker than 5 m. The western maria has thicker regolith (8.8 m, on average) than the eastern maria (7.0 m, on average). The southeast part of the CE-5 landing region has the thinnest regolith in the area; however, only small areas near 41.5°N, 50°W are thinner than 2 m. The CE-5 mission is designed to drill a 2 m-length regolith core. Most of the CE-5 landing area (> 99.9%) has a regolith thickness larger than 2 m that meets the requirement. However, additional attention needs to be paid to the fact that specific sites in the CE-5 landing region probably have a regolith thinner than 2 m that is not as suitable for drilling, taking into account 1) the low resolution of the regolith thickness map (Fig. 5), 2) the uncertainties of the crater morphology method (Section 6.1 in Yue et al., 2019, Uncertainties in regolith thickness), and 3) the large variation of regolith thickness in local areas (e.g., Fa et al., 2014).

2.4. Optical maturity

The maturation of lunar regolith can be quantified by many indices, including Is/FeO, mean grain size, solar wind gas abundance, and agglutinate abundance, etc. (McKay et al., 1991). Optical maturity (OMAT) is an index proposed by Lucey et al. (2000b), reflecting the spectral effects of maturation. OMAT is defined as the Euclidean distance from optimized origin (a hypothetical dark red end-member) to the location of the spectrum of a lunar sample, on the plot of 950 nm/750 nm reflectance versus 750 nm reflectance (Lucey et al., 2000b); high OMAT values mean less mature lunar regolith. The OMAT values (Fig. 6a) of the CE-5 landing region were calculated from Kaguya MI data using the algorithm by Lemelin et al. (2019) (R750corr = 1.51*R750 + 0.020; R950corr = 1.38*R950 + 0.022). This algorithm is adapted from Lucey et al. (2000b), which is suitable for KAGUYA MI data, while Lucey et al. (2000b) is originally derived from Clementine UVVIS data.

According to Lucey et al. (2000b), the OMAT values of Apollo samples have a modest correlation with other maturity indices. The correlation coefficients (r) of OMAT value and mean grain size are 0.32 and 0.18 for <1 cm and <1 mm fractions, respectively (Lucey et al., 2000b). In this study, we used another method to find the relationship between the OMAT values and the mean grain size of lunar regolith, because the lunar regolith measured in the laboratory are not in its natural state, especially after sieving. First, the locations of Apollo soils cataloged in Graf (1993) were found in the Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) data. Second, OMAT values were calculated using KAGUYA MI data. Then, their grain sizes and the corresponding OMAT values (Fig. 7a, in total 71 points) were fitted. The linear relation between mean grain size and OMAT is:

\[
\text{Mean Grain Size} = 505.6 \times \text{OMAT} - 3.357 (r = 0.64, \text{RMSE} = 24.72).
\]

As shown by the correlation coefficients (r = 0.64) of this fit, the relation between mean grain sizes and OMAT values is weak, which means that we cannot calculate the mean grain sizes of the lunar regolith based solely on OMAT values. However, it is clear that the mean grain sizes increase with OMAT values (Fig. 7a), which means that we can compare the relative mean grain sizes by comparing their OMAT values. An area with high OMAT values is coarser than an area with low OMAT values, and vice versa.

The K-Means clustering algorithm was applied to the OMAT map of the CE-5 landing region using ENVI software. A classification map was produced as shown in Figs. 6b, and 5 classes have been clustered. K-Means unsupervised classification calculates initial class means evenly distributed in the data space, then iteratively clusters the pixels into the nearest class using a minimum distance technique (Tou and Gonzalez, 1974).

The OMAT histogram of each class was produced with a bin size of 0.001 (Fig. 7b). From class1 to class5 type regolith, the OMAT values ascend (Fig. 7b), indicating the decrease of maturity (from mature to immature) and the increase of the mean grain size. The western maria are dominated by mature class1 and class2 regolith. Class3 regolith is distributed in the east of the western maria, probably due to the disturbance of large numbers of secondary craters. The eastern maria is dominated by class2 and class3 regolith. The fraction of class3 regolith in the eastern maria is larger than the western maria. Mons Rümker is in the south of the region, covered by large areas of mature class1 regolith.
Immature class 4 and class 5 regolith distribution is limited in the area; nearly all are related to fresh impact structures. Class 4 regolith is found as crater ejecta blankets and class 5 regolith is found as crater walls. Fig. 7b shows that class 2 regolith is the most abundant regolith type in the area, followed by class 3. Class 1 regolith is less than class 2 and class 3 regolith; and there are only small areas with class 4 and class 5 regolith.

In summary, the western mare regolith (regolith in the western maria) is more mature and finer grained than the eastern mare regolith (regolith in the eastern maria). This correlates well with their geologic ages (Imbrian-aged comparing to Eratosthenian-aged); as the lunar regolith is exposed longer (matures), the OMAT values decrease as well as their grain sizes.

3. Lunar simulants

3.1. Manufacture

A series of lunar regolith simulants were manufactured in this study to verify ground drilling experiments. As the CE-5 landing region is dominated by very low-Ti to low-Ti basaltic regolith, with pyroxene and potential olivine, the Liuhe basalts (Nanjing basaltic field, Eastern China) were chosen as the raw material. The most abundant rock type of the Liuhe basalts is alkali olivine basalt, erupted in the early Pliocene of Neogene (Zhi, 1991; Zeng et al., 2013). Liuhe basalts have porphyritic textures: the phenocrysts mainly consist of olivine (Fo = 66–68) and minor clinopyroxene and plagioclase; the groundmass is composed of clinopyroxene, plagioclase, olivine, glass and Fe–Ti oxides, with pilotaxitic or intergranular texture.

The CUG-series lunar simulants (numbered CUG-S1 to CUG-S8, Table 2) were produced from Liuhe alkali basalts after being dried, crushed and sieved into eight grain size levels. The composition and physical properties of the lunar simulants were then measured and shown below.

3.2. Major elements

The major elements of the CUG-series lunar simulants (raw material) were measured by X-ray Fluorescence Spectrometer (XRF) in the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences at Wuhan. Because all lunar simulants were produced from the same raw material with a homogeneous petrology, we assume identical major element compositions as shown in Fig. 8. The composition of Apollo soils (McKay et al., 1991), a widely used lunar simulant JSC-1 (NASA Johnson Space Center; McKay et al., 1994), and two other simulants: CAS-1 (Chinese Academy of Sciences; Zheng et al., 2009) and TJ-1 (Tongji University; Jiang et al., 2012), are also summarized in Fig. 8 for comparison.

The CUG-series lunar simulants are comparable to the composition of Apollo lunar soils (McKay et al., 1991) except for Apollo 16 soils from the lunar highlands. All Apollo lunar soils have lower Na$_2$O + K$_2$O contents than lunar simulants as the terrestrial rocks are more evolved. In general, the CUG-series lunar simulants meet the compositional requirement of making a low-Ti basaltic simulants with different grain sizes for the CE-5 mission.
3.3. Physical properties

The physical properties of lunar regolith have significant influence on ground drilling, and were therefore measured in this study. Scanning Electron Microscope (SEM) photos were taken by the Field Emission Scanning Electron Microscope in the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences at Wuhan (Fig. 9) to evaluate the shape of lunar simulant particles. As shown in Fig. 9, the CUG-series lunar simulant particles mainly have angular, subangular, and elongated shapes, similar to the shape of Apollo soils described by Carrier et al. (1991).

The lunar simulant grain size was measured by a Mastersizer 2000 Laser Particle Size Analyzer in the Materials Research and Testing Center, Wuhan University of Technology. The cumulative weight distribution curves of lunar simulants are shown in Fig. 9b together with the coarsest (14141) and finest (66075) Apollo soils cataloged in Graf (1993) for comparison. The lunar simulant grain sizes increase from CUG-S1 to CUG-S8 (shift right in Fig. 9b). The mean grain sizes are 16.8, 19.6, 54.7, 70.6, 110.1, 131.1, 215.5, and 190.2 μm (Table 2), respectively (Mastersizer 2000 will underestimate the grain size of large particles as they are harder to float in the testing media for analysis by laser). Except for CUG-S1 and CUG-S2, all lunar simulants produced are within the cumulative curve of the coarsest (14141) and finest (66075) Apollo soils. It should be pointed out that Apollo soils cataloged in Graf (1993) are natural lunar soils. However, the lunar simulants produced have been sieved into different grain size levels. Therefore, our finest lunar simulants are finer than natural Apollo soils.

The compaction of lunar regolith generally increases with depth, controlling the physical properties, such as thermal conductivity, shear strength, compressibility, etc. (Meyer, 2007; McKay et al., 1991). The in-situ relative compaction of lunar soil has been found to be about 65% (medium to dense) in the top 15 cm, increasing to >90% (very dense) below a depth of 30 cm (Mckay et al., 1991). Therefore, the lunar simulant physical properties were measured in different relative compaction conditions (90%, 95%, and 100%) (Table 2). Different compaction conditions were achieved using the vibratory method through adjusting the vibratory time (Chen et al., 2016).

Table 2

<table>
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<tr>
<th>Simulants</th>
<th>Relative compaction (%)</th>
<th>Median grain size (μm)</th>
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<th>Void ratio</th>
<th>Cohesion (kPa)</th>
<th>Internal friction angle (°)</th>
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* Mastersizer 2000 will underestimate the grain size of large particles as they are harder to float in the testing media for analysis by laser.

Fig. 8. Major elements of the CUG-series lunar simulants, Apollo soils (McKay et al., 1991), and other lunar simulants (JSC-1, McKay et al., 1994; CAS-1, Zheng et al., 2009; TJ-1, Jiang et al., 2012).

The lunar simulant grain size was measured by a Mastersizer 2000 Laser Particle Size Analyzer in the Materials Research and Testing Center, Wuhan University of Technology. The cumulative weight distribution curves of lunar simulants are shown in Fig. 9b together with the coarsest (14141) and finest (66075) Apollo soils cataloged in Graf (1993) for comparison. The lunar simulant grain sizes increase from CUG-S1 to CUG-S8 (shift right in Fig. 9b). The mean grain sizes are 16.8, 19.6, 54.7, 70.6, 110.1, 131.1, 215.5, and 190.2 μm (Table 2), respectively (Mastersizer 2000 will underestimate the grain size of large particles as they are harder to float in the testing media for analysis by laser). Except for CUG-S1 and CUG-S2, all lunar simulants produced are within the cumulative curve of the coarsest (14141) and finest (66075) Apollo soils. It should be pointed out that Apollo soils cataloged in Graf (1993) are natural lunar soils. However, the lunar simulants produced have been sieved into different grain size levels. Therefore, our finest lunar simulants are finer than natural Apollo soils.

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The physical properties of CUG-series lunar simulants, Apollo soils, and other lunar simulants are summarized in Table 2. Bulk densities, cohesions, and internal friction angles all increase along with the relative compactions. The bulk density varies from 1.40 to 1.97 g/cm$^3$, the void ratio varies from 0.36 to 10.50, the cohesion varies from 2.08 to 5.50 kPa, the internal friction angle varies from 31.0 to 34.6°, respectively. The cohesions of our simulants are larger than the results reported by others (e.g., McKay et al., 1994; Zheng et al., 2009; Jiang et al., 2012), probably because their results were measured in no-compaction conditions.

4. Ground drilling experiments

4.1. The drilling system

The ground drilling experiments were performed in Beijing Spacecrafts, China Academy of Space Technology. The drilling and coring system and the drilling mechanism are described in detail by Chen et al. (2019a, 2019b) and Zhao et al. (2019), and summarized here. The drilling and coring system includes a right-handed auger string, a carbide drilling bit, motors (rotary motor, penetrating motor), and sensors (force sensor, torque sensor) (Fig. 10). The radius of the auger and the bit is 15 mm. The pitch of the auger is 12 mm. The diameter of the inlet in the center of the bit is 9 mm. The radial width and the axial length of helical groove are 0.85 mm and 10.5 mm, respectively. The container of lunar simulants has a length of 2.5 m and a diameter of 0.52 m.

In drilling, the auger string was driven by the servo motors with a constant rotating speed and feeding speed. The lunar simulants were cut and stirred into a fluid state by the rotating and feeding of the bit fixed on the auger. The portion of lunar simulants entering the inlet on the bottom of the bit were cored. The other simulants were discharged by the helical groove of the rotating auger as cuttings.

4.2. Experiment setup

Many of the mechanical parameters of lunar simulants/regolith (e.g., relative compaction, bulk density, internal friction angle, cohesion, adhesion, grain shape, grain size, and thermal capacity, etc.) have great influence on the drilling mechanism (e.g., Zhang and Ding, 2017, 2018). The CUG-series lunar simulants were used to perform more effective ground drilling experiments to facilitate the CE-5 mission.

The drilling mechanism are mainly controlled by two factors on a given drilling target (lunar simulants) with fixed particle properties, 1) particle size distribution (grain gradation), 2) and relative compaction. Particle size distribution and relative compaction would affect the friction angle of lunar simulants and their flow characteristics driven by the drilling tool. In the present research, three mixtures of lunar simulants (Table 3) were used to study the influence of these two factors on drilling.

The disparity of the gravity and air conditions between of the Earth and the Moon would affect the drilling process in some manners (gravity on load curves; air on thermal behavior) but neither is easy to test (gravity) nor likely to alter the drilling results (gravity, air), and therefore are not considered here. Lunar simulants were compacted using the vibration method (Chen et al., 2016). The relative compaction of 80% and 100% were achieved in 3 and 15 min, respectively. All experiments were conducted with a rotating speed of 120 rpm, feeding speed of 120 mm/min. The total drilling depth was fixed at ~ 1 m.

4.3. Experiment results

The drilling load and torque curve of experiments on three lunar simulant mixtures (Table 3) are shown in Fig. 11. In general, all drilling load and torque curves have similar trends. The bit load and torque increase slowly at first, and become stable when reaching a depth of 200–400 mm. Mixture-1 has the smallest bit load and torque, stable at a bit load of 200 N and a torque of 4 Nm. Mixture-2 has a smooth trend, stable at a bit load of 400 N and a torque of 8 Nm. Mixture-3 has the coarsest grain sizes and largest compaction. The bit load and torque of Mixture-3 also increase at first, however much larger than Mixture-1 and Mixture-2, stable at 550 N and 14 Nm, respectively. The bit load and torque of Mixture-3 have a sudden decline at 550 mm and following a dramatic growth at ~ 650 mm depth; the drilling was.
stopped when the bit load increased rapidly to $>800$ N. In total, 274, 291, and 346 g of lunar simulants were cored on Mixture-1, Mixture-2, and Mixture-3, respectively.

5. Discussion

5.1. Interpretations of ground drilling experiments

Lunar simulant/regolith drilling and coring is a dynamic process between the regolith simulant fluid (granular flow) and the drilling tool. The drilling bit disturbs the simulants and drives them flowing either into the helical groove to be discharged or the hollow coring tube to be used in experiments and the total collected samples.

Similarly, if the coring tube resistance is large, more simulants tend to flow into the groove, increasing its pressure. As the groove pressure increases, more lunar simulants will enter the hollow coring tube instead, increasing the bit load and torque, and finally, reach an equilibrium state.

The whole drilling process is divided into three stages by Chen et al. (2019a, 2019b) and Zhao et al. (2019): 1) zero-coring stage, 2) linear-corring stage, and 3) saturated-coring stage, which can be identified of our experiments as well. In drilling, the coring tube resistance and groove pressure is small at first. As the drilling tool penetrates the simulants, more and more simulants enter the hollow stem and the groove, increasing the coring tube resistance and groove pressure as well as the drilling load and torque. When the groove pressure and the hollow coring tube resistance are balanced, the volume ratio between simulant entering the helical groove to the hollow coring tube would stay stable (the smooth trend of below $~200$ mm). If this equilibrium holds, long and high recovery rate core can be obtained.

Under high relative compaction conditions, the internal friction angles of the lunar simulants are large (Table 2), leading to high groove pressure and hollow coring resistance, and can be balanced at high drill load and torque (compare Mixture-1 and Mixture-2, Fig. 9). However, if the lunar simulants only have relatively coarse grains (Mixture-3), the flow of simulants in the hollow coring tube and the groove would not be fluid. If choked, it would cause a rapid increase of the resistance and stop drilling.

Considering that natural lunar soils are even more complex than lunar simulants, the ground experiments teach us that the drilling and coring system onboard CE-5 spacecraft should have the following capabilities, 1) strong abilities to discharge the cuttings; 2) strong abilities to push away grains larger than the bit head; and 3) strong abilities to automatically adapt the drilling parameters to unknown and variable drilling conditions. The ground experiments also prove that drilling the fine mature lunar regolith is easier than drilling the coarse immature lunar regolith.

5.2. Drilling difficulties of different geologic units

For an in-situ exploration mission including a lander, illumination, communication, slope, surface roughness, crater and boulder distributions are always engineering constraints of landing site selection (e.g., Luna-Glob mission, Ivanov et al., 2015, 2018; Luna-25 mission, Kokhanov et al., 2018; lunar polar missions, Lemelin et al., 2014). For the CE-5 mission, a lunar sample return mission, the regolith properties should also be considered. The Rümker region has nine geologic units (1m1, Im2, Im3, Em1, Em3, Em4, IR1, IR2, and IR3), each with distinct volcanic and impact histories (Qian et al., 2018). Different geological histories result in different regolith properties, thus different degrees of drilling and coring difficulties that should be evaluated carefully.

Although the OMAT values of lunar regolith cannot discriminate their absolute grain sizes, they can indeed be used to compare their relative grain sizes (Section 2.4). The class1 and class2 regolith are apparently finer than class3, 4, 5 regolith. The western maria have larger areas of fine mature class1 and class2 regolith (Fig. 6), with longer exposure of space weathering. As demonstrated by our ground experiments, drilling coarse lunar regolith is riskier than drilling fine regolith. This means that in general, the western mare regolith is easier and safer for drilling and coring than the eastern mare regolith.

The rock abundance (RA) map of the CE-5 landing region is shown in Fig. 12. This dataset was produced by Bandfield et al. (2011) using Lunar Reconnaissance Orbiter (LRO) Diviner data, robust for rocks larger than ~1 m. As shown by the rock abundance map, rocky areas (orange to red hue, Fig. 12a) are all related to impact craters or wrinkle ridges. Mons Rümker has the lowest rock abundance across the area. The crater-free areas of the western maria show lower rock abundance with longer gardening history (deep blue hue, Fig. 12a) than the eastern maria (blue hue). The eastern maria has more yellow to green hue spots related to

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Relative compaction (%)</th>
<th>Lunar simulants</th>
<th>Mass percent (%)</th>
<th>Collected samples (g)</th>
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Fig. 11. The drilling load and torque curve of the experiments. Green: Mixture-1; Blue: Mixture-2; Red: Mixture-3. The Y-axis on the left represents the bit load (N), and the Y-axis on the right represents the torque curve (Nm). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 12. (a) Rock abundance map derived by Bandfield et al. (2011) using LRO Diviner data; (b) The rock abundance (RA) was classified into blue (RA < 1 wt%) and yellow (RA > 1 wt%) hues. Crater (>200 m in diameter) areas are overlain on the rock abundance map with a red hue. Yellow and red areas in the map are all not suitable for the CE-5 mission. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In summary, we think that landing, drilling, and coring a mature area with fine lunar regolith is the safest choice for the CE-5 mission. Landing in the class1 and class 2 regolith area away from craters is safer than other areas (Fig. 6). After several years of lunar exploration, China has acquired efficient soft landing strategy as seen in the CE-3 mission (e.g., Sun et al., 2013), and pinpoint landing ability as seen in the CE-4 mission (e.g., Wu et al., 2019). We believe that it is feasible for the CE-5 spacecraft to avoid the hazardous areas (yellow and red areas in Fig. 12) and to land on the smooth and mature areas (class1 or class2 regolith) in the entire landing region. Even if the CE-5 were not to have landed on a mature area, the successful experience of Luna-24 drilling on the rim of a 65 m crater with complex stratigraphy (Barsukov, 1977; Florensky et al., 1977; Robinson et al., 2012; Basilevsky et al., 2013) provides us confidence that the CE-5 mission can fulfill its objectives even in complex conditions.

On the other hand, the scientific outcomes of the CE-5 mission should also be evaluated and maximized. Qian et al. (2018) analyzed in detail the scientific significance of the CE-5 landing region (summarized here). Samples from Em3 or Em4, with an unusually young age, have richer scientific significance than those from the Imbrium-aged basalts, including analysis of recent lunar thermal history, mantle properties, and constraints on the lunar impact flux/history, etc. (Qian et al., 2018). Furthermore, craters in Em4 are likely to excavate and eject the underlying imbrion-aged units, which is then likely to be sampled together with young basaltic regolith, making landing and sampling the young unit doubly scientific meaningful.

All in all, taking the safety and science factors into account, we propose that landing, drilling and coring the young mare terrain (Em4) should be the highest priority for the CE-5 mission. This objective could be accomplished with careful landing site selection, precise landing, and optimized drilling control.

6. Conclusion

In this study, we analyzed the regolith properties of the CE-5 landing region using remote sensing methods, produced lunar regolith simulants based on our analysis, and performed ground drilling experiments using lunar simulants, to support the CE-5 mission. The main conclusions are listed below:

1) Different geologic units of the CE-5 landing region have different regolith properties with different geologic histories. Both the western and eastern mare regolith formed on very low-Ti to low-Ti basalts. The eastern mare regolith is richer in TiO2 and FeO than the western mare regolith. The western mare regolith is finer, thicker and more mature than the eastern mare regolith.

2) CUG-series lunar regolith simulants were produced from Liuhe alkali basalts, which are effective physical and chemical lunar simulants for the CE-5 mission.

3) 274, 291, and 346 g of lunar simulants were collected in the ground drilling experiments using Mixture-1, Mixture-2, and Mixture-3 simulants with a drilling depth of ~1 m. Drilling load and torque will increase with grain sizes and relative compactions. It is easier and safer to drill finer and looser lunar regolith/simulants.

4) The eastern young maria (Em3, Em4) has more scientific significance than the western maria. We propose landing on and drilling in a smooth and mature area in Em4 as the highest priority for the CE-5 mission, through careful landing site selection, precise landing, and optimized drilling control.

Data availability

All the remote sensing data used in this study are available online. Clementine UVVIS data, KAGUYA FeO and mineral abundance data, and LOLA TC merged hillshade map are from USGS Astropedia (https://astrogeology.usgs.gov/search?pmi-target=moon). KAGUYA TC and MI data are from SELENE Data Archive (http://darts.isas.jaxa.jp/plante t/pdap/olsen/index.html.en). M3 data and Diviner rock abundance data are from PDS Geoscience Node (http://pds-geosciences.wustl.edu /default.htm). LROC WAC TiO2 abundance data is from NASA’s LRO website (http://wms.lroc.asu.edu/lroc/view_rdr/WAC_TiO2). CE-1 IIM oxide abundance data, geologic boundaries, the produced regolith thickness map, and K-Means classified lunar regolith data based on OMAT values all have been uploaded into the corresponding Mendeley.
Data.

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Appendix A. Supplementary data

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References


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