Geology and Scientific Significance of the Rümker Region in Northern Oceanus Procellarum: China's Chang'E-5 Landing Region

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Key Points:

- The Rümker region is located in the northwest of the Procellarum KREEP Terrane, experiencing a long and complex geological history.
- We carried out a detailed geological study, and defined and dated 14 geological units.
- The Em4 is the science-richest unit and suitable for landing. It is proposed as the first priority for sample return.

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1029/2018JE005595

Abstract

The Rümker region (41-45° N, 49-69° W) is located in northern Oceanus Procellarum of the Moon. Mons Rümker is the most distinctive geological feature in the area. The region is characterized by prolonged lunar volcanism (Late Imbrian Period to Eratosthenian Period), forming multiple geologic units in the area, including very low-Ti to low-Ti mare basalts, high-Ti mare basalts, and volcanic complexes. Each geologic unit has distinct element composition and mineral assemblages. The Rümker region, overlying the Procellarum KREEP Terrain, was selected as the landing region for China's Chang'E-5 lunar sample return mission. Pre-landing analysis of the geologic context and scientific potential are reported in this contribution. We conducted detailed geological mapping using image, spectral and altimetry data. Fourteen geological units were defined, a geologic map was constructed, and the geologic history was outlined. The western mare units (Im1, Im2, Im3) are Imbrian-aged (~3.4-3.5 Ga) representing the major stage of lunar mare eruptive volcanism. The eastern young mare units (Em3, Em4; <2 Ga) are among the youngest mare basalts on the Moon. They have never been explored in situ or studied in the laboratory. We suggest that samples returned from the eastern mare unit (Em4) could answer many fundamental questions and that this unit should be listed as the top priority landing site for Chang'E-5 sample return mission.

Plain Language Summary

Recent studies find that the geological features and volcanic history of the Moon are far more complex than previously thought, and many of the most interesting areas have been neither explored nor sampled. One such area is the northern Oceanus Procellarum region which consists of very young (<2 Ga) mare materials and hosts one of the largest volcanic complexes on the Moon (Mons Rümker). To document the main themes in the geological history, we studied the Rümker region using a wide variety of lunar orbital data. Surface composition, mineralogy, morphology, and topography were used to create a geological map in which we identified 14 geological units. We found old Ti-poor basaltic units (similar to some Apollo samples) and very young unsampled Ti-rich basaltic units (<1.5 Ga). Samples from the young unsampled unit could answer many unresolved questions in lunar science because of its extremely young age. The area was selected as the landing region for China's Chang'E-5 (CE5) lunar sample return mission in 2019. To maximize the scientific value of the returned samples, we assessed the scientific importance of each unit in our geologic map and suggest that the young mare basalt unit is the most valuable for sample return.

1 Introduction

The Procellarum KREEP Terrane (PKT), is one of the most prominent geochemically anomalous areas on the Moon (Haskin, 1998; Jolliff et al., 2000). It is characterized by high concentrations of heat producing elements (Th, U, K) (e.g. Haskin et al., 2000; Lawrence et al., 2000; Prettyman et al., 2006), a thin crust (Wieczorek et al., 2013), a complex thermal evolution history (Wieczorek & Phillips, 2000; Laneuville et al., 2013), and a long duration of lunar volcanism relative to most of the rest of the Moon (Hiesinger et al., 2000, 2003, 2010, 2011; Morota et al., 2011).

Located in northern Oceanus Procellarum (Fig. 1), the Rümker region is in the northwest part of the PKT (Fig. 2) (Haskin, 1998; Jolliff et al., 2000). Its extended and complex geologic history includes multiple volcanic episodes, each differing in element composition and mineral assemblages (e.g., Pieters, 1978; Hiesinger et al., 2003, 2011; Morota et al., 2011; Zhang et al., 2016).

Earliest geological mapping (Wilhelms & McCauley, 1971; 1: 5 million) defined two mare units in the Rümker region, i.e., Imbrian-aged and Eratosthenian-aged mare units (Im and Em). Scott et al. (1977) combined these into an Imbrian-Eratosthenian-aged mare unit (EIm). Scott and Eggleton (1973) subdivided two non-mare units (Ith and If) and two mare units (Im and Em) in their 1:1 million geological map. The authors concluded that the Ith unit resembles the Alpes Formation and that the If unit is part of the Fra Mauro Formation, both of which are interpreted as ejecta materials from the Imbrium impact basin (Page, 1970; Scott & Eggleton, 1973).

Whitford-Stark and Head (1980) later subdivided four lithostratigraphic formations in Oceanus Procellarum according to surface morphology and spectral characteristics. Three of them occur in the Rümker region, including the Telemann Formation (the western part), the Sharp Formation (the eastern part), and the Hermann Formation (the central southern part). Three basalt endmembers were identified (Dechen Basalt, Lavoisier Basalt, and Roris Basalt) and their sources and emplacement styles were studied in detail (Whitford-Stark & Head, 1980).

More recent stratigraphic works were based on Clementine data. Hiesinger et al. (2003, 2011) used Clementine color ratio data (750 – 400 nm/750 + 400 nm as red, 750/990 nm as green, and 400/750 nm as blue) to map the mare units in Oceanus Procellarum. Three spectrally homogeneous units in the Rümker region were defined and dated by crater size-frequency distribution (CSFD) methods (P9, 3.47 Ga; P10, 3.44 Ga; P58, 1.33 Ga) (Hiesinger et al., 2003; 2011). Using Clementine false-color mosaics (750 nm/415 nm as red, 750 nm/950 nm as green, 415 nm/750 nm as blue), titanium and iron data, Boroughs and Spudis (2001) mapped six lava flows in northern Oceanus Procellarum. Four of them are located within the Rümker region (Flow2, Flow3, Flow5, Flow6).

Mons Rümker (i.e., Rümker Hills), the most distinctive topographic feature in northern Oceanus Procellarum, has long been recognized as one of the three major volcanic complexes in Oceanus Procellarum (Whitford-Stark & Head, 1977). Its morphology, composition, mineralogy, and formation mechanism have been well studied (Smith, 1974; Whitford-Stark & Head, 1977; Wöhler et al., 2007; Campbell et al., 2009; Farrand et al., 2015; Dmitrovsky et al., 2017; Zhao et al., 2017). A comprehensive analysis using recent lunar orbital data (Zhao et al., 2017) identified three geologic units at Mons Rümker and further obtained their model ages by CSFD methods (IR1, 3.71 Ga; IR2, 3.58 Ga; IR3, 3.51 Ga). Zhao et al. (2017) concluded that the steep-sided domes and shallow domes on Mons Rümker are probably formed at different stages of evolution of this volcanic complex.

China’s first lunar sample return mission, Chang’E-5 (CE5) mission, is scheduled to launch in 2019, following the successful Chang’E-3 soft landing and roving exploration of northern Mare Imbrium (44.12° N, 19.51° W) (Xiao, 2014; Ling et al., 2015; Xiao et al., 2015; Zou et al., 2016). The Rümker region in northern Oceanus Procellarum (41-45° N, 49-69° W, ~58000 km^2 in area) is the landing region selected for the CE5 mission (Zeng et al., 2017). Up to 2 kg of lunar samples from the surface and subsurface (up to 2 m in depth) are planned to be collected and returned to the Earth (Wang & Xiao, 2017; Zou & Li, 2017), providing an opportunity to study new lunar samples in terrestrial laboratories since Luna-24 (1976).

The Rümker region remains unexplored by robotic or human landing missions carried out earlier by the United States (Surveyor, Apollo) or the Soviet Union (Luna), and no samples have ever been returned from this broad area (Figs. 1, 2). Understanding its geological context and evaluating the scientific value of materials from this region are key to the further exploration and preparation for sample return and analysis. A detailed study of

Mons Rümker was carried out and several candidate landing sites were proposed by Zhao et al. (2017). However, the extensive mare areas to the north, making up the majority of the landing region (Fig. 3), have not been well studied using newly obtained orbital remote sensing data. Therefore, the goals of this study are: 1) to characterize the geological context of the Rümker region, 2) to assess their science potential for understanding and resolving outstanding lunar science questions, and 3) to propose the most scientifically significant landing and sampling sites for the CE5 mission. To understand better the context of the Rümker region, we extend our study area to 39-46° N, 48-70° W (Fig. 3).

2 Data and methods

2.1 Topography and geomorphology

A Kaguya Terrain Camera global image mosaic with uniform morning illumination (TC Morning Map data) and TC DTM data, with a spatial resolution of ~10 m/pixel (Haruyama et al., 2008, 2014), were mosaicked to analyze topographic and geomorphologic features. TC Morning Map data were used to perform the CSFD measurements on the major mare units to determine their absolute model ages. TC Morning Map and TC DTM data were downloaded from the SELENE Data Archive (http://darts.isas.jaxa.jp/planet/pdap/selene/). Lunar Reconnaissance Orbiter (LRO) Wide-Angle Camera (WAC) DTM data (~118 m/pixel) (Scholten et al., 2012) were applied at a baseline length of 354 m to survey surface slopes. LRO Narrow-Angle Camera (NAC) data were used for more detailed studies of local features, due to their high spatial resolution (up to ~0.5 m/pixel) and more variable illumination conditions (Robinson et al., 2010). WAC DTM data and NAC data were downloaded from the LROC website (http://lroc.sese.asu.edu/).

2.2 Composition

2.2.1 TiO_2 and FeO contents

Kaguya Multiband Imager (MI) data were downloaded from the SELENE Data Archive (http://darts.isas.jaxa.jp/planet/pdap/selene/). MI has five visible bands (415 nm, 750 nm, 900 nm, 950 nm, 1000 nm) and a spatial resolution of 20 m (Ohtake et al., 2008). TiO_2 and FeO abundances were calculated from MI data using the algorithms described by Otake et al. (2012):

$$\theta_{Ti} = \arctan\{[(R_{415} / R_{750}) - 0.208] / (R_{750} + 0.108)\} \tag{1}$$

$$\text{wt\%TiO}_2 = 0.72 * \theta_{Ti}^{14.964} \tag{2}$$

$$\theta_{Fe} = \arctan\{[(R_{950} / R_{750}) - 1.250] / (R_{750} - 0.037)\} \tag{3}$$

$$\text{wt\%FeO} = 20.527 * \theta_{Fe} - 12.266 \tag{4}$$

where R_{415}, R_{750}, and R_{950} are the reflectance at each corresponding band. The standard deviation of the TiO_2 and FeO contents are 0.43 wt. % and 0.81 wt. %, respectively. Caution should be exercised in interpretations when the TiO_2 content is lower than 2 wt. %, at which point the linear correlation between UV/VIS (321 nm/415 nm) and TiO_2 content tends to break down (Sato et al., 2017; Coman et al., 2018).

A false color composite map was produced from MI data by assigning 750 nm/415 nm as red, 750 nm/950 nm as green and 415 nm/750 nm as blue (Pieters et al., 1994). Because of its sensitivity to surface maturity and composition, and its ability to highlight subtle spectral differences (Pieters et al., 1994; Eliason et al., 1999). The false color composite map, together with titanium and iron variation and crater distribution data, were used to determine the nature and boundaries of geologic units.

2.2.2 Mineralogy

Moon Mineralogy Mapper (M^3) reflectance data acquired from the optical period OP2C were selected because of their full spatial coverage over the Rümker region. M^3 OP2C data have a spatial resolution of 280 m/pixel, with 85 bands, spanning from 430 nm to 3000 nm (Pieters et al., 2009). The M^3 data used in this study are calibrated data archived in the Planetary Data System (PDS, version 1 of Level 2), radiometrically corrected (Green et al., 2011), geometrically corrected (Boardman et al., 2011), thermally corrected (Clark et al., 2011), and photometrically corrected (Besse et al., 2013).

To decrease the effects of space weathering and to permit a more robust spectral study, we removed the continuum following the method of Horgan et al. (2014) and Martinot et al. (2018). These authors defined the continuum by maximizing the 1 and 2 micron absorption bands. Spectral parameters such as band centers, band depths, band areas, and band asymmetries were calculated for the 1 and 2 micron absorption bands of each spectrum. M^3 RGB composite maps using these criteria were produced to highlight the mineralogical diversity of the Rümker region (Mustard et al., 2011; Martinot et al., 2018). Both M^3 original and continuum-removed spectra were visually analyzed for definitive mineral identification, performed by comparison of the M^3 spectra with the RELAB reference library (http://www.planetary.brown.edu/relab/).

3 Results

3.1 Topography

The Rümker region is located within the relatively smooth mare plains of northern Oceanus Procellarum (Rosenburg et al., 2011; Kreslavsky et al., 2013) (Fig. 3a). This area is covered by widespread mare basalts and is generally flat. The mean slope of the area is 1.1° (at a baseline length of 354 m), with only 10% of the area exceeding a slope of 2°. The average elevation of the mare area is ~-2145 m. The western maria is 200-300 m higher than the eastern maria (Fig. 3b). The highest point is in the south of Mons Rümker (-1271 m) and the lowest point is at the bottom of Mairan G crater (-3571 m). The regional topography is largely influenced by mare ridges, along which the mare surface is locally raised, up to 100-200 m. Mons Rümker, ~70 km in diameter, stands up to 1300 m above the surrounding mare. It has a mean slope of 2.7°. The individual domes on Mons Rümker are slightly steeper than the plateau.

3.2 Geomorphology

3.2.1 Impact craters

Most of the craters in the area are simple primary craters smaller than 2 km in diameter, characterized by bowl-shaped floors, only few with flat bottoms. Almost all craters larger than 2 km in diameter are found in the western maria. It is also apparent that the western maria have a much higher crater density than the eastern maria. Harding D (centered at 42.8° N, 67.6° W; Fig. 4a) is the largest crater in the area. It has a diameter of 6.3 km and a bowl-shaped floor. Its rim is ~250 m higher than the surrounding mare. This crater formed on a NE-orientated wrinkle ridge.

Secondary crater clusters formed by ejecta from the crater Copernicus (NW trend), Harpalus (NE trend), and Pythagoras (NW trend) are distributed in the area (Fig. 3a) (Scott & Eggleton, 1973). For example, the NE-oriented clusters to the north of Mons Rümker are formed by Harpalus crater ejecta (Fig. 4b) (Scott & Eggleton, 1973). However, the sources of the secondaries that are not characterized by any preferred orientations are mostly unknown.

There are at least 35 buried craters in the study area (39-46° N, 48-70° W) and 15 buried craters that lie within the Rümker region (41-45° N, 49-69° W), mostly in the eastern maria. These pre-mare craters were partially filled by lava flows, leaving only the raised rim crests visible on the surface (Fig. 4c).

3.2.2 Wrinkle ridges

Lunar wrinkle ridges are abundant in the study area (Fig. 3b). Most of the wrinkle ridges have typical shapes as described by Strom (1972) and Sharpton and Head (1988) (i.e., a gently sloping, broad arch at the base, and a sharper but irregular ridge at the top (Fig. 5)). The dimensions of the wrinkle ridges are variable in the Rümker region. In the western maria, the wrinkle ridges range up to 6 km in width, 110 km in length, and are 200 m above the surrounding mare. In the eastern maria, they are smaller than those in the western maria, mostly less than 1.5 km in width, 20 km in length, and are seldom much higher than 50 m above the surrounding mare.

The wrinkle ridges in the Rümker region have three preferred orientations (NW, NNW, NE, respectively). In the western maria, most wrinkle ridges are oriented NW or NNW, consistent with the preferred orientation of those in Oceanus Procellarum as a whole (Yue et al., 2015). For example, the wrinkle ridges between Harding D and Harding H craters in the western maria are parallel and have a distinct NW trend (Fig. 5a). Five independent wrinkle ridges are parallel with each other, with variable lengths (10 km to 100 km) but similar morphologies and slopes. In the vicinity of these parallel wrinkle ridges, a linear fault vertically cuts a wrinkle ridge (Fig. 5b).

In the eastern maria, the wrinkle ridges have a prominent NE trend along the outer ring of the Imbrium basin marked by the shoreline of Mare Frigoris (Wilhelms & McCauley, 1971; Spudis et al., 1988). This trend suggests that the wrinkle ridge formation in the eastern maria was affected by the ring system of the Imbrium basin (Maxwell et al., 1975; Head, 1982).

3.2.3 Sinuous rilles

In the eastern maria, a sinuous rille (Rima Sharp) is incised into the mare plains along the mare/highland boundary (Fig. 3b). Rima Sharp is even the longest sinuous rille on the Moon (Hurwitz et al., 2013). It originates in Sinus Roris, to the north of the Rümker region, at an elevation of -2300 m, and fades into the mare surface to the south at an elevation of -2500 m (Fig. 6). Rima Sharp is 566 km long, 257 km of which are within the study area. The width of Rima Sharp varies from 0.8 km to 3 km. Its depth varies from 20 m to 50 m, and the narrowest parts of the channel have greater depths than those of the wider parts. The channel wall slopes of Rima Sharp fluctuate between 8 and 12°. The regional slope of Rima Sharp (defined as the gradient of the material surrounding the sinuous rille) is -0.02° as measured by

Hurwitz et al. (2013). A thermal erosion formation mechanism is favored for such sinuous rilles (Hurwitz et al., 2012).

3.2.4 Volcanic domes

Volcanic domes are relatively common in the lunar maria (Smith, 1973; Head & Gifford, 1980). They are often observed in clusters, as in the case of Mons Rümker (Smith, 1974; Whitford-Stark & Head, 1977), where most of the volcanic domes in the study area are located. Zhao et al. (2017) identified 22 volcanic domes on the Rümker plateau and divided them into two groups: steep-sided domes and shallow domes (Fig. 7a). The steep-sided domes usually have relatively steep flank slopes (>5°) and greater heights, with associated volcanic features such as possible summit pits and flow features (Fig. 7b). The shallow domes have gentle topographic relief and lower heights (<200 m); only two domes have associated volcanic features. Both dome groups are interpreted to have formed by extrusion of basaltic magma to form small shield volcanoes similar to those in Marius Hills (Head & Gifford, 1980; Lawrence et al., 2013; Head & Wilson, 2017; Zhao et al., 2017).

Another possible volcanic dome (named East Dome in this study; 49.85° W, 43.68° N) is located near the Mairan domes, close to the mare/highland boundary. The East Dome is circular in shape (Fig. 7d), with a diameter of ~3 km and is up to 205 m higher than the mare (Fig. 7e). The flank slope is up to 9°, less than those of the Mairan domes (Head & McCord, 1978; Glotch et al., 2011). This dome is cratered but most of the craters appear to be fresh secondaries that not highly degraded. A circular depression (~1.3 km in diameter) which may be a volcanic depression is outlined in the northwest (the yellow dashed line in Fig.7d). The East Dome was first described as a silica-rich dome by Glotch et al. (2011). Similar features in the vicinity (the Gruithuisen and Mairan domes) are interpreted to have formed from high viscosity silica-rich magmas of rhyolitic or dacitic composition (Wilson & Head, 2003; Glotch et al., 2010, 2011; Ivanov et al., 2016; Boyce et al., 2017; Head & Wilson, 2017).

3.2.5 Kipukas

Kipukas are islands or exposures of earlier structures or units that have been surrounded by later units. Numerous isolated kipukas are identified within the eastern maria. They are hilly to hummocky highland materials of various shapes, and are up to 500 m higher than the surrounding surface. The kipukas have relatively smooth surfaces with fewer craters than the maria, and the few remaining craters are all heavily degraded (Figs. 8a, 8b). At the base of the kipukas, debris from the upper slopes encircles the kipukas and forms a 200-300 m wide deposit zone (Head, 1977). Although the kipukas usually display a scattered distribution in the eastern maria, the highlands in the northeastern part of the study area near Louville P crater have similar morphologies (Fig. 8c). Both the isolated kipukas and highlands near Louville P crater are characterized by subdued shapes and heavily degraded superposed craters, lieing on the possible Imbrium basin ring (Wilhelms & McCauley, 1971).

3.3 Composition

3.3.1 TiO_2 and FeO concentrations

TiO_2 and FeO abundance maps (Fig. 9) were used to estimate the surface TiO_2 and FeO contents. The results show that both the TiO_2 and FeO abundances vary significantly across the area. The TiO_2 contents range up to 7.5 wt. % (Fig. 9a), and the FeO contents vary from 10 wt. % to 18.0 wt. % (Fig. 9b). The western and the eastern maria are dominated by two different types of mare basalts, with distinctly different TiO_2 contents, and varying FeO contents. However, it should be noted that about 45 % of the study area has TiO_2 contents lower than 2 wt. %, a value at which the specific TiO_2 contents are probably not accurate (Coman et al., 2018).

The western maria are characterized by very low-Ti to low-Ti basalts (up to 5.0 wt. %, TiO_2 content) (Neal & Taylor, 1992). The mean content of TiO_2 is 1.6 wt. %. About 80 % of the area has TiO_2 contents lower than 1%. The northwestern part of the western maria exhibits the lowest TiO_2 contents in the study area (1.3 wt. %, mean content). The TiO_2 contents increase from north to south in the western maria and reach an average of 2.4 wt. % to the south of Harding D crater. The FeO contents of the western maria are lower than of the eastern maria. The FeO contents range from 14 to 17 wt. % (15.8 wt. %, mean content), increasing towards the south.

A very low-FeO zone occurs in the northeast of the western maria, without variation of TiO_2 abundances, suggesting an origin due to the emplacement of ejecta from Pythagoras crater (low-Fe and very low-Ti), rather than due to the composition of local bedrock or regolith. Large craters and their surrounding ejecta in the western maria have even lower TiO_2 contents than the mare surface (<1 wt. %); we interpret this to be due to the excavation of underlying very low-Ti lava flows or underlying fresh rocks of the same lithology. This relationship between lava flows and their compositions can be used to obtain the thickness of lava flows (Thomson et al., 2009; Weider et al, 2010), which is discussed in Section 4.1.1.

The eastern maria are clearly more enriched in TiO_2 (4.7 wt. %, mean content) and FeO (16.7 wt. %, mean content) than the western maria. About 65 % of the eastern area has TiO_2 contents between 4-7 wt. %; and about 80 % of the area has FeO contents greater than 16%. Most of the eastern maria are covered by bright (high albedo) ray materials radiating from Copernican-aged Harpalus crater (Fig. 3a), whose bedrock target is low-Ti mare basalts. These materials clearly decrease the surface TiO_2 contents in the eastern maria. Except for these areas covered by ejecta, rocks in the region are classified as high-Ti basalts (TiO_2 contents between 6-7 wt. %) (Neal & Taylor, 1992).

The underlying older low-Ti materials are clearly excavated by superposed impact craters, as shown in the nature of the ejecta from relatively large and fresh craters. This ejecta has TiO_2 contents close to those of the western maria (1.9 wt.%, mean content). The kipukas are expected to show very low TiO_2 and FeO contents due to their origin as highlands (Spudis et al., 1988), but mixture with the surrounding high-Ti basalts by impacts has commonly raised their titanium and iron abundance.

Mons Rümker is dominated by low-Ti basalts (1.8 wt. %, mean content) (Neal & Taylor, 1992). The mean content of FeO is 15.6 wt. %. The FeO content is lower in the northeastern Rümker plateau, due to admixing of highland and basaltic materials (Zhao et al., 2017).

3.3.2 Mineralogy

The color composite maps shown in Fig. 10 highlight the presence of distinct spectral units, represented by different colors. The area is dominated by pyroxene signatures, characterized by broad absorption bands centered around 1 and 2 microns (Adams, 1974). Other common lunar minerals such as olivine or plagioclase have not been detected throughout the study area. Although several parameters, such as surface physical properties and rock texture may also influence the band shape, band center positions are often indicative of the pyroxene cation content (Burns et al., 1973; Adams, 1974; Cloutis & Gaffey, 1991).

The western maria spectra (Fig. 10c) are characterized by greater band depths and band centers at shorter wavelengths than the eastern maria spectra. Spectra from the eastern maria (Fig. 10d) are quite homogenous, with the exception of those taken from the interiors of impact craters with diameters exceeding 900 m, where the spectra have band centers located at shorter wavelengths, consistent with the western maria spectra. It is therefore likely that the impact craters of the eastern maria have excavated material from an older, buried unit, spectrally similar to the western maria. Spectra of the western maria show 1 and 2 micron bands centered around 990 and 2180 nm, consistent with a pyroxene of intermediate-Ca composition such as pigeonite (Fig. 10e). Spectra of the eastern maria have 1 and 2 micron bands centered at ~1010 and 2260 nm, consistent with high-Ca pyroxene such as augite (Fig. 10e). Ling et al. (2017) also conducted spectral observation of the Rümker region. Both Ling et al. (2017) and this survey suggest that there is little low-Ca pyroxenes in the mare area.

Mons Rümker, the Mairan T dome, and the highlands in Montes Jura to the east of the study area are all characterized by weaker pyroxene absorptions bands, which likely indicates a lower mafic component, or more mature regolith (Fischer & Pieters, 1994). The pyroxene component of the highlands is slightly more variable, with absorption bands shifted towards shorter wavelengths (~950 and 2140 nm), suggesting the presence of low-Ca pyroxene rather than the intermediate to high-Ca pyroxene detected in the mare units. The Mons Rümker pyroxene component is closer in composition to the older, western maria in composition (intermediate-Ca pyroxene). The Mairan T dome, Mons Rümker, and the highlands in Montes Jura have higher average reflectance values than the mare units, which may indicate the presence of a less mafic component, such as silica or feldspar, which cannot easily be detected in the VNIR domain when mixed with pyroxene (e.g., Adams & McCord, 1972; Pieters, 1986).

3.4 Geologic units

Fourteen geologic units were defined and mapped in this study, including seven mare units (Im1, Im2, Im3, Em1, Em2, Em3, and Em4), three Rümker plateau units (IR1, IR2, and IR3), one non-mare highland units (Ith), and three dome units (ld, sd, and Idm) (Fig. 11). In order to define the geologic units, we followed the assumption by Hiesinger et al. (2000) that spectrally and compositionally homogeneous units are formed within a short period and each unit represents a single volcanic eruptive phase. Therefore, each spectrally and compositionally homogeneous unit is regarded as a geologic unit. We used TiO_2 and FeO contents, and a false color composite from Kaguya MI data to define spectral and compositional units. The boundaries revealed by TiO_2 and FeO abundance data (Fig. 9) correlate well with those revealed by M^3 color composite data (Fig. 10). Boundaries are shown as black lines in Fig. 11 and black dashed lines in Fig. 9.

CSFD methods were carried out to analyze the homogeneous units using TC Morning Map data to determine their absolute model ages. The results are shown in Table 1 together with optical maturity values, TiO_2 and FeO contents, and their uncertainties (shown as standard deviation). The cumulative crater frequency plots are shown in Fig. 12. Mons Rümker was mapped and surface ages were determined by Zhao et al. (2017), and we used their results in this study.

Im1, Im2, and Im3 are Imbrian-aged mare units (referred to as western maria above), adopting the lunar stratigraphy system by Stöffler and Ryder (2001). Im1 is the oldest mare unit (~3.42 Ga) in the area. It is dark bluish-purple in color with a red hue in the false color map (Fig. 11), dominated by low-Ti basalts (2.4 wt. %, mean content of TiO_2). Im2 (~3.39 Ga) is the largest mare unit in the area, containing five large craters (>3 km in diameter), Eratosthenian-aged Pythagoras secondaries, and large wrinkle ridges. It is orange-red in the false color map (Fig. 11), and the TiO_2 content (1.3 wt. %, mean content) is apparently lower than that of Im1. Im3 is located in the northeast near Louville P crater (~3.16 Ga) (Fig. 11), with a low TiO_2 content (1.4 wt. %, mean content). It is the smallest Imbrian-aged unit in the area, embaying some of the highlands near Louville P. Most of the unit is covered by NE-orientated Pythagoras secondary ejecta, resulting in the largest OMAT value (0.184) in the area. Our mapping results of Imbrian-aged mare units correlate well with previous stratigraphic studies by Whitford-Stark and Head (1980) and Hiesinger et al. (2003).

Em1, Em2, Em3, and Em4 (Em3 and Em4 are referred to as eastern maria above) are Eratosthenian-aged mare units. Em1 (~2.30 Ga) embays Mons Rümker in the southwest. It has similar color ratios and TiO_2 contents as the neighboring unit, Im1, but it is different in its relatively high FeO contents and lower crater density. Em2 (~2.13 Ga) has the lowest TiO_2 contents (1.6 wt. %, mean content) among the Eratosthenian units. It has an orange-red hue in the false color map (Fig. 11) similar to the Im2 unit, but it has fewer craters and a younger model age. Em3 (~1.51 Ga) is located to the east of Mons Rümker. It is purple in the false color map (Fig. 11), characterized by a low-Ti composition (3.6 wt. %, mean content of TiO_2). This unit embays a portion of Mons Rümker in the east.

Em4 (~1.21 Ga) is the youngest mare unit in the area. This unit has a high TiO_2 (6-7%) content, except for the areas covered by Copernican-aged secondary ejecta, as discussed in Section 3.2.1. The FeO contents of Em4 are also high (16.7 wt. %, mean). This unit is purple-blue in the false color map (Fig. 11) and embays dozens of highland kipukas. The wrinkle ridges are smaller than those of western maria, trending NE along the outer ring of the Imbrium basin. Rima Sharp incises this unit at its boundary with Montes Jura.

IR1, IR2, and IR3 are Rümker plateau units, according to the definition and crater counting results of Zhao et al. (2017) (Table 1). IR1 (~3.71 Ga) is a lineated terrain in the north of Mons Rümker, formed by a mixing of Iridum crater ejecta and basaltic materials. IR2 (~3.58 Ga) occurs northeast of Mons Rümker, exhibiting lower TiO_2 contents. IR3 (~3.51 Ga) covers the main portion of Mons Rümker, characterized by higher TiO_2 and FeO contents than IR2 (Zhao et al., 2017).

Three dome units are identified in the area. Two of them (ld, ~3.5 Ga; sd, active until ~3.0 Ga) were defined by Zhao et al. (2017) on the basis of their flank slopes. The silica-rich domes including the East Dome and the Mairan domes (Idm), are mapped as another independent unit with a highland volcanism formation mechanism in the Imbrian Period (Head & McCord, 1978).

Kipukas/highlands are informally defined as massif materials (Wilhelms, 1970) that resemble the Alpes Formation (Page, 1970), interpreted to have been formed by the ejecta of the Imbrium basin in previous studies (Scott & Eggleton, 1973; Spudis et al., 1988). In the current study, we defined it as the Ith unit after Scott and Eggleton (1973). It is the oldest unit in the area, contemporary with the Imbrium basin impact (~ 3.93 Ga) (Snape et al., 2016).

4 Discussion

4.1 Volcanic events and geologic history

4.1.1 Volcanic events

The oldest recognizable mare basaltic unit in Oceanus Procellarum is the Repsold Formation (medium to high TiO_2 content). At present it is only exposed in northwestern Oceanus Procellarum near the Rümker region (Whitford-Stark & Head, 1980). It is inferred to be beneath the uppermost mare basalts defined in this study, on the basis of superposition relationships and its extensive coverage (Whitford-Stark & Head, 1980). The Repsold

Formation was emplaced around 3.75 ± 0.05 Ga (Boyce & Jonnson, 1978) or 3.72 Ga (P28; Hiesinger, et al., 2003, 2011) ago.

The basaltic unit IR1 formed ~3.71 Ga during the same period or shortly after the emplacement of the Repsold Formation, followed by IR2 (3.58 Ga) and IR3 (3.51 Ga) (Zhao et al., 2017). Shallow domes (ld) formed around 3.5 Ga ago (Zhao et al., 2017). Extrusive steep-sided domes formed later by relatively high viscosity magma, and volcanic activity continued until ~3.0 Ga ago (Zhao et al., 2017). The basaltic eruptions in the Mons Rümker region are similar to the western maria flows in elemental composition (low TiO_2), mineralogy (intermediate pyroxene composition), and emplacement ages (Imbrian-aged), suggesting that they may be from the same mantle source region but have different eruption styles.

Although the small silica-rich East Dome has not been dated in this study due to its small area, it most likely formed in the Imbrian Period, contemporary with the Mairan domes (Head & McCord, 1978) and other silica-rich domes, e.g., the Gruithuisen domes (3.7-3.85 Ga, Wagner et al., 2002), and the Hansteen domes (3.65-3.74 Ga, Wagner et al., 2010). On the other hand, its relatively shallow slopes (9°), low thorium abundance (8.6 ppm), and lower silica content compared with other Mairan domes (Glotch et al., 2011) might indicate that it is not completely similar to typical red spots that are formed by more viscous, silica-rich magmas (Wilson & Head, 2003; Glotch et al., 2010, 2011; Ivanov et al., 2016; Boyce et al., 2017; Head & Wilson, 2017).

The Imbrian-aged mare basalts (Im1, Im2 and Im3) defined in the current study comprise the major mare eruption phase during the Late Imbrian Period (3.2-3.8 Ga) (Hiesinger et al., 2000, 2003, 2010, 2011). This eruption phase has a very low-Ti to low-Ti and intermediate pyroxene composition (e.g. pigeonite), suggesting an early magma source regions without ilmenite. The materials excavated from the largest crater (Harding D, 6.3 km diameter) have similar mineral, TiO_2 and FeO contents as those in the surface of the mare, unlike the underlaying Repsold Formation materials, as do other impact craters. This implies that the thickness of the Imbrian mare units is at least 700 m. The sources of the Imbrian-aged basalt units are hard to trace, but the sinuous rilles in Mons Rümker and Aristarchus regions were probably the source of some of these materials (Whitford-Stark & Head, 1980).

The Eratosthenian-aged mare basalts (Em1, Em2, Em3, and Em4) represent the young phase of volcanism, characterized by high titanium content (Pieters, 1978; Blewett et al., 1997; Elphic, 2002) and high olivine content (Pieters, 1978; Staid & Pieters, 2001; Staid et al., 2011; Zhang et al., 2016). The Eratosthenian-aged mare basalts in this area are also rich in iron, especially the Em3 and Em4 units. The Em1 and Em2 units are not as high in TiO_2 and FeO content as the early Late Eratosthenian Period aged Em3 and Em4 units. The spectra from these units have band center positions shifted towards shorter wavelengths from Em3 to Em4 (Fig. 10d), suggesting a slight change in the pyroxene compositions (decrease of calcium) of the eruptive high-Ti mare basalts with time.

Em4 comprises the main member of the Eratosthenian mare units in the area. Rima Sharp is the longest sinuous rille on the Moon and feeds most of the lavas of Em4 from the north in Sinus Roris with the assistance of Rima Mairan from the southeast (Whitford-Stark & Head, 1980). The Em4 lava flow boundaries are undetectable in WAC low solar illumination image data, although Eratosthenian-aged lava flow fronts can be readily observed in Mare Imbrium (Chen et al., 2018; Wu et al., 2018). This observation suggests that the Em4 lava flow unit thickness is too small to be recognized. Spectroscopic observations by M^3 show that materials excavated by craters with diameter greater than 900 m in the eastern maria (Em3, Em4) are different from surface materials associated with Em3 and Em4, and similar to the older western maria. This observation indicates that the eastern Eratosthenian-aged mare units (Em3, Em4) are superposed on the old western Imbrian-aged mare units (Im1, Im2, Im3). Thus, we estimated the thickness of the eastern mare basalt to be less than 90 m using depth/diameter relationships (Pike, 1974). Further constraints on basalt thickness were provided by crater penetrating measurements (Thomson et al., 2009), yielding a thickness of 50~100 m for the young basalts (Em3, Em4) (Table 2), comparable to the 30-60 m estimated by Hiesinger et al. (2002).

In summary, the Imbrian-aged and Eratosthenian-aged mare units in the study area have a significant variation in age, mineralogy, composition and volume, which are interpreted to originate from different mantle source regions or depths (Staid et al., 2011; Kato et al., 2017).

4.1.2 Geological history

The sequence of geologic events in the area, including volcanic activity, tectonism (wrinkle ridge formation) and impact cratering, are now summarized. A geologic map (Fig. 13) was produced and we interpret the geological evolutionary history of the Rümker region as follows:

1. The Imbrium impact at 3.92 Ga ago generated a complex multi-ring system (Snape et al., 2016) and the outer ring materials formed the Ith unit in the area (Scott & Eggleton, 1973; Spudis et al., 1988). Ejecta of the Iridum impact (3.84-3.7 Ga) (Wagner et al., 2002) formed the lineated terrain in the north of Mons Rümker before 3.71 Ga (Zhao et al., 2017).

2. The earliest detectable basaltic volcanism in the area erupted around 3.72 Ga ago (Hiesinger et al., 2003), forming medium to high-titanium mare basalts belonging to the Repsold Formation (Whitford-Stark & Head, 1980).

3. Basaltic volcanism was active from 3.71 to 3.51 Ga ago in Mons Rümker, forming plateau basalts IR1 (3.71 Ga), IR2 (3.58 Ga), and IR3 (3.51 Ga) (Zhao et al., 2017).

4. Silica-rich domes (Idm) formed contemporaneously to, or a little earlier than, Mons Rümker by silica/felsite volcanic activity (Head & McCord, 1978; Wilson & Head, 2003; Glotch et al., 2010, 2011; Ivanov et al., 2016; Boyce et al., 2017; Head & Wilson, 2017).

5. The major phase of basaltic volcanism occurred during the Late Imbrian Period, forming very low-Ti to low-Ti mare basalts (Im1, 3.42 Ga; Im2, 3.39 Ga; Im3, 3.16 Ga).

6. NW-oriented wrinkle ridges in Oceanus Procellarum were tectonically generated around 3.35 Ga ago (Yue et al., 2017).

7. The youngest phase of mare volcanism started at ~2.30 Ga ago and ceased at ~1.21 Ga ago, forming four episodes of mare units (Em1, 2.30 Ga; Em2, 2.13 Ga; Em3, 1.51 Ga; Em4, 1.21 Ga). The youngest mare volcanism (with elevated titanium content) formed the Em4 unit.

4.2 Potential science outcomes from samples return

Laboratory studies of lunar samples from Apollo and Luna missions (landing sites shown in Figs. 1 and 2) solved numerous fundamental scientific issues of selenology and heralded the beginning of a golden age of lunar research that continues to this day (e.g., Hiesinger, 2006; Taylor et al., 2006; Neal, 2009; Jaumann et al., 2012; Taylor, 2014). However, most of the Moon remains unexplored and there are still many unanswered scientific questions (National Research Council, 2007) that remain to be addressed by returned samples (e.g., Crawford et al., 2007, 2012, 2014; Flahaut et al, 2012; Kring & Durda, 2012). China's CE5 lunar sample return mission to the Rümker region provides a great opportunity to solve some of the significant outstanding questions of lunar science. Samples from each geologic unit in the area have specific scientific importance, which should be ranked to maximize the science outcomes.

4.2.1 The young mare units

On the Moon, the phase of mare basalt volcanism that records internal mantle evolution began (cryptomaria; Whitten & Head, 2015) prior to the end of impact basin formation (Oriental basin, ~3.68 Ga; Whitten et al., 2011), peaked between 3 and 4 Ga, and subsequently declined with time, with only a few extrusive mare basalt deposits, widely spaced in the last 50% of the lunar history (Hiesinger et al., 2000, 2003, 2010, 2011; Morota et al., 2011; Head & Wilson, 2017). Where is the youngest mare basalt volcanism, what is its exact radiometric age, and what does its mineralogy and geochemistry tell us about the lunar mantle in the last half of lunar history?

Remote sensing data and counts of superposed impact craters on mare basalt units show that the youngest mare basalts could be as young as 1.2 Ga (Hiesinger et al. 2003, 2011). The youngest mare basalts are concentrated in the northern Oceanus Procellarum region, centrally located in the Procellarum KREEP Terrane (PKT), characterized by elevated abundances of radioactive heat-producing elements such as U, Th and K (e.g. Haskin, 1998; Jolliff et al., 2000; Prettyman et al., 2006).

One (P58, 1.33 Ga) of the five young mare units (others are P56, P57, P59, and P60) occurs in the Rümker region (Hiesinger et al., 2003, 2011). P58 nearly corresponds with Em3 (1.51 Ga) and Em4 (1.21 Ga) in the current study. These two mare units have extremely young model ages, especially Em4, which is one of the youngest mare units on the Moon revealed by crater counting methods (Hiesinger et al., 2000, 2003, 2010, 2010; Morota et al., 2011). These high-Ti basalts (Em3, Em4) are younger than any existing lunar samples, including the youngest lunar meteorites (NWA032, 2.8 Ga) (Fagan et al., 2002).

These factors led scientists to place the return of samples from these young mare basalt units as a top priority for future lunar exploration (National Research Council, 2007). Analysis of these samples in Earth laboratories will: 1) provide exact radiometric dates for the extrusive events and thereby improve our knowledge of lunar chronology, 2) provide new knowledge of the nature of the geochemistry and mineralogy of basaltic source regions and their isotopic and trace element characteristics, 3) permit the testing of the role of the radioactive Procellarum KREEP Terrane in the generation of late-stage mare volcanism, 4) improve understanding of the thermal state of the lunar interior in late lunar history, thereby testing and constraining models for the thermal evolution of the Moon.

Finally, the ages of these young basalts are currently determined by impact crater size-frequency distribution of the craters superposed on the units, calibrated by counts of craters on geologic units radiometrically dated in Earth laboratories from samples collected by Apollo and Luna missions. However, no samples have currently been returned from such young lunar units, and, thus, there is a high level of uncertainty in the size-frequency distribution ages in the last half of lunar impact chronology (Stöffler & Ryder, 2001; Stöffler et al., 2006; Crawford et al., 2007). Return of samples from these young basalts would thus serve to provide an absolute calibration for the cratering flux, an accomplishment that will assist in our understanding of the geological evolution of planetary bodies throughout the Solar System (Crawford et al., 2007; National Research Council, 2007; Kring & Durda, 2012).

4.2.2 Other geological units

The Imbrian-aged mare basalts in the area are low-Ti (Im1) to very low-Ti (Im2, Im3), and dominated by intermediate composition pyroxene such as pigeonite. Samples from the Imbrian-aged mare basalts are similar in age (Imbrian-aged) and composition (very low-Ti to low Ti) to Apollo and Luna samples (Apollo 12 and 15 missions collected low-Ti basalts, and Apollo 17 and Luna 24 missions collected very low-Ti basalts). Samples from these units can provide important ground truth to help evaluate the low-Ti and VLT basalt petrogenesis models (Neal & Taylor, 1992), and reveal mantle source region properties (Snyder et al., 1992).

Steep-sided lunar domes and volcanic complexes have not been sampled in previous lunar missions. Samples from the domes on Mons Rümker and the silica-rich East Dome can reveal the elemental and mineral compositions of these surface materials, providing ground truth for remote sensing data/methods. Geochemical analysis can constrain the nature of magma source regions and test the existing models and mechanism of dome formation (Wilson & Head, 2003; Head & Wilson, 2017; Wilson & Head, 2017). Samples from the silica-rich East Dome can reveal the nature of silica-rich volcanism on the Moon, the effects of thorium concentration on red spot formation, and lead to further understanding of the late stage magmatic evolution of the Moon (Hagerty et al., 2006; Glotch et al., 2010, 2011).

4.3 Proposed sampling sites

Comparing the potential science return of each of the geologic units, we suggest that the Em4 unit has the richest scientific value and should be the top priority landing unit for the CE5 mission. Sampling anywhere in the Em4 unit could return young mare materials and fulfill the desired scientific goals. Thus, we propose the entire Em4 unit as a candidate from which to choose a specific landing site (Proposed landing site A). Our suggestion to land in the young mare unit is supported by Ling et al. (2017) and Jolliff et al. (2017).

Furthermore, sampling the regolith developed on the Em4 unit could readily return samples of the underlying older materials (i.e., Imbrian-aged mare basalts) excavated by impacts. In addition, the secondary clusters and crater rays in the area indicate that material in the soils is likely to contain admixed ejecta from distant craters, such as Copernicus, Harpalus and Pythagoras. Finally, ejecta from craters superposed on the exposed kipukas in the Em4 unit may provide fragments from the underlying Imbrium basin ejecta unit. In contrast, landing in the western maria is likely to return only the Imbrian-aged mare deposits and possible ejecta and fragments (similar in age and composition to Apollo and Luna samples), that could also be sampled in Em4 unit.

Mons Rümker and the silica-rich East Dome are also valuable sampling units of significant scientific interest. We list these as the second and third priority landing sites for the CE5 mission and propose two landing sites within each unit (Proposed landing sites B and C). Proposed landing site B is at a steep-sided dome on Mons Rümker (centered at 58.53° W, 41.41° N). This steep-sided dome is ~ 7.5 km in diameter. The top of this dome is flat and may be suitable for landing (<2°). The third proposed landing site is on the silica-rich East Dome (centered at 49.85° W, 43.68° N), which is discussed in detail in Section 3.2.4 and Section 4.1.1.

These three proposed landing sites (Fig. 14; Table. 3) can be further evaluated to assess the engineering requirements (e.g. surface slopes, rock abundance, crater density) in a future study.

4.4 Engineering advantages of sampling the Em4 unit

The proposed landing site A (Em4) is not only the very highest scientific priority, but also very favorable from an engineering and landing safety point of view. It offers a relatively safe landing site, which is regionally flat, young, and is areally homogeneous and so does not require pin-point landing. These benefits are listed:

1) The Em4 unit is regionally flat (1.1°, mean slope) and very similar to the topography and slopes observed at the Chang'E-3 (CE3) landing site. CE3 landing data can be used to simulate the nature of the landing region.

2) The Em4 unit is very young (1.21 Ga), which means it contains fewer large impact craters and has smoother topography.

3) The Em4 unit is very widely distributed and continuous in the CE5 landing region (Figs. 11, 14), making up almost one third of the total landing region. Landing and sampling anywhere in the Em4 unit would fulfill the primary scientific objectives of the mission.

4) The Em4 unit is a mare unit very similar in age and surface characteristics to that explored by CE3 (Zhao et al., 2014; Qiao et al., 2014), and suited for soft landing by CE5. Ground penetrating radar data from the CE3 landing site (Fa et al., 2015; Xiao et al., 2015; Zhang et al., 2015; Yuan et al., 2017) show the type of vertical structure to be expected in the CE5 Em4 unit.

5 Conclusions

We systematically studied the topography, geomorphology, composition and surface properties of the Rümker region, the target region for the CE5 sample return mission. Principle results include the following:

1. The Rümker region is an unexplored and unsampled area in northern Oceanus Procellarum. It is located within the unusual Procellarum KREEP Terrane (PKT), characterized by levels of high heat producing elements.

2. Fourteen geologic units were defined and mapped, including seven mare units (Im1, Im2, Im3, Em1, Em2, Em3, and Em4), three Rümker plateau units (IR1, IR2, and IR3), one non-mare highland units (Ith) and three dome units (ld, sd, and Idm).

3. The Rümker region experienced long (~3.7 Ga to ~1.2 Ga) and complex volcanic activity, forming multiple volcanic units with distinct composition and mineralogy.

4. Three candidate landing sites are proposed for the CE5 mission. We interpret the Em4 unit (Proposed landing site A) to be the most scientifically valuable and also the safest from a landing and engineering point of view, and should be listed as the top priority for the CE5 mission.

Acknowledgments

This study is supported by the National Scientific Foundation of China (No. 41772050 and No. 41773061), the Fundamental Research Funds for the Central Universities, China University of Geosciences (Wuhan) (No. CUGL160402 and No. CUG2017G02). Wang is supported by the National Scientific Foundation of China (No. 11502277). The work of Flahaut is supported by the CNES (Luna/ExoMars APR). Martinot is supported by the Netherlands Organization for Scientific Research (NWO) grant.

The Kaguya TC Morning Map data, TC DTM data, and Multiband Imager (MI) data are available from the SELENE Data Archive (http://darts.isas.jaxa.jp/planet/pdap/selene/).

The LRO WAC Data and NAC data are available from the LROC website (http://lroc.sese.asu.edu/). The LOLA and Kaguya TC merged hillshade map are available from USGS Astrogeology Science Center (https://astrogeology.usgs.gov/). The M^3 Level 2 data are archived in the Planetary Data System. Spectra for lunar minerals are available from RELAB reference library (http://www.planetary.brown.edu/relab/). The thorium abundance data by Prettyman (2006) are available from the PDS Geoscience Node (http://pds-geosciences.wustl.edu/lunar/lp-l-grs-5-elem-abundance-v1/).

The crater counting files (.scc) are in the Supporting Information (Dataset S1). Crater counting was carried using CraterTools (Kneissl et al., 2011). Statistics on crater size-frequency distribution based on crater counting files (.scc) were performed on CraterstatsII (Michael, 2010). CraterTools, CraterstatsII, and the introduction on how to use this softwares are available from http://www.geo.fu-berlin.de/en/geol/fachrichtungen/planet/software/index.html. The geologic map of the Rümker region (Fig. 13) has been uploaded individually to the Supporting Information (Figure S1).

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Tables

Table 1. Geologic units in the study area.

Unit	Area	Model age (This study)[a]	Hiesinger[b] (2003)	OMAT[c]	TiO_2[d]	FeO[d]
	(km^2)	(Ga)	(Ga)		(wt. %)	(wt. %)
Em4	35905	1.21 (+0.03/-0.03)	1.33, P58	0.173 (0.023)	4.8 (1.2)	16.7 (0.7)
Em3	5396	1.51 (+0.07/-0.07)		0.168 (0.023)	3.6 (0.9)	16.2 (0.7)
Em2	915	2.13 (+0.13/-0.13)		0.164 (0.033)	1.6 (0.4)	16.2 (0.6)
Em1	3928	2.30 (+0.10/-0.10)		0.169 (0.029)	2.4 (0.5)	16.8 (0.4)
Im3	3454	3.16 (+0.06/-0.09)	3.40, P13	0.184 (0.028)	1.4 (0.4)	15.3 (0.7)
Im2	44327	3.39 (+0.02/-0.02)	3.44, P10	0.166 (0.035)	1.3 (0.4)	15.6 (0.8)
Im1	13749	3.42 (+0.02/-0.02)	3.47, P9	0.166 (0.030)	2.4 (0.6)	16.3 (0.6)
IR3	747	3.51 (+0.04/-0.06)[e]		0.156 (0.025)	1.9 (0.4)	15.9 (0.8)
IR2	727	3.58 (+0.03/-0.04)[e]		0.155 (0.019)	1.5 (0.4)	14.9 (0.8)
IR1	2912	3.71 (+0.04/-0.05)[e]		0.157 (0.027)	2.0 (0.6)	15.1 (1.0)

a. Absolute model ages. Absolute model ages of each unit were calculated using CraterstatsII (http://www.geo.fu-berlin.de/). Uncertainties are reported by Michael and Neukum (2010).

b. Geologic units and their model ages defined by Hiesinger et al. (2003).

c. Mean optical maturity (OMAT) values. OMAT values were obtained from Kaguya MI data, using the method described by Lucey et al. (2000) and Lemelin et al. (2016).

d. Mean TiO_2 and FeO contents.

e. The CSFD results by Zhao et al. (2017).

f. The values in parentheses of OMAT, TiO_2 and FeO indicate standard deviation values of each unit.

Table 2. Basalt thickness of the young mare units (Em3 and Em4) and craters used to calculate the thickness.

No	Latitude (°)	Longitude (°)	Diameter (km)	Dt (km)	R_{base} (km)	H_b (m)
1	40.9	50.8	6.1	5.1	5.0	228 (±105)
2	42.1	52.2	1.6	1.4	0.9	119 (±7)
3	40.3	52.8	4.3	3.6	4.4	78 (±78)
4	39.8	53.2	2.0	1.7	1.4	106 (±22)
5	42.6	54.1	1.7	1.4	1.7	50 (±39)
6	43.2	55.5	1.2	1.0	0.7	97 (±3)
7	42.1	55.6	1.8	1.5	1.0	137 (±5)
8	42.3	56.0	3.3	2.8	2.6	132 (±53)

Note. The method applied is described in Thomson et al. (2009). Dt is the transient crater diameter. R_{base} is the radius of ejecta. H_b is the basalt thickness obtained. The error comes from the measurement of R_{base}.

Table 3. Proposed landing sites and their scientific values

Landing site	Center coordinates	Unit	Local feature	Scientific Values
A	Em4	Em4	young mare	1. Unsampled new rock type. 2. Extent of lunar volcanism duration. 3. Properties of late stage lunar volcanism. 4. Deep mantle properties. 5. Concentration mechanism of Th and its role in late stage volcanism. 6. Precise isotopic age of young volcanism. 7. Impact cratering flux history. 8. Improving CSFD dating method and chronology.
B	58.53°W, 41.41°N	sd	Mons Rümker	1. Origin of lunar domes 2. Property of the magma source 3. The duration of Mons Rümker volcanism. 4. Impact cratering flux history. 5. Improve CSFD dating method and chronology.
C	49.85°W, 43.68°N	ldm	silica dome	1. Rock-type characteristic of the dome. 2. Origin of the silica-rich domes. 3. Properties of the magma source. 4. Evolution of magmas. 5. Influence of Th in silica dome formation. 6. The mechanism of Th concentration.

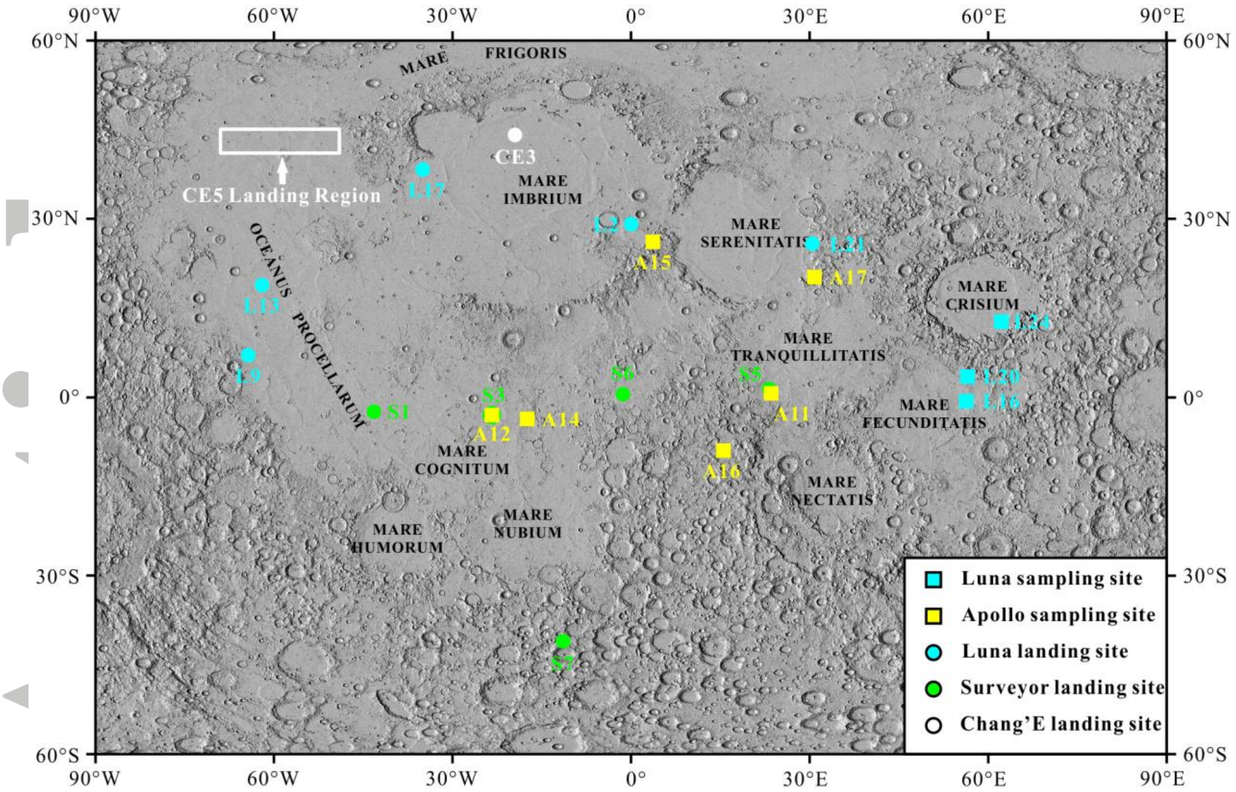

Figure 1. Location of the Rümker region and previous landing sites. The Rümker region is located in northern Oceanus Procellarum, away from previous sampling sites. The basemap is a Lunar Orbiter Laser Altimeter (LOLA) and Kaguya Terrain Camera (TC) merged hillshade map (simple cylindrical projection) (Barker et al., 2016).

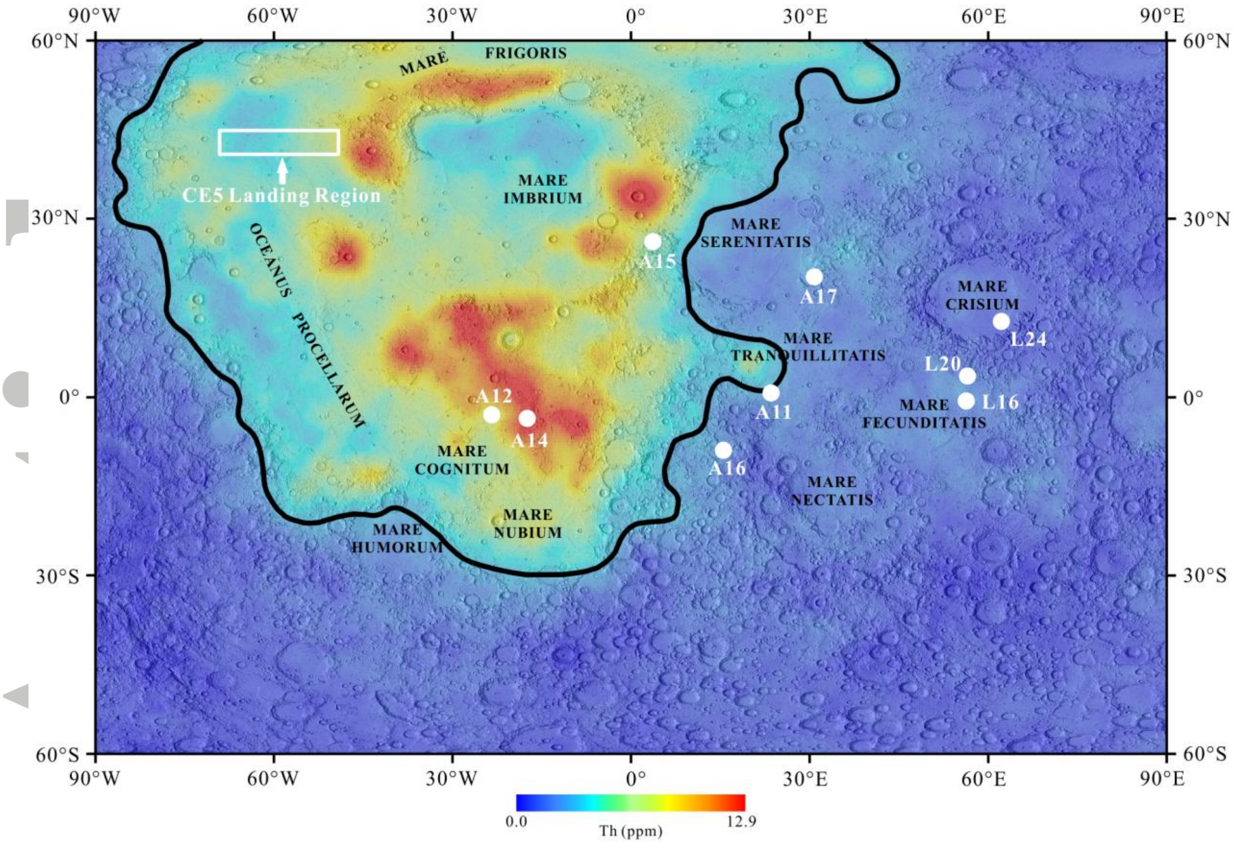

Figure 2. Thorium abundance map of the lunar nearside. The thick black line denotes the boundary of the Procellarum KREEP Terrane (Th >3.5 ppm). "A" represents the Apollo sampling sites; "L" represents the Luna sampling sites. The white box indicates the CE5 designated landing region. The basemap is a LOLA and Kaguya TC merged hillshade map (Barker et al., 2016) superposed on the Lunar Prospector thorium data (Prettyman et al., 2006).

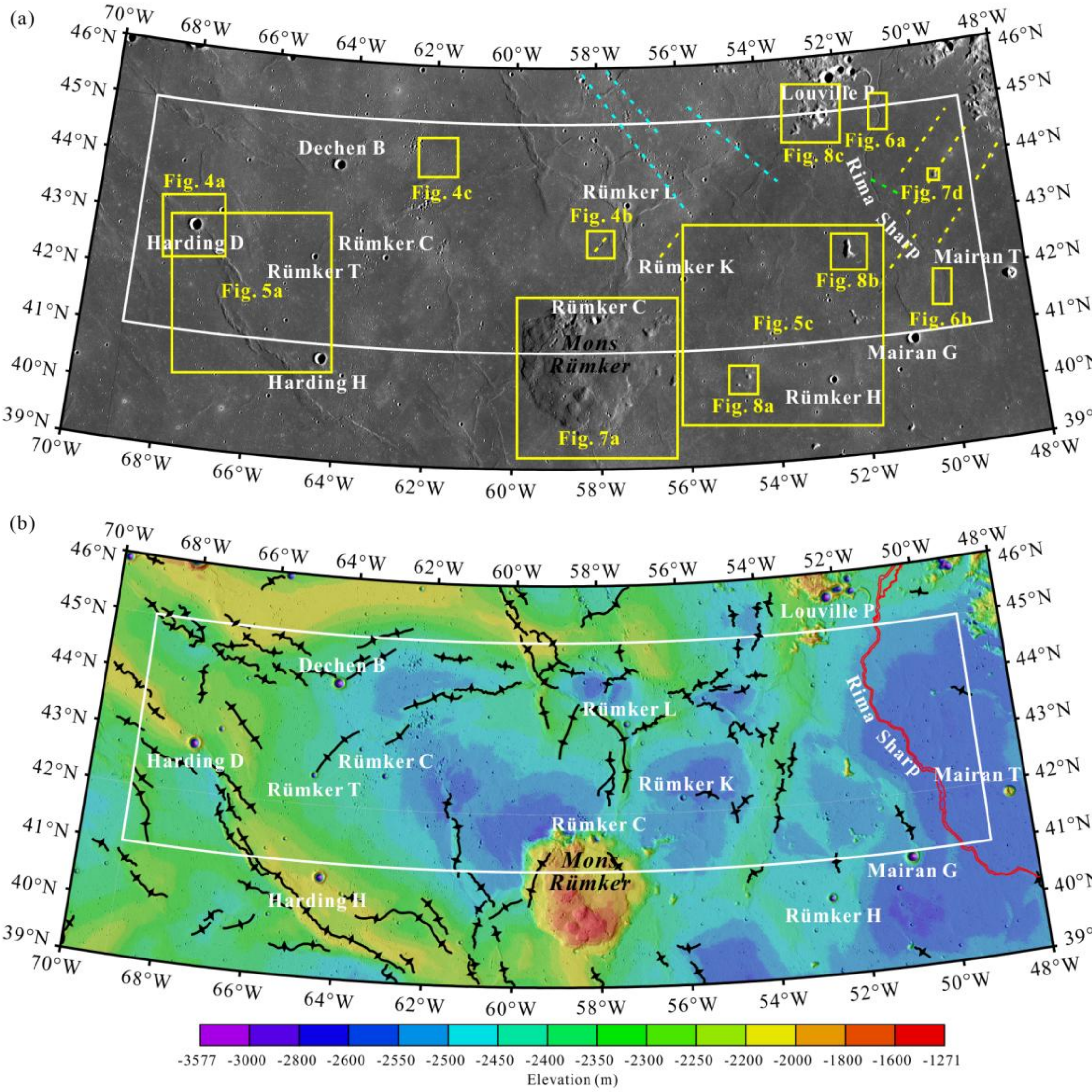

Figure 3. (a) TC Morning Map of the Rümker region (Lambert conformal conic projection). The white box denotes the CE5 landing region. The yellow boxes represent the locations of other figures in this paper. The yellow dashed lines denote the ejecta from Harpalus carter. The blue dashed lines denote ejecta from Pythagoras crater. The green dashed lines denote ejecta probably from Copernicus crater. **(b)** Topography of the Rümker region. The image is a LOLA and Kaguya TC merged hillshade map superposed on the TC DTM data (Lambert conformal conic projection). The white box denotes the CE5 landing region. The black lines denote wrinkle ridges. The red lines denote Rima Sharp.

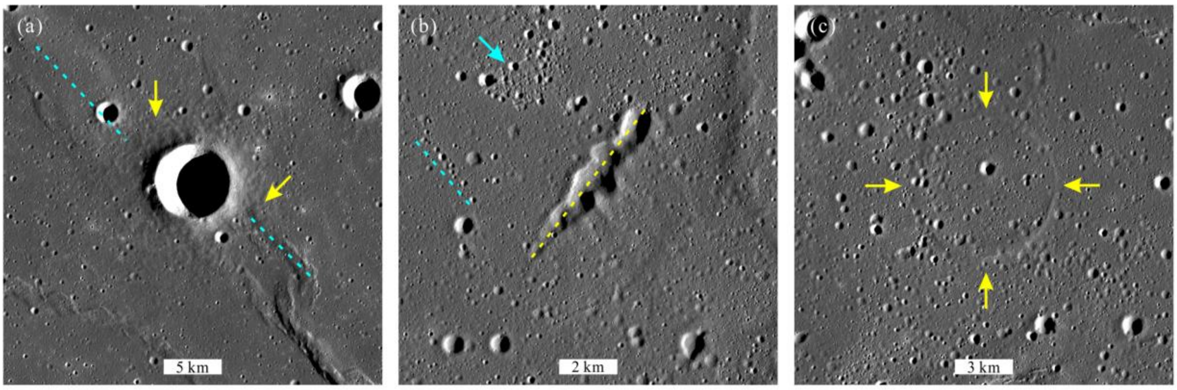

Figure 4. Typical impact crater-related structures in the Rümker region. **(a)** Harding D crater (centered at 42.8° N, 67.6° W; Fig. 3a). This crater formed on a NW-oriented wrinkle ridge (blue dashed lines). Its ejecta (yellow arrow) buries a portion of the wrinkle ridge. **(b)** Secondary crater clusters (centered at 42.9° N, 58.0° W; Fig. 3a). The yellow dashed line denotes Harpalus secondaries (Scott & Eggleton, 1973). The secondary craters denoted by the blue dashed line are radial to Copernicus crater, and are thus probably formed by Copernicus crater ejecta. The blue arrow denotes secondaries without any dominant orientations. **(c)** A buried crater (centered at 44.4° N, 61.9° W; Fig. 3a). The yellow arrows denote the exposed rim crest of the preexisting crater. This preexisting crater is almost completely buried by the later lavas. The subsequent lava flooding is estimated to be less than ~800 m, using the depth/diameter relationships of fresh craters (Pike, 1974).

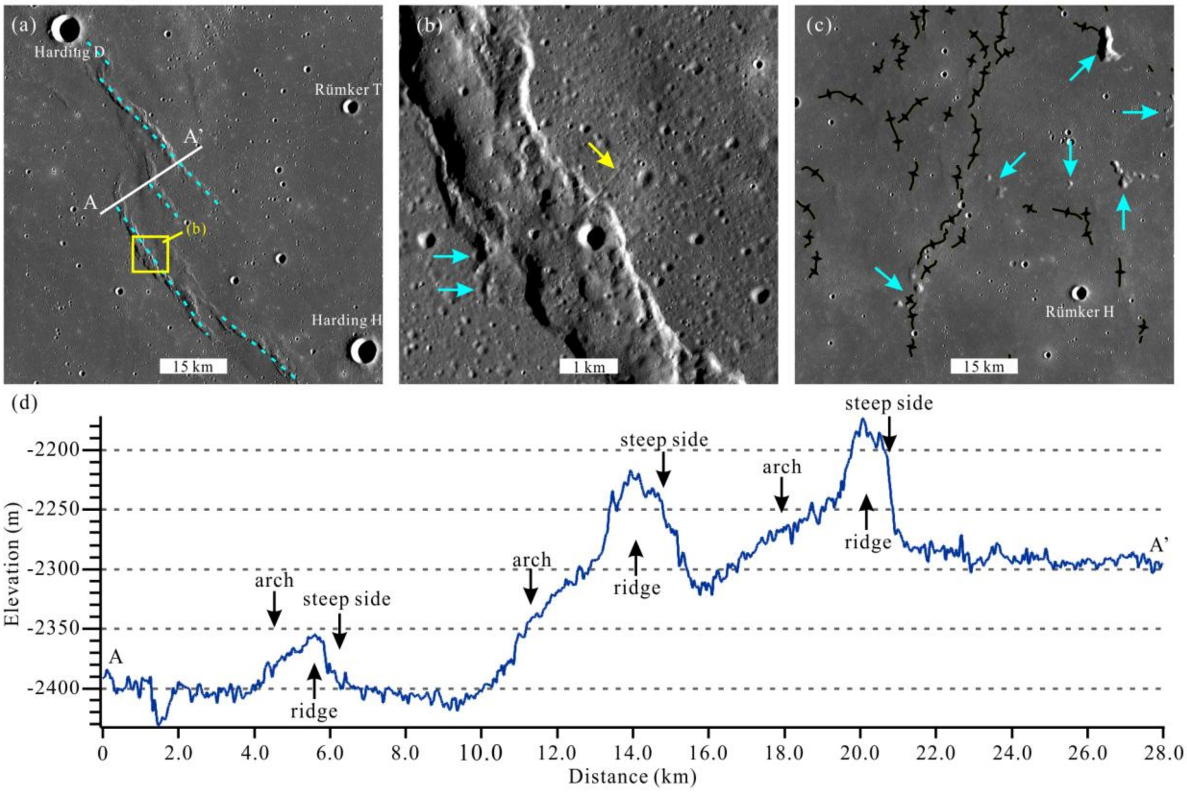

Figure 5. Wrinkle ridges. **(a)** NW-orientated parallel wrinkle ridges (centered at 41.7° N, 66.3° W; Fig. 3a). The blue dashed lines denote parallel wrinkle ridges. AA' shows the location of the profile in Fig. 5d. The yellow box denotes the location of Fig. 5b. **(b)** A southwest trending fault cuts the wrinkle ridge in the area (the yellow arrow). The craters denoted by blue arrows are cross-cut by the ridge front. **(c)** Wrinkle ridges in the eastern maria (centered at 41.3° N, 53.9° W; Fig. 3a). They are oriented NE along the outer ring marked by kipukas (see section 3.2.5). **(d)** Topographic profile across wrinkle ridges (AA' in (a)). The wrinkle ridges in the area display the typical broad arches (2-3°) and sharp ridges (up to 8°) (Strom, 1972; Sharpton & Head, 1988).

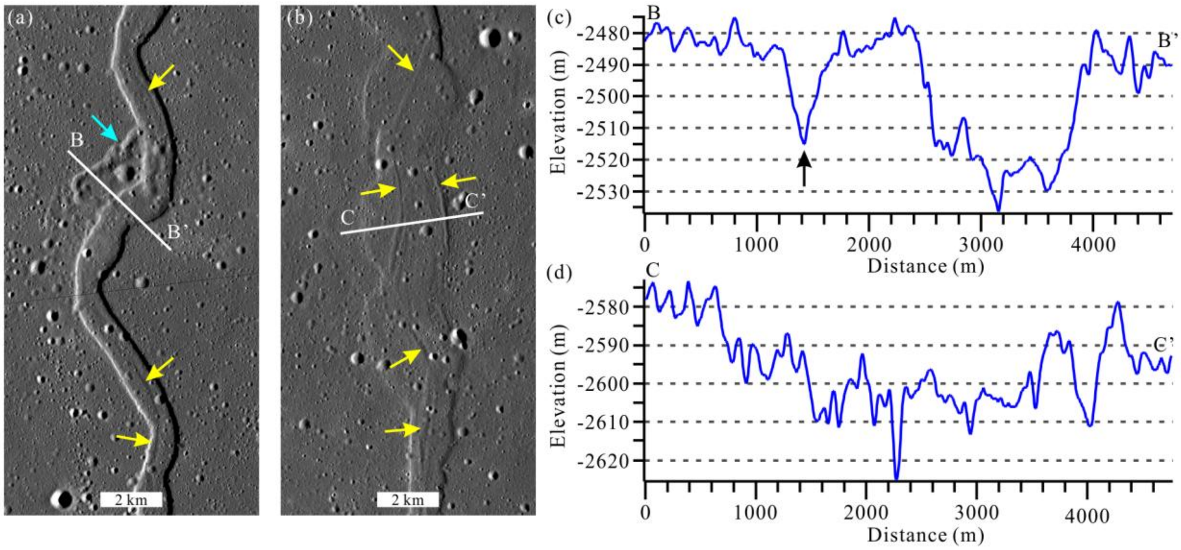

Figure 6. Sinuous rilles. **(a)** The narrow and deep parts of Rima Sharp (centered at 45.0° N, 51.0° W; Fig. 3a). Rima Sharp is ~1.3 km wide and 40-50 m deep in this part. The yellow arrows denote small channels within Rima Sharp. The blue arrow denotes a shallow (~30 m in depth) branch of Rima Sharp. The white line (BB') shows the location of the profile in Fig. 6c. **(b)** The wide and shallow part of Rima Sharp (centered at 41.7° N, 50.0° W; Fig. 3a). Rima Sharp is ~3.1 km wide and ~20 m deep in this part. The yellow arrows denote small channels within Rima Sharp. The white line (CC') shows the location of the profile in Fig. 6d. **(c)** Topographic profile of the narrow part of Rima Sharp. The black arrow denotes a branch of Rima Sharp. **(d)** Topographic profile of the wide part of Rima Sharp.

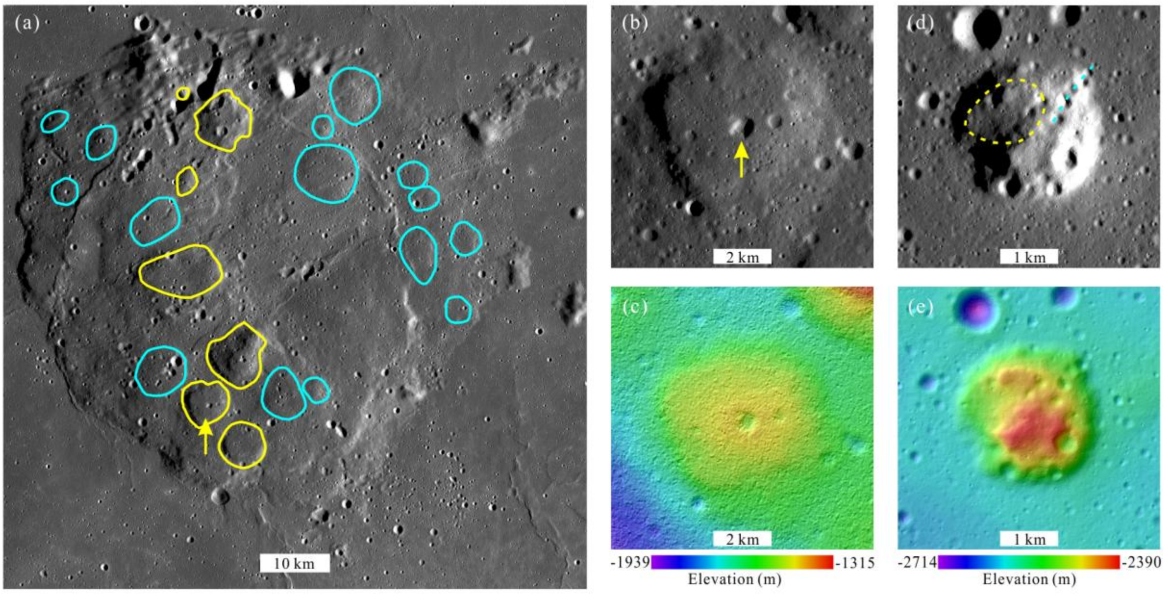

Figure 7. Volcanic domes in the Rümker region. **(a)** Volcanic domes on Mons Rümker. The yellow lines denote steep-sided domes (flank slopes >5°). The blue lines denote shallow domes (flank slopes <5°). The yellow arrow denotes the steep-sided dome in Fig. 7b. **(b)** Steep-sided dome in the southwest of Mons Rümker. The yellow arrow denotes a summit pit, which may be a volcanic crater (Zhao et al., 2017). **(c)** Topography of the steep-sided dome in Fig. 7b. The image is a LOLA and Kaguya TC merged hillshade map superposed on TC DTM data. **(d)** The East Dome (centered at 49.85° W, 43.68° N; Fig. 3a). The yellow dashed line denotes a circular structure that may be a volcanic depression. The blue line denotes NE trending secondary craters. **(e)** Topography of the volcanic dome in Fig. 7d. The image is a NAC hillshade map superposed on NAC DTM data.

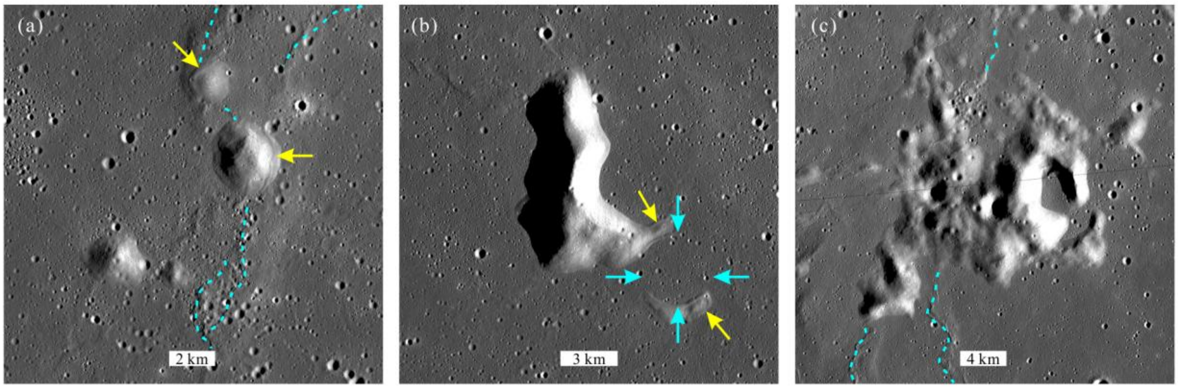

Figure 8. Kipukas in the Rümker region. **(a)** Isolated kipukas (centered at 40.4° N, 54.8° W; Fig. 3a). These kipukas are reshaped by wrinkle ridges (the blue dashed lines), especially in the places denoted by the yellow arrows. **(b)** The largest isolated kipuka (centered at 42.6° N, 52.1° W; Fig. 3a). The yellow arrows denote debris. The blue arrows denote a buried crater (~ 3.9 km in diameter). **(c)** Highlands near Louville P crater, with a morphology that is similar to the kipukas scattered in the eastern maria. The blue dashed lines denote wrinkle ridges.

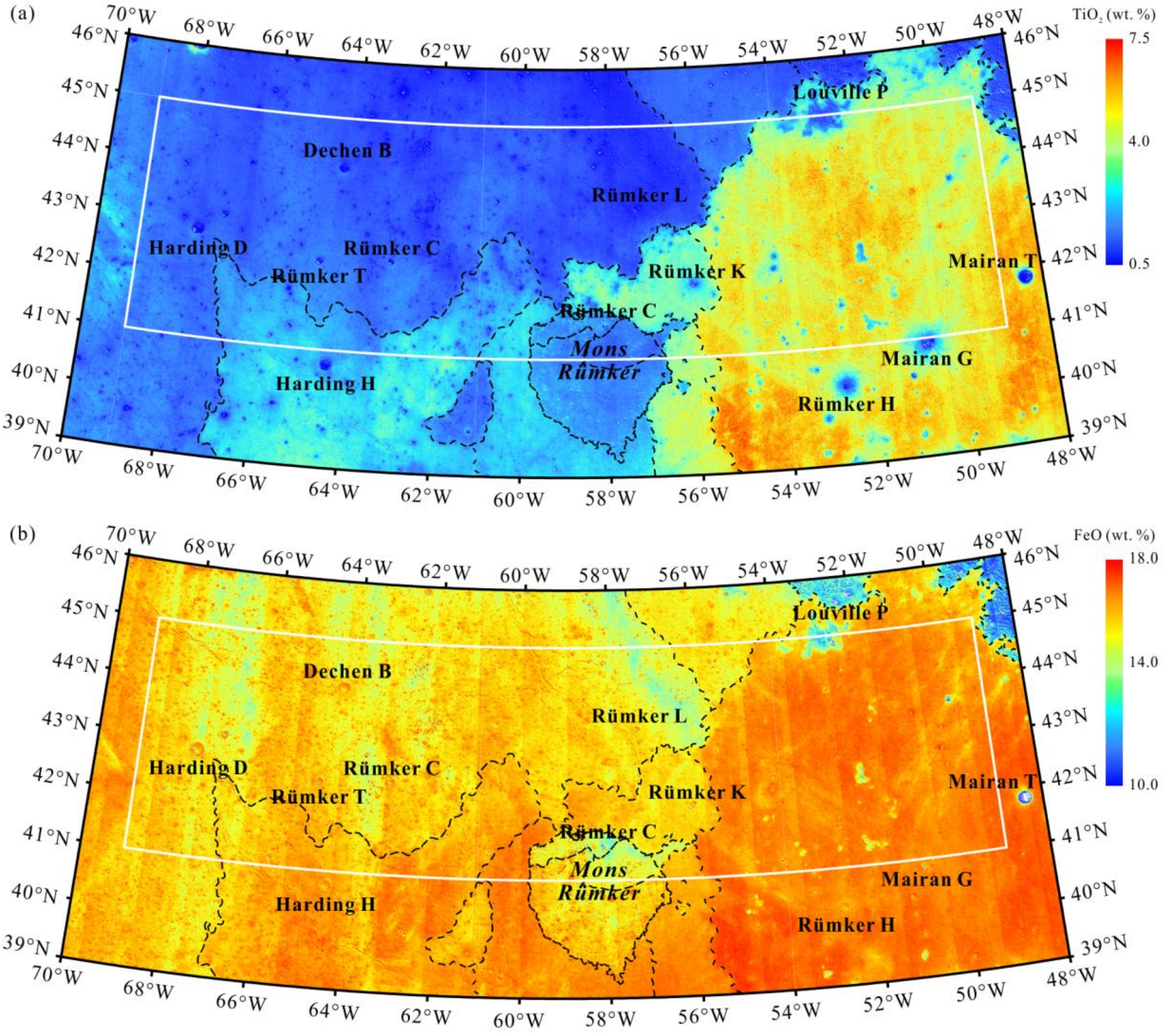

Figure 9. TiO_2 and FeO abundance maps of the Rümker region (Lambert conformal conic projection). **(a)** TiO_2 abundance map of the study area. **(b)** FeO abundance map of the study area. The white boxes denote the CE5 landing region. The black dashed lines denote geologic boundaries discussed in Section 3.4.

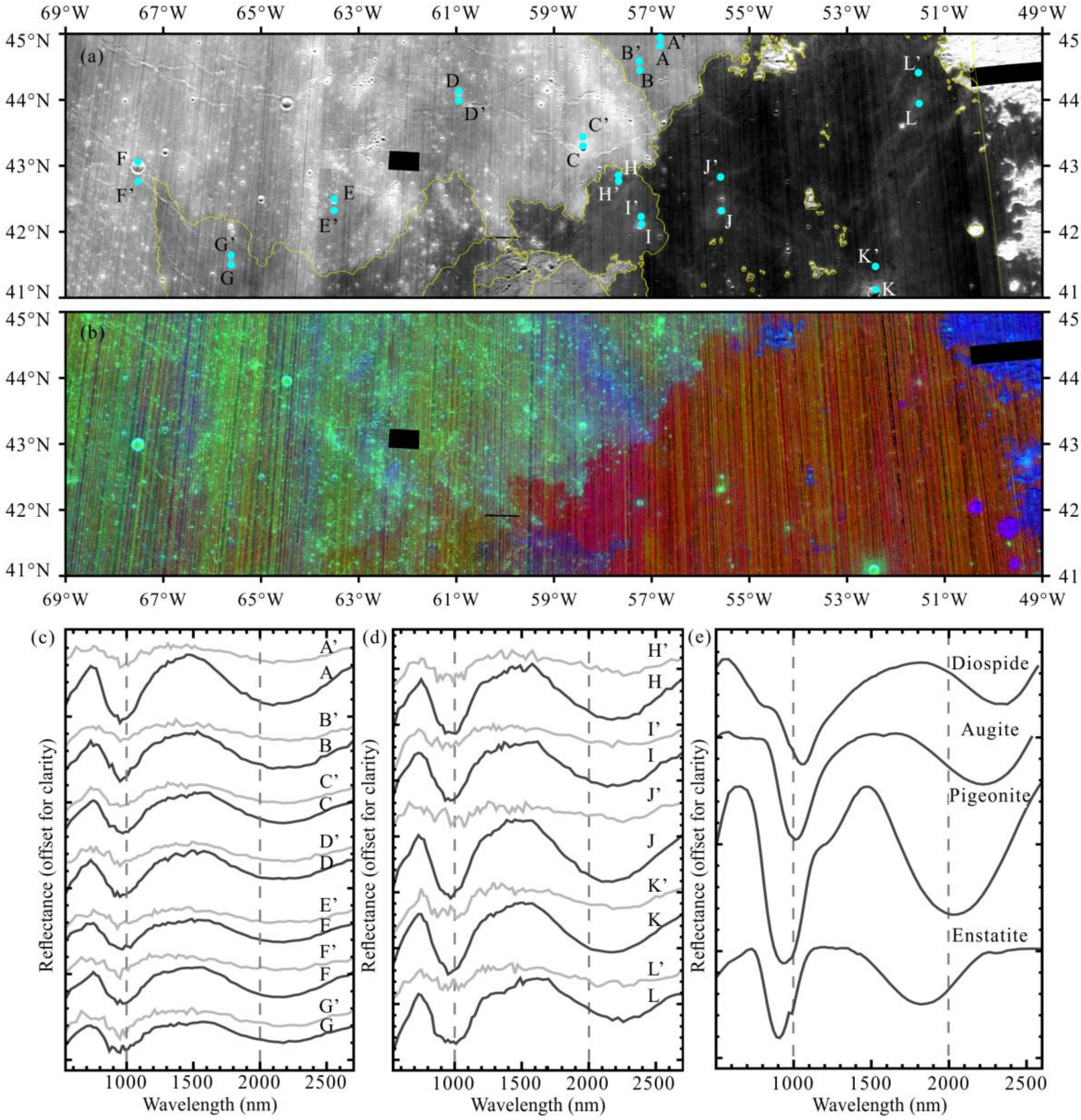

Figure 10. M^3 spectral analysis of the Rümker region. **(a)** M^3 2900 nm mosaic. **(b)** M^3 RGB composite of spectral parameters (R = 2 micron band center, stretched values: 2000-2500 nm; G = 2 micron band depth, stretched values: 0.04-0.13; B = reflectance at 1580 nm, stretched values: 0.085-0.15). **(c)** M^3 continuum-removed 3×3 pixel average spectra (using methods of Martinot et al., 2018) of selected impact craters (A through G) and of nearby maria (A' through G') within the western maria (see positions on Fig. 10a). **(d)** M^3 continuum-removed 3×3 pixel average spectra of selected impact craters (H through L) and of the nearby maria (H' through L') within the eastern mare (see positions on Fig. 10a). **(e)** RELAB database pyroxene spectra processed using the method of Martinot et al. (2018) (respective samples RELAB-ID: PD-CMP-006, AG-TJM-010, DL-CMP-008, and DH-MBW-005 for diopside, augite, pigeonite, and enstatite).

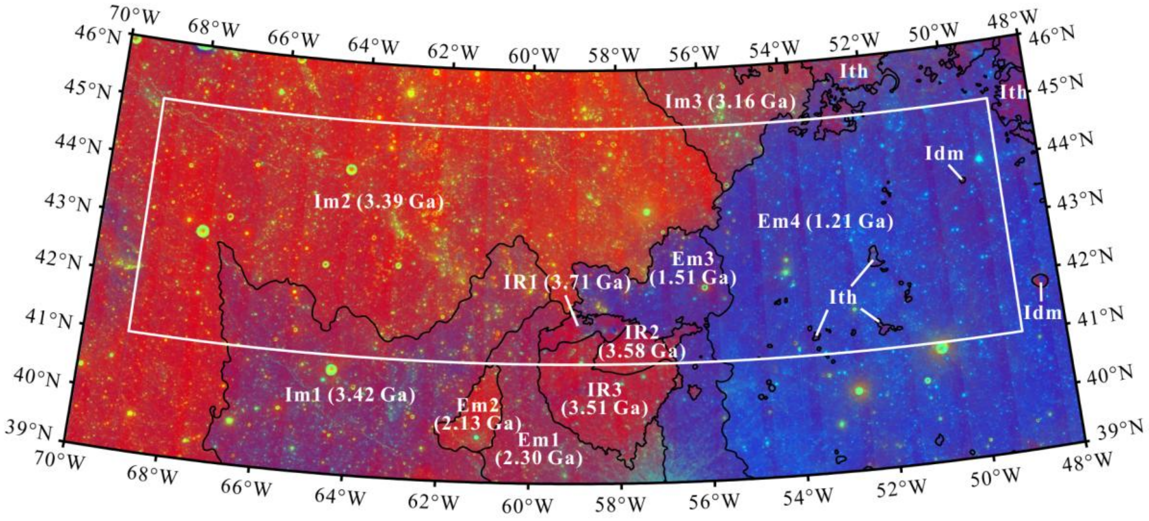

Figure 11. Geologic units of the Rümker region. The black lines denote the geological boundaries. The white box denotes the CE5 landing region. Im1, Im2, and Im3 are Imbrian-aged mare units. Em1, Em2, Em3, and Em4 are Eratosthenian-aged mare units. IR1, IR2, and IR3 are Rümker plateau units. Ith is a highland unit. Idm is an Imbrian-aged dome unit.

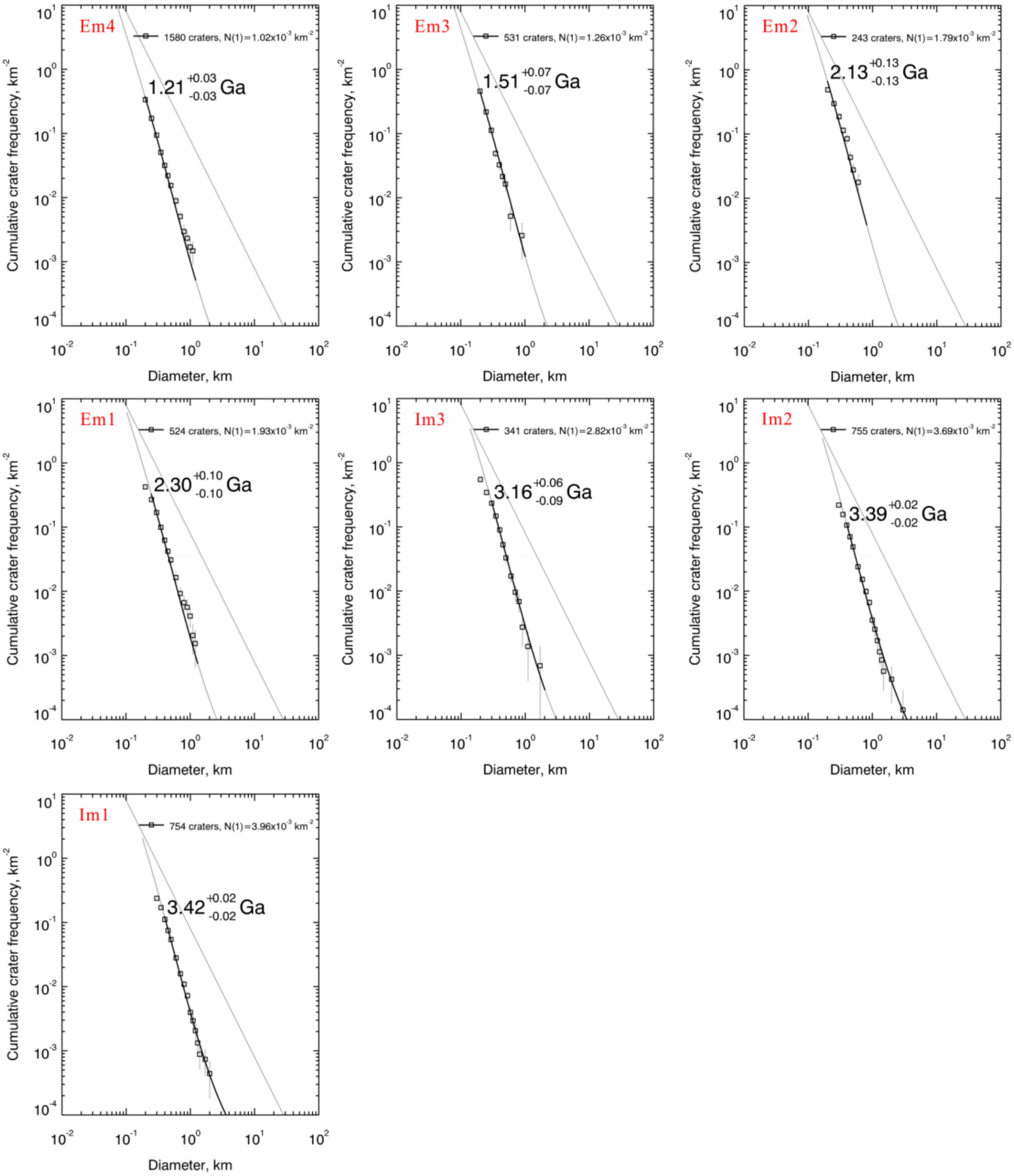

Figure 12. Cumulative crater frequency plots and absolute model ages of the mare units analyzed. See Table 1 for details. The lunar production function and the chronology function are given by Neukum et al. (2001).

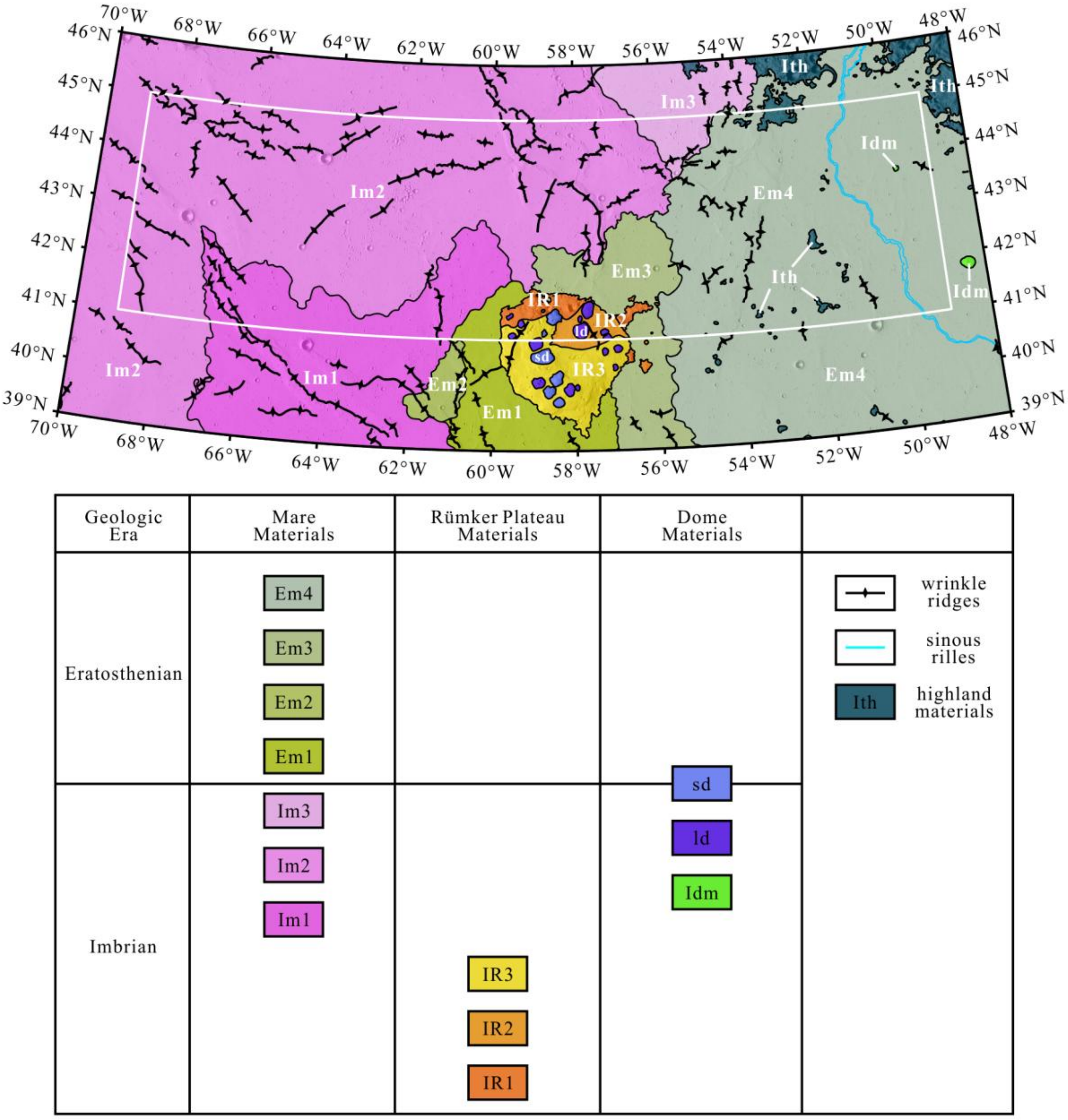

Figure 13. Geologic map of the Rümker region in northern Oceanus Procellarum.

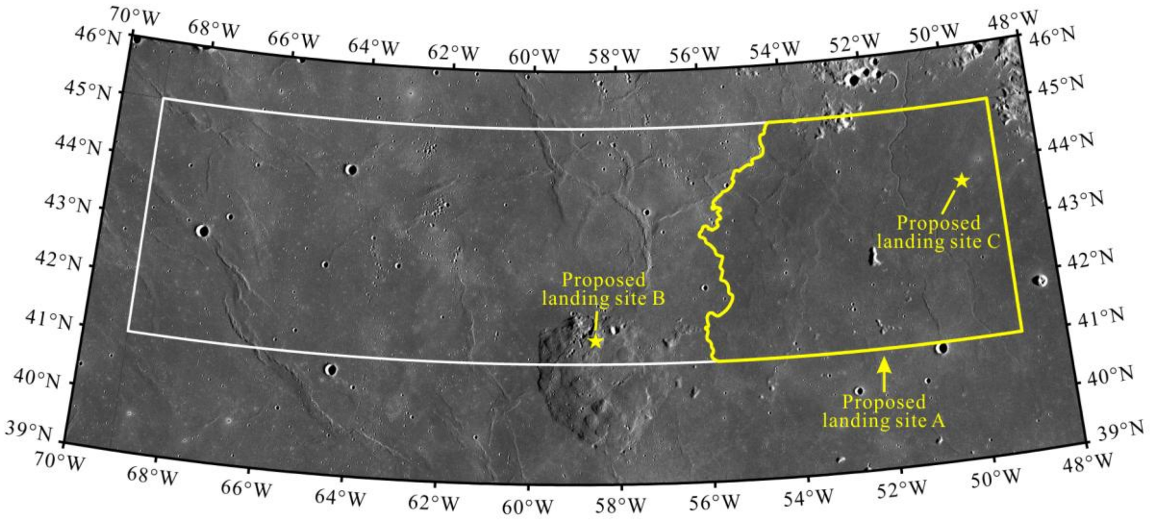

Figure 14. The location of proposed landing sites in this study. Landing site A indicates the region of the Em4 mare unit.