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Geological features and evolution history of Sinus Iridum, the Moon

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ABSTRACT

The Sinus Iridum region is one of the important candidate landing areas for the future Chinese lunar robotic and human missions. Considering its flat topography, abundant geomorphic features and complex evolutionary history, this region shows great significance to both lunar science and landing exploration, including powered descent, surface trafficability and in-situ exploration. First, we use Lunar Reconnaissance Orbiter (LRO) Altimeter (LOLA) and Camera (LROC) data to characterize regional topographic and geomorphological features within Sinus Iridum, e.g., wrinkle ridges and sinuous rilles. Then, we deduce the iron and titanium content for the mare surface using the Clementine ultraviolet–visible (UVVIS) data and generate mineral absorption features using the Chandrayaan-1 Moon Mineralogy Mapper (M^3) spectrometer data. Later, we date the mare surface using crater size-frequency distribution (CSFD) method. CSFD measurements show that this region has experienced four major lava infilling events with model ages ranging from 3.32 Ga to 2.50 Ga. The regional magmatic activities evolved from Imbrian-aged low-titanium to Eratosthenian-aged medium-titanium. The inner Sinus Iridum is mainly composed of pyroxene-rich basalts with olivine abundance increasing with time, while the surrounding highlands have a feldspar-dominated composition. In the northern wall of Sinus Iridum, some potential olivine-rich materials directly excavated from the lunar mantle are visible. The Sinus Iridum region is an ideal target for future landing exploration, we propose two candidate landing sites for the future Chinese robotic and human missions.

1. Introduction

Sinus Iridum is a flat mare region located to the northwest Mare Imbrium on the nearside of the Moon. Considering its flat topography, Sinus Iridum has been selected as one of the important candidate landing areas for the future Chinese robotic and human exploration missions, e.g., Chang'E-5 lunar sample return mission (Qiu and Stone, 2013). Previous studies suggested this region had experienced complex evolutionary history because of the abundant geomorphic features on the surface, including wrinkle ridges, sinuous rilles, impact craters and crater chains, making this region attractive for lunar geology research (e.g., Chen et al., 2010; Gong and Jin, 2012; Huang et al., 2010; Schaber, 1969; Zou, 2011).

The Montes Jura (Fig. 1) surrounding the Sinus Iridum was likely formed by accumulating of ejecta from the Sinus Iridum impact (e.g., Schaber, 1969). The numerous small craters scattered in the inner Sinus Iridum were mainly results of impact activities after the magmatic activities ceased, including both primary and secondary impacts. While the wrinkle ridges present in the connecting region of Sinus Iridum and Mare Imbrium are generally considered to be tectonic landforms which originated from basin-localized folding and faulting over thrust faults (e.g., Maxwell, 1978; Golombek et al., 1991; Watters, 2004). The sinuous rilles distributed in the mare region are thought to be formed by magmatic activities, but the exact formation model is still debated (e.g., Carr, 1974; Hulme, 1973; Hurwitz et al., 2012; Williams et al., 2000). The low spatial resolution of earlier topographic and imagery data prevented the high-resolution quantitative descriptions (sub-meter scale) of these sinuous rilles, which are essential for exploration of their formation. Wilson and Head (1981) developed mathematical models for thermal erosion origin for sinuous rilles and placed constraints on the eruption rates needed to form the rilles. Siewert and Ferlito (2008) investigated the 2001 eruption on Mount Etna, and developed a model for the mechanical erosion origin for the observed sinuous rilles. While Spudis et al. (1988) combined the studies of terrestrial lava tube systems and detailed site geology of the Apollo 15 areas, and proposed that the Hadley Rille was primary constructional features that developed along preexisting structural depressions without substantial thermal or mechanical erosion.

Schaber (1969) concluded that the Sinus Iridum was formed by a large impact after the Imbrium impact which formed the Imbrium basin. Massive ejecta accumulated around the Iridum crater, forming the present Montes Jura. Crater rim and precratering materials slumped into the crater shaping the crater

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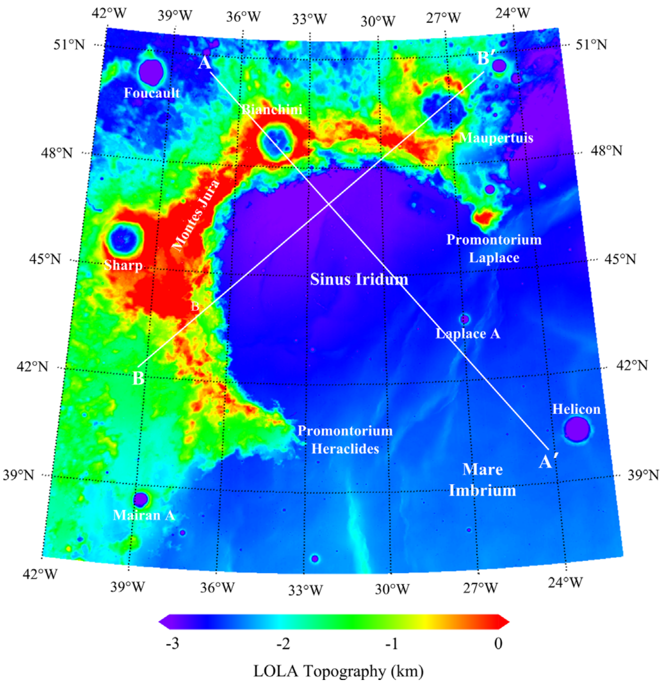

Fig. 1. LOLA topographic data for the Sinus Iridum and surrounding areas. Some key geographic features are labeled with their names, e.g., Montes Jura and Promontorium Laplace. The white solid lines show the location of elevation profiles derived from LOLA topography (Fig. 2). The map projection is Lambert conformal projection, the standard parallels are 42°N and 47°N, and the central meridian is 32°W, up is the north.

wall as steep as we observe now. Filling of basalts in the Sinus Iridum and northwestern Imbrium basin was another major event after the deposition of Iridum impact ejecta. Large amount of basalt flows covered not only the initial crater floor, but also the southeastern part of the primitive Montes Jura and the inner ring of the Imbrium basin. The thickness of mare basalts in the Sinus Iridum was estimated to be about 500 m using the relationship between craters' diameter and depth (Thomson et al., 2009).

This region has experienced several episodes of magmatic activity, indicating a complex and multi-stage evolutionary history. However, due to the limited resolution of imagery data predating Lunar Reconnaissance Orbiter Camera (LROC) images, previous research showed some inconsistency about the geographic extent and time range of these multiple magma filling events. Hiesinger et al. (2000) separated the mare basalts of Sinus Iridum region into four spectral homogeneous units based on the Galileo Earth/Moon Encounter 2 (EM2) multispectral imagery data, and determined the surface age for these units as 3.39–2.96 Ga. Although the Hiesinger et al. (2000) dating results were consistent with the stratigraphic classification described in Schaber (1969), these two studies showed inconsistency of the geographic extent of these multiple magmatic activities. Based on Clementine UVVIS multispectral imaging data, iron and titanium content maps, Bugiolacchi and Guest (2008) divided the inner Sinus Iridum into three units, and calculated surface age of the three units as 3.31 Ga, 2.42 Ga and 2.22 Ga, respectively. The ages derived by Bugiolacchi and Guest (2008) were smaller than that of Hiesinger et al. (2000), especially for the northeastern and midwestern parts. Besides, due to the lack of orbiter hyperspectral data and corresponding analyzing methods, few previous studies had addressed the mineralogical variations of basalts within the Sinus Iridum, which are very important for constraining the compositional properties of magmatic activities in different geological period in this region.

Re-investigation of the geological features and the associated evolutionary history, especially the magmatic activities in the Sinus Iridum, with newly obtained remote sensing data could improve our understanding of the geologic facts in this region and provide additional scientific preparation for the future Chinese missions. Here we systematically study the topographic, compositional, stratigraphic and geological features in Sinus Iridum using new data, i.e., Lunar Reconnaissance Orbiter Altimeter (LOLA) and Camera (LROC), SELENE Terrain Camera (TC), Clementine ultraviolet–visible (UVVIS), and Chandrayaan-1 Moon Mineralogy Mapper (M^3) data. We discuss regional geological and magmatic evolution history, geochemical characteristics of mare basalts in Sinus Iridum, origin of olivine-rich rocks in this region, and propose two specific candidate landing sites for the future Chinese robotic and human exploration missions.

2. Regional geological setting

The Sinus Iridum region is centered at 45.01°N, 31.67°W. It has a diameter of 249 km (based on LOLA 2011 control network). The Sinus Iridum is surrounded by the Montes Jura from northeast to southwest (counterclockwise) and connects with Mare Imbrium by Promontorium Laplace at the northeastern cape and Promontorium Heraclides at the southwestern cape. Three large craters, i.e., Sharp, Bianchini and Maupertuis, are distributed in the northern and western highlands. The largest crater within the mare surface area of Sinus Iridum is the Laplace A crater (43.74°N,26.93°W, $D = 8$ km, Fig. 1).

Previous research of Sinus Iridum mainly focused on the stratigraphy of mare basalts in this region. Schaber (1969) performed the earliest geologic mapping for the mare basalts based on the superposition and cross-cutting relations of the basalts using the Lunar Orbiter IV (90 m/pixel) and Lunar Orbiter V (7 m/pixel) photographs. Schaber (1969) divided the mare basalts within Sinus Iridum into three geological units, i.e., Im1, Im2 and EIm, in order of relative age from old to young. The Im1 and Im2 are later Imbrian stratigraphic unit, and the EIm is Eratosthenian and/or Imbrian stratigraphic unit and has a principal composition of mafic flows and/or ignimbrite deposits. Thus, stratigraphy analysis results indicated multiple magma filling events in Sinus Iridum with a time range from later Imbrian age to Eratosthenian age. The youngest units are small craters scattered on the surface of mare materials, including craters aged in Eratosthenian (unit Ec series) and Copernian (unit Cc series). There are also some large ray patches units and secondary impact crater chains (unit Ccsc), probably formed by ejecta from large crater of Copernian age, e.g., Copernicus, Aristillus and Aristarchus (Schaber, 1969).

Long-term magmatic activities, later tectonic movements and massive impact events had formed abundant geomorphic features within the Sinus Iridum, including sinuous rilles, wrinkle ridges, small craters and crater chains. Sinuous rilles mainly occur at the border between mare areas and the foot of Montes Jura, and they can be ~70 km long. Wrinkle ridges that have different morphologies are widely distributed within Sinus Iridum, especially in the joint region between Sinus Iridum and Mare Imbrium. Several wrinkle ridges are closely intertwined, and the can be ~200 km long. Impact craters in Sinus Iridum are all small bowl-shaped, with relatively simple structures and no central peaks.

3. Data and methods

3.1. Morphology analyses

To study the geomorphology of typical geomorphic features and proposed landing sites for the future Chinese missions, we used multiple imaging data sets, including those from the LROC Wide Angle Camera (WAC, 100 m/pixel), Narrow Angle Camera (NAC, 0.5–2 m/pixel), and the SELENE TC (~10 m/pixel)