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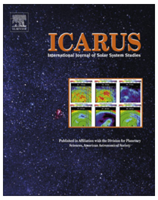

Constraint on subsurface structures beneath Reiner Gamma on the Moon using the Kaguya Lunar Radar Sounder

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ABSTRACT

Reiner Gamma is a sinuous feature in Oceanus Procellarum; it has a higher reflectance of the visible wavelength than the surrounding flat mare basalt, and displays a high crustal magnetic field. Previous studies relating to the origin of Reiner Gamma have provided contradictory depths of magnetic source bodies in the lunar crust as either shallow or deep. If a shallow ejecta layer existed beneath the Reiner Gamma formation, a subsurface lithological boundary between the denser mare basalt and the less dense ejecta blanket would be expected. This study examines subsurface stratifications using the Lunar Radar Sounder (LRS) onboard the Kaguya spacecraft. Taking into account the LRS-determined dielectric constants, the influence of surface clutter, and the energy loss of the LRS radar pulses in the high frequency band (5 MHz), no evidence was found of subsurface boundaries down to a depth of 1000-m at Reiner Gamma. Given the LRS range resolution of 75-m, the source of the magnetic anomaly is considered to be either strongly magnetized thin breccia layers at depths shallower than 75-m, or less magnetized thick layers at depths deeper than 1000-m.

1. Introduction

It is acknowledged that although the Moon has no global magnetic field it has strong crustal magnetic anomalies (Richmond and Hood, 2008; Mitchell et al., 2008; Tsunakawa et al., 2010), the origin of which is a topic of long-standing debate in lunar science (Hood 1987; Hood and Artemieva, 2008; Dwyer et al., 2011; Le Bars et al., 2011; Shea et al., 2012; Wieczorek et al., 2012). Reiner Gamma is an enigmatic feature on a flat surface that is associated with one of the strongest magnetic anomalies on the Moon. It is located at approximately 7.5°N 301.5°E, and measures about 70-km long within Oceanus Procellarum in a region of flat basaltic lava flows. Its alignment is nearly radial to the center of the Imbrium basin (Hood et al., 2001), suggesting the source may be of Imbrium ejecta deposits. From a shadow analysis, Hood (1980) suggested the probable maximum thickness of the ejecta to be 100-m for Reiner Gamma. From a distance 1000-km away from the crater center of the Imbrium-like basin, and using the three-dimensional hydrocode SOVA (Shuvalov, 1999) simulation, Hood and Artemieva (2008) suggested that the ejecta thickness measures several hundreds of meters (300–1000-m). However, Wieczorek et al. (2012) estimated that an ejecta thickness of several hundred meters to a few kilometers would be required to generate a 10-nT magnetic anomaly 30-km above the lunar surface, if the projectiles were similar to chondritic meteorites. In the case of the Orientale basin, the impact ejecta layers are horizontal deposits, and their thickness in flat regions measures less than about 1000-m (Fassett et al., 2011). Nicholas et al. (2007) determined that an ejecta layer would require magnetizations of 1 A/m if it measured 1000-m in thickness, or 10 A/m if it had a thickness of 100-m. Since the maximum remanence intensities of returned lunar materials measure up to 1 A/m, it is important to determine if the ejecta layer has a thickness of 1000-m to constrain whether the remanence intensities of Apollo-returned materials are usual.

Hemingway and Garrick-Bethell (2012) modeled the same part of the anomaly as a grid of 208 dipoles buried 1600-m below the surface, with a magnetic moment of 1.4×10^{13} A m^2, to reproduce the swirl morphology. However, Kurata et al. (2005) calculated the south western part of the Reiner Gamma anomaly as a single dipole buried about 11.1-km below the surface, with a magnetic moment of 1.1×10^{13} A m^2, based on a point-source analysis of magnetic field data from the Lunar Prospector. These determinations of the source depth by magnetic inversion calculations show an order-of-magnitude difference for the same magnetic anomaly

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region, suggesting ambiguity in the thickness estimation for the source depth. Therefore, an alternative constraint from subsurface structures would be considered useful to model the source depth beneath the Reiner Gamma, and in this study we thus apply the KAGUYA Lunar Radar Sounder technology to assess the anomaly source.

The penetration depth of electromagnetic radar waves depends on their wavelength (frequency), in addition to the dielectric constant and the loss tangent of the rocks being investigated (Guéguen and Palciauskas, 1994; Takahara et al., 2010). Waves with longer wavelengths have larger penetration depths; for example, penetration depths of several thousand meters are possible at a wavelength of 60-m (5 MHz), but no more than a few meters can be achieved at a wavelength of 12.6-cm (2.38 GHz: S-band). The radar wave is backscattered at the surface as the nadir surface echo, and as reflected echoes from boundaries between underground strata at different depths if the lunar surface consists of relative smooth regions. The surface roughness, dielectric constant, and loss tangent (radar energy dissipation) of the lunar materials are important parameters influencing the possible depth of investigation.

There are a large number of magnetic anomalies on the Moon, some of which are stronger than that of Reiner Gamma (Blewett et al., 2011), and a comprehensive test for the origin of the anomalies is required. However, as the Lunar Radar Sounder (LRS) is unable to detect subsurface layering beneath rough surfaces, such as anomalies on lunar Highlands, this study focuses on lunar magnetic anomalies on relatively smoothed mare regions. Although the Apollo 17 Lunar Sounder Experiment was the first radar experiment on the Moon to use the HF band to reveal the presence of subsurface layers over Mare Crisium and Serenitatis (Phillips et al., 1973; Peeples et al., 1978), no observations were carried out in the Reiner Gamma regions. It is also of note that the Lunar Reconnaissance Orbiter S-band Mini-RF synthetic aperture radar (SAR), penetrating to depths of several meters, provided the first radar observations of lunar swirls, and found no evidence for bulk compositional differences between swirl and non-swirl regions (Neish et al., 2011). In this paper therefore, we explore the presence or absence of subsurface lithological boundary layers for Reiner Gamma at depths shallower than 1000-m, as the LRS prefers a flat surface to image subsurface structures. Data were obtained by the Lunar Radar Sounder (LRS) high frequency (HF; 5 MHz) radar onboard the Kaguya spacecraft.

The LRS is able to detect reflected echoes from subsurface boundaries between materials that have different dielectric constants. Kiefer et al. (2012) updated the comprehensive density database for lunar mare basalt with values of 3010–3270 kg/m^3 and Imbrium ejecta (the Fra Mauro Formation) as 2360–2520 kg/m^3. The density difference generates a dielectric contrast between the two materials, in accordance with the strong correlation between the dielectric constant and the density of lunar materials (Olhoeft and Strangway 1975), such as $\varepsilon = 5.0 \pm 1.1$ for ejecta and $\varepsilon = 8.0 \pm 2.2$ for mare basalt. However, the radar of the LRS HF band is not able to image subsurface stratifications beneath nearside Maria that lie deeper than 1000-m (Ono et al., 2009). However, using the above values, ejecta blankets that lie on, or between, basalt layers are detectable by LRS observations.

2. LRS and lunar compositional data

The main purpose of the LRS is to perform radar sounding in order to clarify the evolution of the Moon, using an investigation of stratigraphic and tectonic lunar subsurface features (Ono et al., 2010). The raw echo power data used in the A-scope display (a plot of signal amplitude versus depth) was obtained from the JAXA-SELENE data archive at https://www.soac.selene.isas.jaxa.jp/archive/. The LRS uses electromagnetic waves in the HF band (5 MHz), and the vertical resolution of the LRS is 75-m in vacuum (Ono and Oya, 2000; Ono et al., 2008a,b). To obtain a clear identification of subsurface echoes, we also utilized the synthetic aperture radar (SAR) technique for subsurface images provided by Kobayashi et al. (2011). The SAR processes carry out a correlation analysis between the observed and calculated waveforms of echoes from subsurface targets at given locations, thus reducing the intensity of hyperbola patterns associated with surface clutter and off-nadir sources, and enhancing the intensity of coherent echoes.

Although SAR processing of LRS radar echoes reduces the intensity of random clutter components, it is still necessary to determine the influence of small-scale surface roughness. In the present study, the surface clutter level is calculated from the surface roughness using a method based on Bruzzone et al. (2011). For the roughness parameters in Reiner Gamma, we assumed a Hurst exponent of 0.5, and a root mean square (RMS) slope of 5 degrees for a baseline of 17-m, based on Rosenburg et al. (2011).

Given the large relative dielectric constant of the titanium-bearing phase, it could be expected that the LRS HF radio waves would be strongly absorbed by ilmenite ($FeTiO_3$) present in the rocks (e.g., Fa and Wieczorek, 2012). Ilmenite is one of the common opaque minerals existing within mare basalt and the ejecta blanket. Zheng et al. (2005) showed that the real part of the dielectric constant and the loss tangent for ilmenite are both of an order of magnitude greater than those for other common lunar minerals. To estimate the radar penetration depth beneath the magnetic anomaly regions, we used the iron and titanium content map for the Moon released by the Lunar and Planetary Institute Clementine Mapping Project (http://www.lpi.usra.edu/lunar/tools/clementine/). Furthermore, we adopted the method reported by Lucey et al. (2000) to evaluate the representative FeO and TiO_2 contents at the surface of Reiner Gamma.

3. Results

Fig. 1 shows six of the LRS ground tracks over Reiner Gamma. The star mark indicates the location of the representative FeO and TiO_2 contents at the surface of Reiner Gamma, based on Clementine multiband spectroscopic data; spectroscopic measurements determined the FeO and TiO_2 contents as 16.45 and 3.80 wt%, respectively. Fig. 2 is a radargram that shows cross sections obtained from the LRS (depth versus latitude) of subsurface features beneath Reiner Gamma (a)–(f), and Mare Imbrium (g). SAR processing with a single (vacuum) medium model (Kobayashi

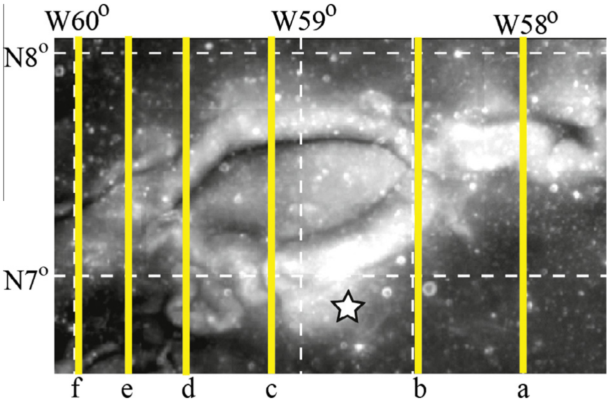

Fig. 1. Six LRS ground tracks over Reiner Gamma. Six yellow lines are subsurface cross sections shown in Fig. 2. The background image around Reiner Gamma was obtained as grayscale image from the Map-a-Planet website (http://www.mapaplanet.org/explorer/moon.html). The star mark represents the locality at which the spectroscopic measurements of iron and titanium contents were made. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)