Icarus 243 (2014) 48–57

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Subsurface structures of large volcanic complexes on the nearside of the Moon: A view from GRAIL gravity

Qian Huang *, Zhiyong Xiao, Long Xiao

Planetary Science Institute, School of Earth Sciences, China University of Geosciences, Wuhan, Hubei, China

ARTICLE INFO

Article history:
Received 28 March 2014
Revised 22 August 2014
Accepted 3 September 2014
Available online 16 September 2014

Keywords:
Moon
Geophysics
Volcanism
Interiors

ABSTRACT

The lunar nearside large volcanic complexes, such as the Rümker Hills, Aristarchus Plateau, and Marius Hills are likely sites of intense and sustained magmatic activity. These volcanic complexes, recently proposed to be shield volcanoes, are generally located at regionally high elevations and some feature relatively well-localized positive gravity anomalies. Applying localized spectral analyses on high-resolution gravity data obtained from the Gravity Recovery and Interior Laboratory (GRAIL) mission and topography data returned from the Lunar Reconnaissance Orbiter (LRO) spacecraft, we study the subsurface structures of these volcanic complexes. The gravity signal is predicted using a thin elastic lithospheric model that considers both surface and subsurface loads. Best-fit crustal and load densities show that the topographic highs of Rümker Hills, Marius Hills, Gardner and Kepler are mainly composed of material that has a density of more than 2850 kg m^{-3}, which is consistent with that of emplaced igneous rocks. Both the Aristarchus Plateau and Hortensius have relatively lower crustal and surface load densities, with mean values around 2550 kg m^{-3}, which are well consistent with the average bulk density of the lunar highland crust. These results, together with evidence of multiple volcanic edifices on the surface, suggest that the shallow crusts of the Rümker Hills, Marius Hills, Gardner and Kepler are mainly composed of dense intrusive/extrusive magmatic units, and those of the Aristarchus Plateau and Hortensius are mainly composed of low density materials with only small amounts of superimposed volcanic material. To further constrain the subsurface structures beneath these volcanic complexes, we analyze the Bouguer gravity anomalies for these regions. Results show that dense materials that might be solidified intrusions exist beneath Rümker Hills, Marius Hills, Gardner and Prinz, but no substantial dense materials have been detected beneath the Aristarchus Plateau, Hortensius, Kepler or Cauchy. The different subsurface structures among these large volcanic complexes suggest that the volcanism style at the lunar nearside is different from each other, even for those formed at the same geological time.

1. Introduction

Large volcanic complexes on the lunar nearside are topographic prominences that have a high concentration of various volcanic features on the surface, such as domes, pit craters, cones and rilles (Guest and Murray, 1976; Whitford-Stark and Head, 1977; Wilhelms, 1987). These regions are likely sites of intense and sustained magmatic activity that occurred during the main phase of marse volcanism on the lunar nearside (e.g., Head, 1976; Whitford-stark and Head, 1977, 1980). They open an important window on studying the thermal evolutionary history of the lunar nearside crust and mantle. Previous studies on these regions mostly focused on their surface morphological and geochemical characteristics using imagery and reflectance spectral data (e.g., Whitford-Stark and Head, 1977; Head and Gifford, 1980; McEwen et al., 1994; Weitz and Head, 1999; Gaddis et al., 2003; Wöhler et al., 2006; Hagerty et al., 2009; Chevrel et al., 2009; Campbell et al., 2009; Mustard et al., 2011; Besse et al., 2011; Lawrence et al., 2013). However, little work has been performed to resolve their subsurface or interior structures, which are important on deciphering their formation mechanisms (e.g., Head and Wilson, 1991, 1992; Wöhler et al., 2006, 2007; Kiefer, 2013).

Using recently obtained high-resolution imagery and topographic data, Spudis et al. (2013) recognized eight large volcanic complexes on the nearside of the Moon and argued that these features were large shield volcanoes equivalent to those on Mars, Earth and Venus. These complexes are Rümker Hills (Rumker, ~70 km in diameter, centered at 301°E, 40°N), Aristarchus Plateau

* Corresponding author at: Planetary Science Institute, School of Earth Sciences, China University of Geosciences, 388 Lumo Road, Wuhan, Hubei 430074, China.
E-mail address: qianhuang@cug.edu.cn (Q. Huang).

http://dx.doi.org/10.1016/j.icarus.2014.09.009
0019-1035/

(Aristarchus, ~240 km; 310°E, 25.4°N), Marius Hills (~330 km; 308°E, 14°N), Prinz (~150 km; 317°E, 26°N), Kepler (~270 km; 322°E, 8°N), Hortensius (~300 km; 331°E, 13°N), Gardner (~70 km, 34.1°E, 16.1°N) and Cauchy (~560 km; 35°E, 8°N). Six of them are located within the Oceanus Procellarum and the remaining two are located in the eastern Mare Tranquillitatis (Fig. 1). All the volcanic complexes are peripheral to the large and deeply flooded Imbrium and Serenitatis basins at locations, suggesting a potential genetic relationship between these volcanic complexes and the impact basins (e.g., McGovern and Litherland, 2011). Morphological studies indicated a variety of developmental states of these volcanic complexes (Spudis et al., 2013), ranging from nearly completely developed shield (e.g., Marius Hills) to proto-shield built on highland block (e.g., Aristarchus). The main evidence for the argument that these complexes are large shield volcanos is that both their morphology and general topography are comparable with those observed on terrestrial planets (Spudis et al., 2013), but whether or not these complexes have comparable subsurface structures with those on terrestrial planets is not known. Here we do not take bias on whether or not these complexes are indeed shield volcanoes, but we concur that their existence is an important supplement for understanding the variety of volcanism on the Moon and also the evolution of mare volcanism on the lunar nearside (Spudis et al., 2013).

A key supplement to constrain the identity of these volcanic complexes is their subsurface structures, which are largely reflected by mass concentrations with depths. However, so far little subsurface evidence has been achieved on whether or not crystallized intrusive magma units occur beneath these volcanic complexes, and less constraints on their potential subsurface structures. Gravity and topography joint-analysis has long been proved to be an efficient method to study the subsurface and interior structures of a planet (for a review, see Wieczorek, 2007). This method has been successfully employed to resolve subsurface structures on Mars, especially for large martian shield volcanoes (e.g., McGovern et al., 2002; Kiefer, 2004; Belleguic et al., 2005; Grott and Wieczorek, 2012; Beuthe et al., 2012). For the eight lunar volcanic complexes discussed in Spudis et al. (2013), only the subsurface structures of Marius Hills (Kiefer, 2013) and Aristarchus Plateau (Huang et al., 2013) have recently been investigated using gravity data obtained from previous lunar missions.

Recently, the GRAIL mission has mapped the lunar gravity field with unprecedentedly high resolution, which is more than a factor of 4 times compared with any previous global gravity model (Zuber et al., 2013; Wieczorek et al., 2013). The up-to-date 660 degrees and orders gravity model has a spatial resolution better than 15 km (Konopliv et al., 2013; Lemoine et al., 2013), which is sufficient to distinguish the large volcanic complexes on the lunar nearside. Combining the new gravity and topographic data, we carry out localized spectral admittance analyses for the eight volcanic complexes studied by Spudis et al. (2013) to probe their subsurface structures (Fig. 1). The admittance spectra between gravity and topography are interpreted in terms of a thin elastic lithospheric model that considers both surface and subsurface loads. We investigate their crustal densities, volcanic load densities, elastic lithosphere thicknesses, as well as parameters that could identify the presence of potential subsurface loads. To further constrain the subsurface structures for these complexes, we then calculate the Bouguer gravity anomalies from the gravity and topography data. Our results show that the subsurface structures of these large volcanic complexes are different from each other, indicating a complicated intrusive and extrusive history of volcanism on the lunar nearside.

2. Data and methodology

2.1. Gravity and topography data

In this paper, we use the most recent gravity data returned from GRAIL (GL0660B, Konopliv et al., 2013) and topography data obtained by the Lunar Orbiter Laser Altimeter (LOLA; Smith et al., 2010) onboard the LRO spacecraft. The GL0660B is a 660 degrees and orders spherical harmonic model that shows unprecedented detail of the gravity field of the whole Moon. To avoid observational noises, we truncate the gravity model to harmonic degree at 330, which is the real observational resolution of the GRAIL

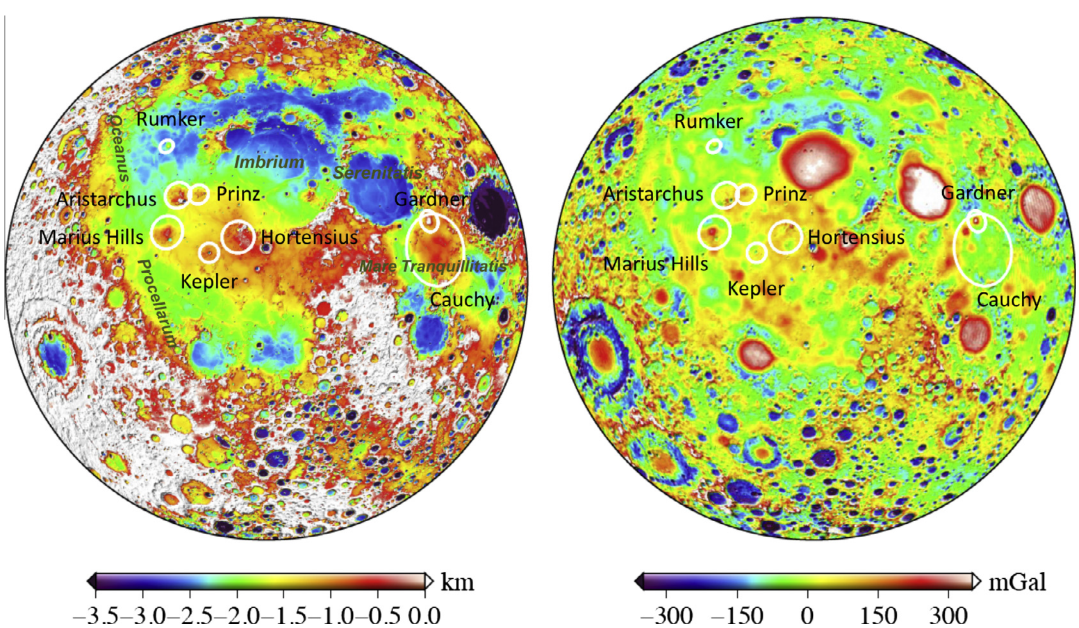

Fig. 1. Topography (Left) and gravity map (Right) of the lunar nearside. The topography is derived from the LOLA 720 model (lro_ltm04_720_sha.tab, http://pds-geosciences.wustl.edu/lro/lro-l-lola-3-rdr-v1/lrolol_1xxx/data/lola_shadr/) and the free-air gravity is from the newly released GL0660B gravity model (jggrx_0660b_sha.tab, http://pds-geosciences.wustl.edu/grail/grail-l-lgrs-5-rdr-v1/grail_1001/shadr/). Both models are truncated at spherical harmonic degree 330. The white circles indicate the locations of the eight large volcanic complexes studied here. Both panels are centered at 0°N, 340°E and are in Lambert Azimuthal Equal Area projections.