**RELEVANCE OF THE VOLCANO COMPLEXES IN THE WESTERN OCEANUS PROCELLARUM, MOON**

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**Introduction:** In western part of the Oceanus Procellarum of the lunar nearside, there are several large-scale volcanic complexes, in which volcanic geographycal features, e.g., domes, cones, lava flows and rilles, are highly concentrated. The volcanic activities of these areas are believed to play important roles in lunar evolution. The timing and duration of the volcanic activities are connected to the thermal state of the mantle. Thus, to better understand the lunar thermal history, it is very important to study the volcanisms of these areas.

The magmatism and volcanic eruption mechanisms of these volcanic complexes have been discussed from geophysical and geochemical perspectives using data sets acquired by lunar explorers. In these data sets, precise gravity field data obtained by Gravity Recovery and Interior Laboratory (GRAIL) gives information on mass anomalies below the lunar surface, useful for estimating the location and mass of the embedded magmas. Using GRAIL data, Andrews-Hanna et al. [1] prepared a gravity gradient map of the Moon. They discussed the origin of the large quasi-rectangular pattern of narrow linear gravity gradient anomalies located along the border of Oceanus Procellarum and suggested that the underlying dikes played important roles in the magma plumbing system.

In this study, GRAIL-derived lunar gravity field data is used to investigate the geophysical relevance of the four major volcanic complexes in the western Oceanus Procellarum, i.e., Rumker Hills, Aristarchus Plateau, Marius Hills, and Flamstead Basin. One of our concerns is whether the volcanisms of these complexes are caused by common factors or not.

We first estimate the mass and depth of the embedded magmas as well as the directions of the linear gravity anomalies. The results are interpreted by comparing with the chronological map of the lunar surface. Finally, we discuss whether the magmatism and volcanisms of these four volcanic complexes are related or not.

**Data Analysis:** *Estimation of Bouguer gravity anomaly.* The NASA GSFC lunar gravity field model from GRAIL and its extended mission (GRGM900C) [2] and the lunar topography model from the Lunar Reconnaissance Orbiter (MoonTopo2600pa.shape) [3] were used for estimating the Bouguer gravity anomaly of the Moon. Although the maximum degree/order in spherical harmonics of these models are 900 and 2600, respectively, we truncated them at degree and order 570, corresponding to a spatial resolution of about 9.5 km at the equator. The error of the gravity field over degree 570 is considered to be large because of low correlation with the topography. 2560 [kg/m$^3$] was used for the average density of the crust. The Bouguer gravity anomaly was calculated from the gravity field and topography models using SHTOOLS [4].

*Estimation of horizontal directive tendency of lunar Bouguer gravity anomaly.* The magnitude of the horizontal directive tendency (HDT), which is also known as the differential curvature, is useful for emphasizing the mass anomalies of shallower sources. HDT was calculated from the Bouguer gravity anomaly potential using the following equations [5].

$$HDT = \sqrt{(\Gamma_{xx} - \Gamma_{yy})^2 + (2\Gamma_{xy})^2} \qquad (1).$$

Here, $\Gamma_{xx}$, $\Gamma_{yy}$, and $\Gamma_{xy}$ are elements of the gravity gradient tensor (horizontal and vertical second derivative of the Bouguer anomaly potential).

*Estimating mass and depth of the embedded magma.* The subsurface load model developed by Kiefer [6] was used to estimate the mass and depth of the magma below each volcanic complex. In the model, magma is modeled as finite-thickness spherical caps with constant thickness and radially varying density. The parameters of mass and thickness were varied and the optimal mass and depth were estimated by forward calculation of the Bouguer gravity field.

**Results:** Figure 1 (a) depicts the Bouguer gravity anomaly map on and around the four volcanic complexes. As shown in the figure, although the locations of the volcanic complexes do not exactly correspond, (positive) gravity anomalies, which are expected to be embedded magmas, exist near each complex. Bottom ends of all of these anomalies are at the depth of some to several km, as a result of the mass and depth estimation.

On the other hand, although the locations of the anomalies are basically the same as the ones in Fig. 1 (a), finer structures are found in the HDT map (Fig. 1 (b)). As mentioned above, the HDT map emphasizes shallower mass anomalies than the gravity anomaly map. Thus, these fine anomaly structures are considered to reflect the distributions of shallower magma sources, which are supposed to largely affect the surface volcanic geographical features in the complexes.

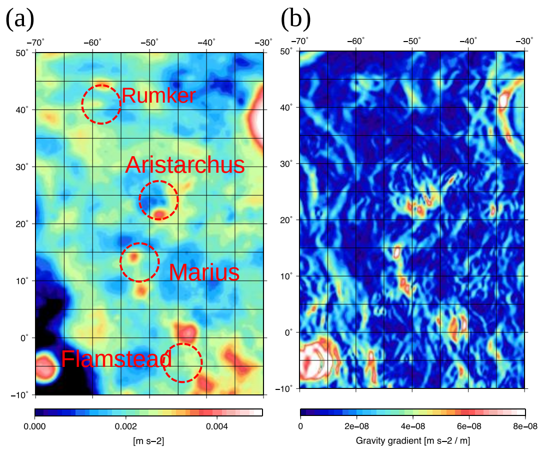


Fig. 1 (a) Bouguer gravity anomaly map of the west part of Oceannus Procellarum. Red dotted circles show the locations of the volcanic complexes in this study. (b) HDT map of the same region as (a).

Noteworthy in Fig. 1 (b) is the anomalies of the linear structure, which seem to linearly connect the magmas at Aristarchus Plateau, Marius Hills, and Flamstead Basin, while the magmas at Rumker Hills are independent of this.

**Discussion:** As with the large quasi-rectangular pattern revealed by Andrews-Hanna et al. [1], the observed linear structures in Fig. 1 (b) are considered to be initially created by cooling of lava, typically from the exposed surface of a lava lake or flood basalt flow [7, 8].

The linear structures lie inward of the quasi-rectangular pattern. These are not clearly observed in the Bouguer gravity anomaly map (Fig. 1 (a)), while the quasi-rectangular pattern is observed in both Figs. 1 (a) and (b). The linear structure is thus much shallower than the quasi-rectanguler pattern. Considering that, the quasi-rectangular pattern should have been created earlier than the linner inear structure. After the quasi-rectangular pattern was created, magma rose to the surface through the cracks [1]. The linear structure in Fig. 1 (b) is supposed to be created through cooling of the overflowed magma.

According to Morota et al. [9] and Besse et al. [10], the geological units, which the linear structures go through, are younger than that of the outer quasi-rectangular pattern. Therefore, these inward geological units are considered to be created by younger volcanism. The linear cracks created by cooling are weaker than other locations. Therefore, magma probably rose easier than in other area. That may be why the three currently observed volcano complexes (Aristarchus Plateau, Marius Hills and Flamstead Basin) lie on the same linear structure.

**References:** [1] J.C. Andrews-Hanna et al. (2014) *Nature*, *514*, 68-71. [2]F.G. Lemoine et al. (2014) *GRL*, *41*, 3382-3389. [3] M. Wieczorek (2013) http://www.ipgp.fr/~wieczor/SH/SH.html. [4] M. Wieczorek (2015) http://shtools.ipgp.fr/index.html. [5] A.H. Saad (2006) *The Leading Edge*, *8*, 942-949. [6] W.S. Kiefer (2013) *JGR*, *118*, 733-745. [7] L. Goehring (2008) *JGR*, *B113*, B10203. [8] L. Goehring (2013) *Phill. Trans. R. Soc. A*, *371*, 20120352. [9] T. Morota (2011) *EPSL*, *302*, 255-266. [10] S. Besse et al. (2011) *JGR*, *116*, E00G13.