MARE VOLCANISM: REINTERPRETATION BASED ON KAGUYA LUNAR RADAR SOUNDER DATA.

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Introduction: The secular change in the effusion rate of mare basalt is a clue to the thermal evolution of the Moon. Recently, the thicknesses of mare basalt units defined by previous lithofacies maps were indirectly estimated from Clementine multispectral data [1]. That is, the depth-diameter relationship of the craters fringed with ejecta from the underlying basaltic units placed the constraints for the estimation. However, this method is useful only in limited areas in Oceanus Procellarum and Mare Serenitatis.

At present, the geological structures in the lunar maria can be directly investigated using the observation data of the Lunar Radar Sounder (LRS) onboard Kaguya (SELENE), which detected echoes from layers at depths of several hundred meters [2-4]. LRS was a chirp radar using a wavelength of ~60 meters to detect echoes from subsurface discontinuities where the permittivity changes abruptly [5]. Subsurface layers were found in several nearside maria, consisting of about 9% of all lunar maria (0.6×10^6 km^2). The depths of the reflecting interfaces, as well as the parallelism with the surfaces of the maria, indicate that the reflectors are not the basements of the mare but interfaces between such mare basalts [2-4] that have sharp differences in FeO contents, which were identified by multiband images at the impact craters [6]. In addition, model calculations using the simplified radar equation indicate that the subsurface reflectors are not compositional interfaces but layer boundaries with a high-porosity contrast [6]. This result implies that the reflectors are regolith layers formed during the long interval between one series of mare volcanism and another. The dielectric constant of the regolith layer can be much less than that of the basalt rock layer due to its high porosity. Therefore the LRS data have great potential to determine a lava effusion volume (not a single flow volume) during a series of magmatism in lunar maria and its time dependence.

Comparison between the reflectors detected in the LRS data and surface age maps indicating formation age of each basalt unit [7-11] allows us to discuss the volume of each basalt unit and its space and time variation. This paper aims at evaluating lava eruption volume and rate, and its secular change in order to understand the characteristics of lunar volcanisms and constrain a thermal history of the Moon.

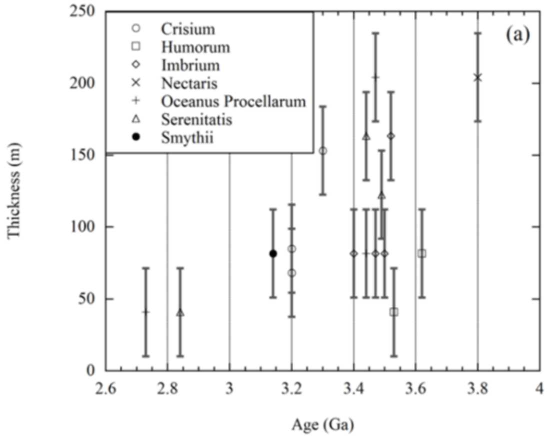
Approach: Thicknesses and volumes of mare basalt units are directly estimated from the LRS data in some cases. We relate the reflectors to previous studies' lithofacy maps [7-11] using the same technique as [2]. Thickness of a unit was obtained from the apparent thickness divided by a square root of the relative permittivity of the unit. The error of the apparent thickness is defined as the range resolution of the LRS data in vacuum, that is, 75 m, The relative permittivities of most of the geological units examined in this study are unknown. Since the common value of relative permittivity among the previous studies [e.g., 2, 12] is about six, we adopt six as an averaged relative permittivity of all basalt units. A unit volume is estimated by multiplying the representative thickness by the distribution area. We obtain the eruption rates on long-term average of mare basalts from the estimated unit volumes and the unit ages, that is, by dividing unit volumes by age difference between one unit and another closest to it in age according to the method used by [1].

Estimated unit thicknesses, volumes, and flow rate: The units examined in this study range in age from 2.7 to 3.8 Ga [7-11]. The estimated thicknesses were of the order of 10^1 to 10^2 m, and showed a positive correlation with their ages within the same mare basin (Figure 1a). The resolution of our estimation was limited by the range resolution of the LRS data. Previous studies of most sites indicated that the typical thicknesses of single basalt flows were about 10 m or less [e.g., 13] Accordingly, each geologic unit is made up of dozens of lava flows.

The volumes of the geologic units estimated in this study were of the order of 10^3 to 10^4 km^3, and showed a clear positive correlation with their ages within the same mare (Figure 1b). Namely, the older the units, the larger the volumes. Again, the resolution of our method was limited by the range resolution of the LRS data in a vacuum, that is, 75 m. This volume range is consistent with the total amount of erupted lava flows derived from numerical simulations of a thermal erosion model for lunar sinuous rilles formation [14]. The total volume for large sinuous rilles (about 50 km in length) is up to 1.2×10^3 km^3 [14]. The volume range derived from our study is comparable to the maximum known volume of individual flows in the Columbia River flood-basalt province (on the order of 3×10^3 km^3), for example [15]. On the other hand, the volumes of the geologic units vary among different maria in comparison with others within the same age range.

The eruption rate estimated from the unit volumes, indicating instantaneous flow rates of mare basalts but representing long-term average rates including dormant periods of magmatism, were of the order of 10^{-5} to 10^{-2} km^3/yr (Figure 1c). The flux of lava extrusion was not constant but peaked during the Imbrian period [16]. An average eruption rate in the lunar basins is estimated to be of the order of 10^{-2} km^3/yr by assuming steady emplacement throughout the late Imbrian [16]. Our study indicates large variations in the eruption rate during the late Imbrian and the average eruption rate in this period is estimated to be about an order of magnitude less than this value. That of the Eratosthenia is presumed to be of the order of 10^{-5} km^3/yr [16].

On the other hand, an instantaneous flow rate of a Mare Imbrium lava flow was calculated to have been 2×10^3 km^3/yr [17]. If the instantaneous eruption rate of the Mare Imbrium lava flow (~10^3 km^3/yr) is typical of values during the late Imbrian period in this mare, formation periods of each geologic unit are calculated to have been a few to more than a dozen years on the basis of the estimated unit volumes (Figure 1b). This result suggests that the quiescent intervals between lava extrusion events on Mare Imbrium during the late Imbrian period are extremely longer (10^7–10^8 years) than those between major eruptions of flood basalts on the Earth (10^3–10^4 years) [18] in spite of having the same range of single unit volumes (10^3–10^4 km^3). It was suggested that the heat flux on the Moon during the late Imbrian period is significantly lower than that on the Earth during the formation period of continental flood basalts (after the Paleozoic) [e.g., 19]. Therefore, such longer quiescent intervals possibly imply that an eruption mechanism and/or a formation mechanism of mare basalts on the Moon differ from those on the Earth.



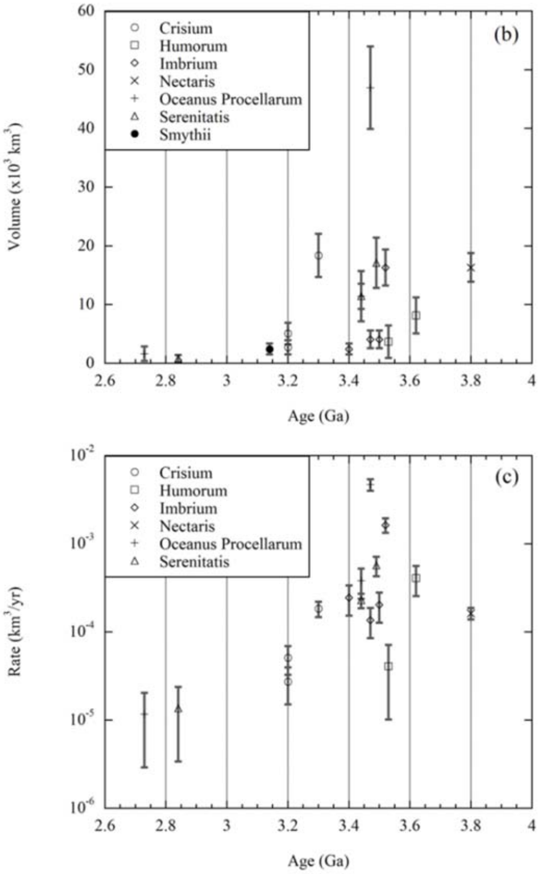


Figure 1. (a) Estimated thicknesses and (b) volumes of mare basalt units defined by previous studies [7-11]. (c) Average eruption rate of mare basalt estimated from (b). Estimated errors result from the range resolution of the LRS data (75 m in a vacuum).

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