Regional Variability in the Density of Lunar Mare Basalts and Implications for Lunar Gravity Modeling

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Introduction

Lunar gravity observations provide our primary tool for understanding lateral variability in the structure of the Moon's crust and mantle. Accurate gravity models require the use of densities and porosities for geologically appropriate compositions. Although many bulk density measurements were reported in the Apollo-era literature, they commonly had errors of 10% or more or had no reported uncertainty [1] and are not useful for geophysical modeling. A small number of samples were measured hydrostatically by immersion in toluene [e.g., 2]. However, toluene commonly failed to fully penetrate the pore space and the reported densities have errors of up to 5% [3]. Thus, there remains an important need for accurate measurements of density and porosity of lunar rocks. We analyze measurements of bulk density, grain density, and porosity for 7 mare basalts. The inclusion of 4 lunar meteorites makes the results more globally representative than for Apollo samples alone [4]. Our results show a strong dependence of density on composition, and we show how remote sensing observations can be used to estimate densities for mare units that have not been sampled. These results are an important new constraint for interpreting lunar gravity observations, such as from the GRAIL mission.

Methods

We measured both the bulk density, ρ_{bulk}, and the grain density, ρ_{grain} [5]. The bulk density is based on the entire volume of the sample, including any pore space. The grain density is based solely on the solid material, excluding the pore space. Bulk density is important for calculation of gravity anomalies, and grain density is used for studying systematic trends in density as a function of rock composition. Porosity is calculated as $P=1-(\rho_{bulk}/\rho_{grain})$. These measurements are fast, non-destructive and non-contaminating [6,7]. The bulk volume is measured by immersion in glass beads, approximating an Archimedean fluid. Grain volume is measured by helium pycnometry. Errors are determined by repeated measurements of each sample and are typically 10-20 kg m^{-3} (< 0.6%) for grain density provided that the sample mass exceeds 10 gm.

Results

The primary chemical classification applied to lunar mare basalts is low Ti versus high Ti, although even low Ti mare basalts are high in Ti by terrestrial basalt standards. Important secondary classifications include the amount of Mg, either as the MgO concentration or as Mg# (the molar ratio MgO/(MgO+FeO), and the abundance of Al [8,9]. All three of these geochemical factors are likely to be important to the overall grain density of basalts. Other chemical variations, such as low K versus high K, are unlikely to be important for density. We have studied mare basalts with a broad range of compositions (Figure 1).

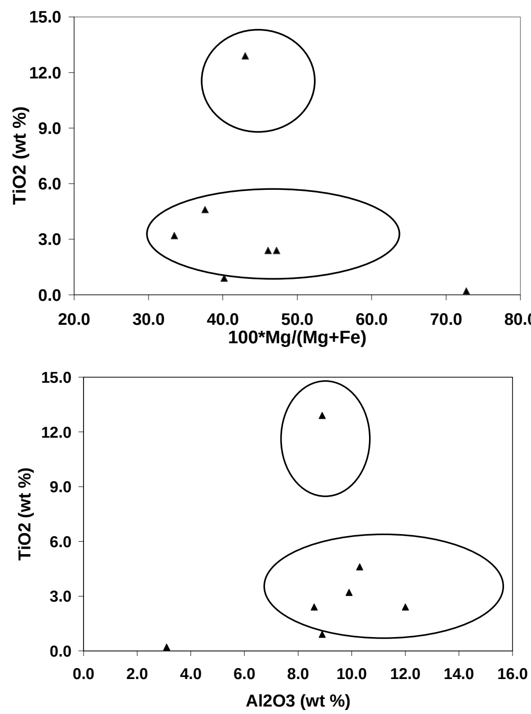

Figure 1: The chemical composition of the mare basalts in this study in terms of Mg#, TiO_2 abundance, and Al_2O_3 abundance. Ovals show the approximate range of compositions measured for mare basalts collected during the Apollo program [8].

Our results demonstrate a strong dependence of ρ_{grain} on chemical composition (Table 1). High Al basalt Northwest Africa (NWA) 4898 has a high abundance of Al_2O_3 and thus of the low-density mineral plagioclase [10], and has a grain density of only 3270 kg m^{-3}. The low Ti basalts in Table 1 [11-14] form a tight cluster with ρ_{grain}=3350 kg m^{-3}. High Ti basalt 70215 contains a high abundance of dense ilmenite (13%) and only 18% plagioclase [15], resulting in high ρ_{grain} of 3460 kg m^{-3}. Northwest Africa 2977, an olivine gabbro interpreted as a shallow cumulate, consists mainly of olivine and pyroxene with only about 10% plagioclase [16, 17] with a relatively high density of 3410 kg m^{-3}. All of the basalt densities in Table 1 are significantly larger than for terrestrial basalts, reflecting the much higher abundance of FeO in lunar basalts than in terrestrial basalts. Because of porosity, the bulk density is always less than the grain density, with measured values between 3010 and 3270 kg m^{-3}.

Mare basalts have a relatively simple mineralogy, dominated by plagioclase, pyroxene, olivine and ilmenite. It is therefore reasonable to consider if the grain density is controlled by just a few chemical components. Fe and Mg control the density of pyroxene and olivine, Al controls the abundance of low density plagioclase, and Ti controls the abundance of high density ilmenite. We have calculated least squares regressions between basalt grain densities from Table 1 and various choices of 1 and 2 chemical components, selected from Al_2O_3, FeO, MgO, and TiO_2. The best fit uses TiO_2 and Al_2O_3 (in weight %):

$$\rho_{grain} = 3470 + 10.8TiO_2 - 17.8Al_2O_3 \quad . (1)$$

This relationship has an RMS density misfit of 16 kg m^{-3}, which is comparable to the uncertainties in the measured grain densities, and it accounts for 92% of the total variance in the raw density data. The best single component fit is for Al_2O_3, which accounts for 39% of the data variance [3]. Recently acquired data on additional Apollo mare basalt samples [5] have not yet been incorporated into this analysis.

Basalt densities are important parameters in some lunar gravity models. For example, models of lunar mascons require removing the gravitational contribution of the mare in order to constrain the deeper crustal structure. Due to lack of data, prior mascon models were forced to assume a uniform density for all mare basalts [e.g., 18, 19]. However, the lunar mare have considerable regional variability in composition and presumably also in density. Constraints on the chemical composition of lunar basalts have been derived from a variety of observations, including the Clementine UV-VIS imager [20], the Lunar Prospector Gamma Ray Spectrometer (GRS)[21], and the Kaguya GRS [22]. These measurements refer to the top surface of the basalt, which are several km thick at the basin center. Averaging over the various ages and compositions of surface flows in a basin should reduce the scatter in the spectral data and provide a better average of the composition of the full volume. We are currently assessing the best combination of observations for estimating basalt densities. Preliminary results suggest that density variations of ~150 kg m^{-3} exist among the mare. Equation 1 provides grain densities, but bulk densities are needed for gravity models. Table 1 shows that a typical basalt porosity is ~7%, so we can take $\rho_{bulk} \approx 0.93\ \rho_{grain}$.

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Table 1: Mare Basalt Densities and Porosities

Sample	Mass (gm)	Rock Type	Bulk Density (kg m^{-3})	Grain Density (kg m^{-3})	Porosity (%)
12051,19	12.2	Low Ti Basalt	3270 ± 50	3320 ± 20	1.8 ± 1.7%
15555,62	33.0	Low Ti Basalt	3110 ± 30	3350 ± 10	7.1 ± 0.9%
70215,312	9.1	High Ti Basalt	3170 ± 80	3460 ± 50	8.3 ± 2.7%
LAP 02205,72	25.0	Low Ti Basalt	3010 ± 40	3350 ± 20	10.3 ± 1.4%
MIL 05035,51	9.3	Low Ti Basalt	3240 ± 100	3350 ± 50	3.4 ± 3.2%
NWA 2977	19.1	Olivine Gabbro	3130± 60	3410 ± 20	8.3 ± 1.9%
NWA 4898	19.1	High Al Basalt	3030 ± 40	3270 ± 10	7.2 ± 1.2%