Density and Porosity of Lunar Feldspathic Rocks 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 previously reported density and porosity results for 13 lunar samples covering a broad range of compositions [3]. Here, we analyze measurements of bulk density, grain density, and porosity for feldspathic highland rocks, including 3 Apollo samples and 21 lunar meteorites (4 of these samples were included in [3]). The inclusion of 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 can be combined with remote sensing observations to estimate densities for highland units that have not been sampled. These results are an important new constraint for interpreting lunar gravity observations, such as from the on-going GRAIL mission.

Methods

We measured both the bulk density, ρ_{bulk}, and the grain density, ρ_{grain} [5,6]. 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. 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 10-30 kg m^{-3} (< 0.9%) for grain density and 1-3% for porosity provided that the sample mass exceeds 10 gm.

Results

The upper part of the Moon's highland crust is composed predominantly of plagioclase, averaging 80 volume per cent, with a smaller amount of mafic minerals [7,8]. The mafic minerals have varying relative abundances of Mg and Fe. Differences between Apollo samples and lunar meteorites suggest the possibility of regional variability in Mg# [9] , which is the molar ratio of MgO/(MgO + FeO).

The samples reported here are all composed predominantly of calcium-rich plagioclase (anorthite), which we interpret as samples of the Moon's feldspathic highland crust. They vary in bulk composition between 22 and 35 weight percent Al_2O_3, with values between 26 and 30% being most common. These rocks are thus 60-95% anorthite, and by igneous classification are anorthosites, noritic anorthosites, and anorthositic norites [10]. The mafic content varies between 0.5 and 18.9 weight percent FeO+MgO, with Mg# between 44 and 80 [9, 11-16]. Rocks in the Moon's upper crust have experienced 4+ billion years of impact processing, and each of the samples we measured has experienced substantial post-igneous crystallization processing, such as brecciation, shock melting, thermal annealing, and addition of meteoritic material [14, 17-20]. We did not consider regolith breccias or meteorites that are mingled mixtures of feldspathic and basaltic material in this work, regardless of composition. We also did not consider samples that are interpreted to be ejecta units from large basins, such as the Fra Mauro Formation.

Grain density and porosity results are shown in Figure 1. Grain densities are a strong function of the abundance of mafic minerals, with the most plagioclase rich rocks, such as 60025, being the least dense and the most mafic rocks, such as 15418 and NWA 5744, being the densest. We are currently developing a model that predicts grain density from bulk composition such as Al_2O_3, FeO, and MgO, similar to work we did for mare basalts [3]. Combining such a model with remote sensing observations [21-23] will allow us to estimate how the highland crust density varies with location across the Moon. In turn, improved knowledge of the lateral variations in crustal density will improve global models of crustal thickness estimated from gravity inversions [24, 25]. Porosities range from effectively 0 to 20%, although most are in the range 7-13%. Some of the low porosity values are due to thermal annealing to a granulite texture [16, 17] and are indicated by gray circles in Figure 1. Meteorite regolith breccias have been proposed to have low porosity due either to the effects of ejection from the Moon or landing on Earth [26]. A similar process might contribute to the low porosities of some meteorites in Figure 1, although it is unclear how this might be affected by differences in strength between regolith breccias and other types of lunar rock.

For gravity modeling, bulk density is the essential parameter. Most of the samples (63%) reported here have bulk densities between 2350 and 2650 kg m^{-3}, with a mean of 2580±170 kg m^{-3}. However, high porosity samples have bulk densities as low as 2200 kg m^{-3} [27]. Low porosity samples, such as granulites, have bulk densities up to 2840 kg m^{-3}, which approach their grain densities.

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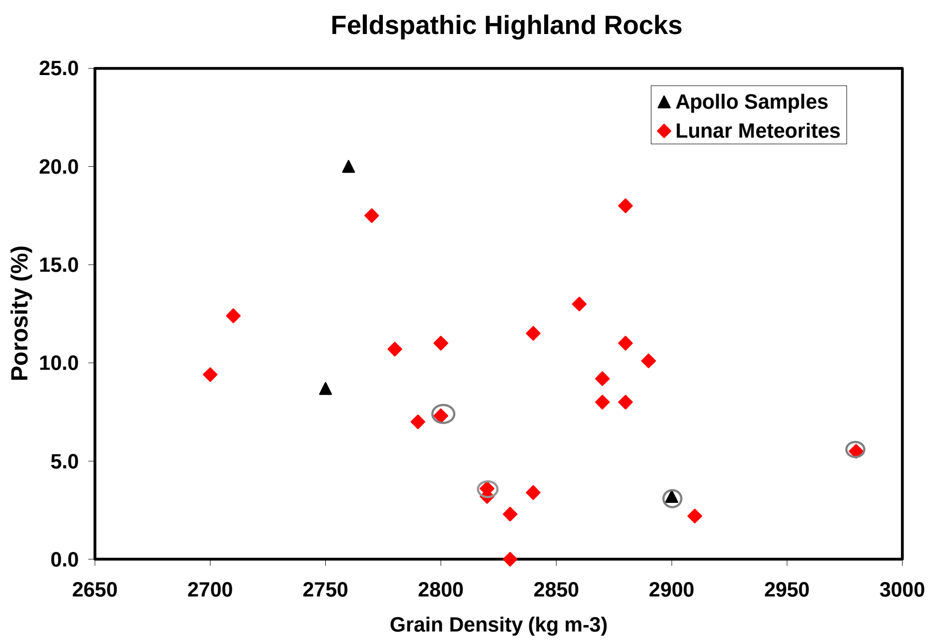

Figure 1: Grain densities and porosities for the feldspathic lunar rocks measured in this study. Apollo samples are shown as black triangles and lunar meteorites are red diamonds. Gray circles indicate rocks with granulitic textures.