The Bulk Density of the Small Lunar Volcanos Gruithuisen Delta and Hansteen Alpha: Implications for Volcano Composition and Petrogenesis

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Introduction: Most lunar volcanic complexes [1] are basaltic in composition. However, morphology and near-infrared, thermal-infrared, and gamma ray spectroscopy show that a small number of lunar volcanic complexes have felsic compositions. These include the Gruithuisen domes [2-4], Hansteen Alpha [3-6], Lassell Massif [3, 4, 7], the Mairan domes [8], and Compton-Belkovich [9, 10]. One limitation of remote sensing methods is that they reveal the composition of material only in the outermost few centimeters (or less). This limitation is partially mitigated where impact craters provide exposures of deeper material. In the case of the Gruithuisen and Mairan domes, estimates of magma rheology from dome topography help to constrain the overall composition of the domes [11].

Gravity modeling is another technique that can be used to constrain the density and thus the composition of these volcanos. Gravity modeling of these relatively small volcanos (e.g., Compton-Belkovich, [12]) has been made possible for the first time by the high-resolution gravity field observations made by the Gravity Recovery and Interior Laboratory (GRAIL) mission [13, 14] (**Figure 1**). We focus here on analysis of GRAIL observations of the Gruithuisen domes and of Hansteen Alpha and on the implications of these observations for volcano composition and magma petrogenesis.

Method: At spherical harmonic degrees > 150 on the Moon, the gravity field can be used to map regional variations in crustal density [15]. Based on the observed topography (including the effects of finite amplitude topography to 16th order), we calculate model gravity fields for various choices of crustal density. We calculate the RMS misfit between the observed free-air gravity (model GRGM900C, [14]) and the model gravity over spatial domain boxes drawn around each volcano (black square in Figure 1). Both the observed and modeled gravity fields include spherical harmonic degrees 200-600, with cosine tapers applied at both ends of the frequency range to minimize the effects of spectral ringing. This corresponds to a block size (half-wavelength) resolution of 9 km in the gravity maps. Based on the shape of the RMS misfit curve, we determine both the mean crustal density and its uncertainty in our study regions.

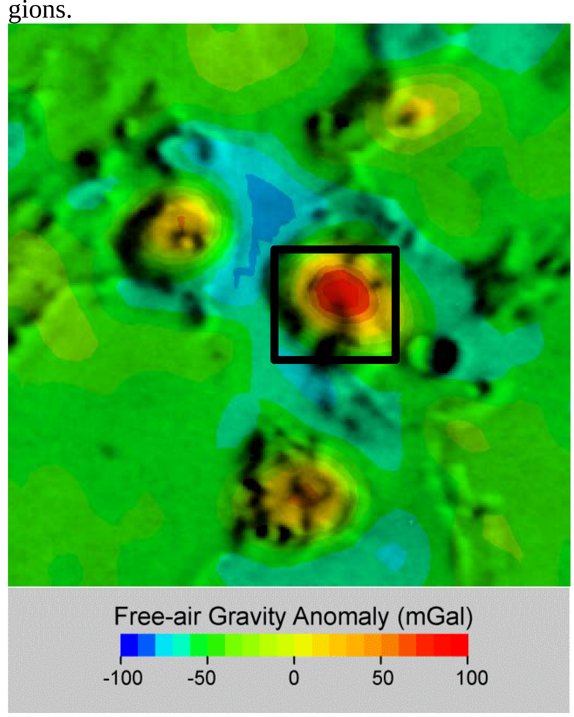

Figure 1: The free-air gravity anomaly for the Gruithuisen dome region. GRAIL resolves distinct anomalies for Gruithuisen Delta (right) and Gruithuisen Gamma (left). The region is 100 km across.

Results: Model results for the Gruithuisen Delta dome are shown in **Figure 2** and indicate a bulk density of 2150±150 kg m^{-3}. The minimum RMS misfit of 1.8 mGal corresponds to a variance reduction of 99.7% of the observed free-air anomaly.

The extremely low density places strong constraints on the composition of the dome. Lunar mare basalts have bulk densities exceeding 3000 kg m^{-3} [16] and cannot explain the Gruithuisen Delta results. Although highly vesicular basalts such as Apollo 15 sample 15556 can fit the results in Figure 2, this would require an implausible amount of volcanic gas (~180 km^3 at Gruithuisen Delta). More importantly, FeO contents are much lower (4-8 wt %) than those in mare basalts (18-20 wt %) [17]. A far more likely explanation is that the volcanic dome consists of low density, felsic material. This includes minerals such as albite (grain density 2620 kg m^{-3}), orthoclase (2570 kg m^{-3}), and quartz (2650 kg m^{-3}). Rocks with such compositions are known as small clasts in some Apollo impact breccias [18]. Mare basalts have typical porosities of 5-9% [16]. Assuming that a similar porosity applies to this dome, the resulting bulk density is 2350-2450 kg m^{-3}. Thus, it is still necessary to invoke an additional large-scale porosity of ~10% from vesicularity or pyroclastic deposition. Pyroclastic volcanism has been inferred in this region from geologic observations [19]. Another likely factor contributing to low density is volcanic glass, which tends to be less dense than the corresponding minerals (2390, 2380, and 2200 kg m^{-3} for albite, orthoclase, and quartz composition glasses, [20]).

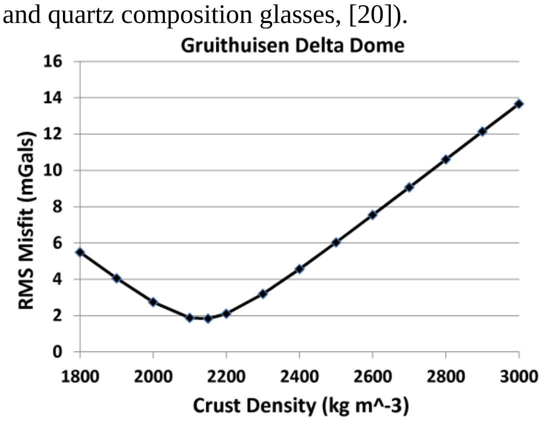

Figure 2: The gravity misfit as a function of assumed crustal density for Gruithuisen Delta.

The combined volume of the Gruithuisen Delta and Gamma domes is 760 km^3 [19]. Assuming that the Delta and Gamma domes have the same bulk density (a subject of on-going modeling), the two domes contain a felsic mass of $1.6 \cdot 10^{15}$ kg. The silica-rich magma required to fit our density observations can be produced either by crustal melting induced by basaltic underplating or by silicate liquid immiscibility (SLI) [3]. Basaltic underplating can produce a crustal rhyolitic melt composition that is consistent with our inferred bulk density and observed dome FeO concentrations (4-8 wt %). Modeling using MELTS shows that 10-35% partial melting of KREEP basalt (driven by the heat from mare basaltic intrusions and the intrinsic radioactivity of KREEP) would produce significant volumes of rhyolitic magma with the right range in FeO. Based on terrestrial analogs and geochemical modeling, this process can also explain the high thorium abundance observed both in Gruithuisen as well as at other lunar felsic domes [3].

SLI from a mare basaltic magma can produce a small amount of silica-rich magma that is consistent with our model densities but inconsistent with the high observed abundances of thorium [3, 18]. SLI requires that the Fe-rich and Si-rich immiscible melts separate from the basaltic magma and each other, Both the dense cumulates formed by fractional crystallization of a parent mare basalt magma and the Fe-rich immiscible melt would need to pond at substantial depth in the crust to avoid creating a positive gravity anomaly that is not observed in the data.

Results for Hansteen Alpha are broadly similar, implying a crustal density of 1500-2000 kg m^{-3}, with the larger uncertainty resulting from the smaller relief relative to Gruithuisen Delta. Thus, the magma composition and petrogenesis results for Gruithuisen are likely to also apply to Hansteen Alpha. An additional possibility at Hansteen is the presence of rhyolitic material in the shallow subsurface that was subsequently buried by later mare basalt flows, a possibility that we are working to quantify. Superposition relationships suggest that this mechanism is probably not important for the Gruithuisen domes.

References: [1] Spudis et al., *J. Geophys. Res.: Planets* 118, 1063-1081, 2013. [2] Chevrel et al., *J. Geophys. Res.* 104, 16,515-16,529, 1999. [3] Hagerty et al., *J. Geophys. Res.* 111, 2005JE002592, 2006. [4] Glotch et al., *Science* 329, 1510-1513, 2010. [5] Hawke et al., *J. Geophys. Res.* 108, 2002JE002013, 2003. [6] Wagner et al., *J. Geophys. Res.* 115, 2009JE003359, 2010. [7] Ashley et al., *Icarus*, in press. [8] Glotch et al., *Geophys. Res. Lett.* 38, 2011GL049548, 2011. [9] Jolliff et al., *Nature Geosci.* 4, 566-571, 2011. [10] Wilson et al., *J. Geophys. Res.: Planets* 120, 92-108, 2015. [11] Wilson and Head, *J. Geophys. Res.* 108, 2002JE001909, 2003. [12] Jansen et al., *Lunar Planet. Sci. Conf.* 46, abstract 2185, 2015. [13] Konopliv et al., *Geophys. Res. Lett.* 41, 1452-1458, 2014. [14] Lemoine et al., *Geophys. Res. Lett.* 41, 3382-3389, 2014. [15] Wieczorek et al., *Science* 339, 671-675, 2013. [16] Kiefer et al., *Geophys. Res. Lett.* 39, 2012GL051319, 2012. [17] Crites and Lucey, *Am. Mineral.* 100, 973-982, 2015. [18] Taylor, *Proc. Conf. Lunar Highland Crust*, 339-352, 1980. [19] Ivanov et al., *Icarus*, in press. [20] Fluegel, *J. Am. Ceramic Soc.* 90, 2622-2625, 2007.