SMALL-SCALE DENSITY VARIATIONS IN THE LUNAR CRUST AS SEEN IN GRAIL DATA. J. C. Jansen[1], J. C. Andrews-Hanna[1], J. W. Head III[2], Y. Li[1], W. S. Kiefer[3], J. M. Soderblom[4], G. J. Taylor[5], and M. T. Zuber[4], [1]Department of Geophysics, Colorado School of Mines, Golden, CO 80401, jjansen@mines.edu, [2]Department of Geological Sciences, Brown University, Providence, RI 02912. [3]Lunar and Planetary Institute, Houston, TX 77058, [4]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139-4307, [5]Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, HI 96822.

Introduction: Analysis of data from the Gravity Recovery and Interior Laboratory (GRAIL) mission has shown that ~99% of the gravity signal at short wavelengths (high spherical harmonic degrees) arises from the effects of the topography [1]. However, the remaining 1% of the signal contains important information about density variations in the crust. This high frequency signal is well above the noise threshold [1], and often does not have a clear relationship with any surface features.

In this study we examine different explanations for the source of these anomalies. The low-degree Bouguer gravity anomalies are likely dominated by the effects of variations in the relief of the crust-mantle interface [2]. However, downward continuation of the gravity anomalies into the subsurface causes a degree-dependent amplification, resulting in instabilities in the crustal thickness models at higher degrees. The high-degree Bouguer anomalies are likely caused by small-scale (10's of km) shallow density variations.

In this study, we concentrate on a small area on the Moon that lacks clear large-scale features such as impact basins larger than 80 km in diameter that would dominate the gravity anomalies (Fig. 1). We use 3D inverse modeling in order to relate the observed gravity to density variations in the subsurface. The density models are then used to test possible interpretations.

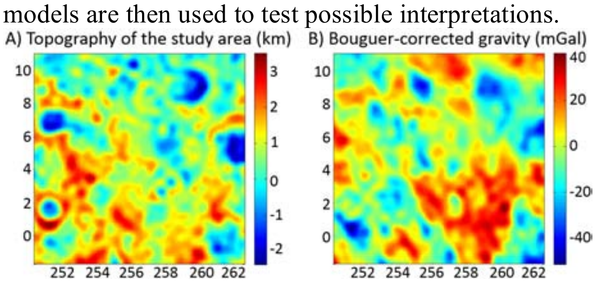

Figure 1. A The topography of the study area referenced to the geoid. **B** Bouguer-corrected map of the study area from degree 30 to 500 with high- and low-pass cosine tapers applied at degrees 30–40 and 480–500. In both figures the x-axis is east longitude and the y-axis is north latitude.

Method: For our inversion we use the program GRAV3D. This program uses the gravity data to find the three-dimensional density variations that fit the data by minimizing the objective function [3,4]:

$$\phi = \phi_d + \beta \cdot \phi_m$$

where ϕ_d is a measure of the data misfit, ϕ_m is the model objective function, and β is a regularization parameter. The model objective function includes the assumptions made regarding the desired model characteristics. In this case, we use model smoothness, defined as the square of the first derivative of the model in each direction. The regularization parameter weighs the relative importances of the model objective function and the data misfit in the inversion. A large value of β emphasizes the minimization of the model objective function and forces the density model to be smooth at the expense of a poor fit to the data. A small value of β may over fit the data (i.e., fitting the noise as well as the signal) resulting in large density anomalies.

We used the Bouguer-corrected gravity to isolate anomalies arising in the subsurface (Fig. 1B). We removed the low degree (l<30) content from the signal that is likely dominated by the relief along the crust-mantle interface. We applied a low-pass cosine taper between degrees 480 and 500 to reduce ringing from the truncation of the spherical harmonics.

Possible causes of the density anomalies in the crust include porosity variations, igneous intrusions, or compositional variations in the bulk lunar crust. Each of these end member scenarios is associated with different limitations and implications. We interpret the gravity anomalies in the context of each of these three end-member scenarios.

Lunar samples include a suite of intrusive rocks that are relatively magnesium rich, referred to as the magnesian suite (Mg suite). GRAIL gravity gradients revealed evidence for large linear intrusions [5]. Floor-fractured craters also provide evidence for shallow magmatic intrusions and sill formation [6]. Pervasive irregular gravity anomalies could be related to small irregular intrusions throughout the crust. If we assume that the intrusive material is of the Mg-suite we can adopt an average density of 3150 kg/m^3 [7] for the intrusive material compared to an average density of the lunar crust of 2550 kg/m^3 [2]. Assuming that the lowest densities correspond to unintruded crust, we can calculate the fractional volume of the intrusive material throughout the model domain.

We also consider the end member assumption that all density anomalies are due to changes in porosity.

We assume that the average density in the study area has a porosity equal to the global average of 12% [2] and all of the density variations above or below the mean are are due to a deviations from this porosity.

The last end member assumption is that of density anomalies arising from variations in the composition of the crust. Remote sensing indicates that the bulk of the lunar highlands surface is comprised of a mixed feldspathic layer, likely composed of a mixture of anorthositic norite and noritic anorthosite [8,9]. Outcrops of pure anorthosite are less common and may represent deeper levels of the crust. Both compositions are exposed in the Orientale basin, to the south of this study area. Anorthositic norite and noritic anorthosite have similar grain densities (2840-2910 kg/m^3), but ferroan anorthosite has a lower grain density (2710-2750 kg/m^3) [7] and will result in lower gravity anomalies.

Results: We investigated a range of parameter space, including the depth of the base of the model and the regularization parameter. Here we focus our discussion on a model with a bottom depth of 50 km, and a regularization parameter β equal to 10^{-2}. A maximum depth of 50 km is a reasonable upper bound on the crustal thickness in this area [2], while the choice of β yields a reasonable tradeoff between model smoothness and data misfit. The resulting model from this inversion shows density anomalies in the range of -90 to 80 kg/m^3 (Fig. 2). The density anomalies do not show any clear correlation with the topography.

For the end-member scenario in which the density anomalies arise from mafic intrusions, the results predict that on average ~12% by volume of the lunar crust in this region would be made up of intrusive material, up to a maximum of 37% (Fig. 2). This value is comparable to the upper bound on the fraction of the lower crust comprised of intrusions based on the lack of extensive farside maria [10], and to the recent constraint of 15-45% post-magma ocean igneous materials such as norite, troctolite, and gabbro within the crust [11].

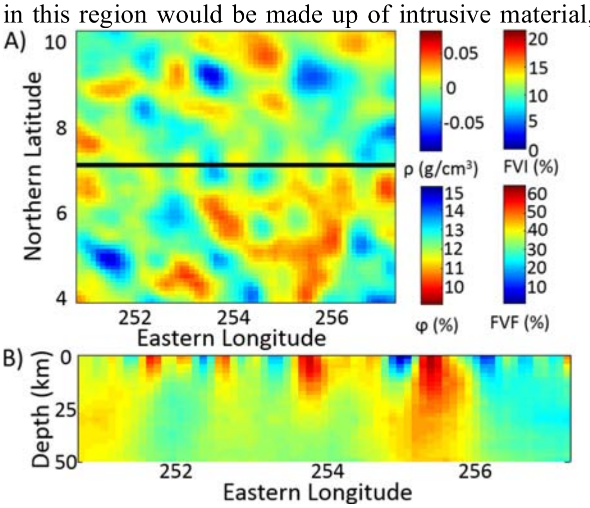

Figure 2. A Plan view of the model results at 25 km depth, with scale bars for the density (ρ),fractional volume of the intrusions (FVI), porosity (ϕ), and fractional volume of the ferroan anorthosite (FVF). The black line shows the location of the cross section shown in **B**.

Assuming that the gravity anomalies arise from variations in porosity, the resulting map is identical to that of the fractional volume of intrusions map but with reversed axes (Fig. 2). The range in porosity values is ~6% centered around the mean value of 12%. Measured porosities of lunar highlands samples of 2.2 to 20% indicate that the model results fall within the expected range [7]. Therefore, the density variations that we see in this area can be completely explained by variations in porosity. Bouguer gravity lows beneath craters suggests at least some anomalies are due to locally enhanced porosity generated by impacts [12].

Interpreting the gravity anomalies as arising from variability in crustal composition, the map of the fractional volume of ferroan anorthosite (with the remainder being more noritic) predicts that on average ~23% by volume of the crust in this region is made up of ferroan anorthosite, consistent with the abundance of outcrops of pure anorthosite observed at Orientale [9].

Conclusions: These results show that the pervasive small-scale gravity anomalies observed by GRAIL are consistent with expectations for density variations due to Mg-suite-like intrusions, local porosity variations, or compositional variations between ferroan anorthosite and more noritic materials. The true source of the density anomalies is likely a combination of these end-member scenarios. Determining the balance between compositional and porosity effects will require a comparison of the density model with constraints from orbital spectroscopy. Regardless of the source of the density anomalies, the significant small-scale density variations revealed by GRAIL have important implications. Previous work revealed long-wavelength variations in the density of the lunar crust [2]. This variability in crustal density at a range of scales complicates interpretations of lunar gravity data.

References: [1] Zuber M. T. et al (2013), *Science, 339,* 668-671 [2] Wieczorek M. A. et al. (2013), *Science, 339*, 671-675 [3] Li Y. and Oldenburg D. (1996), *Geophysics, 61*, 394-408 [4] Li Y. and Oldenburg D. (1998), *Geophysics, 63*, 109-119 [5] Andrews-Hanna J.C. et al. (2012), *Science, 339,* 675-678 [6] Jozwiak L. M. et al. (2012), *JGR, 117,* E11005 [7] Kiefer W. S. et al (2012), *GRL, 39,* L07201 [8] Hawke, B. R. et al. (2003), *JGR, 108*, 5050 [9] Cheek L. C. et al. (2013), *JGR, 118,* 1-16 [10] Head III J. W. and Wilson L. (1992), *Geochim Cosmochim. Acta, 56,* 2155-2175 [11] Crites, S. T., et al. (2014), *LPS, XLV,* this volume. [12] Soderblom et al., (2014), *LPS*, *XLV,* this volume.