SEISMIC AND GRAVITY MODELING OF THE LUNAR MEGAREGOLITH. Nicholas C. Schmerr[1], Shin-Chan Han[2], [1]Dept. of Geology, University of Maryland, College Park, Maryland, U.S.A nschmerr@umd.edu, [2]NASA-GSFC Greenbelt, MD 20771 USA shin-chan.han-1@nasa.gov.

Introduction: Lunar crustal thickness and structure hold key constraints on the bulk composition, evolution, and formation of the Moon [1]. Over the past 4.5 billion years, the lunar anorthositic crust has been globally modified by extensive impact cratering, creating a 1-3 km thick layer of megaregolithic materials overlying fractured and faulted crustal rock [2, 3]. Subsequent nearside mare volcanism and modification by more recent impacts has created large-scale regional variations in the thickness and layering of the lunar megaregolith [**Fig. 1**]. High resolution gravity from the Gravity Recovery and Interior Laboratory (GRAIL) mission and reanalyis of Apollo seismic data are providing exciting new opportunities to geophysically explore the structure of the lunar megaregolith.

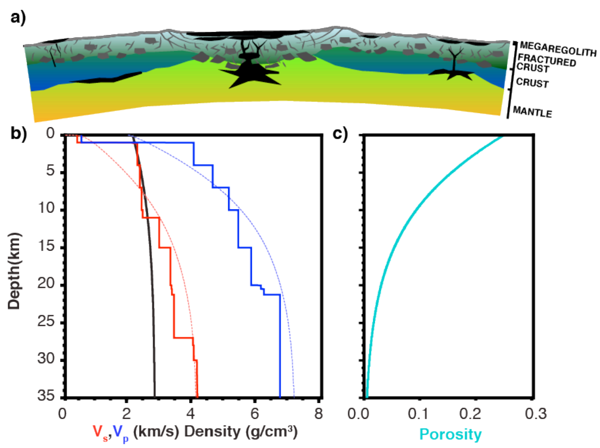

Fig. 1 Lunar crustal structure from joint seismic/gravity modeling of crustal elastic parameters and porosity. a) Schematic cross section of lunar crustal structure. b) Average seismic velocity model [4] (thick lines) and experimentally derived (narrow lines) velocity and density profiles from a depth dependent porosity distribution [5]. c) Porosity with a closure pressure of 175 MPa, and surface porosity of 0.25.

Background: Recently, NASA's Gravity Recovery and Interior Laboratory (GRAIL) provided new high-resolution maps of variations in lunar gravity, including constraints on crustal density, porosity, and thickness of the crust [6, 7]. The bulk crustal densities and lateral variations retrieved by GRAIL are on the order of 2550±250 kg m^{-3}, considerably less then the 2800-2900 kg m^{-3} that are typical for anorthositic crustal materials [6]. This low density requires a considerable amount of porosity (4-21%) in the lunar crust, likely resulting from the extensive impact gardening of lunar crustal materials.

Porosity arises from fracturing of crustal rocks (i.e., cracks, joints, and faults), as well as intragranular pore space in poorly consolidated ejecta fragments and brecciated sedimentary materials [8]. It is expected that the majority of intragranular pore space would be eliminated near 5-10 km depth (40 MPa) by viscous deformation and compaction of crustal materials [6] though it is unclear how far porosity extends into the lunar crust. New results from higher-frequency GRAIL gravity data sensitive to shallow layers of the crust [9] indicate that the lunar bulk crustal density estimate decreases while topography correlation stays close to unity. This implies a stratified density structure in the lunar crust, with the lower crustal density closer to anorthosite (2800–2900 kg/m^3), and higher porosity near the surface.

Seismic observations of megaregolith structure are provided by the Apollo Passive Seismic Experiment (APSE) , a four station seismic network deployed on the nearside of the Moon by the Apollo 12, 14, 15, and 16 astronauts [10], the Active Seismic Experiment (ASE) from Apollo 14 and 16 [11], and Lunar Seismic Profiling Experiment (LPSE) from Apollo 17 [12]. These experiments provided *in situ* seismic measurements of the thickness and elastic properties of the lunar megaregolith, indicating that the layer is ~3 km thick beneath the stations, with compressional wave velocities on the order of 300 m/s [13] [**Fig. 1**]. The lowered seismic velocities of the megaregolith layer are similar to those observed near impact craters and dry soils on Earth, and are compatible with the reduced rigidity and compressibility found in porous, fractured, and brecciated rock [14]. In addition, seismic waves passing through fractured materials will be highly scattered, producing long duration codas of energy that typically decay with travel time [15]. This is characteristic of lunar seismograms; the relatively low attenuation of seismic waves in the lunar interior produces codas that extend over 1-hour or longer [16].

Approach: Here we investigate the hypothesis that the megaregolithic pore space is removed with increasing overburden pressure at depth, and that the resulting stratified density with depth is responsible for a frequency dependence in the GRAIL admittance spectrum and the decrease in seismic velocities observed in the megaregolith [9]. We introduce a simple, experimental model for rock compaction with pressure [5] (i.e., depth) to describe the distribution of density within the lunar crust and calculate the expected gravity admittance [9]; we then model the seismic velocity of anorthositic breccia using Modified Biot-Gassman theory [17].

Compaction profiles of porosity as a function of depth are dependent upon the material properties of the sediments and pore fluids involved [5], though on the Moon, the effect of pore fluids is neglible. [**Fig. 1**] shows an example relationship between porosity and density distribution with depth for a depth-dependent porosity model. Closure pressure is defined as the pressure at which porosity falls below ~1% (0.01). For both the gravity and seismic models, we explore a range of porosities (0.0–0.8) at pressures appropriate for the lunar crust (0–400 MPa) and anorthosite densities (2650–2950 kg/m^3) [**Fig. 2**]. In general, models with low closure pressure result in steep porosity gradients across the crust, which are further steepened at higher surface porosities. Models with high closure pressure produce more gradual porosity gradients, as does reducing the surface porosity. The model does not explicitly include temperature dependent viscosity and grain boundary annealing, effects that would further reduce porosity with depth [6].

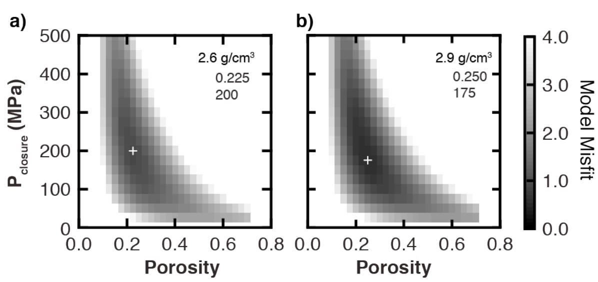

Fig. 2 Joint solutions for porosity and closure pressure in the lunar crust from gravity and seismic velocity constraints. Solutions are shown [small crosses] for a) low anorthosite density (2.6 g/cm^3) b) high anorthosite density (2.9 g/cm^3). Model misfit is calculated from a weighted average of the chi-square misfits for each parameter.

Joint Model: We forward modeled the gravity admittance, shear and compressional velocity, and calculate the reduced chi-square fit of each model to GRAIL gravity observations and an averaged seismic velocity profile of the lunar crust [4]. To jointly constrain density and seismic velocity structure, we normalize and sum the reduced chi-square misfits for gravity, shear, and compressional velocity to find the misfit minimization that satisfies all three parameters [**Fig. 2**]. The seismic parameters are less sensitive to our choice of starting density and more to the stratified nature of the porosity in the lunar crust. The best fitting solution suggests a starting porosity near 20-25% and closure pressure of 175-200 MPa; this implies porosity extends throughout the lunar crust, though is stratified in nature, with the highest porosity near the surface. Our model estimates the surface density of the Moon should be near 2.0-2.2 g/cm^3, in good agreement with density measurements of lunar rock samples, meteorites, and regolith [14, 18].

Further Implications: Our study constrains the depth extent of the fracturing and bedrock disruption in the Moon and the associated crustal porosities, significantly reducing the uncertainties in models of density distribution in the lunar crust. Density distribution is an important constraint for studying global gravity models of crustal thickness and understanding local variations in crustal thickness and density [6]. Future instrumentation may be able to resolve porosity differences between nearside mare basins infilled with basalt and farside anorthositic crust. High porosity maintained throughout the lunar crust may also serve as a reservoir for volatiles either primary or from impact processes. Impact brecciation is major process present in the megaregolith of other planetary objects and this approach can be used to establish the detailed character of the seismic wavefield at the proposed locations of potential landing sites of future seismometer deployments.

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