VOLUMES OF VISIBLE MARE AND HIDDEN CRYPTOMARE BASALTS ON THE MOON FROM GRAVITY DATA AND DARK HALO CRATERS.

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Introduction: The present-day volume and distribution of mare basalts on the Moon provides clues to the thermal and volcanic history of this planetary body. In particular, buried mare deposits are important for constraining the timing of lunar volcanism because the dearth of visible mare deposits older than ~3.9 Gy could be explained by the burial of ancient deposits due to the high impact flux of the heavy bombardment [1].

Previous estimates of the total volume of cryptomaria range from 0.4–4.8 $\times 10^6$ km^3, constrained by a variety of lunar surface properties, including mineralogy, albedo, surface roughness, gravity, and topography [1], [2]. Additionally, the presence of dark halo craters (DHC) (Fig. 1a and 1b) has been used as geologic evidence of buried volcanic material [3].

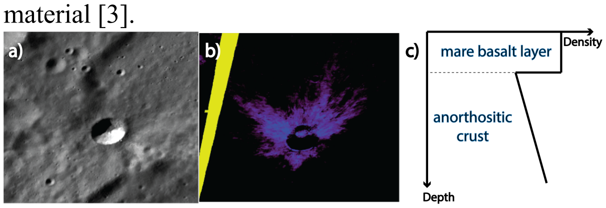

Figure 1. Dark halo crater (DHC) and subsurface density model. a) Albedo and b) Iron content image of a DHC showing a lower albedo and higher iron content ejecta. The ejecta is formed from the underlying volcanic material exposed by the impact. c) Density model used to represent the subsurface of regions with exposed or buried mare basalts.

In this work, we use the effective density spectrum (ρ_{eff}) to search globally for cryptomare in the lunar crust. ρ_{eff} is a function of gravity and topography and has been used to constrain visible mare locations and thicknesses because of the sensitivity of gravity to the excess density of basalts [4], [5]. We claim that ρ_{eff} is sensitive to cryptomare too, not only exposed mare, if the ejecta layer overlaying the deposits is thin enough. Our work provides important advantages compared to previous approaches to cryptomare search. Using ρ_{eff} allow us to directly constrain the volume of cryptomare regions instead of only the surface area, validate our results through the accurate identification of visible mare regions, and constrain the volumes of visible mare regions, which are uncertain.

To our knowledge, a global database of DHCs is not available in the literature. Therefore, we perform a new independent global mapping of DHCs to compare with the inferred locations of cryptomare deposits obtained with gravity data.

Methods: *Gravitational inference of mare basalts.* We use gravity data from the GRAIL mission [6] and topography data from LRO's LOLA instrument [7] to compute the observed ρ_{eff} at 10242 locations uniformly distributed over the Moon. We use $\rho_{eff}\,(l) = S_{gb}(l)/S_{bb}\,(l)$ where S_{gb} is the cross-power spectrum between free air gravity (g) and Bouguer correction per unit density (b) [4], [5]. We use the gravity model in [8] and the topography model in [9] to obtain the global g and *b.* We then localize g and b at each node on our grid using a multitaper approach and Slepian windows with radius $r = 15°$ and concentration factor $\lambda > 0.99$. We use the Python module SHTools [10] to localize the gravity and topography data and to compute ρ_{eff}.

We model the subsurface distribution of density at each node in our grid using two models: one with a layer of mare basalts (Fig. 1c) and one with a linear increase of density with depth representing anorthositic crust only (no mare layer). For each of the two models, we find the parameters that best fit the localized observed ρ_{eff} using a Bayesian Markov chain Monte Carlo inversion [11], [12] and the theoretical expressions of the model ρ_{eff} in [4], [5]. At every location on the Moon, we compare both models according to their Bayes factors and conclude that a mare layer exists only if the evidence *strongly* supports the model in Fig. 1c over the other model with no mare.

Mapping of dark halo craters. We use images from LRO's LROC instrument and iron content data from the Clementine mission [13] to search for craters with ejecta that is both darker and has higher in iron content than the surrounding area (e.g., Fig. 1b). We search for DHCs over the whole surface of the Moon with diameters D>1 km. The DHCs are mapped independently, without knowledge of the potential cryptomare locations found using ρ_{eff}. More details of the mapping are presented in an associated LPSC abstract [14].

Results and Discussion: The best-fitting inferred total volume of visible mare basalts is 3.4 $\times$ 10^6 km^3, assuming a basalt density of 3460 kg/m^3. This volume is within the uncertainty found by previous studies — e.g., [2]. Our methods match the visible mare locations without any prior information about where mare is expected to be, validating our approach.

We identify several areas that are outside the boundaries of the visible maria, but where the existence of a high-density near-surface layer is preferred over the model of anorthositic crust only. These are potential cryptomare deposits. Fig. 2b shows the inferred candidate cryptomare deposits (assuming a basalt density of 3460 kg/m^3) and the location of the DHCs mapped in this work. Assuming all of these candidate deposits are cryptomare yields a best-fitting cryptomare volume of 3.6 × 10^6 km^3 and cryptomare area of 26% of the lunar surface. In average, cryptomare deposits are thinner than visible mare but they are more widespread over the lunar surface. We argue, however, that only a subset of the potential cryptomare deposits shown in this figure are in reality cryptomaria.

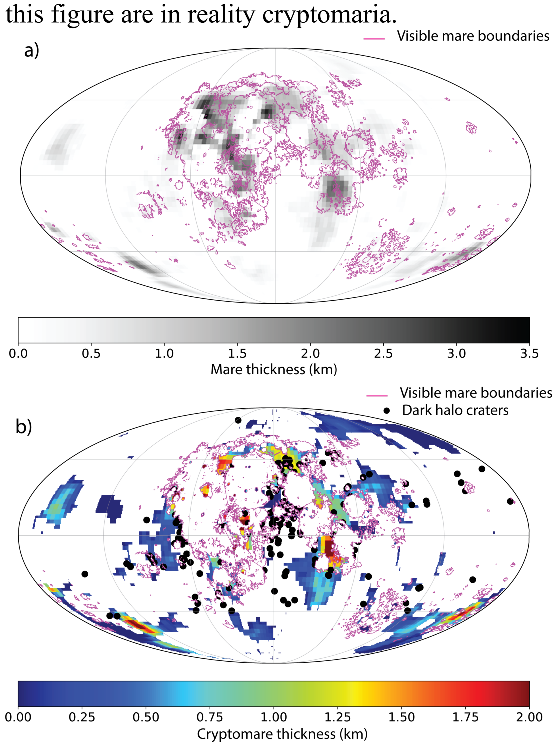

Figure 2. Most likely global distribution of mare basalts on the Moon. a) Thickness of visible mare and cryptomare consistent with the observed effective density at 10242 regions on the Moon. b) Candidate cryptomare thicknesses and locations of DHCs mapped in this work.

The strongest candidates of cryptomaria are those deposits that are near visible maria, DHCs, or near geological evidence of cryptomaria from previous work. Many of the candidate deposits in Fig. 2b match these criteria. We find potential cryptomare deposits that border the visible maria, on the nearside and in the SP-A basin. We find a cryptomare region and a DHC near the Schiller-Schickard region (40°W 55°S), previously proposed to contain cryptomare [1], [2], [15]. There is also a significant overlap between the cryptomare distribution we find and the one proposed in [1].

The least likely candidates of cryptomaria are two regions that had not been proposed before and are not located near DHCs. Compared to [1], we find three new potential cryptomare regions at 100°W 20°N, 120°E 65°N, and 30°E 25°S but only one of them, the last one, contains a DHC. Removing the contribution of the two new cryptomare regions that lack DHCs results in a best-fitting cryptomare volume of 2.8 × 10^6 km^3 and cryptomare area of 19% of the lunar surface.

There is a mismatch between some locations of DHCs and gravitationally inferred cryptomare regions. Locations where DHCs exists but lack a gravitationally inferred cryptomare region could have a very thin cryptomare deposit that does not have a strong enough signature in the observed ρ_{eff}. Locations having gravitationally inferred cryptomare but no DHCs, could have an ejecta layer thicker than the excavation depth of the DHCs.

Finally, the expression for ρ_{eff} used in this work relies on the assumption that density varies with depth as layers in-phase with the surface relief [4] but this assumption is broken within mare regions. While the detection of mare regions is robust to this assumption [4], [5], as future work, we will find the locations of mare-filled craters following [16] and update our mare volumes at these regions.

Conclusions: We find the global distribution of DHCs and mare regions in the Moon consistent with a spectral function of gravity and topography. We match the location and volume of visible mare, and we find previously proposed cryptomare regions. Additionally, we find new candidate cryptomare regions, especially in SPA and other regions in the far side of the Moon. These new far-side deposits might be buried ancient mare deposits but further investigation is needed to confirm their basaltic origin. If confirmed, these deposits would challenge the paucity of farside volcanism

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