(16) PSYCHE'S INTERNAL STRUCTURE MAY HAVE LOW AND HIGH DENSE SILICATE LAYERS ON TOP OF A METALLIC CORE.

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Introduction: (16) Psyche is the largest metallic asteroid (~150 km in diameter) in the main belt. NASA's Psyche will explore this object with the primary science goal of understanding its possibly exposed nickel-iron core that can give vital insights into early planet formation [1]. One of the leading hypotheses for Psyche's structure is a stripped-mantle core possibly driven by hit-and-run impacts [2]. While its metal-rich surface composition is supported by remote sensing observations [3-5], the reported bulk density is ~4.0 g cm^{-3}, significantly lower than that of metallic materials.

Given this low bulk density, a key issue is Psyche's internal structure. We note that several remote sensing observations show potential indications of silicate materials on the surface of Psyche [6-8]. This body may consist of metal for 30 – 60 vol% and silicate for the rest [5]. If the hit-and-run scenario is the right process of Psyche's formation, both the core and mantle would be highly fragmented, increasing porosity. This would be another constraint on the mass balanced with the bulk density and volume, inferring Psyche's internal structure. Importantly, Psyche is much larger than any asteroids (rubble pile bodies and shattered bodies like Eros [9]) but smaller than dwarf planets. Thus, we speculate that Psyche may be within a transition that exhibits the nature of these objects: the mantle and core would be denser than the surface layer.

Here, we use our FEM approach to investigate Psyche's possible internal structure. We introduce three hypothetical layer conditions (metallic core, dense silicate mantle, and less dense silicate surface layer). Comparing the derived pressure results with the crushing limit of silicate layers, we constrain these layers' sizes. Later, we denote the dense silicate layer as a "mantle", while it may not follow the traditional meaning of this term.

Methodology: We developed a FEM approach to compute the pressure distribution of Psyche. The structure of Psyche is represented by a three-layer model that consists of a metal core and two silicate layers.

FEM approach. This model computes the stress distribution based on linear-elastic deformation. For the boundary condition, we apply three constraints for translation and then use an iterative conjugate gradient algorithm for the least-squares method, allowing us to mitigate the singularity issues [10].

We set up our simulation as follows. Psyche is assumed to rotate along the shortest principal axis with a constant spin period of 4.2 h [3]. Using Gmsh, we develop a 4-node FEM mesh from the radar-derived shape model [3]. The generated FEM mesh consists of 2161 nodes and 9196 tetrahedral elements. For all the simulations, the total bulk density of Psyche is fixed at 4.16 g cm^{-3} [11]. Poisson's ratio and Young's modulus are set to be 0.25 and 10^7 Pa [12], while we note that the stress field is independent of Young's modulus [10].

Three-layer model. The present model contains three layers: metallic core, denser silicate-rich mantle, and less dense silicate-rich surface layer. We assume that the core and mantle have spherical shapes and are surrounded by the surface layer (e.g., Fig. 1). The surface and mantle are majorly made of silicates with different porosity, while the core is metallic [6, 8]. The surface would be less dense, similar to what has been seen on small rubble piles [13, 14] and shattered asteroids that exhibit loosely aggregated rocks [15]. On the other hand, while fragmented, the mantle and core are denser due to high pressure compression crushing pore.

We model that each layer has a different bulk density, depending on the combination of porosity and a grain density of the composition. The surface layer has high porosity (~25%) with a grain density of 3.5 g cm^{-3} for silicate-rich meteorites [16], which is consistent with the bulk composition of Eros [17]. For the denser mantle and core, the porosity is fixed at ~13%, based on a recent report discussing the porosity of the lunar crust [18]. The grain density of the mantle is the same as that of the surface. For the core, it is set to be 7.5 g cm^{-3}, which is a typical value for iron meteorites [19].

Results: This model contains two free parameters: the core radius and the mantle thickness. To determine these parameters, we first add the constraint that the total mass is constant, given the bulk density of 4.16 g cm^{-3}. We also incorporate the following geometrical constraint; the core is placed below the mantle, and the mantle radius cannot exceed ~93.5 km with the current shape model. Figure 2 shows that the core radius is located between 80 – 83 km in radius, resulting in the mantle thickness being within ~14 km.

Using the derived range, we further narrow down the core radius and the mantle thickness by using the pressure distribution data from our FEM simulations. The mantle and surface are distinguished based on whether silicate layers are crushed. If the applied pressure reaches the crushing limit, this area cannot sustain the current porosity anymore and should have lower porosity. We set the threshold of the crushing limit as ~10 MPa by referring to earlier works [20, 21]. Figure 3 shows the unique case where the boundary layer between the surface and the mantle almost matches the crushing limit of ~10 MPa. The surface is located within the pressures less than the crushing limit, while the mantle is affected by the higher pressures (Fig. 1).

Discussion: Considering that the core and mantle are simply a sphere and a spherical shell, respectively, our model suggests that the core radius is ~81.4 km, the mantle thickness is ~12.1 km, and the rest may consist of an uncrushed layer that contains shattered layers like Eros and rubble pile layers like Itokawa, Ryugu, and Bennu [13]. Given the pressure range, Psyche may have a unique environment having the geologic features of differentiated planetesimals, undifferentiated rocky asteroids, and rubble pile bodies, all of which have had different formation processes.

If the silicate layer is thinner than ~50 km, predicted by [9], there is a chance for Psyche to have experienced Ferrovolcanic surface eruptions. Although other constraints (i.e., the vertical extent of sulfur-rich FeNi melts and sulfur content) should be considered, high excess pressures may happen and propagate the core material up to the surface. Our analysis shows that the mantle layer with a ~12.4 km thickness may be exposed around the poles. This area is likely to undergo this procedure, producing the mixed material of metal and rocky components (i.e., pallasites). The estimated core radius of ~81.4 km is also compatible with top-down core crystallization, which is the requirement of Ferrovolcanism [22]. If Ferrovolcanic surface eruptions truly exist, polar regions would likely be one of the possible target observation sites that can test this hypothesis.

We finally note that recent radar data have shown high reflectance on Psyche, implying its metal-rich surface and possibly challenging the existence of silicate-rich, low-density surface layers. If this is the case, the bulk porosity reaches ~50%, similar to ~500-m-sized rubble pile asteroids [14], and is unlikely given the high compression environment. We anticipate that impact cratering processes likely mix mantle materials [23], and thus core materials may be exposed on the surface at some levels. This hypothesis partially explains that Psyche has the highest radar albedo in the mass-deficit region [3]. With detailed observations by NASA's Psyche, the present analysis will further constrain the surface and internal conditions of this asteroid.

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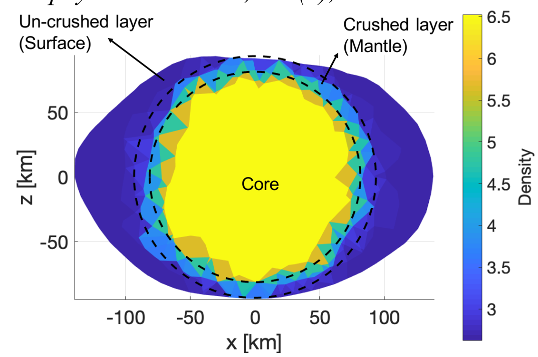

Fig. 1. Density distribution of a three-layer model.

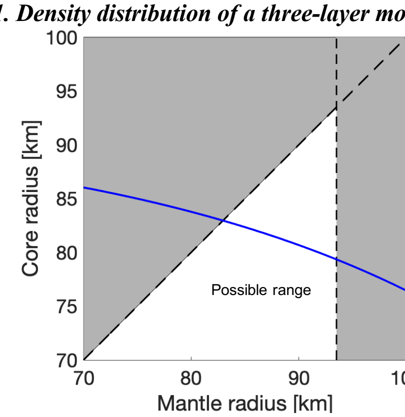

Fig. 2. Core radius constraints. The blue line shows the relationship between the core radius and mantle radius in the density requirement of 4.16 g cm^{-3}.

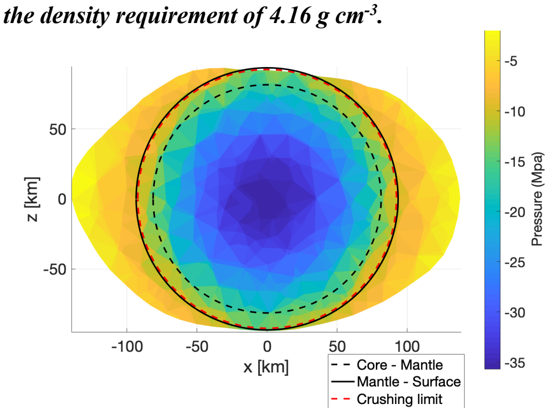

Fig. 3. Pressure distribution of a three-layer model.