POSSIBLE SURFACE CHARACTERISTICS OF (16) PSYCHE

Elkins-Tanton and the Psyche science team, August 2019

For internal team information only

Planning for the Psyche mission includes speculating about what features, compositions, and textures we might find on the asteroid's surface, and then further speculating about how those characteristics might be reflected in the data we gather. To support this exercize we have Earth-based observations about Psyche and other asteroids, and we have meteorites that have fallen to Earth.

COMPOSITION OF PSYCHE JUDGED FROM DENSITY

The current best estiimate for the density of Psyche is around 4,000 kg m^{-3}, placing it between the density of iron-nickel metal and that of silicate rock (Elkins-Tanton et al. in prep.). Based on this and other observational data, we therefore suspect that Psyche is either a mixture of metal and rock, or a mixture of metal and pore space and fractures, or of all three.

Psyche's metal regions may resemble the texture of the Hoba meteorite on the small scale. The Hoba meteorite, about 3 meters across, lies where it fell in Namibia (https://en.wikipedia.org/wiki/Hoba_meteorite). Its surface may be an example of what metal bedrock might look like on this scale, though entry through Earth's atmosphere may have altered its appearance.

The color of any metal regions, however, remains speculative; Hoba is oxidized from being on Earth, and Psyche's metal regions will be affected mainly by space weathering and by interactions with silicates.

Based on bulk density some writers (*e.g.* Viikinkoski et al (2018)) have proposed Psyche might be a mixture of silicate and metal, perhaps analogous to one of the following meteorites:

The Estherville mesosiderite (image from Ebay seller: meteoritemadness)

The IVA iron Steinbach from http://www.marmet-meteorites.com/id3.html

One of the greatest challenges we face is trying to extrapolate to what features will look like on the scale of the whole, 200-km wide body. Grain-scale features, like those above, will be invisible. But bulk density is also consistent with a largely metal body with silicate regions on the kilometer scale, either from fallback of rock from the parent body, or later impacts. In fact, whether Psyche has an intimate mixture of rock and metal on the scale of the images above or not, it almost certainly has rock on its surface from impactors. Rock regions associated with shallow impacts may be fallback from its parent body (low relative velocity produces little cratering)

The appearance of fractures is even harder to anticipate than is the appearance of the surface solids.

COMPOSITION OF THE SURFACE JUDGED FROM REMOTE SENSING DATA

Conclusions on Psyche's surface surface composition remain elusive.

Hardersen et al (2005) used near IR spectral evidence to describe Psyche as a body mostly of metal, with ~10% of high-magnesian pyroxenes on its surface, consistent with reducing conditions. Shepard et al

(2017) concurred with the conclusion of a metal surface, but added information about albedo differences, particularly in a crater near the south pole of the body. Then, using the Hubble Space Telescope's Space Telescope Imaging Spectrometer, Becker and al. (2017) concluded that (16) Psyche's UV spectrum between 0.16 - 0.3 μm is inconsistent with significant amounts of pyroxene on the surface. At almost the same time, Spitzer Space Telescope data in the mid-infrared (5-14 μm) indicates that (16) Psyche is most likely a smooth metallic body with fine-grained (< 75 μm in grain size) silicates intermixed with iron grains (Landsman et al 2018).

Takir et al (2016) reported a 3-μm spectral absorption feature, indicting hydroxyl or water, in the region of Shepard's crater (the water or hydroxyl is likely bound into crystalline silicates, and is not free ice).

Together, this data is consistent with a metallic body with some silicate (possibly orthopyroxene-dominated) regions, and a crater in the southern hemisphere perhaps caused by a water-bearing chondritic impactor, but with a critical caveat: Psyche's spectrum is almost entirely flat and devoid of features (Binzel et al 1995, Johnson & Fanale 1973), and that precludes a definitive diagnosis of metal or silicate. A flat spectrum is similarly observed on Lutetia (Coradini et al 2011), and Lutetia is now known to have a silicate surface. The planet Mercury has a similarly flat spectrum (McClintock et al 2008). Therefore, the spectral information for Psyche is inconclusive as to composition.

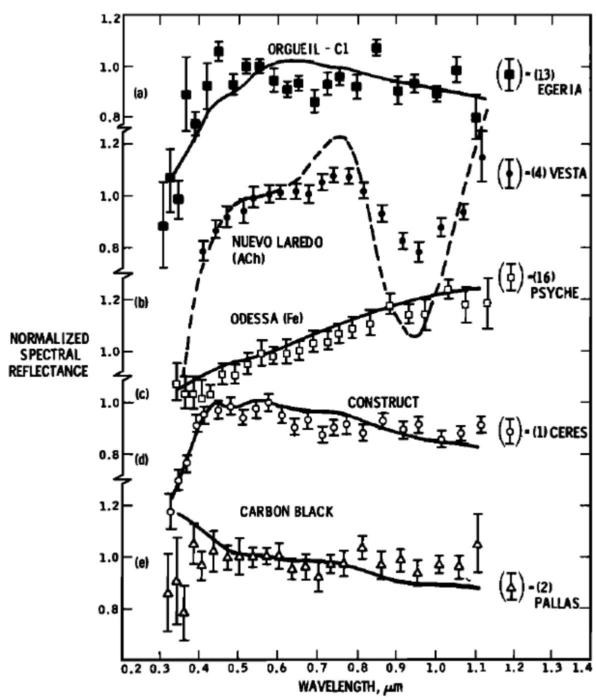


Fig. 16. Normalized spectral reflectance (0.3–1.1 μm) for five asteroids compared with laboratory reflectances of meteorites, our mixture of montmorillonite and carbon black, and pure carbon black. The asteroid spectral reflectances are from *Chapman et al.* [1973] and *McCord et al.* [1970]. The curve for Nuevo Laredo also comes from *McCord et al.* [1970].

A still-relevant 46-year-old comparison between a Psyche spectrum and the spectrum of an iron meteorite, from Johnson and Fanale (1973).

Finally, polarimetry may be definitive: Dollfus et al. (1979) comparing the change in polarization of reflected light of metal materials to M-type asteroid polarimetry:

> *The polarimetric signature of the light reflected by the so-called M-type asteroids indicates that these bodies cannot be made of silicates. Nor are their surfaces metallic fractures. Their surface texture is a powder of small metallic fragments with grain diameters around 20 to 50 μm.*

HILLS AND SLOPES

Slopes of movable soil determined not just by the geologic processes that create topography, but by the nature of the material and the size (gravity) of the body.

One of the key results from study of asteroid Vesta is that its surface is intensively populated with hills and slopes. Vesta's topography to radius ratio *(DR_{topo}/R)* ~30%, meaning that topography locally adds or subtracts 1/3 of the body's average radius! This compares to a ~1% ratio for the Moon and Mars. Some of this huge radius ratio is caused by the two giant impacts at the south pole (Veneneia and Rheasilvia) and their attendant excavated holes, along with the fallback of their ejecta in equatorial and northern latitudes.

Many small bodies show craters from one or more huge impacts, and Psyche is suggested to have a similarly large impact near its south pole. Shepard et al (2017) identified these features as shown below in color, and beneath that the similar results of Viikinkoski et al (2018).

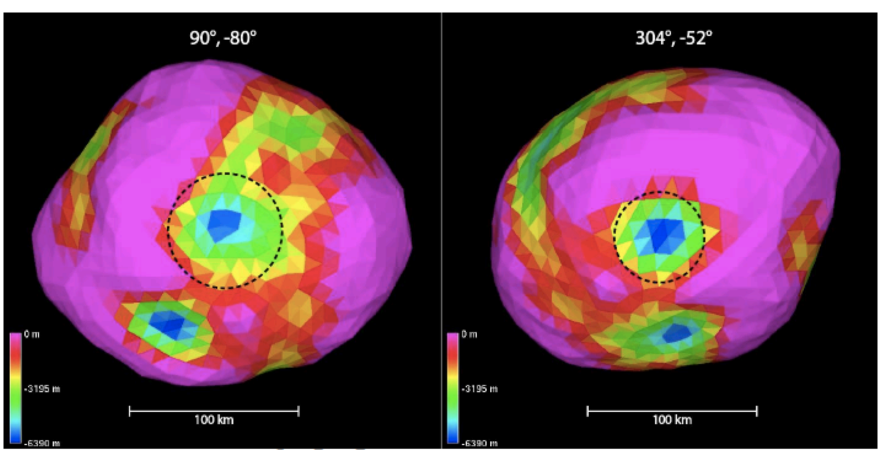


Figure 10 from Shepard et al (2017).

Figure 10. Illustration of two depressions on Psyche. The topography has been color coded to show the dynamic elevation (see text); values > 0 km are saturated in pink to emphasize the depressions. The views are centered on the longitude and latitude given at the top of each figure, and these approximate the position of each feature. The left figure shows the wider and shallower depression (D1); the dashed circle is 67 km wide. The right figure is centered on the smaller but deeper depression (D2); the circle is 53 km in diameter. We assign uncertainties of ±15 km (approximately one triangular facet) for each diameter estimate.

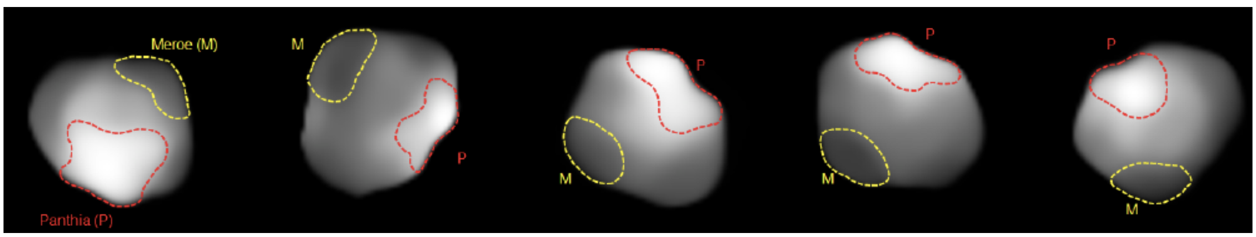
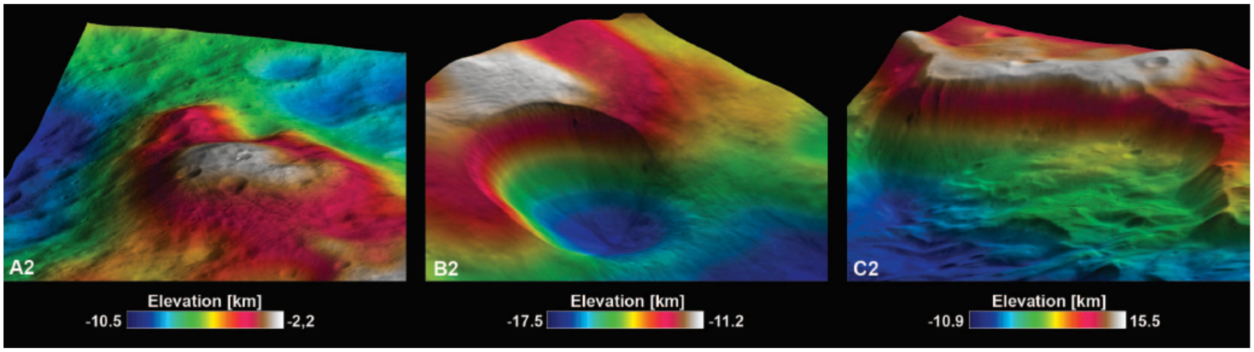


Figure 1 from Viikinkoski et al (2018). The high albedo feature outlined in red is thought to be a crater with radius 80 – 100km. The low albedo feature outlined in yellow is thought to be ~90km in diameter, and ~10km deep. (Note that the IAU does not want anything named prior to our spacecraft being in cruise, and that these suggested names are frowned upon and should not be perpetuated.)

From these results alone, the topography to radius ratio *(DR_{topo}/R)* for Psyche is likely to be at least 10%.

The shapes of craters on Psyche will be of great interest, especially if there are large areas of metal. Many solar system bodies have, upon close exploration and inspection, yielded new shapes and kinds of craters. Vesta has many asymmetric craters, formed by impacts on steep slopes, which results in a sharp upslope crater rim, and a muted downslope crater rim (because of preferential accumulation of ejecta downslope).



Wide altitude range shown in color, draped onto surface textures for rocks material on Vesta. Figure 3 from (Jaumann et al 2012).

The angle of repose of freely moving grains is higher on smaller bodies: lesser gravity allows grains to pile at higher angles before slipping down. Ermakov et al. (2019) finds that the angle of repose on Vesta and Ceres is around 34°, while on the Moon and Mars it is closer to 30°, and on the Earth lower still. This means that where regolith is formed on asteroids, we can expect it to pile into steeper slopes than we are used to seeing on Earth.

Psyche's mass is 2.28×10^{19} kg (Baer et al 2011), while Vesta's in 2.589×10^{20} kg (Google, so I assume this is close enough to right). Therefore, with Psyche's even lower gravity, its angle of repose may be even higher than that of Vesta.

We do not know if metal forms a regolith at all. Regolith may be mainly rocky material, either native to Psyche's parent body, or delivered by later impacts. And we do not know the nature of metal regolith, if it exists: is each grain less regular, and therefore more interlocking, and therefore capable of forming even steeper slopes? Or would it be mainly smooth tektites formed by impacts into metal, and therefore slipperier and forming shallower slopes? See further caveats below.

Size of regolith materials: sand, pebble, cobble, boulder?

The grain sizes of regolith on asteroids can be predicted from Earth-based observations including thermal, polarimetric, photometric, and spectroscopic data (*e.g,* (Hiroi et al 1994)). Capria et al. (2014) used VIR thermal data to estimate the thermal inertia of Vesta's surface, and thereby estimate the surface particle size range. As they note, there are a number of parameters that determine thermal inertia, and grain size is only one of them (next two paragraphs paraphrased from Capria):

> *Thermal inertia is a function of the thermal conductivity, the density, and thermal capacity of the material and depends on regolith particle size and depth, degree of compaction, exposure of rocks, and composition in the first centimeters of the surface. Thermal inertia provides a quantified expression of how fast a material is able to store heat during the day and to release it at night. As such, it is the key property controlling surface temperature variations on airless bodies and is a*

sensitive indicator of the presence of dust, regolith, or rock, since these materials are more or less thermally insulating.

Thermal inertia is defined as $TI = \sqrt{K\rho c}$ with units of J m^{-2} $s^{-0.5}$ K^{-1}, where K is the thermal conductivity, ρ is the density, and c is the specific heat. For silicate rocks, dust-sized materials have low values of thermal inertia (5–30 J m^{-2} $s^{-0.5}$ K^{-1}) [Putzig, 2006]; sand-sized particles have higher values (i.e., about 400 J m^{-2} $s^{-0.5}$ K^{-1} for Mars [Mellon et al., 2000] that are higher still on an atmosphere-less body [Presley and Christensen, 1997]); and rocks and exposed bedrock have values sometimes higher than 2,500 J m^{-2} $s^{-0.5}$ K^{-1}) [Jakosky, 1986].

Using thermal inertia to solve for grain size therefore gives somewhat non-unique answers; the exact density, thermal conductivity, and specific heat of the material cannot be known, because all observed planetary surfaces are mixtures of various crystalline and non-crystalline materials, and also because the mixture of grain sizes and their compaction are not known.

Capria et al. (2014) divides Vesta into regions of thermal inertia: 10 ± 5, 20 ± 10, 30 ± 10, 40 ± 10, and 50 ± 5 m^{-2} $s^{-0.5}$ K^{-1}, and they conclude that Vesta has a regolith with sizes and properties similar to that of the Moon, with a size range from microscopic to multi-meter blocks. (For a more complete methodology for calculating grain size that unfortunately does not consider Psyche, see Gundlach and Blum (2013)).

Vesta’s regolith is up to 1 km thick, but variable in thickness according to Denevi et al. (2016). The evidence that regolith is a thick layer on Vesta, the Moon, and other bodies indicates that it is created primarily by meteoroid bombardment. Thus, to speculate about regolith on Psyche, we need to consider the likely outcomes of bombardment on metal in addition to the more familiar bombardment on rock.

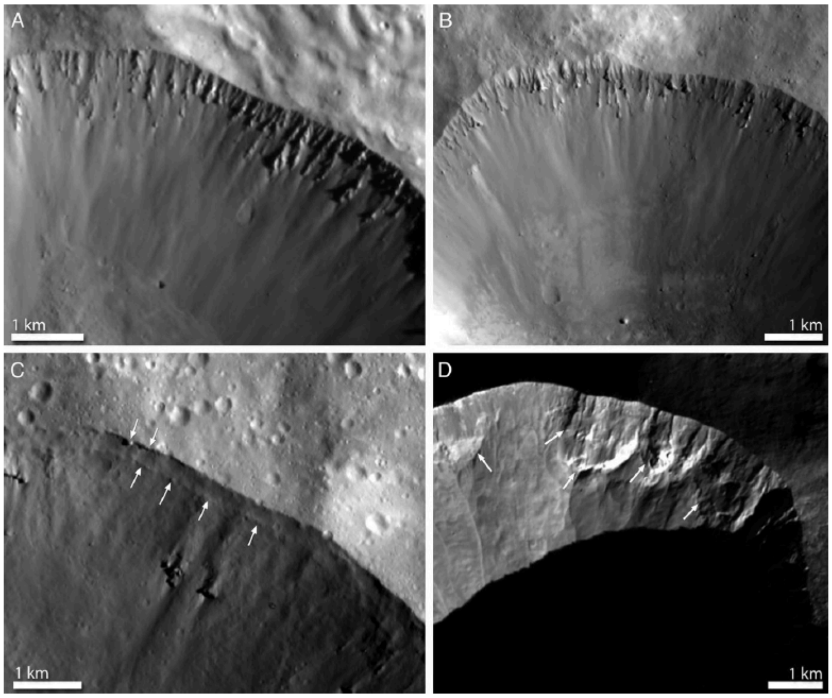


Fig. 3. Examples of exposures of coherent material within vestan crater walls. A) Spur-and-gully–type features in the wall of a ~15 km crater centered at 58.7°S, 200.7°E (image FC21A0014923_11355163605F1A). B) Spur-and-gully–type features in the wall of a ~12 km crater centered at 32.8°S, 294.8°E (image FC21A0015762_11363045345F1A). C) A resistant layer ~250 m below surface (lower arrows) and a possible resistant layer and overhang of material at the surface (upper arrows). Crater is ~22 km in diameter, scene centered at 40.0°S, 205.5°E (image FC21A0015710_11361221112F1A). D) Competent material just below the rim of the 10.5 km crater Arruntia at 40.0°N, 72.1°E (image FC21B0017965_12033014506F1D).

Bedrock shows in some crater walls on Vesta: Figure 3 from Denevi et al. (2016).

Presumably impacts into a metal substrate will cause fracture from shock and thus production of a megaregolith (kilometer-scale displaced bedrock units) in the case of giant impacts, and perhaps blocks in the meters to tens-of-meters range. Will blocks in this size range remain angular and intact, a breccia, or will the heat transfer properties of metal partially melt anything broken on this scale? Will these blocks be angular breccia, or effectively giant tektites, or both, or a hybrid?

At least some data exists for smaller tektites, which can be confidently predicted for the surface of a metal asteroid. Ames gun experiments by Simone Marchi and Carol Polanskey for our project have yielded a variety of metal microtektites.

We will therefore need to think about the relative behaviors of mm- and cm-sized metal tektite spheres, dumbells, and commas interacting silicate particles. Silicate particles may exist on smaller scales still, if they are preferentially pulverized by impacts and if metal tektites have some smallest size range; these interactions and aspects are unknown.

Shaking from impacts and sliding on hillslopes may sort the material. Would we see larger particles falling downward and the surface dominated by fines, or the reverse? (These effects are commonly called the Brazil nut or reverse Brazil nut effects, named after the ways assorted nuts sort in containers that are shaken.) Metal tektites and shards from impact may pool in the bottom of craters, or appear as ejecta rays. The interactions of metal and silicate particles, thus, are possibly complex and difficult to predict.

Summary

Psyche probably has the following characteristics:

- Metal and rock coexisting on a centimetric scale and on a kilometer and greater scale
- Fractures and pore space, possibly hidden under regolith
- Rock regolith on many scales, perhaps extant only regionally
- Metal tektites and blocks but possibly no persistent or deep metal regolith
- Topography on a scale of at least 10% of the average radius

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