THE MAGNETIC FIELD SIGNATURE OF A FERROVOLCANIC (16) PSYCHE S. W. Courville[^1], J. G. O’Rourke[^1], C. J. Bierson[^1], L. T. Elkins-Tanton[^1], D. A. Williams[^1], B. P. Weiss[^2], R. Oran[^2], C. T. Russell[^3], 1Arizona State University, Tempe, AZ. 2Massachusetts Institute of Technology, Cambridge, MA. 3University of California at Los Angeles, Los Angeles, CA. *swcourvi@asu.edu.

**Introduction:** NASA’s Psyche mission launched in October 2023 and will arrive at the asteroid (16) Psyche in 2029. The asteroid may be a metal-rich protoplanet from the dawn of the solar system. A key objective of the mission is to test whether (16) Psyche formed from a metal core [1]. Once thought to be an entirely metal, exposed iron core of a protoplanet (i.e., [2]), recent density estimations now suggest that (16) Psyche is 30-60% metal by volume [3,4]. This means that (16) Psyche could still have a metal core, but it must also contain void space and/or less dense silicates [5].

From telescopic observations of (16) Psyche’s surface, de Kleer et al. (2021) found that the asteroid must have at least 20% metal on its surface [6]. (16) Psyche’s shape indicates a history of large impacts [7]. Possibly, it was once a protoplanet with an iron core that was destroyed by impacts and then reaccreted into a mix of metal and silicates. However, the patchiness of surface metal signatures might suggest another process: ferrovolcanism.

Ferrovolcanism is the hypothetical process by which a molten core that solidifies inwardly could erupt sulfur-enriched, molten iron upward into an overlying mantle, and perhaps to the surface [8,9]. The Psyche mission can test this hypothesis with its suite of instruments. The Imager will search for evidence of ferrovolcanic eruption features [1]—and the Neutron Spectrometer will hunt for localized concentrations of metal on the surface [1]. Here, we highlight open questions about the mechanics and plausibility of ferrovolcanic eruptions. And we explore how Psyche’s Magnetometer can work together with the other instruments to look for subsurface magnetic records of ferrovolcanism.

**Can iron-rich core liquids be forced, as dikes, into a silicate mantle?** Ferrovolcanism, as proposed by Johnson et al. (2021), could occur during the solidification of a molten iron core that contains sulfur [8]. Assuming pure Fe solidifies first, the remaining molten material becomes enriched in S, eventually reaching the Fe-S eutectic point, ~31 wt.% S, where Fe and FeS both solidify. If core solidification occurs inwardly, perhaps as the growth of dendrites [2], then pockets of sulfur-enriched iron melt become trapped within solidified iron. Because the pockets of melt are less dense than the surrounding pure iron, they experience pressure and a buoyancy force upward. The pressure gradient could force the intrusion of sulfur-rich iron alloy into the overlying mantle [8,9]. The intrusions may form metallic dikes in the mantle (e.g., Fig. 1). However, the intruding metal would be denser than the silicate mantle, thus it may spread laterally onto the core-mantle boundary depending on the strength of the mantle. An analog would be Brumalia Tholus on (4) Vesta, which is interpreted as a laccolith of denser diogenitic material pushing through a more howarditic-eucritic crust [10]. The geometry and extent of intrusions determine whether they may be detectable by the Psyche mission.

**Could magnetized dikes be detected from orbit?** Ferrovolcanism may be an origin for pallasite meteorites [8]. Paleomagnetic studies of the main group pallasites indicate that these meteorites acquired remanent magnetization within the mantle of a protoplanet [11]. Eruptions of iron-rich material into the rocky mantle could create dikes that, when cooled, acquire remanent magnetization from a magnetic core dynamo. A ferrovolcanic world may, therefore, contain magnetized dikes of pallasite-like material (e.g., Fig. 1).

**What is the fate of sulfur during core formation?** Ferrovolcanism presupposes gradual sulfur enrichment as the core solidifies. However, studies of core compositions suggest that, at the onset of core solidification, the molten material would separate into an immiscible FeS fluid and the remaining metal alloy [14]. Thus, (16) Psyche’s core may have differentiated into a metallic core with an overlying troilite (FeS) layer. It’s unclear how this structure reconciles with ferrovolcanism. We will analyze various core compositions to determine eruptive potential.

**Figure 1. Ferrovolcanic dikes might record remanent magnetization.** Sulfur-enriched molten iron may erupt into the mantle during core solidification. If a dynamo operates within the solidifying core, the dikes could acquire magnetization as they cool in the mantle.
Key to answering whether ferrovolcanic dikes exist, and whether they would be magnetically detectable, is determining what the core fluid composition is and whether the silicate mantle can support upward intrusion of core fluid. Here, we assess whether dikes may form on (16) Psyche with numerical modeling.

**Methods:** We use 1D thermal conduction and convection models as described by ref. [13] to model the thermal history of (16) Psyche. Fig. 2 displays a possible thermal evolution, beginning when (16) Psyche separates into a metallic core and an overlying silicate mantle. From ~0.7 to 7 Myr, the mantle is convective. From then on, the mantle is conductive. Fig 2. assumes an immiscible S fluid does not form. After ~18 Myr, the core-mantle-boundary reaches the Fe-S liquidus temperature and begins solidifying pure Fe, enriching the rest of core in sulfur. Based on ref. [8], Fig. 2 also shows the height that a ferrovolcanic dike may reach into the mantle. We evaluate the magnetic detectability of a dike [14, 15] assuming it becomes magnetized at the strength observed in iron meteorites (Fig. 3).

**Results and Discussion:** For (16) Psyche to display ferrovolcanic dikes that are magnetically detectable, we find that eruptions of core fluid on the order of ~10 km must occur into the silicate mantle. The ferrovolcanism hypothesis is promising for (16) Psyche because it could reconcile the asteroid’s density and heterogeneous, metal-rich surface [1]. Magnetometry provides a synergistic investigation because it could unveil the extent of subsurface dikes and tie the dikes to the asteroid’s dynamo evolution. Based on experience at (4) Vesta [16], it is unlikely that surface eruption features survive intact, and instead are pulverized by impacts over Solar System history, so subsurface evidence of ferrovolcanism may be crucial. However, several open questions remain about the plausibility of iron-rich fluids erupting from a solidifying core. If ferrovolcanic-like eruptions are plausible, then we predict that the observed magnetic field of (16) Psyche could be consistent with dike structures. Measurements of (16) Psyche’s magnetism are thus essential for understanding the compositional and thermal evolution of (16) Psyche’s interior.

**Figure 3. Magnetic field strength from magnetized ferrovolcanic dikes.** As a function of the metallic core depth, the curves plot the approximate magnetic field strength 75 km above (16) Psyche’s surface from a dike with a magnetization strength of $10^{-3}$ Am$^2$/kg$^1$ [14].