FERROVOLCANISM, PALLASITES, AND PSYCHE. B. C. Johnson[1*], M. M. Sori[2], and A. J. Evans[1], [1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, USA (*Brandon_johnson@Brown.edu), [2]Department of Planetary Science, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA.

Introduction: Recent work by Scheinberg et al. [1] suggests that solidification of the 100 km radius core of a mostly mantle-stripped body may progress from the outside-in mediated by the growth of iron-nickel dendrites. Such growth is now supported by paleomagnetic measurement of iron meteorites [2] and is suggested even for bodies with intact mantles [3]. The late stages of this dendritic growth results in pockets of isolated sulfur-enriched iron-nickel melts surrounded by solid iron-nickel [1]. Here we show that these isolated low density melt pockets should collapse, causing sulfur-enriched iron-nickel melts to propagate in dikes. Thus, core material of the cooling planetesimal may be intruded into the rocky mantle of a planetesimal or even erupted onto its surface. We refer to these processes collectively as ferrovolcanism and suggest it as a possible origin for pallasite meteorites. We then discuss implications for Psyche and other metal-rich worlds.

Ferrovolcanism: For a 100-km core radius, the region of iron-nickel dendrites and unsolidified pockets of sulfur enriched melt is ~10–30 km in scale [1]. Individual kilometer-scale dendrites would be stable for ~10–10^5 yr depending on assumed viscosity; this timescale is inversely proportional to the size of the dendrites [1]. Figure 1 shows the magmatic overpressures associated with maintaining a buoyant pocket of sulfur enriched melt with a vertical scale h. The overpressure depends on sulfur content, h, and gravitational acceleration (size of the core). Even though our calculations ignore the possibility of excess pressure in these possible magma chambers, for melt pockets larger than 10 km in scale, overpressures capable of causing magmatism occur. For comparison, terrestrial dikes have typical excess pressures of a few to 10 MPa [4]. Thus, our conservative estimates suggest that these melt pockets are likely capable of causing dike initiation.

Next, we consider how far such a ferrovolcanic dike could propagate into the mantle of a body or if volcanism (i.e., surface eruptions) might occur. It is important to note that eruption can occur even when the magma is much more dense than the surrounding material (e.g. mare basalts) [4]. Figure 2 shows an estimate of how far into the mantle of a body a core melt might propagate using a very simple energy balance calculation.

Although simple, these calculations are relatively conservative and assume the top of the magma chamber is at the core-mantle interface. Considering deeper sources, including some initial excess pressure in the magma chamber, and considering pre-existing stress gradients could all lead to conditions more conducive to eruption. Even neglecting these effects, our calculations suggest that ferrovolcanic eruptions may be possible, especially for sulfur-rich melts and bodies with relatively thin mantles.

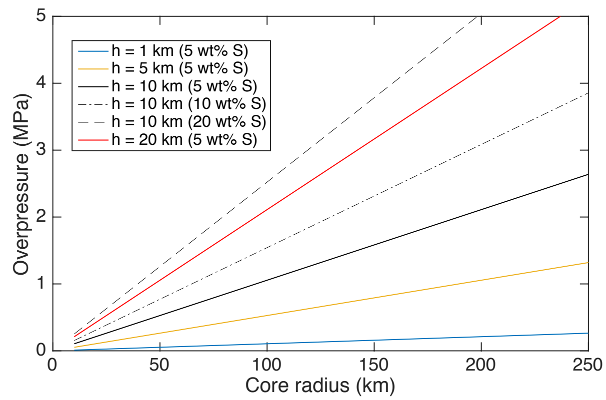

Figure 1: Overpressure calculated as $P_o = (\rho_{Fe} - \rho_{FeS})hg/2$, where $\rho_{Fe} = 7500$ kg/m^3 is the assumed density of solid iron [1]. The density of sulfur rich melt is given by $\rho_{FeS} = 6950 - 5176\chi - 3108\chi^2$ kg/m^2 where χ is atom fraction sulfur [5]. Note eutectic composition is 31wt% S [e.g. 1].

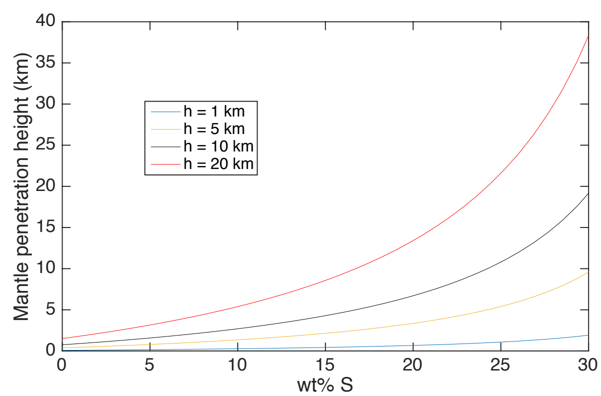

Figure 2: Mantle penetration of ferrovolcanic dike as a function of sulfur content. The penetration height, t, is calculated by setting the magmatic overpressure (e.g. Figure 1) equal to the negative buoyancy force $t(\rho_{FeS} - \rho_{mantle})g = (\rho_{Fe} - \rho_{FeS})hg/2$, where $\rho_{mantle} =$ 3300 kg/m^3 is the assumed mantle density. Note t is independent of g and core size.

Pallasites: Pallasites are an enigmatic class of meteorites composed of olivine crystals entrained in a matrix of iron-nickel metal [6]. Many pallasites have a low iridium content implying their metal matrix is sourced from a highly evolved up to ~80% crystalized metallic melt [7]. Ferrovolcanism offers a mechanism to explain pallasites as intrusions of evolved core magmas into the olivine-rich mantle of a body. Main group pallasites have an average sulfur content of 2.3 wt% suggesting intruded core material would have a sulfur content of ~5 wt% [6]. This sulfur content is inconsistent with a highly evolved melt leading some to consider the possibility that sulfur-rich pallasites, like Phillips County [8], are simply underrepresented in the meteorite record [9]. Although the amount of sulfur in pallasite source material is debated, even at typical ~5 wt% sulfur, core material could have been intruded a few km into the mantle of the pallasite parent body and possibly farther if the magma chamber is further pressurized (Figure 2).

Paleomagnetic studies show that pallasites record the magnetic field of their pallasite parent body [10]. To record such a field, pallasite source material must have been cooled to below ~360 K while a liquid core was still convecting [10]. Thermal models of [10] assuming conventional outward core growth suggest that pallasites originated from less than 40 km deep in the mantle of a 200-km diameter body to achieve these low temperatures. The thermal models of [1] with inward core growth, however, suggest even outer core material may reach these low temperatures while the inner portions of the core remain liquid. Although further thermal evolution models with inward core solidification are warranted, it is likely that a ferrovolcanic origin for pallasites is consistent with paleomagnetic measurements and thermal constraints [10, 11] even if the intruded core material does not reach the shallow mantle.

Psyche: Our findings have implications for Psyche, an asteroid that is the target of an upcoming NASA spacecraft mission [12]. Psyche was argued to be an intact planetary core on the basis of high density and radar albedo measurements, but more recent and precise density estimates have made this interpretation more uncertain. The most recent estimate of bulk density is 4160 ± 640 kg/m^3 [13], a number that likely implies an important compositional role for metal but is much lower than the density of iron meteorites. One possibility for Psyche's structure is that it represents the core of an ancient, differentiated planetesimal that was exposed by hit-and-run collisions [14], and contains high macroporosity. A second plausible structure is that it represents an undifferentiated mix of rock and metal, and perhaps is the parent body of the mesosiderite class of meteorites [13].

Ferrovolcanism offers a third possible structure for Psyche consistent with density measurements and observations of both metal [15] and orthopyroxene [16] on the surface. We considered a two-layer structure where a metal core is surrounded by a silicate mantle. Assuming an average diameter of 226 km, a core density of 7000 kg/m^3, and a mantle density ranging between 2500–3500 kg/m^3, we calculate that an average mantle thickness as low as 22 km is consistent with bulk density estimates (Figure 3). This silicate thickness is compatible with ferrovolcanism if sulfur content and pocket size are sufficiently high (Figure 2). Ferrovolcanism may have transported core material to the surface, causing the radar detections of metal. Testing this hypothesis of Psyche as a differentiated rock-metal body with ferrovolcanic surface units can be achieved by the upcoming Psyche mission. Furthermore, such a structure would be consistent with the exciting possibility that Psyche is a pallasite parent body.

References: [1] Scheinberg A. et al. (2015) *JGR Planets, 121,* 2–20. [2] Bryson J. F. J. et al. (2017) *EPSL, 472,* 152–163. [3] Williams Q. (2009) *EPSL, 284*, 564–569 [4] Rubin A. M. (1995) *Annu. Rev. Earth. Planet. Sci., 23,* 287–336. [5] Morard G. et al. (2018) *American Minerologist, 103,* 1770–1779. [6] Boesenberg J. S. et al. (2012) *GCA, 89,* 134–158. [7] Scott E. R. D. (1977) *Mineralogical Magazine, 41,* 265–272. [8] Scott E. R. D. (1977) *GCA, 41,* 693–710. [9] Ulff-Møller F. et al. (1998) *MAPS, 33*, 693–710. [10] Tarduno J. A. et al. (2012) *Science, 338*, 939–942. [11] Bryson J. F. J. et al. (2015) Nature, 517, 472–475 [12] Elkins-Tanton L. T. et al. (2016) *47th LPSC* 1631. [13] Drummond J. D. et al. (2018) *Icarus, 305*, 174–185. [14] Asphaug E. et al. (2006) *Natur,e 439*, 155–160. [15] Shepard K. et al. (2017) *Icarus, 281*, 388–403. [16] Hardersen P. S. et al. (2005) *Icarus, 175*, 141–158.

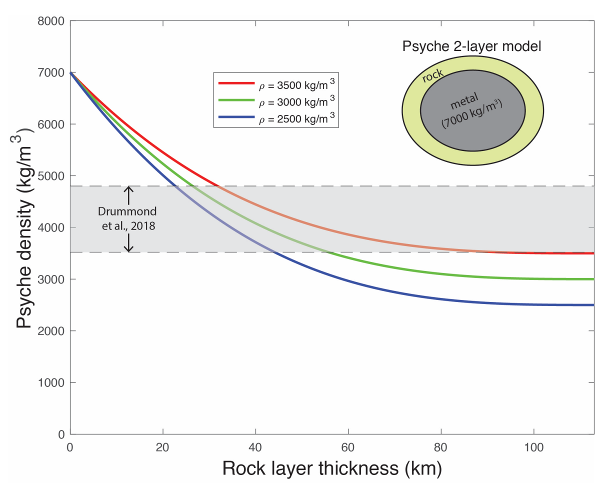

Figure 3: Modeled density of Psyche assuming a two-layer structure of a metal core and a rocky mantle compared with the observed density [11].