POROSITY EVOLUTION OF PSYCHE AND OTHER M-TYPE ASTEROIDS. Fiona Nichols-Fleming[1*], Alexander J. Evans[1], Brandon C. Johnson[2,3], and Michael M. Sori[2], [1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, USA (*fiona_nichols-fleming@brown.edu), [2]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN, USA, [3]Department of Physics and Astronomy, Purdue University, West Lafayette, IN, USA.

Introduction: M-type asteroids, of which 16 Psyche is the largest [1], are generally hypothesized to have metal-rich surfaces. This hypothesis is due to their relatively featureless VIS/NIR spectra [2–4] as well as their high average radar albedos [1, 5–7]. The masses, and therefore bulk densities, of these bodies still have high uncertainty, but a few robustly have inferred densities much lower than that of iron requiring either a very large bulk porosity (>40 vol%) or a substantial lower density component. In particular, Psyche's density of $4{,}000 \pm 200$ kg/m^3 [8] is lower than the uncompressed densities of Mercury, Venus, and Earth. This current Psyche density estimate would require a pure iron Psyche to have a bulk porosity of ~52 vol% [9].

M-type asteroids are generally considered to be the parent bodies of iron meteorites [10, 11]. Many of the magmatic iron meteorites show evidence for fractional crystallization indicative of differentiated parent bodies [12] as well as cooling rates that imply a lack of an overlying insulating mantle [13–15]. Therefore, a commonly invoked formation hypothesis for M-type asteroids is that these bodies are remanent stripped cores of differentiated bodies [13]. These stripped cores could be produced by one or more hit-and-run collisions within the first ~1.5 Myr of the solar system, after which the newly exposed cores would continue to cool and could be further fractured by subsequent impact events [13, 16, 17].

Here we identify the upper limits for temperatures at which high porosities can be retained in pure iron bodies with masses on the order of 10^{17} – 10^{19} kg by considering the effects of self-gravity and viscous closure of pore space. We find that a Psyche-mass body would need to cool to and remain below 800 K to retain 52 vol% bulk porosity while lower mass iron bodies could be as warm as 925 K and retain similarly high porosities.

Thermal Evolution Model: To determine the temperature limits for high porosity iron bodies, we use a 1-D forward time, central space finite difference model of thermal conduction coupled with porosity evolution for a spherical geometry. The initial temperatures of our models represent the conditions at the time when porosity is added to the iron body. Each model has an isothermal initial condition and a constant surface temperature of 137 K, the average surface temperature of Psyche [18]. We use the density of kamacite (7,780 kg/m^3; 19) for the metallic iron component following [9].

Although porosity, in general, can be removed via plastic failure and/or viscous pore space closure, pressures within Psyche and other M-type asteroids (< 70 MPa) are much lower than the strength of iron (~175 MPa; 20). Therefore, minimal porosity will be removed by plastic failure and the final porosity structure will depend primarily on viscous closure and the thermal evolution of the body. The change in porosity in our model is included as a function of viscosity and pressure following [21]. We assume a Newtonian viscosity and vary the thermal conductivity linearly with porosity, both of which may result in an underestimate of the porosity removed. Therefore, the critical temperatures determined in this work represent upper limits on the temperatures needed to retain a given porosity structure. Mass is conserved as described in detail in [22] and timesteps are recalculated after each step to maintain the numerical stability of the model.

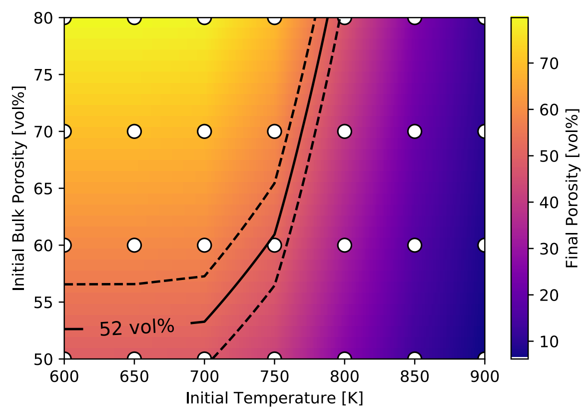

Figure 1. Final bulk porosities for pure iron Psyche models with initially uniform temperatures and porosity profiles. Locations of modeled runs are denoted by white circles. A bilinear interpolation was performed to fill the parameter space between models. The black line delineates the inferred bulk porosity for a pure iron Psyche of 52 vol% and the dashed lines indicate bulk porosities of 48 and 56 vol%, corresponding to the one sigma bounds for a pure iron Psyche based on the errors on Psyche bulk density as determined by [9].

Results: We use the mass estimate of Psyche from [9] to model a pure iron Psyche with initial isothermal temperatures of 600 – 900 K and initial uniform porosities of 50 – 80 vol%. The results of these models are shown in Figure 1 with a bilinear interpolation applied between model results. Generally, we find that for initial temperatures greater than 800 K, a pure iron Psyche cannot maintain the high bulk porosities required to match Psyche mass and density estimates. At temperatures greater than 800 K, porosity is annealed on the timescale of millions of years. The sharp corners in the contour line for 52 vol% porosity shown in Figure 1 are due to the highly sensitive relationship between viscosity and temperature.

Iron bodies less massive than Psyche will have internal pressures lower than 70 MPa and therefore would experience the removal of porosity to a lesser extent than a pure iron Psyche at similar temperatures. Using masses between 10^{17} and 5×10^{18} kg, we model smaller iron bodies with initial isothermal temperatures of 750 – 950 K and initial porosities of 70 vol% to compare with our pure iron Psyche models. These masses were chosen to cover the effective diameter range of known M-type asteroids, which range from 32 ± 3 km (i.e., 413 Edburga) [7] up to ~222 km (i.e., 16 Psyche) [7,8], when bulk densities are assumed to match Psyche. The final bulk porosities of these models are shown in Figure 2 along with the pure iron Psyche models with the same initial porosity and temperatures and a bilinear interpolation between modeled results. Although high porosities (>40 vol%) can be maintained for temperatures up to 925 K for the least massive case considered, all of the modeled iron bodies must have had temperatures below 925 K before introduction of pore space to retain high amounts of porosity.

Implications: These models provide insights into the formation of high porosity, pure iron M-type asteroids. First, any surface remanent magnetization produced by an internal core dynamo on these bodies likely predates their porosity structure. This is because our models show an iron body must cool to at least 925 K to retain high porosities and the Curie temperature for iron is 1043 K [23]. Additionally, the location of the magnetic pole produced by an internal dynamo may not be well preserved for a highly porous iron body since the event that added porosity would have had to occur after the body cooled through its Curie temperature. If a disrupting impact was the source of porosity, the impact may have caused reorientation of magnetized materials and may obscure locations of paleopoles.

For an intact planetesimal or stripped core corresponding to the size of Psyche, the time to cool below 800 K [24–26] exceeds the estimated hit-and-run collision and catastrophic impact epochs of the early solar system [13, 27]. Because of this, a collision scenario for the formation of a highly porous, pure iron Psyche is not likely. Less massive M-type asteroids however, can retain high porosity at slightly warmer temperatures and would conceivably cool on timescales much shorter than 100s of Myrs, potentially permitting these small asteroids to be more readily explained as a porous metal bodies.

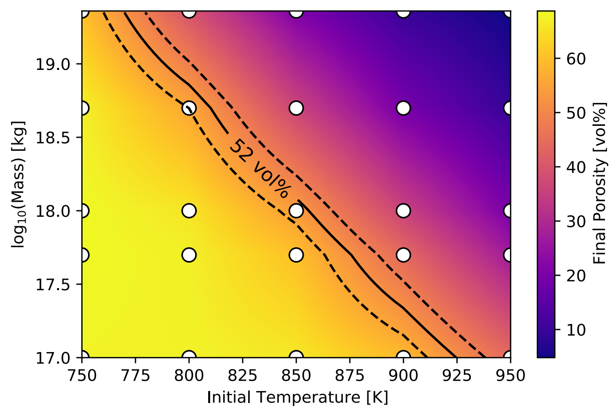

Figure 2. Final bulk porosities for iron bodies with initially uniform temperatures between 750 and 950 K and masses between 10^{17} and 2×10^{19} kg. In each case the initial uniform porosity is 70 vol%. Symbols and lines are as denoted in Fig. 1.

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