MODELING THE SIZE OF PALLASITE PARENT BODIES USING CONSTRAINTS FROM THE FUKANG PALLASITE N. Habib, D.N. DellaGiustina, D.S. Lauretta. Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, 85721. (nhabib@orex.lpl.arizona.edu)

Introduction: Pallasites are highly differentiated stony-iron meteorites containing Fe-Ni metal and olivine with minor troilite, chromite, schreibersite, pyroxene, phosphates, and other phases [1]. Pallasites are classified into four groups, Main-group, Eagle-Station group, Pyroxene bearing group, and ungrouped pallasites, based on siderophile trace-element abundances, olivine composition, and oxygen-isotope ratios [2]. Thus, pallasites represent a minimum of four different parent bodies; however, up to six parent bodies have been proposed to explain differences in Main-group pallasites alone [3-4].

Here we develop a model to determine the upper bound of the size of the parent body of Main-group pallasites, which are the most abundant type of pallasite (90-95%). We assume that pallasites formed at the core-mantle boundary of a differentiated planetesimal. Specifically, the model was developed using constraints from the Fukang pallasite. Our model applies to other pallasites, given appropriate boundary conditions.

Model and Derivation: To examine the conditions present at the core-mantle boundary of a spherical differentiated planetesimal, we model the pressure experienced in the body as a function of radius assuming hydrostatic equilibrium:

$$\frac{dP}{dr} = -\rho g \quad (1)$$

$$g = \frac{GM}{r^2} \quad (2)$$

In equation (1), P is the pressure of the parent body as a function of the radius (r), ρ is the total density of the parent body, and g is gravitational acceleration exerted by the body. Equation (2) defines the gravity term as a function of radius, the total mass of the parent body (M), and the universal gravitational constant (G).

We determine the total mass of the parent body by expressing the mass as a function of the total radius of the parent body and integrating this equation:

$$\frac{dM}{dr} = 4\pi r^2 \rho \quad (3)$$

This formulation allows us to simplify the hydrostatic equilibrium pressure equation as:

$$\frac{dP}{dr} = -\frac{4}{3}\pi G \rho^2 r \quad (4)$$

To integrate Equation 4, we must first define the density as a function of radius:

$$\rho = \begin{cases} \rho_{metal} & 0 < r \leq R_{metal} \\ \rho_{silicate} & R_{metal} < r \leq R_{Total} \end{cases} \quad (5)$$

where $R_{Total} = R_{metal} + R_{silicate}$ (6)

ρ_{metal} is the density of Fe-Ni metal

$\rho_{silicate}$ is the density of silicate

Note, given the equation for the total radius (6), we define the silicate radius as the radial length between the Fe-Ni metal core and planetesimal surface. This assumption of density as a linear piecewise function of the parent body radius provides a limitation on the final results because we assume the composition is solely silicate or Fe-Ni metal, instead of a mixture. To account for this limitation, we established upper and lower density estimates for both the silicate and Fe-Ni metal density values (Table 1). We then evaluated the pressure both at a lower bound (using the lower density estimates) and an upper bound (using the upper-density estimates).

Table 1 Upper and lower density estimates used to evaluate pressure at the core-mantle boundary as a function of radius

Lower Bound ρ_{metal}	7000	kg/m^3
Lower Bound $\rho_{silicate}$	2500	kg/m^3
Upper Bound ρ_{metal}	8000	kg/m^3
Upper Bound $\rho_{silicate}$	3000	kg/m^3

Finally, by evaluating the hydrostatic equilibrium pressure (Equation 4), we determine the pressure at the core-mantle boundary in terms of radius:

$$P|_{CMB} = \frac{2}{3}\pi G \rho_{silicate}^2 (R_{Total}^2 - R_{metal}^2) \quad (7)$$

We also evaluate the integral to determine the total pressure at the core of the planetesimal:

$$P|_{Core} = \frac{2}{3}\pi G \left[\rho_{metal}^2 R_{metal}^2 + \rho_{silicate}^2 (R_{silicate}^2 + 2R_{silicate} R_{metal}) \right] \quad (8)$$

Assumptions: We assume that the Main-group pallasite protolith started with different proportions of metal and silicates. We estimated a protolith for three different starting compositions that roughly match the H Chondrites (20 wt. % Fe-Ni metal), L Chondrites (10 wt. % Fe-Ni metal), and LL Chondrites (5 wt. % Fe-Ni metal). Given these assumptions, we developed a relationship for the fractional volume (F_R) of Fe-Ni metal to silicates in the parent body:

$$F_R = \frac{V_{metal}}{V_{silicate}} = \frac{wt\,\%\,Fe\text{-}Ni\,metal}{1 - wt\,\%\,Fe\text{-}Ni\,metal} * \frac{\rho_{silicate}}{\rho_{metal}} \quad (9)$$

Boundary Conditions & Evaluating the Size of the Main-group protolith: To solve for the size of the Main-group protolith, we write the fractional volume as a function of radius:

$$R_{Total} = R_{metal} \left(\frac{\alpha}{\alpha - 1}\right) \quad (10)$$

$$where \quad \alpha = (1 + F_R)^{\frac{1}{3}} \quad (11)$$

Using Equations 10 and 11, we derived the following expressions to evaluate the pressure experienced at the core-mantle boundary (CMB) and the pressure experienced at the core as a function of the fractional volumes (F_R) of silicate to Fe-Ni metal:

$$P|_{Core} = \frac{2}{3}\pi G R_{Total}^2 \left[\rho_{metal}^2 \left(\frac{\alpha-1}{\alpha}\right)^2 + \rho_{silicate}^2 \left(1 - \left(\frac{\alpha-1}{\alpha}\right)^2\right)\right] \quad (12)$$

$$P|_{CMB} = \frac{2}{3}\pi G R_{Total}^2\, \rho_{silicate}^2 \left(1 - \left(\frac{\alpha-1}{\alpha}\right)^2\right) \quad (13)$$

Boundary Conditions: We observed multiple inclusions hundreds of microns in length in Fukang. These inclusions contain a Cr-rich silicate, silica crystals, and k-rich orthoclase-normative glass. We identified the silica crystals as monoclinic tridymite using Raman spectroscopy [5] and further characterized this phase using Electron Probe Microanalysis (EPMA). The presence of tridymite provides a constraint on the size of the pallasite parent body since tridymite is a SiO_2 polymorph that only crystallizes in a narrow range of pressures (<0.40 GPa) and temperatures (870–1470 °C) [6]. The pressure stability for tridymite varies in the literature (0.15 – 0.40 GPa) due to the presence of impurities that catalyze its formation [7]. For this model, we constrain the radius of the planetesimal parent body by limiting the pressure at the core-mantle boundary to be within a tridymite pressure stability range of 0.15 – 0.40 GPa.

Evaluating the Size of the Main-group protolith: We plotted Equation 13 over a range of total planetesimal radius values from 0 to 700 km. We show the tridymite stability range pressures on the same figure as a pressure boundary condition at the core-mantle boundary. We evaluated Equation 13 as a function of upper density and lower density values to provide a range of radius values for the planetesimal (Fig. 1). We also evaluated the intersection of the curve at the upper and lower tridymite-stability pressures (Table 2 and Fig. 1). The results show that Fukang formed from a parent body no larger than 690 – 1350 km in diameter, assuming formation at the core-mantle boundary.

Table 2 Radius bounds for upper and lower density estimates for the pressure constraints provided by tridymite

Tridymite Pressure	Boundary Conditions	H-Chondrites Radius (km)	L-Chondrites Radius (km)	LL-Chondrites Radius (km)
15 GPa	Upper density estimate	345.45	345.33	345.31
15 GPa	Lower density estimate	414.53	414.40	414.37
40 GPa	Upper density estimate	564.12	563.93	563.89
40 GPa	Lower density estimate	676.92	676.71	676.66

Implications for Main-group Pallasites: The presence of tridymite allows us to provide an upper estimate on the diameter of Fukang's parent body (690 – 1350 km). Assuming that pallasites formed at the core-mantle boundary of a differentiated planetesimal, we conclude that Main-group pallasites likely originated from a large planetesimal. Our estimate is limited by the uncertainties in the silica phase diagram for tridymite as a function of purity.

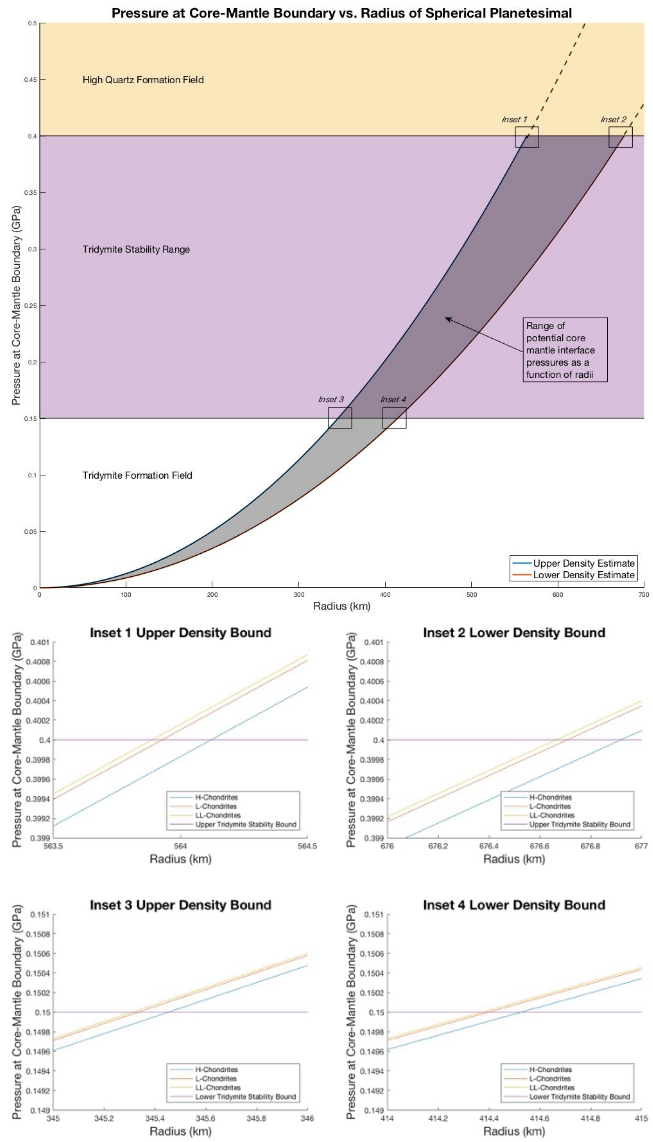

Figure 1 Range of parent body radii for Main-group pallasites assuming hydrostatic equilibrium pressure with upper and lower density estimates.

References: [1] Buseck (1977). GCA 41(6), 711-721, 723-740. [2] Yang et al. GCA 74(15), 4471-4492. [3] Bosenberg et al. (2012). GCA 89, 134-158. [4] Scott et al. (2010). Planetary Science Research Discoveries. [5] Lauretta (2010). LPSC XXXVII, #1462 [6] Swamy et al. (1994). Journal of Geophysical Research 99(B6), 11, 787-11,794. [7] Roy and Roy. (1964). American Mineralogist 49(7-8), 952.