DIFFERENTIATION IN PLANETESIMALS WITH APPLICATIONS TO ASTEROID (16) PSYCHE.

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Introduction: Differentiated planetesimals are thought to have accreted from primitive material within about two million years after formation of the first solids in the solar system (e.g., [1-9]). In this scenario, sufficient ^{26}Al was present to melt the interior of planetesimals larger than ~20 km radius and allow a metallic core to differentiate from a silicate mantle (early-forming planetesimals are thought range in size to as large as Vesta or larger). Over time the molten silicate portion would further differentiate into olivine- or pyroxene-rich cumulates and later-stage evolved silicate melts. The planetesimal would be capped with a lid of either primitive unmelted material, or magmatic eruptions from the interior (Fig. 1).

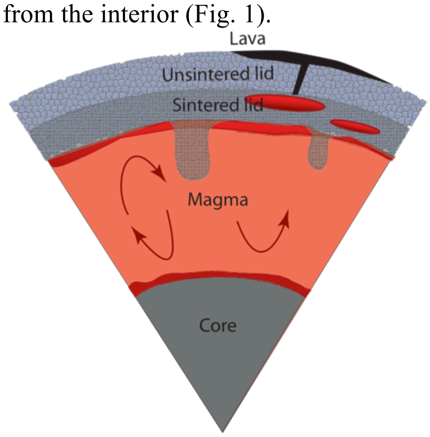

Fig. 1. Schematic cross-section of planetesimals internally melted by radiogenic heat.

Here we explore the likely compositional ranges of the silicate planetesimal interiors and consider their application to the possible silicate remnants on the surface of the asteroid (16) Psyche and in the IVA iron meteorites.

Application to Psyche: Psyche is a 240x185x145 km M-type asteroid, the taxonomic class most likely to be composed of iron [see also [10, 11]]. It has one of the highest radar albedos of all M-types, 0.58±0.15 [12], suggesting its surface is composed of powdered iron. Psyche's bulk density has been inferred from its perturbations on the orbits of other asteroids during mutual close encounters; these values are largely consistent with an exposed iron core: 6980 ± 580 kg m^{-3} [13], 6490 ± 2940 kg m^{-3} [14, 15], or 7600 ± 3000 kg m^{-3} [12]. In addition, Hardersen (personal communication) finds that the asteroid's visual albedo (0.23±0.05) and spectra match laboratory samples that are made of 90% Fe-Ni metal and 10% high magnesian pyroxene.

The surface of Psyche likely represents the core-mantle boundary of a differentiated body, the only such available for observation in the solar system.

How Psyche lost its mantle silicates is not well constrained, but the most widely accepted proposal is that one or more massive collisions stripped the body of its silicate crust and mantle, leaving behind an almost naked core. It appears to be impossible to achieve mantle stripping by hitting proto-Psyche with smaller planetesimals [e.g., [16]. The most plausible scenario to do this is a so-called hit-and-run collision [17] between a Vesta-sized and perhaps Vesta-like world and a much larger protoplanet. The event likely stripped the Vesta-sized world of its crust and mantle and created a surface that was 90% metal, Davis et al. [18] point out that the unstripped Psyche would be about the size of Vesta.

Connections with IVA irons: The class IVA iron meteorites have cooling rates from 100 to 6,000 K yr^{-1} [19, 20]. Yang et al. [19] find that their inferred cooling rates require that they came from a body about 150 km in radius that lacked an insulating silicate mantle. They further suggest that the body was likely the result of a hit-and-run collision between its parent body and a Moon- to Mars-sized impactor, and that Psyche is a candidate. Given that the IVAs are recent arrivals to Earth, their source is likely still in the asteroid belt. Whether Psyche is their source or not, the IVAs appear to have come from a stripped planetesimal core. Some IVAs are almost pure Fe-Ni metal, while others contain pyroxenes and silica [21].

The mantle that would result from magma ocean solidification on a planetesimal: Fig. 2 shows a range of bulk chondritic silicate compositions that are candidates for the mantle magma oceans on planetesimals. At the low pressures in planetesimals, almost all these possible bulk compositions would begin solidification by crystallizing olivine alone. Only for the most silica-rich bulk compositions at the lowest possible pressures would the first solids be pyroxenes.

Why is the first crystallizing mineral of interest? Settling requires low crystal fractions and sufficient time [22]. Thus, the first-crystallizing mineral is the one most likely to be the silicate remnant on the surface of Psyche, and it may be the silicates in pallasite meteorites, if they represent samples of the core-mantle boundary. This simple magma ocean analysis shows that olivine is the likely mineral in the overwhelming number of cases.

However, the silicate minerals in the IVA iron meteorites (and the possible silicates on Psyche) are pyroxenes, not olivine. Pyroxene may be formed through reduction of olivine at the very low oxygen fugacity conditions of the core [23, 24]. This still requires a very simple system, one with only olivine present. Wasson et al. [25] suggests that a tectonic event produced a eutectic-like liquid and injected it together with unmelted pyroxene grains into fissures in the solid metal core. This may be hard to support with a system that appears to contain only pyroxene, silica, and iron; where are the other silicate oxides?

Conclusions: The simplicity of the mineral assemblages in IVA irons, and possibly on the surface of Psyche, strongly supports successful crystal settling of olivine alone at the beginning of magma ocean solidification on an internally differentiated planetesimal. Later processes, such as impacts into silicate surfaces, or eutectic melts, would produce far more complex mineralogies.

The different compositions expected from silicate differentiation on planetesimals (olivine cumulates, pyroxene cumulates, primitive chondrites, and achondrites) could be discriminated from each other using measurements of abundances of major elements (Fig. 3).

References: [1] Miyamoto (1981) *LPSC*, 12, 1145. [2] LaTourrette (1998) *EPSL*, 158, 91. [3] Ghosh (1998) *Icarus*, 134, 187. [4] Young (1999) *Science*, 286, 1331. [5] Young (2003) *EPSL* 213, 249. [6] Merk (2002) *Icarus*, 159, 183. [7] Ghosh (2003) *MAPS*, 38, 711. [8] Sahijpal (2007) *MAPS 38.* [9] Elkins Tanton (2011) *EPSL*, 305, 1. [10] Magri (1999) *Icarus*, 140, 379. [11] Ostro (1985) *Science*, 229, 442. [12] Shepard (2008) *Icarus*, 195, 184. [13] Kuzmanoski (2002) *Ast & Astroph*, 395, L17. [14] Baer (2011) *ApJ*, 141, 1. [15] Lupishko (2006) *Solar Syst. Res.*, 40, 214. [16] Love (1996) *Icarus*, 124, 141. [17] Asphaug (2006) *Nature*, 439, 155. [18] Davis (1999) *Icarus*, 137, 140. [19] Yang (2007) *Nature*, 446, 888. [20] Haack (1996) *GCA*, 60, 3103. [21] Mittlefehldt (1998) Planetary Materials, 195. [22] Suckale (2012) *JGR*, 117, E08005. [23] Ruzicka (2006) *MAPS*, 41, 1959. [24] Scott (1996) *GCA*, 60, 1615. [25] Wasson (2006) *GCA*, 70, 3149. [26] Jarosewich (1990) *MAPS*, 25, 323. [27] Elkins-Tanton (2011) *EPSL*, 304, 326. [28] Stolper (1980) *CMP*, 74, 13.

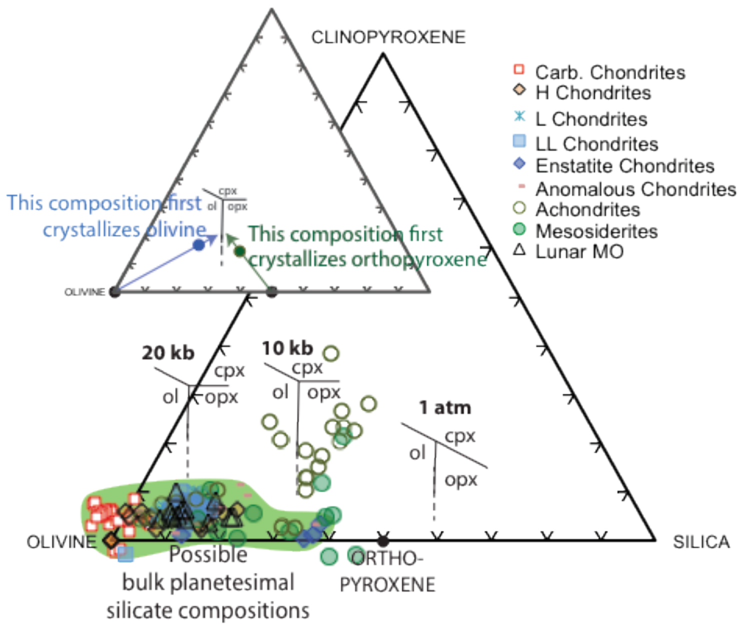

Fig 2. Bulk chondritic silicate compositions [26] enclosed with a green field. Possible lunar magma ocean bulk compositions (see refs. in [27]) plot in the same region. Approximate phase boundaries for solidification from [28]. Given the low pressure of planetesimal interiors, virtually all bulk compositions would begin to solidify by crystallizing only olivine.

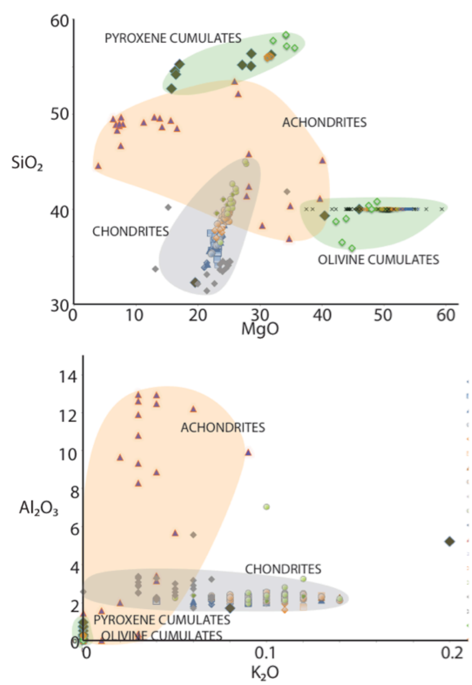

Fig 3. Two plots of composition showing major elements can help discriminate among achondrites (crustal or melt compositions), pyroxene and olivine cumulates (fractionated silicates, probable mantle analogs), and chondrites (undifferentiated primitive material). Data from [21, 24, 26].