PLACING VESTA IN THE RANGE OF PLANETESIMAL DIFFERENTIATION MODELS. Linda T. Elkins-Tanton[1], Ben E. Mandler[2], and Roger R. Fu[2], [1]DTM, Carnegie Institution, 5241 Broad Branch Road NW, Washington, DC 20015 (ltelkins@ciw.edu), [2]MIT, Dept. Earth, Atmospheric, and Planetary Science, 77 Massachusetts Ave., Cambridge, MA 02139, bmandler@mit.edu, rogerfu@mit.edu.

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 ~7 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). The planetesimal might be capped with a lid of either primitive unmelted material, or magmatic eruptions from the interior (Fig. 1), or it may melt all the way to its surface.

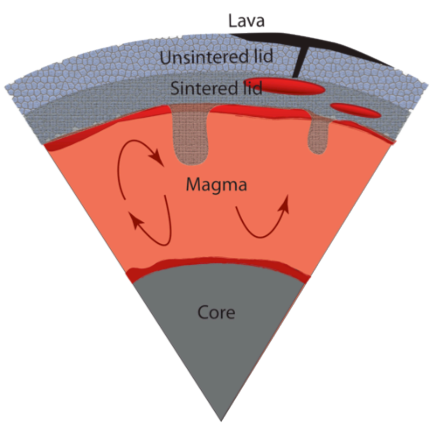

Fig. 1. Schematic cross-section of a molten planetesimal. Melting might also extent to the surface, or be limited to a partial melt retained at depth.

Questions remain about the circumstances under which a body would melt entirely, or only partially; how complex fractionation and rise of melt into and through the crust might be, including formation of secondary magma chambers; and when melts might erupt.

Hydrous fluid mobilization occurs before silicate melting: As temperature rises in a young planetesimal interior, the silicates will pass through the stability zones for several possible hydrated silicate minerals, but then a free hydrous fluid will be released (this hydrous fluid may also interact with iron metal before core formation begins – a possibility that merits further inquiry). The free hydrous fluid will be positively buoyant and will rise away from the planetesimal interior before silicate melting begins. Thus, silicate melts are likely to form from a relatively dry source and not be volatile-saturated. The buoyant fluid itself may freeze in any conductive lid, after metasomatizing some regions, or it may be lost to space [5].

Silicate melting from ^{26}Al may not be complete: If accretion is rapid and aluminum remains in the matrix, then the planetesimal is rapidly and completely melted (*e.g.,*[10]). Accretion could begin before ~1.7 Ma after CAIs, when ^{26}Al can produce some internal melting, and could then continue and permit an internally molten body to retain and add to an undifferentiated crust [8, 9, 11]. Wilson & Keil [12] predict fire-fountaining lava eruptions on Vesta driven by volatiles in magmas. Ghosh & McSween [3] describe an end-member model for Vesta in which all melt from the interior erupts onto the surface and another end-member model in which no melt extrudes; their efforts demonstrate the difficulty of arguing completely for one or another eruptive scenario.

If the silicate portion of the planetesimal has been dried by heating before melting, then magma density (and not volatile content) may dictate whether or not magmas erupt. If melt is positively buoyant with respect to its surrounds [13-16], it would also carry much of the aluminum budget with it while it rises, and prevent further internal melting, resulting in only a layer of melt at shallow depths.

Fu and Elkins-Tanton [16] find that some chondritic bulk compositions have buoyant melts, while for other bulk compositions melt is not buoyant and is therefore unlikely to erupt. For example, an unsintered crust of CV carbonaceous chondrite composition may have a density between ~2,600 and 2,900 kg m^{-3}, whereas the density of molten CV chondrite over a range of temperatures and pressures is between ~2,800 and 2,900 kg m^{-3} [16].

First minerals crystallizing from a cooling planetesimal magma ocean: At the low pressures in planetesimals, almost all the candidates for bulk chondritic silicate compositions would begin solidification by cystallizing olivine alone (Fig. 2).

Why is the first crytallizing mineral of interest? It is the mineral most likely to settle to the core-mantle boundary. Settling requires low crystal fractions and sufficient time [17]. Thus, the first-crystallizing mineral, olivine, is the mineral most likely to be in iron meteorites such as pallasites, if they represent samples of the core-mantle boundary.

Continued solidification of the planetesimal magma ocean: Over the ~0.5 kbar mantle pressure range of a planetesimal ~200 km in radius, the solidus will change by only about 10°C, and the adiabat by only ~2°C. As it cools, therefore, the entire depth of the magma ocean will contain some crystal fraction.

The magma ocean will have a high effective viscosity, perhaps in the range of hundreds to thousands of Pa s. Combined with the high heat flux of a small body cooling without an atmosphere, mineral grains would have to be large, perhaps several to 10 cm, to settle from the magma ocean.

Thus, only the earliest-forming crystals will settle, in the time before crystallinity rises. The rest of the planetesimal's mantle will solidify in bulk and *never produce an olivine cumulate*. This may be why we have no such samples in our collections.

Application to Vesta: Fractional crystallization cannot have been a dominant early process in the Vestan magma ocean because it leads to excessive Fe-enrichment in the melt [18], reinforcing the non-fractional processes predicted by the simple physical models above. Models that are dominated by equilibrium crystallization cannot produce orthopyroxene cumulates (diogenites). The best models of [18] invoke 60– 70% equilibrium crystallization of a magma ocean followed by continuous extraction of the residual melt into shallow magma chambers.

Fractional crystallization in these magma chambers combined with continuous or periodic addition of more melt from the slowly compacting crystal mush (magmatic recharge) can produce all of the igneous HED lithologies (noncumulate and cumulate eucrites, diogenites, dunites, harzburgites, and olivine diogenites). Magmatic recharge can also explain the narrow range in eucrite compositions and the variability of incompatible trace element concentrations in diogenites.

Conclusions: The simplicity of the mineral assemblages in pallasites and other iron meteorites strongly supports successful crystal settling of olivine alone at the beginning of magma ocean solidification on an internally differentiated planetesimal.

Later solidification would occur in bulk, and thus planetesimal magma oceans will not produce olivine + pyroxene cumulate, such as are predicted for the Moon, but would produce melt extraction from mushes consistent with observations from Vesta.

References: [1] Miyamoto, M. et al. (1981) *Proc. Lunar Planet. Sci. Conf.*, 12, 1145. [2] LaTourrette, T. and G. J. Wasserburg (1998) *EPSL*, 158, 91. [3] Ghosh, A. and H. Y. McSween Jr. (1998) *Icarus*, 134, 187. [4] Young, E. et al. (1999) *Science*, 286, 1331. [5] Young, E. et al. (2003) *EPSL*, 213, 249. [6] Merk, R. et al. (2002) *Icarus*, 159, 183. [7] Ghosh, A. et al. (2003) *MAPS*, 38, 711. [8] Sahijpal, S. et al. (2007) *MAPS*, 42, 1529. [9] Elkins Tanton, L. T. et al. (2011) *EPSL*, 305, 1. [10] Hevey, P. and I. Sanders (2006) *MAPS*, 41, 95. [11] Šrámek, O. et al. (2012) *Icarus*, 217, 339. [12] Wilson, L. and K. Keil (1997) *MAPS*, 32, 813. [13] Wilson, L. and K. Keil (2012) *Chemie der Erde*, 72, 289. [14] Moskovitz, N. and E. Gaidos (2011) *MAPS*, 46, 903. [15] Neumann, W. et al. (2012) *Astron. Astrophys.*, 543. [16] Fu, R. R. and L. T. Elkins-Tanton (2013) *EPSL,* submitted . [17] Suckale, J., et al. (2012) *JGR*, 117, E08005. [18] Mandler, B. E. and L. T. Elkins-Tanton (2013) *MAPS* . [19] Jarosewich, E. (1990) *Meteoritics*, 25, 323. [20] Elkins-Tanton, L. T. et al. (2011) *EPSL*, 304, 326. [21] Stolper, E. M. (1980) *Contrib. Min. Pet.*, 74, 13.

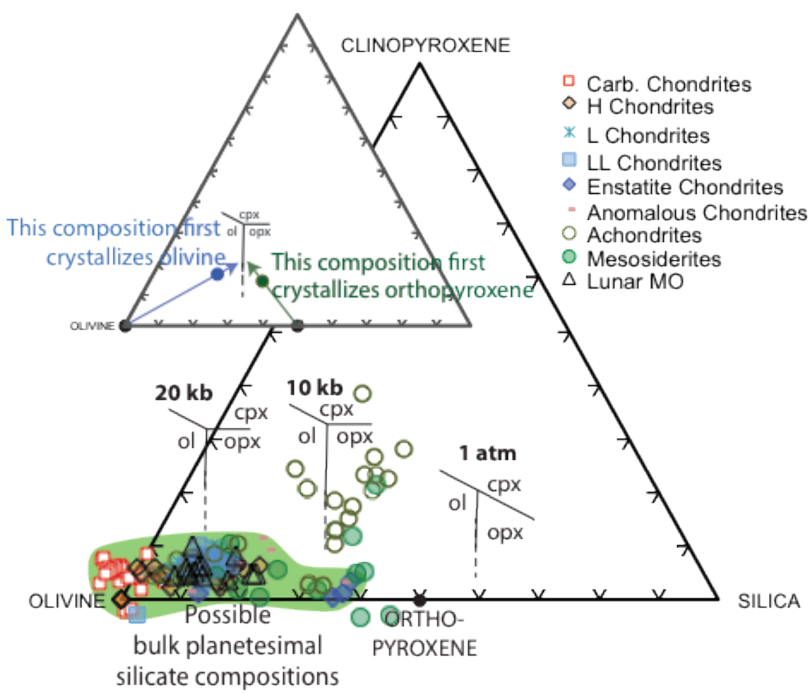

Fig 2. The silicate portions of bulk chondritic compositions [19] plotted in a ternary diagram, and described with a green field. Possible bulk compositions for a lunar magma ocean (compiled in [20] plot in the same green region. Phase boundaries for solidification of a magma ocean of peridotitic composition as an approximation of how these chondritic magma oceans would solidify, from [21]. Given the low pressure of planetesimal interiors, virtually all bulk compositions would begin to solidify by crystallizing only olivine.