THE FATE OF WATER IN EARLY-ACCRETING INTERNALLY HEATED PLANETESIMALS.

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Introduction: Increasing evidence exists for partial differentiation in planetesimals in the early solar system, and by extension, for the existence of partially differentiated asteroids today. Iron meteorites indicate early differentiation, within the first million years after calcium-aluminum inclusions solidified (*1*). Remanent magnetism in angrites and in Allende indicates they had core dynamos, requiring internal melting and core formation (*2, 3*). Vesta, Ceres, Pallas, and Lutetia have densities and moments of inertia consistent with internal differentiation (*4-6*). This melting is thought to be caused be the heat of radioactive decay of ^{26}Al (*7-9*).

Metamorphism and melting of planetesimals through radiogenic heat in the first few million years after CAIs have been modeled by a variety of researchers over the past 30 years (*10-18*). Our understanding of the physics and chemistry of planetesimal melting and solidification processes, however, are incomplete, such that multiple plausible processes may be posited for the same steps in planetesimal evolution.

Here we discuss the processes of fluid mobilization, melting, and solidification, and their possible consequences for the physical and chemical structure of the resulting planetesimal. Some of the least constrained but most important processes are release and transport of hydrous fluids, rise and eruption of silicate magma, development and cessation of convective heat transport in the interior magma ocean, settling of crystals from fluid flow, growth or erosion of any conductive lid, and patterns of growth of the solids in the iron-nickel core.

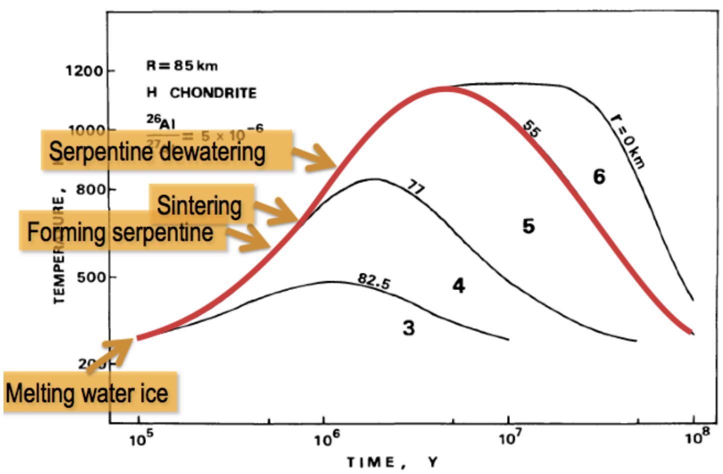

Figure 1. Temperature evolution at 55 km depth (highlighted in red) in a parent body 85 km in radius, demonstrating possible time scales for serpentinization, sintering, and dewatering before iron-sulfur or silicate melting begin. From Miyamoto et al. (*10*).

Heating and dewatering. Radiogenic heat builds in the planetesimal interior. As temperatures rise, first ices melt, then serpentine forms by reaction between silicates and fluids, at about 350°C (*19*) (Figure 1). Void space will be lost and the material will sinter into a denser solid at about 430°C (*20*). Shortly after sintering some serpentine begins to dewater, and at 600°C serpentine dewatering accelerates (*21*). Thus, before any iron-sulfur or silicate melting begins, the primitive meteorite material has dewatered and sintered. Released fluids will rise through the meteorite matrix through pressure head and buoyancy. I argue, then, that eventual silicate melting in the planetesimal interior is likely to occur in dry silicate material.

Conductive Lid. The conductive lid of the planetesimal is likely to be heterogeneous from fluid rise frfom the interior: dewatering and fluid rise predicts veins and porous flow regions of hydrous metamorphism (*16, 22, 23*), rather than a homogeneous and pervasive metamorphism. A lid formed at one time would be radially symmetric in thermal metamorphism, but ongoing accretion to the surface of the planetesimal will produce complex sectors of thermal and hydrous metamorphism. The lowest parts of the unmelted lid will be dense from sintering and rise and freezing of melts from the interior. The outer lid, in contrast, will be porous and fluffy and less dense than the interior magmas (*24*).

Melting. The first component to melt is likely to be eutectic melting of iron and sulfur at about 950°C; silicate melting may not begin until 1100°C is reached (*25*). Melting silicates through increasing internal heat is a process of melting that very seldom occurs on Earth. On Earth melting occurs through adiabatic decompression (at mid-ocean ridges, for example), and through addition of incompatible components, including water (at subduction zones, for example).

The process of melting in early planetesimals, in contrast, may well produce low-volatile magmas that are not prone to bubble nucleation until they are very close to the surface and may not therefore commonly produce explosive eruption. The sintered lid will be denser than the melt, and thus magmas may pond beneath the lid. The possibility of a primitive, unflooded lid surface is strong.

The newly-formed iron metal core will accept almost no aluminum, and so radiogenic aluminum will be concentrated in the melting mantle (^{60}Fe is a more minor contributor). Heating from ^{26}Al is highly energetic and rapid, and in many cases modeling shows rapid and near-complete internal melting of the planetesimal. The mantle will continue to heat, and heat will be conducted initially both into the core and outward through the lid.

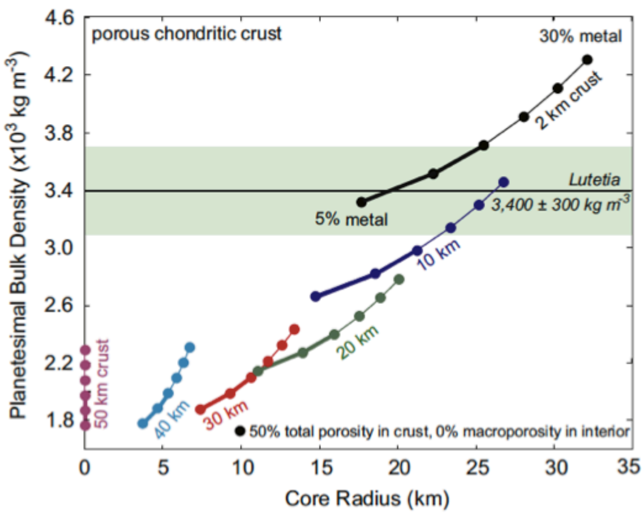

Figure 2. Predicted planetesimal bulk density as a function of percentage of metal in the original bulk material (determines core fraction) and thickness of conductive "crust", from 2 to 50 km for a 50-km radius body. This analysis suggests that Lutetia may be partially differentiated; figure from Weiss et al. (*6*).

Cooling. After radiogenic heating from short-lived aluminum ends and cooling has proceeded to the solidus of the mantle silicates, minerals grains will form in the internal magma ocean. These grains will have slow settling speeds because of the low gravity of the planetesimal, but cooling may take tens of millions of years because of the insulating conductive lid. This time period may be sufficient for settling and thus fractional solidification of the interior. The interior will cool adiabatically as long as convection persists, and the lid will thicken only by clinging crystals.

Implications. Some partially differentiated planetesimals may still exist in the asteroid belt, and samples of others may be available in the library of meteorites. Models for thermal evolution and transport of fluids in planetesimals make specific predictions for the heterogeneity and composition of planetesimals lids and thus are partly testable. The water in these bodies will be minimal in the interior, and heterogeneous throughout the lid. The lid interior may even contain areas with water contents higher than the original bulk material, where water has been added through flux from the interior. Water may be in the form of hydrous minerals or ices.

Partial differentiation results in planetesimals with radii and bulk densities that vary by total mass, time of accretion, bulk radiogenic content, and, of course, the physical processes expected during heating and cooling. Predictions of these quantities can also be made and compared against observations, as is being done with Lutetia and Vesta (Figure 2).

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