PARTIALLY DIFFERENTIATED PLANETESIMALS MAY RETAIN PRIMITIVE CRUSTS

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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. Remanent magnetism in angrites (*1*), meteorites from Vesta (*2*), and the Allende CV chondrite (*3, 4*) indicates that their parent bodies had core dynamos, requiring internal melting and core formation. Ceres, Pallas, and Lutetia (*5*) have densities and moments of inertia consistent with internal differentiation. Lutetia also has a largely intact chondritic surface overlying a possibly differentiated interior. The hypothesis of a partially differentiated body, with a primitive lid overlying a differentiated interior, relies on the physics and chemistry that preserves the lid and is the topic of this abstract.

Here we will present calculations of melt and crustal densities, taking into account the time dependence of volatile release and the density of silicate melts to constrain the eruption or suppression of rising magmas in the primitive lid of a heating, internally differentiating body.

Heating may drive off volatiles: Bubble formation by volatiles coming out of solution in magmas is one of the primary drivers of eruptions on the Earth, and may also have driven fire-fountaining eruptions on the Moon. On the Earth, the most volatile-rich magmas are formed when volatiles are introduced at subduction zones. In contrast, on early-forming planetesimals, radiogenic heating may first drive off volatiles before silicate melting begins. At first, water would be liberated from melting ices, and then possibly react with silicates to form hydrous phases. However, upon further heating such hydrous phases become unstable, and the free water would rise to the planetesimal's crust or erupt to space.

In peridotitic compositions, Till et al. (*6*) updated the phase diagram of Ohtani et al. (*7*) to show that at the very low pressures relevant for small bodies, the amphibole stability field ends around 950 °C, leaving a large gap in temperature in which there is no stable hydrous silicate phase. Schmidt and Poli (*8*) studied a wet basaltic composition and report that above 500 °C at the highest there is no hydrous phase present.

Therefore as temperatures rise above some temperature between 500 and 950 °C, depending upon bulk composition, water will be released as a free fluid. If the free fluid migrates away, the resulting dry chondritic material will not melt until it heats to around 1,200 °C (*9*).

If the fluid migrates away before silicate melting begins, then magmas on planetesimals would have very low volatile contents, consistent with measurements of achondrites and highly metamorphosed chondrites (*10*). The migration of free water from the deep interior of planetesimals is also consistent with the oxygen isotopic signatures of aqueously altered chondrites (11). The ability for the free fluid phase to migrate away and leave a dry melting region will depend upon a competition between the upward flow velocity of the fluid, and the rate of heating of the body.

Volatile loss would be rapid: Young et al. (*11, 12*) find that in bodies small than about 40 km radius thermocapillary forces dominate fluid flow and flow is sluggish. Rapid, buoyancy-driven flow becomes important in bodies larger than 60 km in radius; in these larger bodies, the fluid would not have lingered long enough even to metamorphose the silicates at low temperatures, and would have largely escaped to space, or have been trapped in a thin cold crust (*12, 13*).

Darcy flow calculations for larger bodies, perhaps Vesta-sized, indicate that hydrous fluids would move upward through their matrix at speeds from 100 to 1,000 km per year, assuming grain sizes from mm to cm in diameter, gravitational acceleration of 0.2 m s^{-2}, difference in density between the fluid and the matrix of 2,000 kg m^{-3}, and fluid viscosity of 0.1 Pa s. Using the techniques from (*14, 15*), we find that in the fastest possible case (instantaneous accretion at the time of first CAIs), a planetesimal with radius 250 km reaches 1,100 to 1,200 °C between 150,000 and 200,000 years after accretion.

Thus, fluid would be liberated and percolate upward via Darcy flow efficiently long before the melting point of the silicates is reached. The planetesimal's interior would be as dry as it can be made by heating before melting ever begins, and the resulting melt will be correspondingly dry.

Relative densities of dry melts: Dry melts are thus expected to be the norm for the interiors of planetesimals larger than Young et al. (*12*)'s thermocapillary flow limit (60 km radius). Smaller bodies have far slower fluid flow rates. Small bodies that melt (and bodies as small as 20 km in radius may melt if accreted fast enough) are more likely to have volatile-rich, and thus buoyant and explosive, magmas.

In Fig. 2 we show the hand-sample densities of several chondrites and achondrites, and then calculate the densities of a range of melts using experimental data and fluid density code after Kress and Carmichael (*16*) and subsequent papers.

Some of the least dense chondrites (CV and CM groups) produce melts that are unlikely to erupt from either volatile driving or inherent melt density. Thus early-accreting planetesimals of those compositions may retain a primitive undifferentiated lid and thus mask their partial differentiation. H, LL, and EH chondrites, in contrast, produce melts that may be buoyant enough to erupt, if they do not freeze into the lid on ascent.

Conclusions: Planetesimals that accrete before about 2 Myr after the first CAIs and have a low density composition similar to that observed in chondrites may internally differentiate but never erupt magmas onto their surfaces. These bodies may mask internal differentiation under a primitive lid. Small bodies (less than ~60 km in radius) will not efficiently dehydrate, but neither do they have a strong gravitational driving force for eruption. These bodies may internally differentiate without a surface expression, but they are also liable to undergo fire-fountaining and other volatile-driven eruptive styles.

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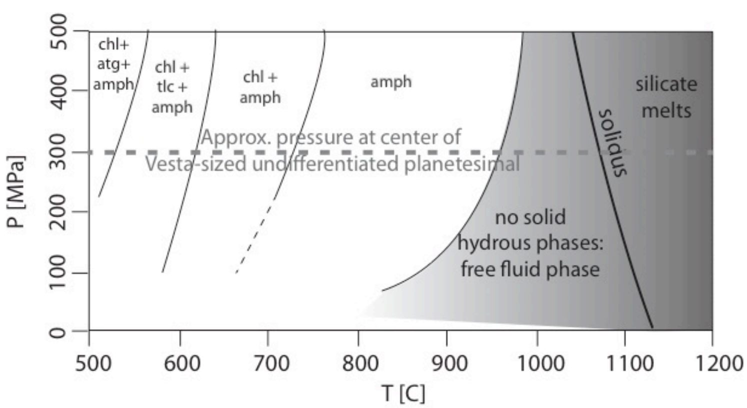

Fig. 1 (LEFT). Stability of hydrous silicate phases in a peridotitic bulk composition. A wide temperature range exists in which fluids can percolate out of the melting region before melting begins. Figure after Till et al. (*6*); chl = chlorite, atg = antigorite, amph = amphibole, tlc = talc.

Fig. 2 (BELOW). Densities of meteorites, their porous equivalents (expected in planetesimals' unsintered lids), and their melts. CV and CM compositions produce melts too dense to erupt through buoyancy alone. These planetesimals may internally differentiate without any surface expression.