CHONDRITES AS SAMPLES OF DIFFERENTIATED PLANETESIMALS. L. T. Elkins-Tanton and B. P. Weiss, Massachusetts Institute of Technology, Department of Earth, Atmospheric, and Planetary Sciences, Cambridge MA, USA, ltelkins@mit.edu, bpweiss@mit.edu.

Introduction: Bodies that accreted to more than ~20 to 80 km radius before ~1.5 Myr after CAIs likely contained sufficient ^{26}Al to begin to melt internally from the insulated cumulative effects of radiogenic heating [1, 2]. Hevey and Sanders [1] and Sahajipol et al. [2] demonstrate that early-accreting bodies will melt from the interior out, sometimes forming a body with an interior magma ocean under a solid, conductive, undifferentiated shell.

We suggest that this starting model provides a framework from which to explain a variety of observations from meteorites, possibly including the magnetization present in achondrites (e.g., angrites) and in CV carbonaceous chondrites, the variety of liquid compositions that apparently metasomatized otherwise primitive chondrites.

Weiss et al. [3] reported magnetization in angrites, and postulated that core dynamos on the angrite parent body produced the fields recorded in those meteorites. They found that small bodies with internal magma ocean could feasibly generate a core dynamo magnetic field potentially lasting for tens of millions of years. Here we further investigate the physical and compositional effects of an internal magma ocean on the solid, undifferentiated outer shell of a planetesimal.

Body is heated, but not melted: Radiogenic heating in meteorite parent bodies would have produced elevated temperature and the release of hydrous fluxes over several million years, leading to the metasomatism observed in meteorite samples [4-9]. In this "onion shell" model, meteorites with the highest metamorphic grade originated nearest the center of the parent body. Here we further consider physical and compositional characteristics of meteorites that can best be explained by the existence of an internal magma ocean.

Body is fully molten, with a free surface: Bodies that are heated maximally may melt to within a few kilometers of their surfaces [1, 2]. With sufficient gravity the thin crust may be infiltrated with magma and founder, leaving a body completely molten with a free surface. This is now a fully differentiated planetesimal, and its free surface will be maintained for a period by foundering quench crusts.

The ~0.6 kbar internal pressure range on a Vesta-sized (radius ~265 km) body leads to a mantle solidus and liquidus that are nearly constant over the depth of its mantle: the solidus will vary by only ~10°C. Therefore once cooling has brought the magma ocean temperature near the liquidus, in the absence of other forces, the entire depth of the magma ocean will contain some crystal fraction.

Early in the solidification process, grains will likely settle, convection will be vigorous, and heat will be lost quickly – a possibly scenario for a core dynamo – but this phase will last only a few hundred years. The crystal fraction rises rapidly and ultimately ends convection at a temperature we estimate to be near 850°C. Cooling then proceeds largely conductively. The final body will be solid within only hundreds to thousands of years and will not have created a magnetic field, although it will have a differentiated silicate mantle and possibly a basaltic crust.

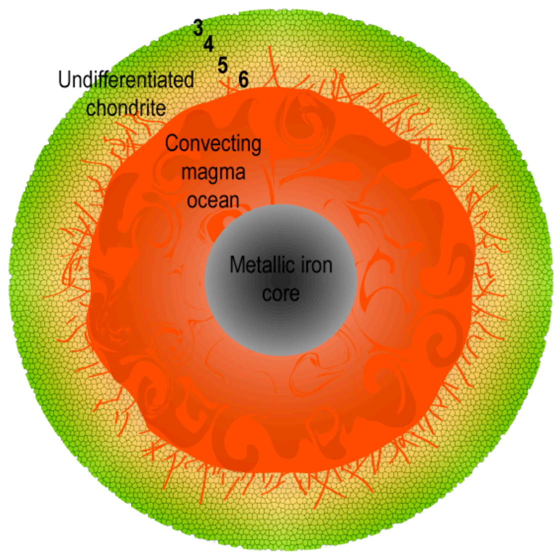

Fig. 1. Model of a meteorite parent body with molten and differentiating (achondritic) interior and variably metamorphosed, unmelted chondritic crust.

Body has an interior magma ocean under an unmelted shell: In this model (Fig. 1), interior melting is incomplete and the magma ocean remains capped by an undifferentiated chondritic shell. The conductive lid insulates the internal magma ocean, slowing its cooling and solidification by orders of magnitude, but still allowing sufficient heat flux from the planetesimal core to produce a core dynamo and with a magnetic field consistent with magnetization in angrites [3]. Heat can be modeled as conducting through the undifferentiated shell using the heat conduction equation in spherical coordinates. These calculations produce temperature histories for internal magma oceans as shown in Fig. 2.

Assuming that convection is slowed or ended below 850°C by a high crystal fraction, these planetesimals may be able to retain an internally-generated magnetic field lasting for tens of millions of years.

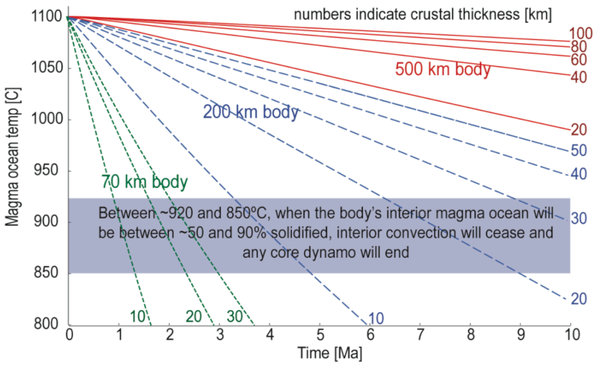

Fig. 2. Internal magma ocean temperature evolutions with time. The shortest-lived convecting magma ocean predicted by these models is on the order of 1 Myr.

Previous studies differ on whether core segregation occurs near 950°C, at the iron alloy liquidus, or nearer 1,170 to 1,570°C, the solidus and liquidus of the silicate portion ([2] and references therein). If core segregation occurs at the lower temperature, then after core segregation the silicate portion would continue to heat radigenically, and the magnetic field generation will be delayed by the time required to bring the core and magma ocean into thermal equilibrium. Then these models proceed as described.

The fate of the chondritic crust: The stable chondritic crust on such a planetesimal will contain high thermal gradients, from ~1,500°C at its bottom boundary to space equilibrium blackbody temperatures at its surface [1, 2]. Depending upon pressure, at temperatures above about 430°C [1] the porous chondritic material sinters into a stronger solid.

At about the same temperatures hydrous, sulfidic, and carbon-rich fluids may be released from the chondritic materials, producing metasomatized chondrites. Silicic fluids from the underlying magma ocean may also buoyantly infiltrate the chondritic crust. Though all these potential fluid phases are buoyant with respect to the chondritic matrix, even in its porous, non-sintered form, their ascent toward the surface will be hindered by the low gravity of these small bodies.

A body a little smaller than Vesta would have a gravity of about 0.2 m/s^2. In such a body, basaltic magma would rise by Darcy flow through chondritic crust of 50% porosity at ~50 to 500 m/yr for grain sizes of 1 mm to 1 cm. In contrast, hydrous fluids will rise at tens of kilometers per year through the same chondritic shell. Lowering the porosity to 10% reduces these velocities by ~95%

Hydrous, sulfidic, or carbon-rich fluids will be able to rise through the chondritic crust pervasively at these rates. Basaltic or picritic magmas, by contrast, will be cooling and solidifying as they rise, and so their radius of maximum rise will be limited in many cases. Only in the hottest bodies with the thinnest crusts will basaltic magmas erupt; otherwise the surface will remain chondritic with various stages of metasomatism.

Application to CV chondrites: The metasomatic fluids expected to percolate through the chondritic crust is likely responsible for for the ferromagnetic sulfides and oxides observed in CV and chondrites. The timing of this alteration event is consistent with the expected lifetime of a core dynamo on > ~80 km diameter bodies with interior magma oceans (Fig. 2 and [3]). These minerals would then acquire a thermoremanent or thermochemical remanent magnetization in this field. This provides an explanation for the longstanding mystery of postaccretional remanent magnetization in the CV chondrite [4].

Possible existence of differentiated bodies in the asteroid belt today: Because of the limited lifetime of ^{26}Al and the longer apparent period over which chondrite parent bodies were forming, the likeliest scenario in these parent bodies is heating without significant melting. However, the earliest-forming parent bodies are likely to have experienced a partial interior magma ocean, and in even rarer cases, to have melted entirely and become bodies like Vesta [1].

Bodies that are internally differentiated in the manner described here may well exist undetected in the asteroid belt. They likely have lost their hydrostatic shape through later impacts, and their surfaces may never have been covered with erupted basalt; surfaces of these bodies may have remained chondritic throughout this process. Their surfaces will therefore be irregular weathered primitive material, perhaps with highly altered or even differentiated material at the bottoms of the largest craters and in crater ejecta. This can explain the mismatch between the enormous diversity (> 130) of parent bodies represented by achondrites and paucity (< 10) of basaltic asteroids.

References: [1] Hevey and Sanders (2006) *MAPS, 41*, 95-106. [2] Sahijpal et al. (2007) *MAPS, 42,* 1529-1548. [3] Weiss et al. (2008) *Science, 322*, 713-716. [4] Taylor et al. (1987) *Icarus, 69*, 1-13. [5] Göpel et al. (1994) *EPSL, 121*, 153-171. [6] Trieloff et al. (2003) *Nature, 422*, 502-506. [7] Scott et al. (2007) *Workshop on Chronology of Meteorites* Abst. #4075. [8] Kleine et al. (2008) *EPSL*, doi:10.1016/j.epsl.2008.03.013. [9] Sanders (2006) 69th Met. Soc., Abst. #5206. [10] Gaffey (2007) *LPS XXXVIII*, Abstract #5296. [11] Weiss et al. (2008) *LPSC XV*, submitted. ref [12] Schmidt and Poli (1998) *EPSL*, *163*, 361-379. [13] Meibom and Clarke (1999) *MAPS, 34*, 7-24.