The early dynamics and density structure of Mercury's mantle

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The composition of the surface of Mercury is a long standing problem, and a key goal for *MESSENGER*. The fractional crystallization of a magma ocean inherently produces stratigraphies that are more dense near the surface of a planet; this process of magma ocean solidification is indicated by the petrology of the Moon. The shallow dense material is prone to founder deep into the mantle as the planet reorganizes its interior by density in a process called overturn. However, cool temperatures and high viscosities may render the high density material immobile near the planetary surface [1]. If this is the case, this material may be near enough to the present day surface (which has been subsequently flooded with lavas) to be excavated by crater impacts or thrust faults, or erupted by magmatic activity from impacts or standard planetary convection. Conversely, any dense material that founders will produce an anomalously high-density lower mantle.

Models : We investigate the fate of the high density material after magma ocean crystallization for different initial bulk compositions using a spherical axisymmetric 2D finite element fluid flow code, SSAXC, which is based on Conman [2]. We assume for simplicity here that solidification is complete before overturn; the numerical models begin immediately after the entire magma ocean has crystallized, prior to overturn (future models will address overturn before solidification is complete).

We focus on 0.79 radians in longitude of the presently sized 600 km mantle (shown in Figure 1), with the left vertical boundary acting an as axis of symmetry. In the future we will expand the simulation to include a larger proto-Mercury than may have lost much of its silicate mantle. The model has 150 nodes in the radial direction and 300 nodes in the azimuthal direction, corresponding to 4 km per element in the radial direction and 6.4 km in the azimuthal. We have performed resolution tests and concluded that this resolution is sufficient for these experiments. Boundary conditions are the same for all models: free-slip on the top and side boundaries, and a flow-through bottom boundary.

The temperature along the bottom boundary is set to the maximum initial temperature in the mantle, 1400°C, while the top boundary is set to an average surface temperature on Mercury, 170°C [3]. The initial radial temperature profile is set to the model solidus used in [4]. The initial radial density profile is calculated from the models, discussed in [4], based on bulk composition, and an example is shown in Figure 1a. Viscosity is calculated using a temperature and stress-dependent law and reaches a cut-off value of 10^{23} (if indeed it does) near the colder surface to avoid numerical error.

We focus on compositions that produce dramatically different density profiles after magma ocean solidification, and therefore would produce different density structures after overturn. These compositions include a Bencubbinite chondrite (CB) composition, an enstatite chondrite composition, and an Earth-like composition.

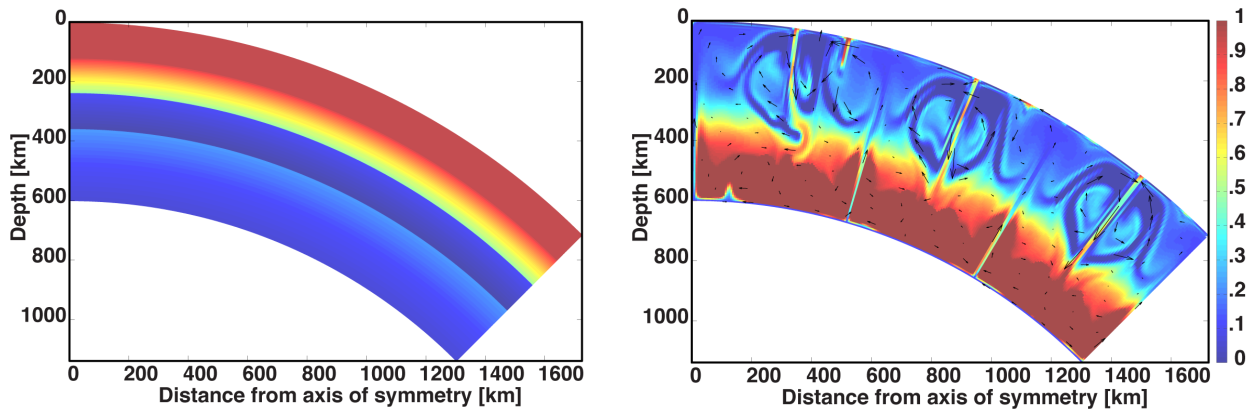
Important parameters in these numerical experiments include (1) the non-dimensional Rayleigh number, which indicates the thermal convective vigor, (2) the non-dimensional compositional Rayleigh number, which indicates the vigor of compositional convection, (3) the viscosity of the phases, (4) the density of the dense phases, and (5) the solidus temperature of the dense phases. We vary these parameters over their reasonable range (Table 1) to investigate the early dynamics of planet Mercury.

For all compositions, the solidus temperatures for the dense phases are likely lower than the model solidus we use. We investigate these effects on the dynamics by, in some cases, conductively cooling the mantle until the all the dense phases are below the solidi at a temperature less than 1170°C, and then run overturn.

Table 1: Ranges of Important Parameters, ϕ = dense phases. All densities are calculated at a reference pressure of 1 atm.

Parameter	Min	Max
Rayleigh #	10^4	10^7
Compositional Rayleigh #	-10^5	-10^9
Reference viscosity [Pa S]	10^{18}	10^{21}
ϕ density [$\mathrm{kg\ m^{-3}}$]	3100	4500
ϕ solidus temperature [°C]	1170	1400

Results : Preliminary results show that for an initial CB chondritic bulk composition, after magma ocean solidification most of the dense material drips by Rayleigh-Taylor instabilities deep into the planetary interior, spanning 80-100 km in thickness above the core. This deep



(a) At the onset of overturn

(b) After overturn

Figure 1: Density of Mercury's mantle pre- and post- overturn for a Hart and Zindler Earth-like bulk composition (iron = 7.65 wt%). Density is calculated at a reference pressure of 1 atm; a value of zero corresponds to 2920 $\mathrm{kg\ m^{-3}}$ and a value of one corresponds to 3250 $\mathrm{kg\ m^{-3}}$. The arrows are proportional to velocity.

dense layer has a mean density of 3082±11 $\mathrm{kg\ m^{-3}}$ (calculated at a reference pressure of 1 atm), compared to the upper mantle material with a mean density of 3055±8 $\mathrm{kg\ m^{-3}}$. The Earth-like Hart and Zindler composition models also result in the dense material moving near the core; however, in this case the layer is much thicker, on the order of 150-250 km and has a mean density of 3212±55 $\mathrm{kg\ m^{-3}}$ compared to the mean density of the rest of the mantle, 3000±60 $\mathrm{kg\ m^{-3}}$ (Figure 1b).

In models for lunar magma ocean crystallization, the oxide-bearing layer has a density of 3700 to 3800 $\mathrm{kg\ m^{-3}}$. The lower density of the sinking layers in this model is controlled by the models for mineral assemblage used in [4]. A higher density is possible for the bulk compositions used here, as well; the correct mineral assemblage can only be determined by experimentation.

For the cases in which we conductively cool the mantle, the drips are more resistant to forming and instead the dense phases are more likely to remain near the surface[1]. Here, the dense phases are near the surface with a thickness in the range of 100-250 km based on initial bulk composition.

Implications for the Formation of Mercury : In further work we will calculate the density structure, moment of inertia, and wavelength of overturn given different initial compositions over the range of input parameters shown in Table 1. This study may shed light into Mercury formation mechanisms, based on bulk composition, with the help of data resulting from *MESSENGER*.

References

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