**The Influence of Mantle Melting and Differentiation on the Tectonic, Magnetic and Compositional Evolution of Mercury** G. A. Peterson[1], A. Lenardic[1], C. L. Johnson[2,3], A. M. Jellinek[2], Rice University, Houston, TX 77005, USA,[2]Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, BC, V6T 1Z4 (gpeterson@rice.edu), Canada, [2]Planetary Science Institute, Tucson, AZ 86819, USA.

**Introduction:** The early evolution of Mercury is marked by three major geological events. First, the planet underwent widespread effusive volcanism and produced a secondary crust, that is on average 15 - 60 km thick, by 4.0-3.5 Ga [1]. Major elemental compositions suggest this crust was the result of mantle partial melting of a source with composition similar to that of an enstatite chondrite [2]. Second, Mercury's surface is characterized by extensive tectonic structures indicative of crustal shortening, resulting from 1-10 km of radial contraction during secular cooling of the planet [1,3,4]. Third, in addition to a present-day internally-generated magnetic field, crustal magnetic fields suggest a core dynamo was also active at ~4-3.5 Ga [5]. Mercury's ancient dynamo is nominally thought to have been "thermally-driven" [6], whereby cooling to the overlying mantle drives vigorous core convection and magnetic field generation. In [7], we showed that incorporating the strong cooling effects of mantle melting and effusive volcanism into a steady-state parametrized mantle convection model predicts early strong mantle cooling that favors an ancient dynamo, explains the contractional history of the planet and is consistent with crustal thickness estimates. However, parametrized convection calculations cannot capture several inherently 2D or 3D processes, such as mantle partial melting, depth-dependent viscosity and the thermal influence of the delivery and storage of melts within the lithosphere [8].

Here, we revisit the thermal evolution of Mercury using a 2D numerical model that includes mantle melting, crustal production and tracks the geochemical composition of the mantle and crust. The goal of this study is to satisfy the following constraints: (1) A thermally-driven dynamo until at least until 4.0 Ga; (2) A total of 1-10 km of radial contraction; (3) Volcanism and crustal production that ended by ~3.5 Ga; (4) A crust with average thickness 15 - 60 km; and (5) The observed spatial geochemical heterogeneity of major elements (MgO, $SiO_2$, CaO) inferred from satellite measurements at the surface of the planet [2,9].

**Method**: We use the geodynamic framework Underworld [9] to solve the equations of conservation of mass, momentum, and energy using a particle in cell finite element method. Calculations are carried out in a 2D Cartesian geometry. Radiogenic heating in the mantle is for an enstatite composition given by [10] for Mercury. Free slip boundary conditions are applied to all sides of the model domain. Insulating boundaries are applied to the right and left walls, and the top wall is held constant at 275 K. At the bottom wall, or core-mantle boundary an initial temperature of $T_c$ = 1900 K is applied, and we employ a core cooling condition using the method by [12] for Mercury.

Lagrangian particles allow for multiple material properties to be tracked in time and space. This is key to the implementation of partial melting in numerical convection models. When the temperature of a particle is super-solidus, we evaluate the melt fraction, $F$, using the method by [13] which gives the maximum melt fractions as a function of pressure, temperature and $H_2O$ concentration. The mantle melt volume is calculated by integration over the particles, and is advected to the surface to form the crust. We track MgO, $SiO_2$, and CaO based on melting experiments on enstatite chondrites, where the concentration in crustal lavas depends on $F$ at melting [2]. We also track concentrations of $H_2O$, K,U, and Th of the crust and mantle assuming a batch melting model.

Mantle melting and crustal formation have four important thermal consequences: (1) Crust emplaced at the surface or lithosphere advects mantle downwards, which brings colder material temperature to greater depths; (2) During adiabatic melting, latent heat is extracted from the mantle during partial melting [13]; (3) Progressive melt extraction to form the crust decreases mantle concentrations of U, K and Th, which reduces the rate of internal radioactive heating; (4) Similar to radioactive elements, $H_2O$ partitions into the melt phase. Water loss increases the mantle solidus and the mantle viscosity [7], which in turn reduces melt production and increases mantle viscosity.

**Models without Volcanism:** Fig. 1 shows a typical model run. Although 1 – 10 km of radial contraction is predicted (Fig. 1c), low heat loss in solid-state models causes the mantle to warm when radioactive heating is high early in the evolution (Fig. 1a). This initial mantle warming does not allow a thermally-driven global magnetic field at ~4.0 Ga [5]. To have a magnetic field, the core-mantle boundary heat flux, $q_c$ must be at least as large as the core's adiabatic heat flux (~8 – 15 $mWm^2$) [7], and $q_c$ falls below this by 4.3 Ga (Fig. 1b).

**Models with Volcanism:** The inclusion of mantle melting and volcanic resurfacing has several important implications for the early geological record of Mercury: 1) The enhanced core and mantle cooling can explain shortening structures forming at 3.9 Ga (Fig.

1c) and produce less than 10 km of radial contraction over Mercury's evolution [3,4]. 2) Early rapid mantle cooling sustains high core heat loss rates, which allows for an ancient dynamo to be thermally driven at 4.0 Ga (Fig. 1b). 3) Extensive early volcanism is predicted and ending by 3.5 Ga, consistent with formation of Mercury's secondary crust [1]. The greatest concentration of melting, and consequently the thickest crust is at upwellings, where hot undepleted mantle material is advected upwards. Crustal thickness ranges from 35 km to100 km (Fig. 2b), consistent with estimated values for Mercury [15]. An average 60 km thick crust was emplaced by 3.5 Ga (Fig. 1d). 4) The composition of lavas are consistent with the average and range of major elements observed at the surface of Mercury (Fig. 2 c-e). Adiabatic decompression melting driven by thermal convection produces lateral variations in melting, with the highest and lowest *F* values found at upwellings and downwellings, respectively (Fig. 2b,f). Our simulations suggest that the heterogeneous composition across Mercury's surface is controlled by the early convective planform structure (Fig. 2b,f).

**Conclusions and Future Work:** Our approach and results show that mantle melting and crustal formation control the contractional, magnetic, volcanic and compositional evolution of Mercury. In future work, we will explore how intrusive magmatism effects the evolution of Mercury, as large fractions of mantle melt can be stored within the crust and lithosphere and never reach the surface [16]. This can substantially warm the lithosphere, prompting thinning of the stagnant lid and increased mantle cooling [8].

**References:** [1] Byrne P. K. et al. (2018) *Cambridge Uni. Press* 249-286 [2] Boujibar et al. (2016) 48h LPSC, Abstract #2925 [3] Watters R. T. (2021) *Nature Communications,* [4] Crane K. T. and Klimczak C. (2017) *Geophys. Res. Lett.,* 44(7) 3082-3089 [5] Johnson C. L. et al. (2015) *Science*. 348(6237) 892-895 [6] Hauck et al. (2018) *Cambridge Uni. Press* 249-286 [7] Peterson et al. (2021) *Science Advances,* eabh2482 [8] Lourenco et al. (2020) *Geochem., Geophys. Geosystems*, 15252027 [9] McCoy T. et al. (2018) *Cambridge Uni. Press* 249-286 [10] Moresi et al. 2007 Phys. *Earth Planet. Inter.,* 163(1):69–82 [11] Peplowski et al (2011) *Science* [12] Thirelt et al. (2019) *Phys. of Earth and Planet. Inter.,* 9201(18) [13] Katz et al. (2003) *Geochem., Geophys. Geosystems*, 1073 [14] Phillips-Morgan J. (1997) *Earth and Planet. Lett.,* 213-232 [15] Beuthe et al. (2011) *Geophy. Research Letters.,* 15066 [16] Karlstrom et al. (2017) *Nature Geoscience, 17520908*

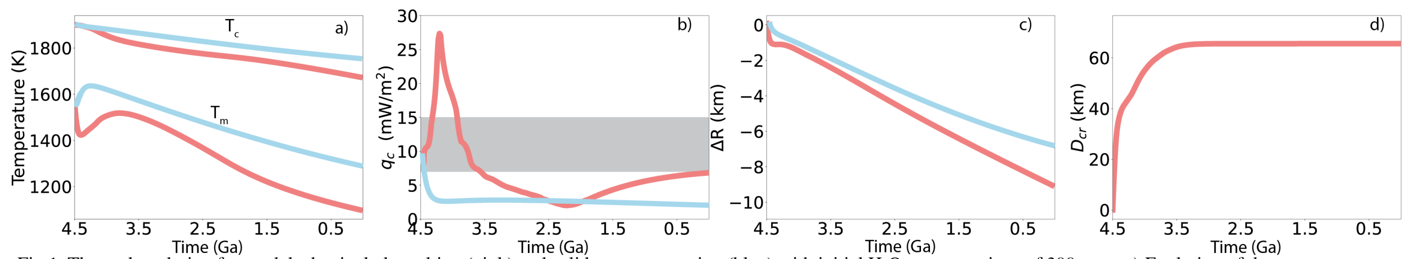


Fig 1. Thermal evolution for models that include melting (pink) and solid-state convection (blue) with initial $H_2O$ concentrations of 300 ppm. a) Evolution of the average temperature of the mantle, $T_m$, and core, $T_c$, for each model. b) The evolution of the average core-mantle boundary heat flux, $q_c$. To sustain a thermally-driven dynamo $q_c$ must be higher than the estimated core adiabatic heat flux[7] given by the shaded gray box. c) The evolution of radial contraction, ΔR. d) Evolution of the average crustal thickness.

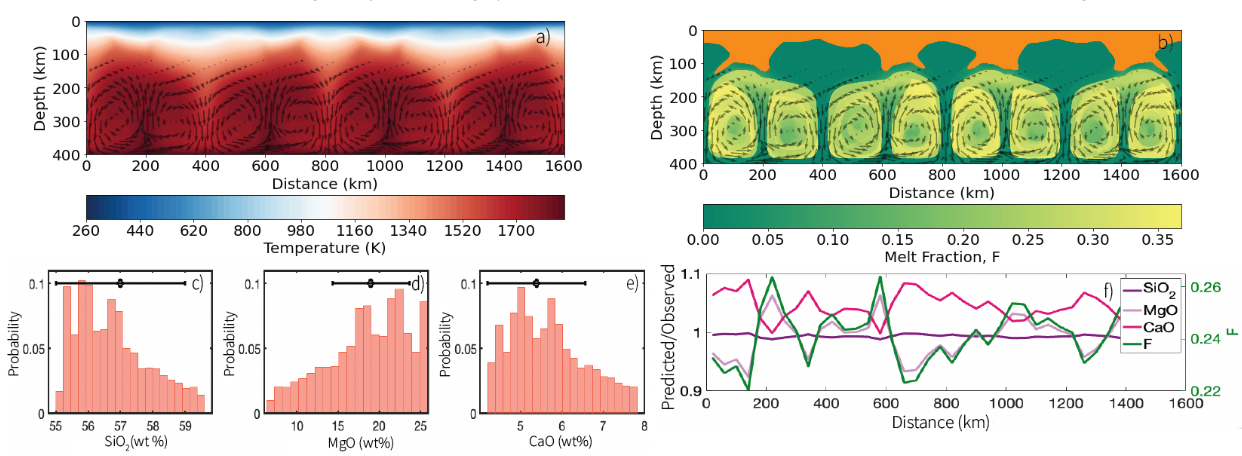


Fig 2. Snapshot of the temperature profile (a) and depletion (b) with velocity arrows at 4.0 Ga for Mercury's mantle for the same model in Fig. 1 that includes mantle melting. The shaded orange in b) is the emplaced crust. c-e) The crustal composition of $SiO_2$, MgO, and CaO, respectively from this study (pink) compared with average and standard deviation of Mercury's surface composition (black). f) The average melt fraction produced in this study as a function of distance (green). The average concentration of $SiO_2$(purple), MgO(lavendar), CaO(pink) predicted from this study as function of distance normalized by Mercury's observed average concentration for each major element.