GRAVITATIONAL INSTABILITIES IN MERCURY'S MANTLE PRODUCE DIVERSE VOLCANIC SOURCE REGIONS.

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Introduction: The surface of Mercury is geochemically and morphologically diverse, representing different periods of volcanic history. The surface ranges in composition with regions like the Borealis Planatia being more Al-rich and Ca- and Mg-poor, and the Heavily Cratered Terrain-Intercrater Plains (HCT-IcP) being more Mg- and Ca-rich [e.g., 1-4]. This geochemical diversity suggests a heterogeneous mantle with distinct basaltic source regions [e.g., 5,6]. An investigation into crystal fractionation in Mercury's magma ocean suggests the structure of Mercury's juvenile mantle is largely dictated by the presence or absence of a flotation crust on the magma ocean [7]. If the magma ocean had a graphite flotation crust [8,9], it would have fractionally solidified, producing distinct mineralogical layering in a cumulate pile. Source regions of the HCT-IcP are thought to be lherzolitic (i.e., composed of olivine and low and high-Ca pyroxenes). In a scenario where the magma ocean fractionally solidified, it is unlikely that any layers in the cumulate pile would have been lherzolitic, suggesting some process by which early and late cumulates of the magma ocean formed mixtures, then melted to produce the HCT-IcP.

One mechanism for forming mixed layers in the Mercurian cumulate pile is by the development of negatively buoyant, density-driven gravitational (Rayleigh-Taylor) instabilities of late magma ocean cumulates that sink into underlying early cumulates. An analogous process known as cumulate overturn is thought to have occurred in the Moon. Solidification of the lunar magma ocean produced a dense ilmenite-bearing layer atop a cumulate pile of less dense mafic minerals (e.g., olivine, pyroxene) [e.g., 10]. The late cumulates sank as viscous solids into the underlying cumulate mantle [e.g., 11-13]. Although Mercury's mantle has very little iron, similar scenario is possible depending on the mineralogy of layers in the juvenile Mercurian cumulate mantle (Fig. 1). A reasonable liquid line of descent for a fractionally crystallizing Mercurian magma ocean would produce a negatively buoyant pyroxenite layer over a harzburgite. Our analysis suggests the pyroxenite layer could "overturn" into the underlying mantle in negatively buoyant Rayleigh-Taylor instabilities, producing the lherzolitic mantle source regions of the HCT-IcP.

Modeling Mercury's Cumulate Mantle:

Mineral and Cumulate Densities. The abundance of sulfur on the surface of Mercury indicates that sulfides may play a role in the interior mineralogy. Here, we assume Mercury's mantle is comprised of forsterite, enstatite, diopside, albite (at low pressures; ≤1 GPa) and possibly low- or high-density sulfides (e.g., oldhamite, niningerite, troilite; perhaps solids in the former cases and liquid in the latter case).

The densities of the mantle minerals and layers were calculated using a third order Birch-Murnaghan equation of state as a function of pressure (0-7 GPa) and temperature (from a potential temperature of 1300°C with an adiabatic gradient of 0.1 °C/km) (Fig. 1). The stratigraphy assumed, a heterogeneous mantle produced after fractional solidification of a magma ocean with a graphite flotation crust, is (from bottom to top): dunite, harzburgite, pyroxenite, and gabbro (Fig. 1b). The analysis shown in Fig. 1 demonstrates that without any sulfides, gravitational instabilities could form among the silicate layers. Sulfides could promote the formation of gravitational instabilities or neutralize them depending on their depth and density [14].

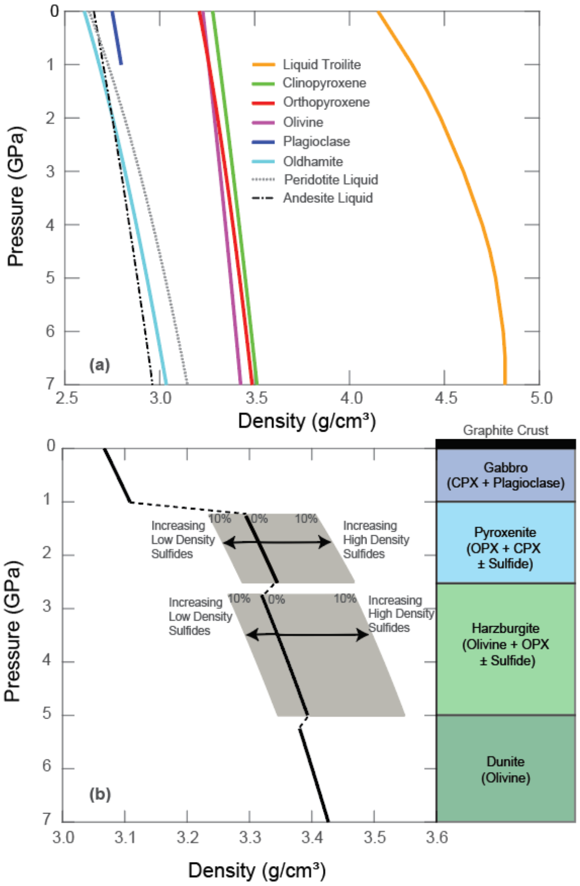

Figure 1. (a) Densities of mafic silicates, sulfides, and andesite and peridotite liquids from 0-7 GPa. calculated using a 3rd order Birch-Murnaghan Equation of State. (b) A model of a juvenile Mercurian mantle (right) and the bulk density of the cumulate layers (left).

Density Stratification. The density stratification produced after solidification of a magma ocean (without sulfides) is gravitationally unstable (thick black line in Fig. 1b). Heterogeneous mixing of late and early cumulate layers by gravitational instabilities in such a mantle would produce diverse mantle sources with variable amounts of late and early magma ocean cumulates. Melting of the resultant mantle sources can explain the chemical diversity seen on the surface of Mercury. The composition and saturation depths of sulfides in the Mercurian magma ocean are quite uncertain [14]. Thus, here we treat the sulfide-free scenario as a reference case and consider scenarios with sulfide-bearing layers at different depths and densities in the cumulate pile.

If sulfides in the mantle were produced early in the crystallization sequence [14] there would be an abundance of sulfides lower in the mantle. Low-density sulfides at depth would further exaggerate the gravitational instability between the harzburgite and pyroxenite layers (Fig. 1b). On the other hand, precipitation of immobile, high-density sulfides at depth could neutralize the potential for formation of gravitational instabilities (Fig. 1b). If sulfides were produced later in the crystallization sequence [14] they would be concentrated in shallower layers in the mantle. In this scenario, if the sulfides were high density, they would exaggerate the gravitational instability and promote formation of downwelling instabilities (Fig. 1b). If the sulfides were abundant and sufficiently low density, they could neutralize the gravitational instability (Fig. 1b).

Scale and Timing of Overturn. Here, we use scaling relationships to evaluate the spatial and timescales for formation of cumulate instabilities in Mercury's mantle. We explore a range of possible mantle viscosities for the overlying pyroxenite (μ_1; 10^{20}–10^{23} Pa·s) and underlying harzburgite (μ_2; 10^{20}, 10^{21} Pa·s) layers, at two density contrasts ($\Delta\rho$) of 100 and 400 kg/m^3 between the pyroxenite and the underlying harzburgite layers, and a range of possible pyroxenite layer thicknesses.

The timing of formation of the downwelling instability determines whether mixing between layers can occur (Eq. 2 [12]). Fig. 2a shows instability formation timescales in a scenario where the harzburgite layer has a viscosity of 10^{20} Pa·s. In all cases considered, instabilities form within hundreds of thousands to tens of millions of years.

The wavelength of the downwelling instabilities is shown in Fig. 2b (Eq. 3 [12]) for different pyroxenite layer viscosities. Higher overlying/underlying viscosity ratios promote shorter wavelength instabilities that will sink slower. Conversely, lower viscosity ratios favor longer wavelength instabilities that will sink faster.

Implications for Mercury's Surface Geochemistry: Given the large uncertainties in the model parameters (pyroxenite layer thickness, density contrast, and layer viscosities), the most likely outcomes for Mercury are unknown. However, this analysis highlights the potential for formation of a well-mixed, lherzolitic Mercurian mantle composed of harzburgite and a multitude of "small" downwelling pyroxenite Rayleigh-Taylor instabilities that sank over hundreds of millions of years; or a mantle that experienced less efficient mixing between harzburgite and larger downwelling instabilities that sank relatively rapidly.

Volcanic resurfacing on Mercury likely occurred around 3.5–4 Gyr [15,16] therefore the HCT-IcP source regions could have formed any time between magma ocean solidification and eruption of the HCT-IcP. Mixing of late and early magma ocean cumulates by formation of downwelling instabilities is possible in all scenarios explored here withing 500 Myr of magma ocean solidification. Conditions favoring more complete source mixing include larger viscosity contrasts, longer instability formation timescales, and slower sinking velocities. Under a variety of plausible conditions, density-driven cumulate mixing may be expected to occur in Mercury's early history, providing distinct sources that can explain the planet's chemically diverse surface.

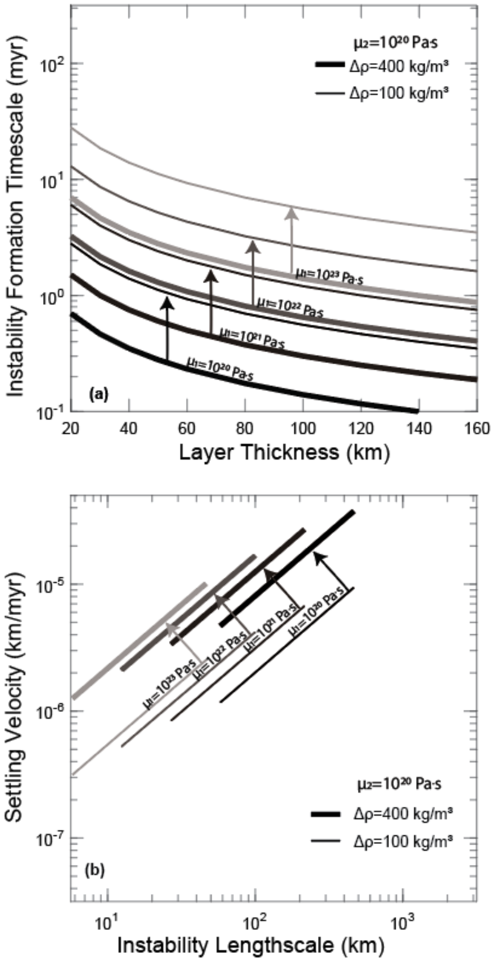

Figure 2. Model scenarios for a harzburgite with a viscosity of 10^{20} Pa·s. (a) Instability development timescale as a function of overlying pyroxenite layer thickness. (b) Settling velocoity according to size of gravitational instability. Arrows indicate the progression of a small density contrast to a larger density contrast between overlying and underlying layers. Viscosity of the overyling pyroxenite layer is indicated on 100 kg/m^3 cases.

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