Fractional Crystallization of a Martian Magma Ocean and Formation of a Thermochemical Boundary Layer at the Base of the Mantle

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Abstract

To characterize how moderately large impactors might alter the differentiation and internal structure of Mars, we examine the fractional crystallization of intermediate depth magma oceans, and document that residual liquids ultimately become denser than normal Martian mantle, establishing unstable density gradients and inducing extensive magma descent within an evolving Mars. Fractional crystallization of intermediate depth magma oceans on Mars is likely to produce liquids that are dense enough to descend to the core-mantle boundary (CMB) and thus form a stably stratified thermochemical boundary layer at the Martian CMB. If this layer cooled sufficiently to crystallize, its mineralogy would be dominated by garnet and ferropericlase, or stishovite and ringwoodite, with changes in the descending liquid's bulk composition having relatively minor effects on the resulting phase assemblage. While the size of Mars' core remains uncertain, the addition of such a thermal boundary layer would impede the stabilization of (Mg, Fe)SiO3-perovskite at depth in Mars, although it would contain modest amounts of CaSiO3-perovskite. Such a compositionally distinct thermal boundary layer at the base of the Martian mantle would substantially elevate the inferred temperature of the Martian core, and also produce markedly lowered heat flow at the top of its core, with a potentially causal relation with the current lack of an internally generated Martian magnetic field. We calculate the seismic velocity anomalies that would be expected to be associated with such a layer, and find that the shift in mineralogy at depth should produce a seismic discontinuity that could prospectively be detectable by Martian seismic deployments.

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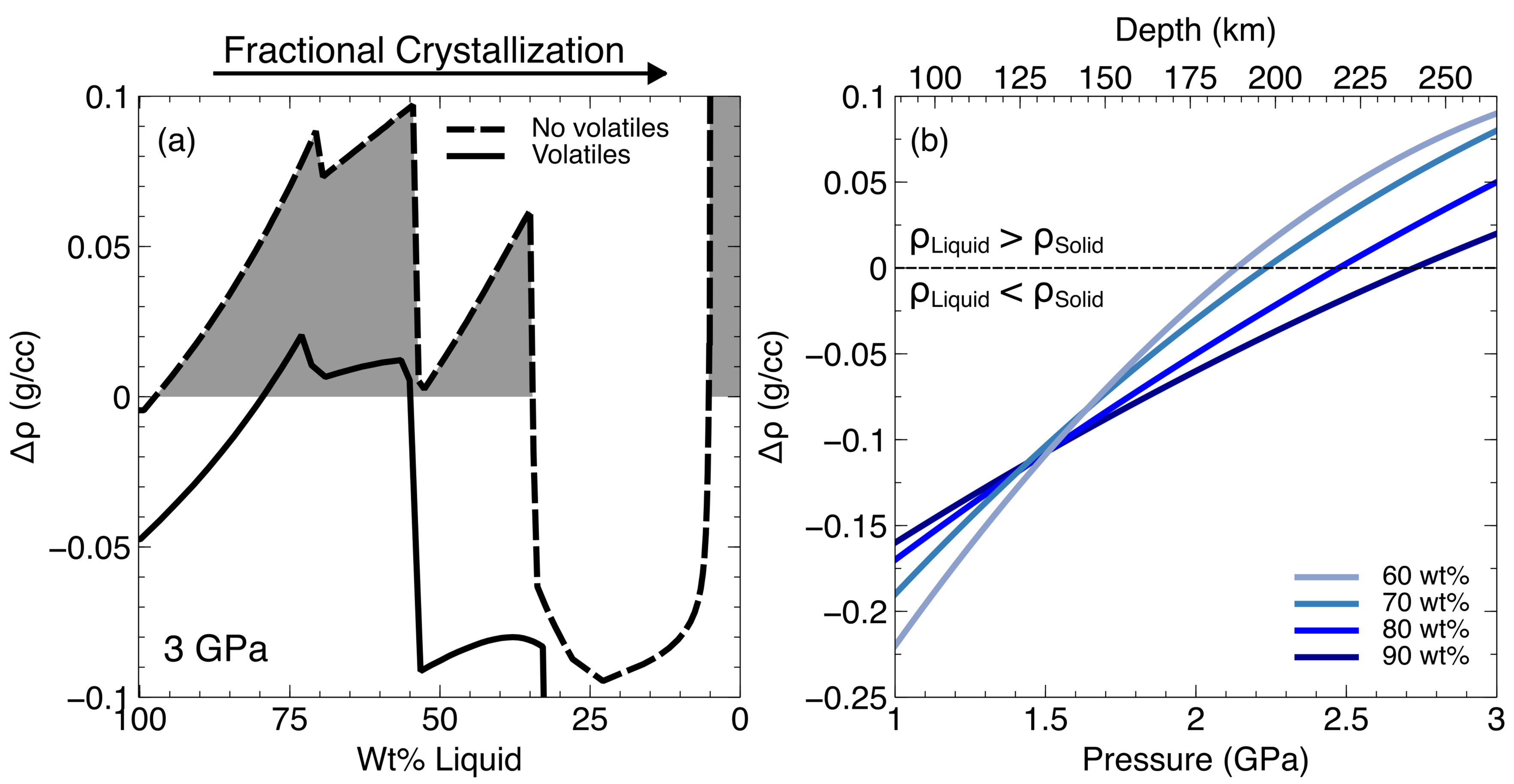
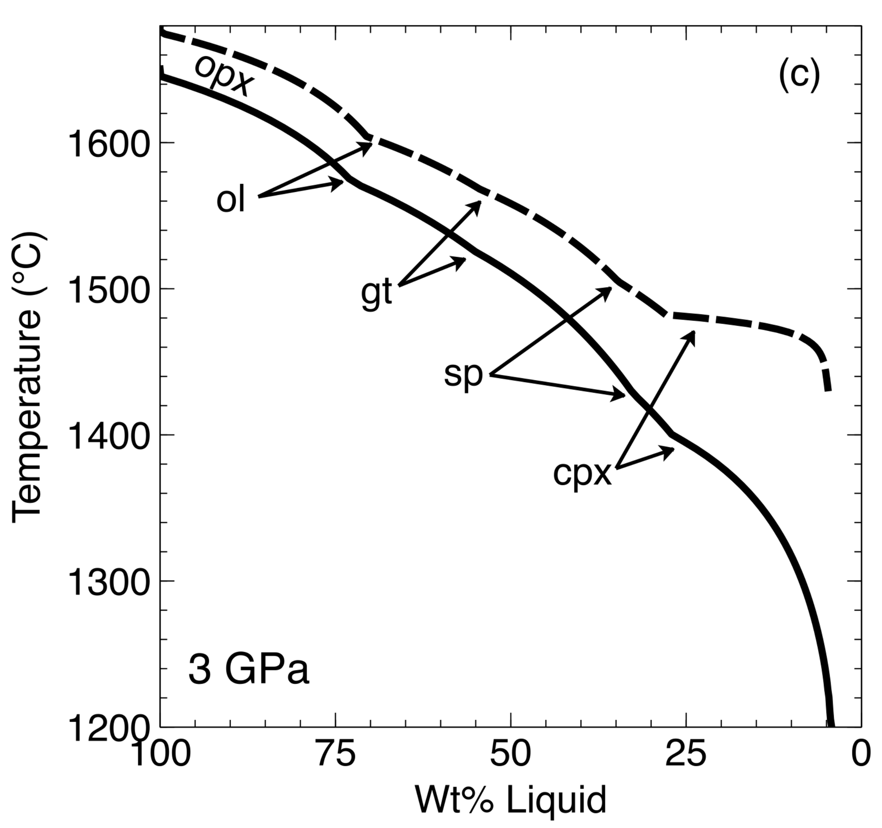
Key Points

1. Large impacts in the early history of Mars induce mid-mantle melting.
2. As magma oceans crystallize, residual melts can become dense enough to descend to the core-mantle boundary and form a thermochemical boundary layer around the core.
3. Such a chemically distinct boundary layer could play a role in the present lack of a Martian dynamo and, as a dense basal layer, potentially contribute to the fixity of mantle plumes on Mars.

For a more detailed treatment, see Zeff & Williams (2019)[1].

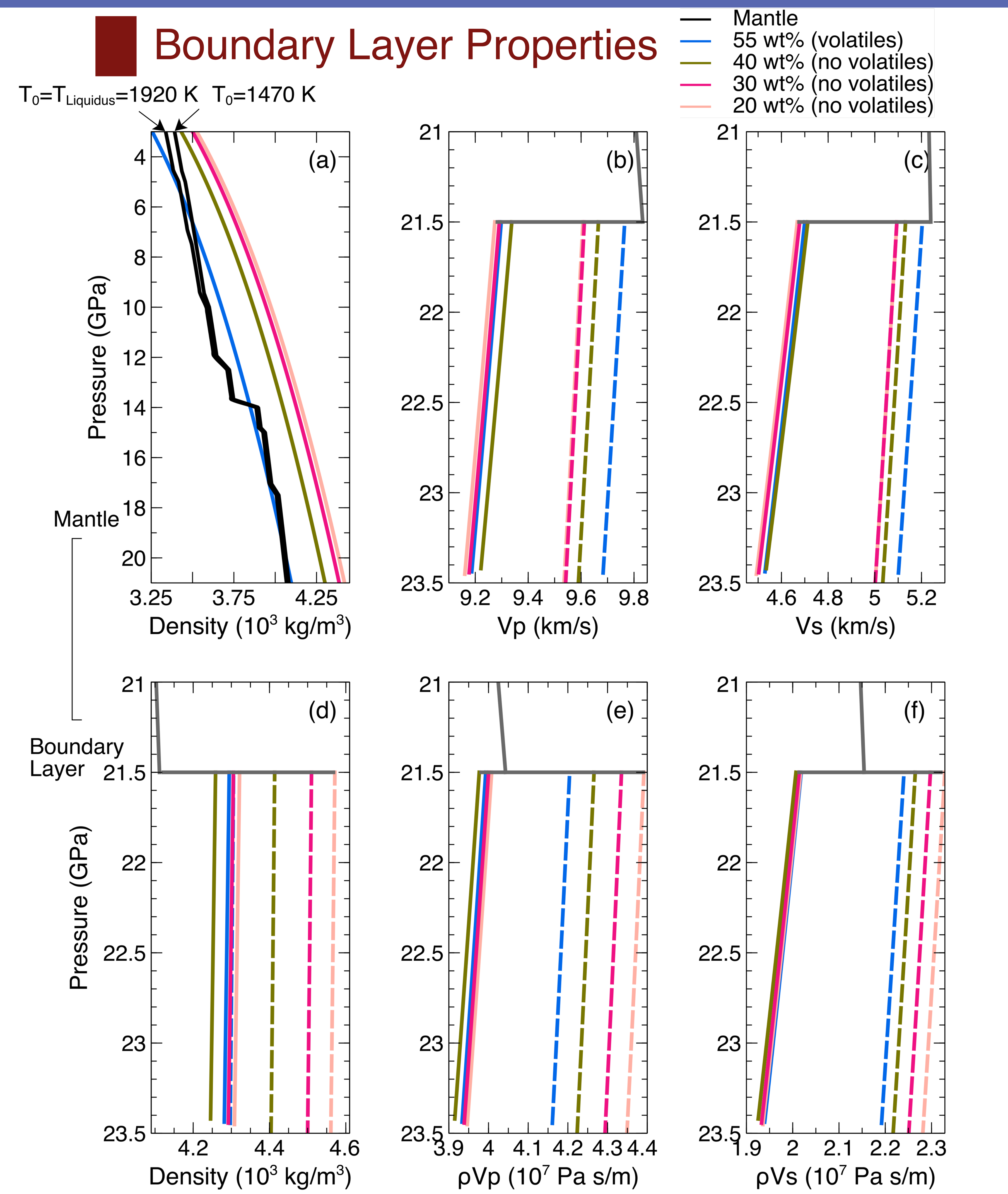
Magma Ocean Fractional Crystallization (3 GPa)





(a) Density differences between residual liquid and coexisting solids at 3 GPa. Shaded region represents magma descent conditions. (b) Density differences between liquid and coexisting solids as a function of pressure for a range of melt compositions. (c) First appearance of solid phases for a fractionally crystallizing magma ocean, as derived from pMELTS[2] simulations.

Boundary Layer Properties



(a) Density profiles of Mars' mantle and fractionally crystallized magma ocean liquids. Mantle density profiles were calculated in BurnMan[3] assuming an adiabatic temperature gradient, starting at different initial temperatures. In (b)–(f), solid lines represent Assemblage 1 (ringwoodite-dominated), and broken lines represent Assemblage 2 (garnet-dominated); gray lines between 21 and 21.5 GPa represent the bulk lower mantle assemblage (gt + rwd). (b)–(c) Calculated P and S wave velocities of lower mantle and thermochemical boundary layer (TCBL) assemblages. (d) Density profile of lower mantle and TCBL assemblages. (e)–(f) P and S wave impedances of the lower mantle and TCBL assemblages.

Solid Mantle and Melt Compositions

	Solid Mantle[4]	HM55	AM40	AM30	AM20
SiO_2	43.90	36.89	35.67	35.20	35.43
Al_2O_3	3.15	5.03	4.57	3.76	2.50
Fe_2O_3	—	2.33	2.65	2.93	3.07
FeO	18.80	25.06	30.26	33.87	35.56
MgO	31.66	25.76	22.14	18.52	17.42
CaO	2.50	3.84	4.71	5.71	6.01
H_2O	—	0.90	0.00	0.00	0.00
CO_2	—	0.18	0.00	0.00	0.00
Density	—	3.26	3.43	3.50	3.53

Total iron in the solid mantle is reported as FeO. The first two letters in the name of each melt composition indicate an initially anhydrous (AM) or hydrous mantle (HM). The number indicates wt% melt. Melt compositions were generated in pMELTS. Density reported in g/cc.

Boundary Layer Mineralogy

	Solid Phase	Composition	HM55	AM40	AM30	AM20
Assemblage 1	Ca-perovskite	$CaSiO_3$	8	9	10	10
	Garnet	$(Mg_{0.8}Fe_{0.2})_3Al_2Si_3O_{12}$	6	5	4	2
	Ringwoodite	$(Mg_{0.75}Fe_{0.25})_2SiO_4$	60	47	37	35
	Wüstite	FeO	20	30	36	37
	Stishovite	SiO_2	6	9	13	15
Assemblage 2	Ca-perovskite	$CaSiO_3$	7	9	10	10
	Garnet	$(Mg_{0.8}Fe_{0.2})_3Al_2Si_3O_{12}$	5	5	3	2
	Majorite	$(Mg_{0.6}Fe_{0.4})SiO_3$	42	54	49	47
	Ferropericlase	$(Mg_{0.85}Fe_{0.15})O$	20	13	8	10
	Wüstite	FeO	26	20	29	31

Mineralogy in mol %.

References

1. Zeff, G., & Williams, Q. (2019). *Geophys. Res. Lett.* **2.** Ghiorso, M.S., et al. (2002). *Geochem. Geophys. Geosyst.* **3.** Cottaar, S., et al. (2014). *Geochem. Geophys. Geosyst.* **4.** Elkins-Tanton, L.T., et al. (2003). *Meteorit. Planet. Sci.*