On the competition of volatile outgassing and cumulate compaction in the solidification of magma oceans.

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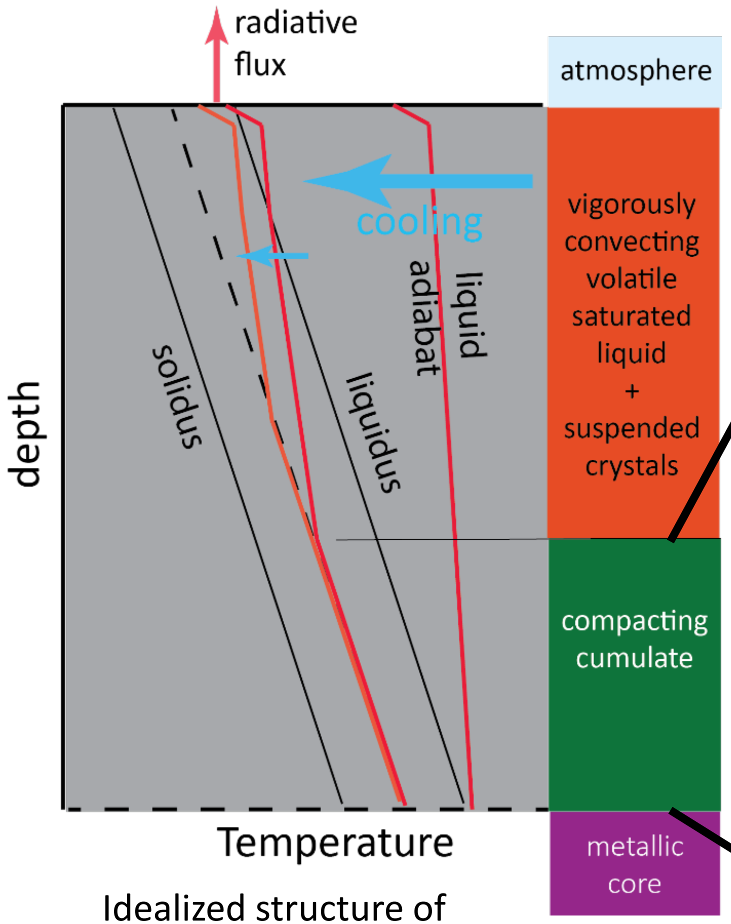
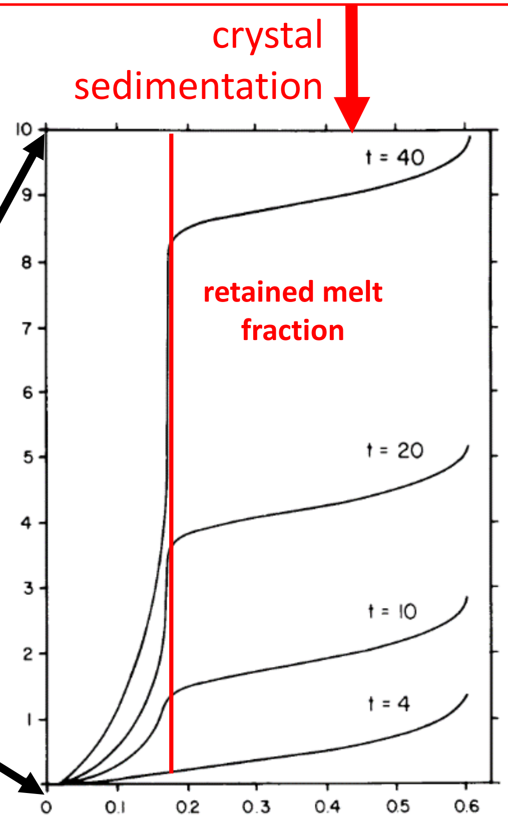
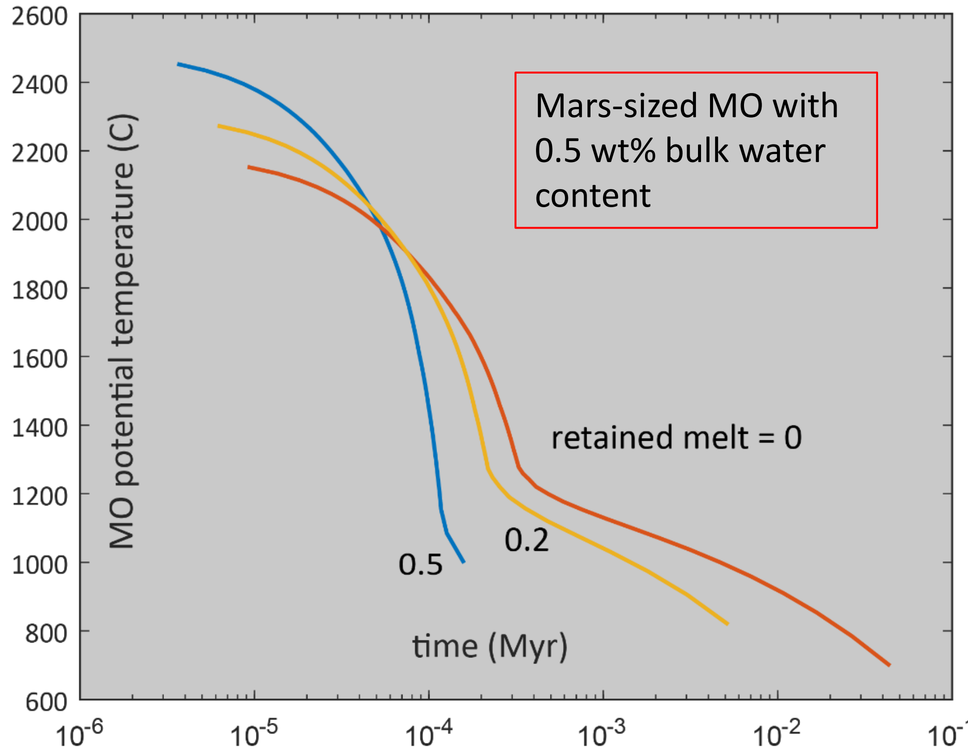


Idealized structure of crystallizing magma ocean (MO) cooling by radiation through planetary atmosphere.

<u>Atmosphere-cumulate coupling</u>:
sedimentation rate ∝ radiative flux
retained melt = *f* (sedimentation rate)

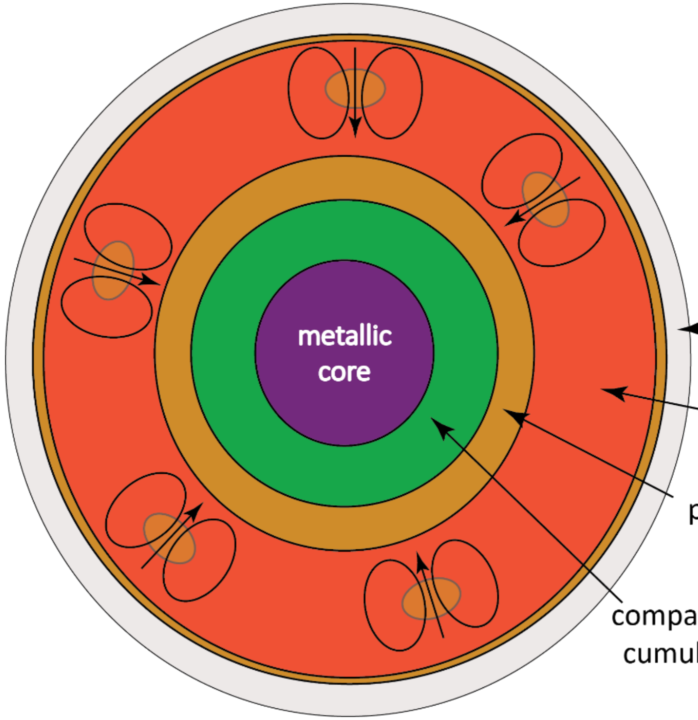


Melt fraction as a function of depth in compacting cumulate at 4 times (Shirley 1986)



Cooling and crystal sedimentation rate is controlled by radiation through atmosphere devolatilized from the vigorously convecting MO. Retained melt in cumulate does not contribute volatiles to the atmosphere on MO solidification time scales allowing increased radiative flux and significantly reducing solidification time: nearly an order of magnitude for retained melt fractions ≥ 0.2 predicted for reasonable melt viscosity and cumulate grain size.

On the competing roles of volatile outgassing and cumulate compaction in the solidification of magma oceans (EGU21-9238)



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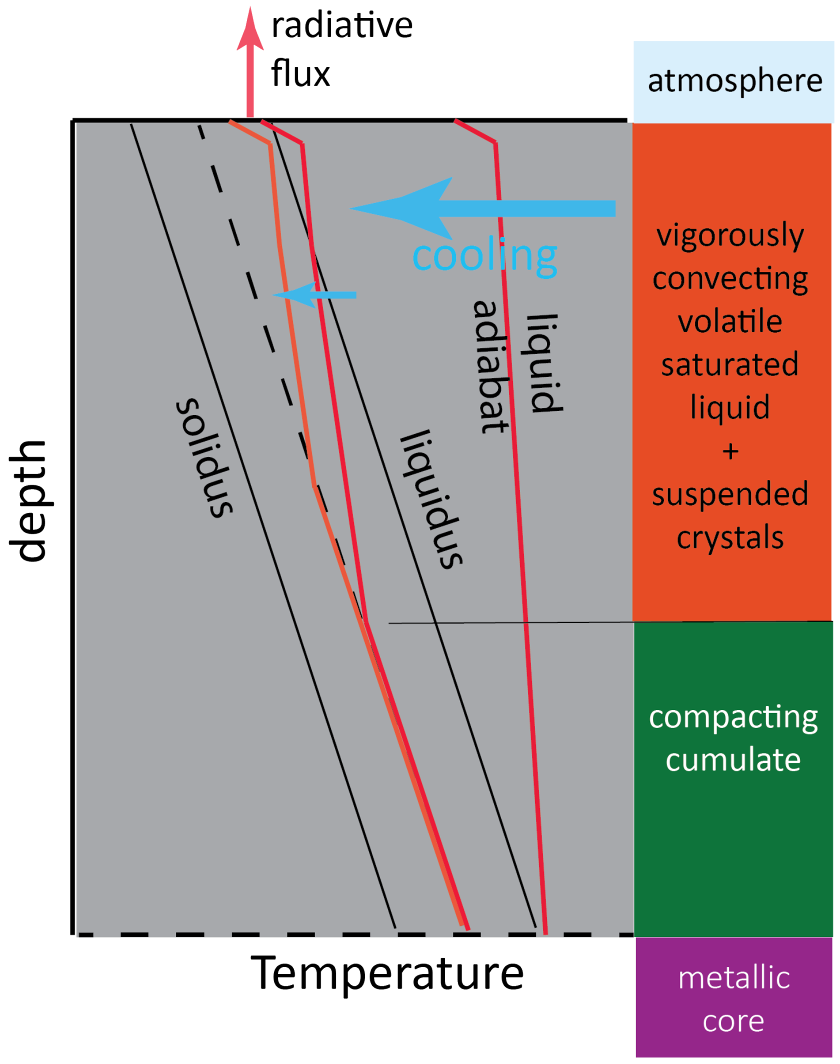
Overview of the thermal evolution model



Magma ocean energy conservation following Elkins-Tanton (2008)

$$\frac{d}{dt}(latent\ and\ sensible\ heat\ in\ magma\ ocean) = 4\pi R^2 f$$

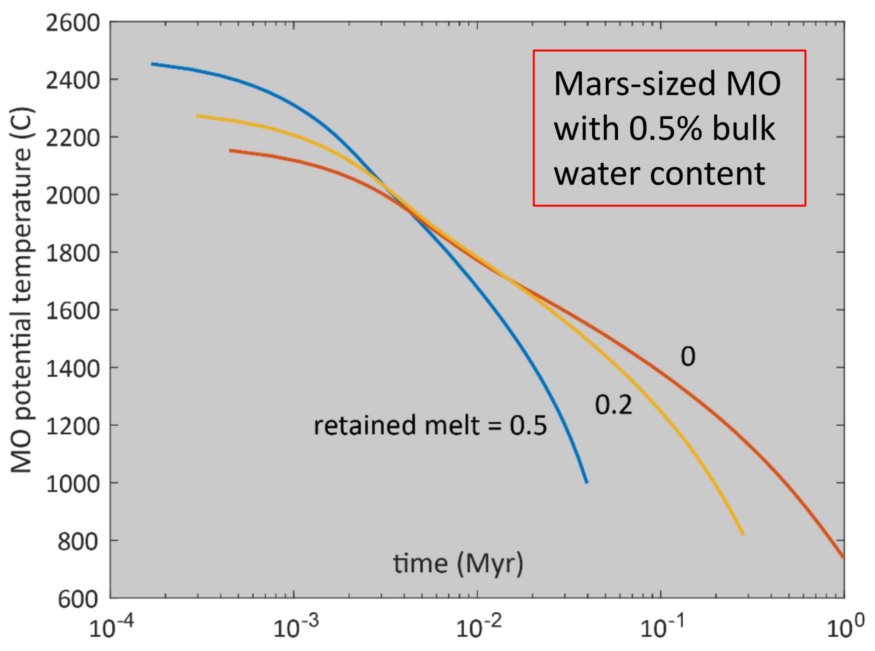
Radiative flux Matsui and Abe (1986) grey, plane atmosphere

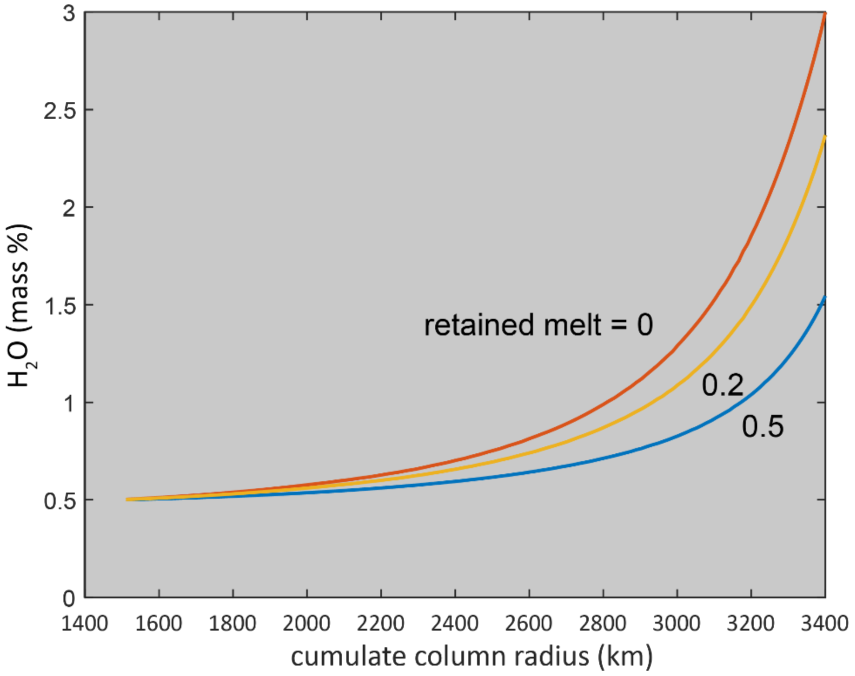
$$f = \varepsilon\sigma\left(T_{surface}^4 - T_\infty^4\right) \qquad \varepsilon = \frac{2}{\sum\tau + 2}$$

$$\tau = \left(\frac{3M_{atm}}{8\pi R^2}\right)\left(\frac{k_0 g}{3p_0}\right)^{1/2}$$

$$M_{atm} = 4\pi p\, R^2/g$$

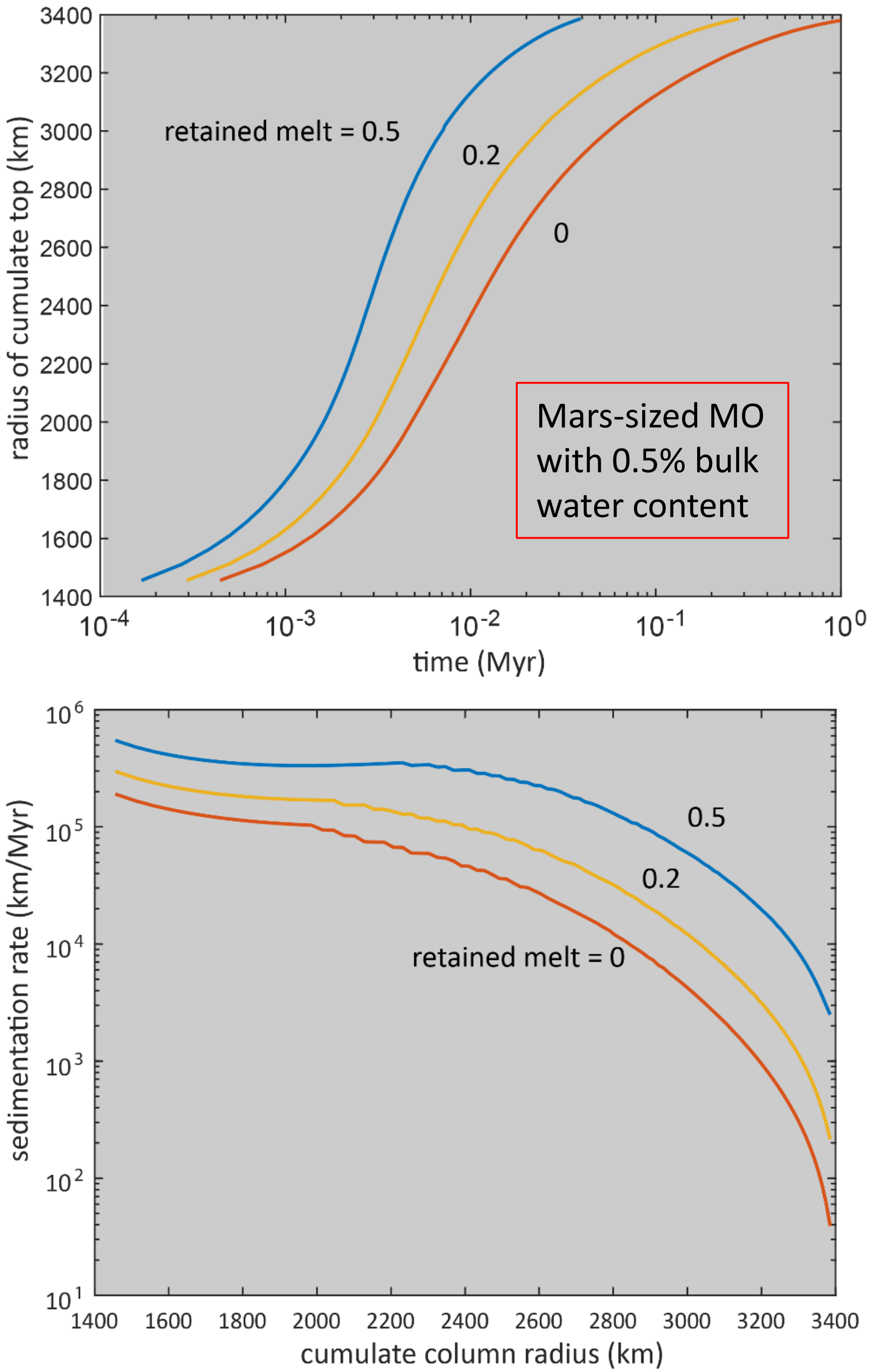
ε	emissivity
τ	optical depth
k_0	absorption coefficient at pressure p_0
p	volatile partial pressure at surface





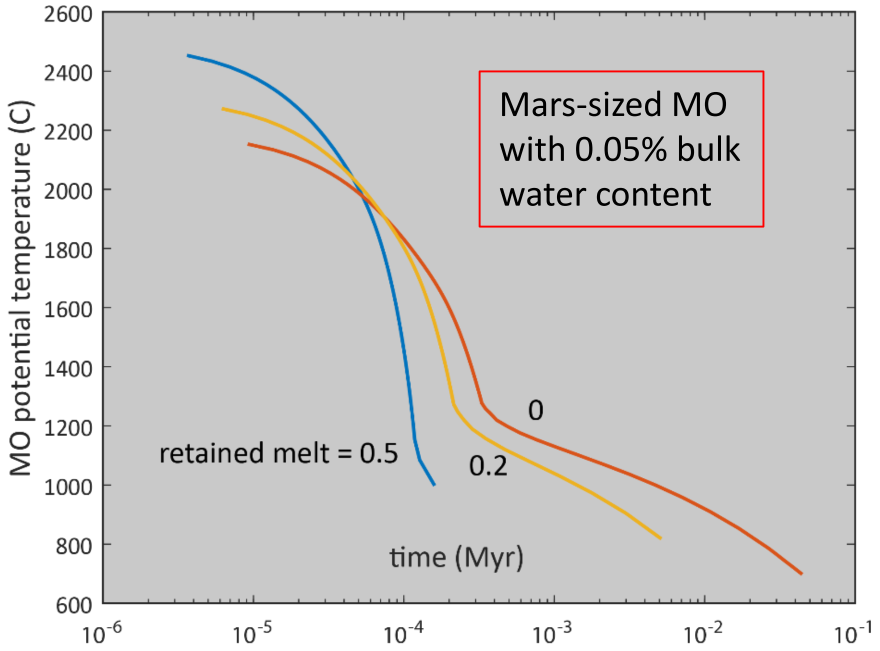
Evolution of MO potential temperature and H_2O mass fraction. As the MO cools and shallows, the water mass fraction in the MO liquid increases. The model assumes a constant prescribed value of the melt fraction retained in the cumulate. This example considers a whole mantle MO on a Mars-sized planet with a bulk water content of 0.5 wt%.

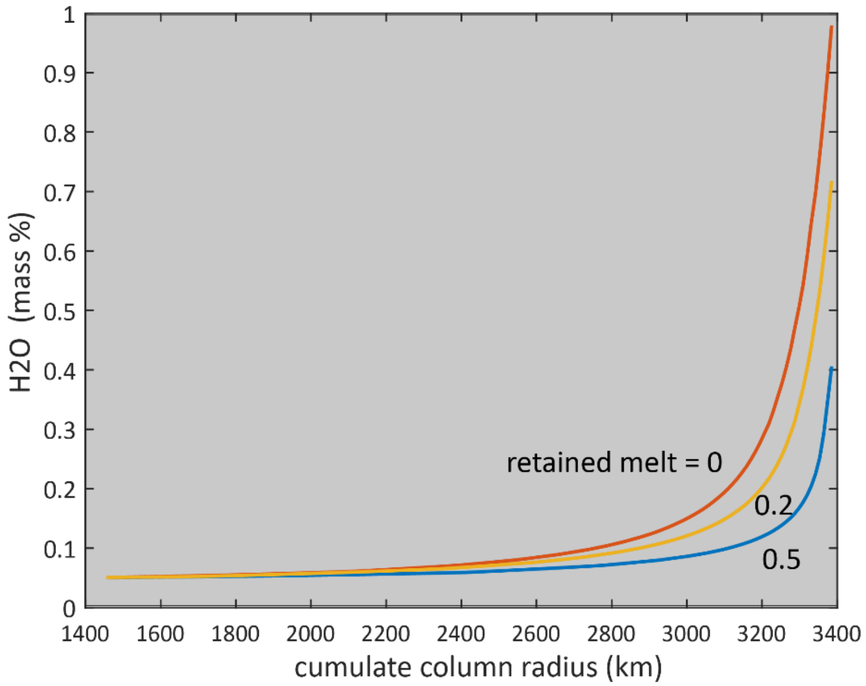
In all cases the H_2O mass fraction in residual MO melt increases as MO potential temperature decreases and solid crystallizes. The increase is most rapid for the case of no retained melt as a water-free cumulate is progressively removed the residual liquid MO. The increase is less rapid for a larger retained melt fraction in the cumulate since H_2O retained in the cumulate melt is removed from the MO liquid.



Radius to the top of the cumulate increases as the MO potential temperature decreases. In all cases the radius increases from the core radius to the radius of the planet.

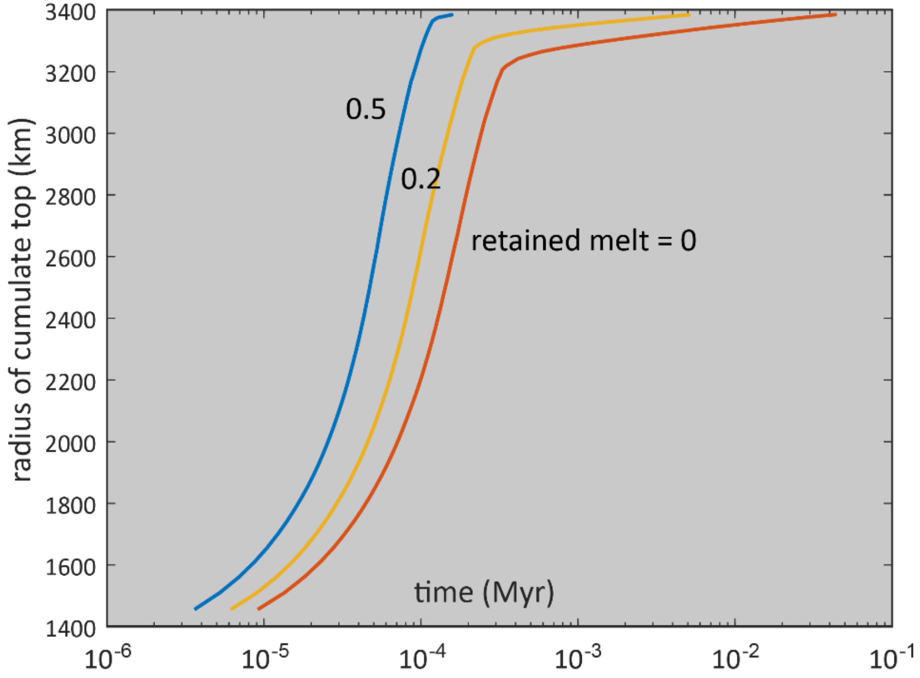
Cumulate sedimentation rate is at first relatively constant and then decreases in the later stages of cumulate deposition. As discussed later, cumulate compaction rate is not consistent with the prescribed constant values of retained melt fraction. Retained melt fraction should decrease with decreasing sedimentation rate.

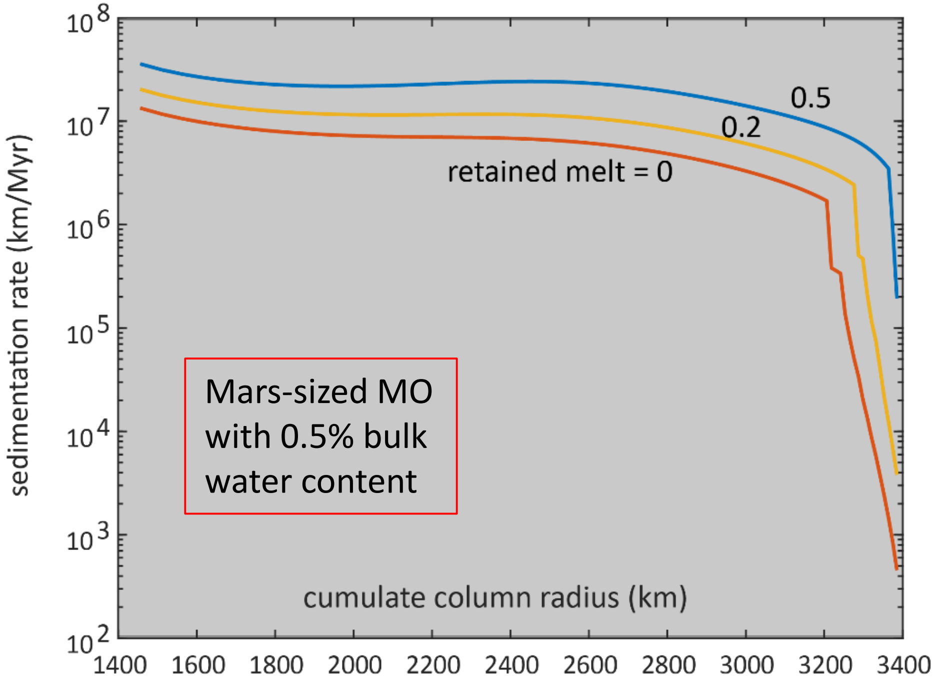




Evolution of MO potential temperature and H_2O mass fraction. As the MO cools and shallows, the water mass fraction in the MO liquid increases. The model assumes a constant prescribed value of the melt fraction retained in the cumulate. This example considers a whole mantle MO on a Mars-sized planet but with a smaller bulk water content of 0.05 wt%.

In all cases the H_2O mass fraction in residual MO melt increases as MO potential temperature decreases and solid crystallizes. The increase is most rapid for the case of no retained melt as a water-free cumulate is removed the liquid MO. The increase is less rapid for a larger retained melt fraction as discussed above.





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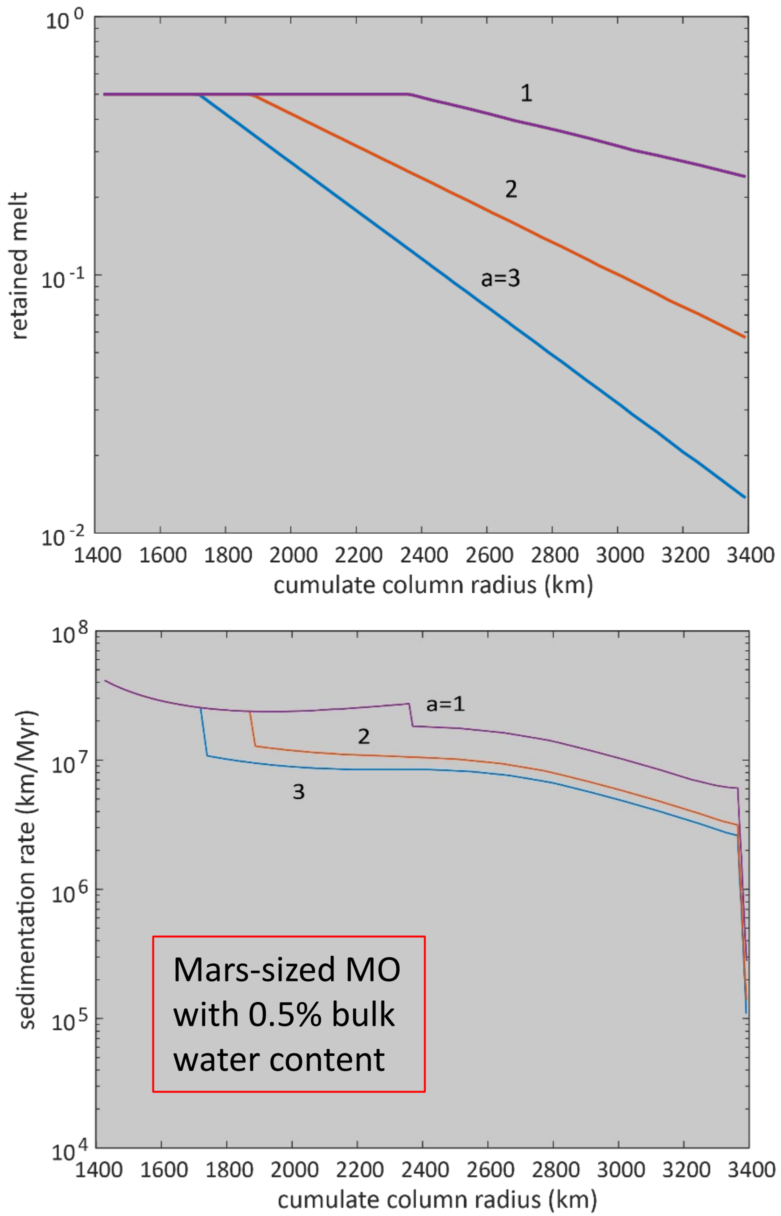
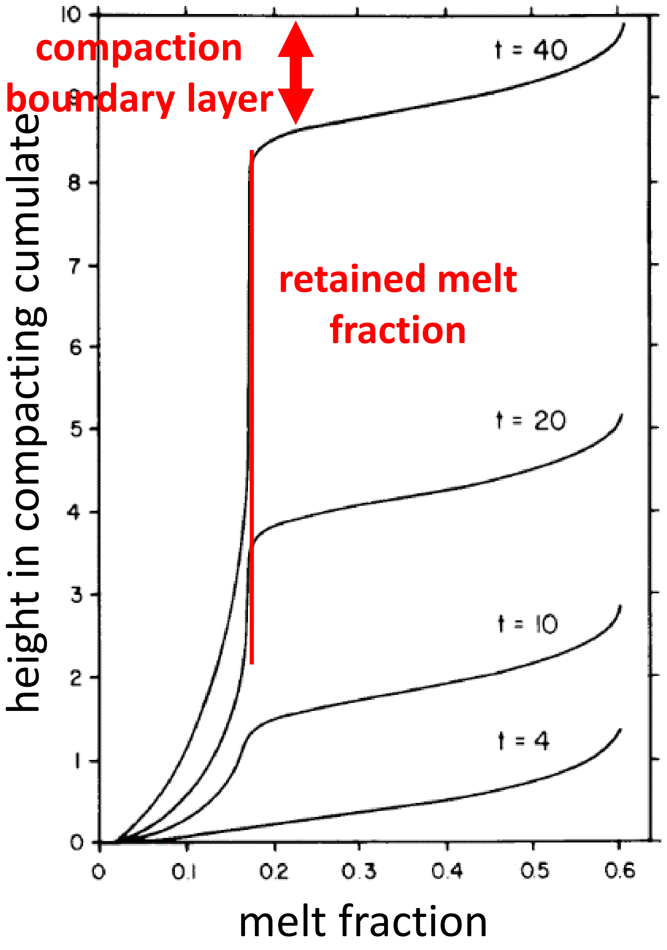
Cumulate sedimentation rate is at first relatively constant and then decreases in the later stages of cumulate deposition. As discussed later, cumulate compaction rate is not consistent with a prescribed constant value of retained melt fraction. Retained melt fraction should decrease with decreasing sedimentation rate.

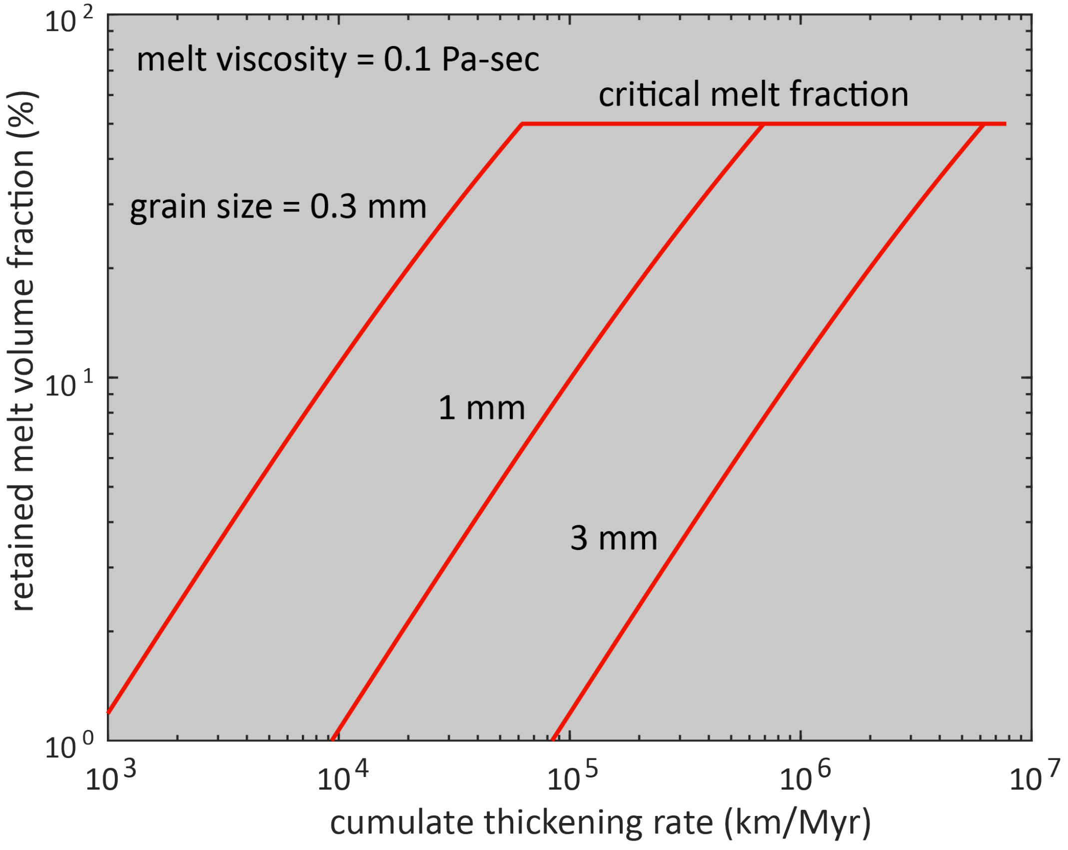


Example with 0.05 wt% bulk H_2O and <u>prescribed variation</u> of retained melt fraction during the evolution. Note the broad similarity with the above cases in which shows a comparable range of prescribed <u>constant</u> retained melt fractions.



Shirley (1986)

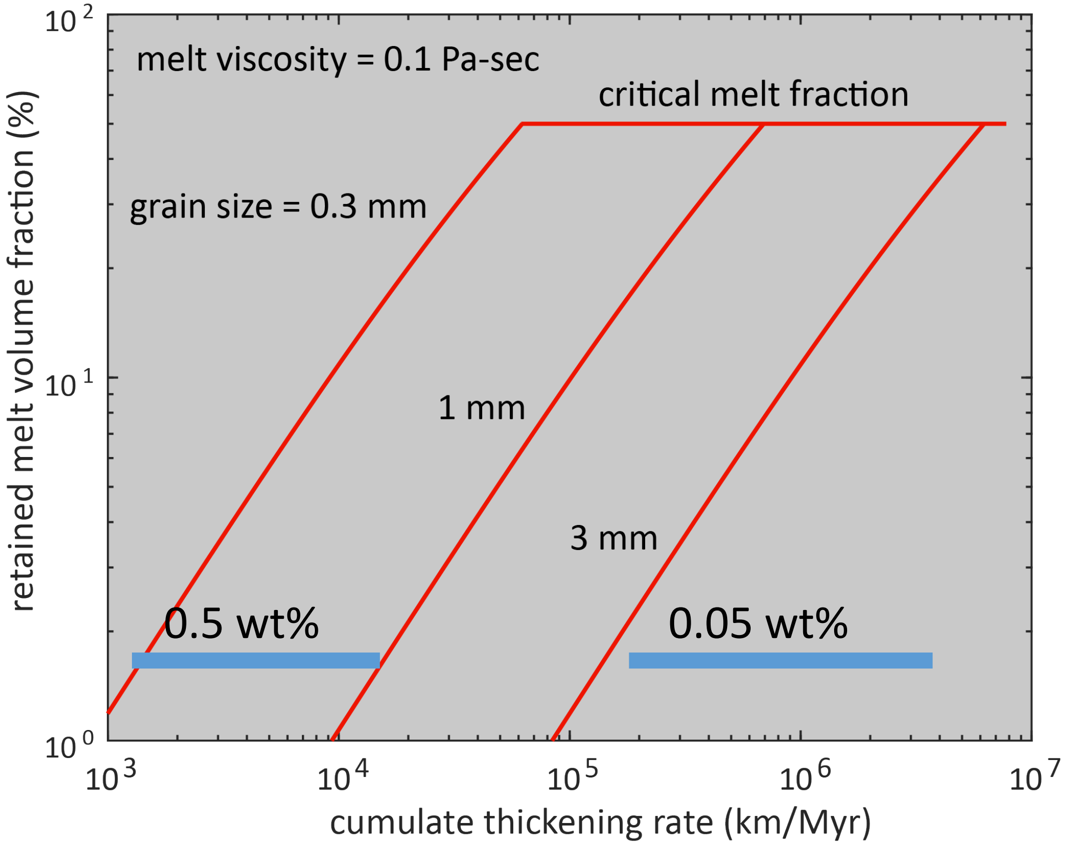
For a constant sedmentation rate, the melt fraction as a function of height within the compacting cumulate attains a nearly constant value at which the upward buoyant migration of melt balances the sedimentation rate. A compaction boundary layer forms at the top of the cumulate. The relatively constant thickness of this boundary layer scales with the compaction length in the underlying cumulate (which is one unit of height in the example from Shirley, 1986). The compaction length in planetary mantle cumulates is expected to be on the order of 1-10 km.



The buoyant upward flux of retained melt is inversely proportional to melt viscosity and is proportional to the permeability K of the cumulates which is function of the retained melt fraction ϕ

$$K = \frac{a^2}{300}\,\frac{\phi^3}{(1-\phi)^2}$$

where a is the cumulate grain size. Calculated retained melt volume fraction is as a function of cumulate thicknening rate is shown for a range of grain sizes considered appropriate for MOs (Solomatov and Stevenson, 1993). Above the critical melt fraction the cumulate solid matrix is disaggregated to form a suspension of solid grains with a viscosity approaching that of the melt. This melt fraction defines the top of the compacting cumulates on to which sedimentation occurs.



The horizontal blue bars show the range of sedimentation (cumulate thickening) rates for models with 0.5 and 0.05 wt% bulk H_2O. For the small grain size of 0.3 mm, the retained melt fractions in the range of 1-10% are relevant for 0.5 wt% water. Much smaller retained melt fractions would be expected for larger grain sizes. Even for a grain size as large as 3 mm, retained melt fractions in the higher range of values exceeding 10% are relevant for 0.05 wt% water. This stresses the importance of cumulate grain size in determining the role of cumulate compaction and its interaction with atmospheric evolution from magma ocean degassing.

An important next step is better defining this interaction and its feedbacks from models which allow the retained melt fraction to vary with the sedimentation (cumulate thickening) rate as the MO cools and crystallizes. A simple case would be one following a curve of constant grain size shown here.