Formation d'un Océan de Magma profond: un modèle numérique

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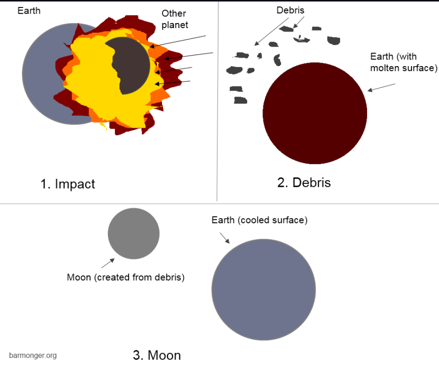
Big Impact

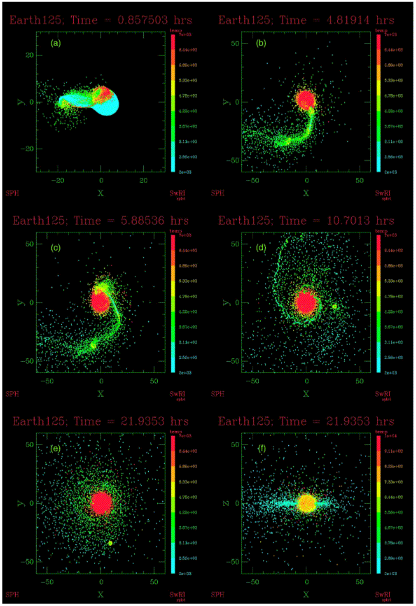


Earth
Other planet
1. Impact
Debris
Earth (with molten surface)
2. Debris
Moon (created from debris)
Earth (cooled surface)
barmonger.org
3. Moon

Big Impact

Late lunar-forming impact.
(a) - (e) are looking down onto the plane of the impact, with particles withT >6440 K shown in red.
(f) is the final state viewed on-edge.

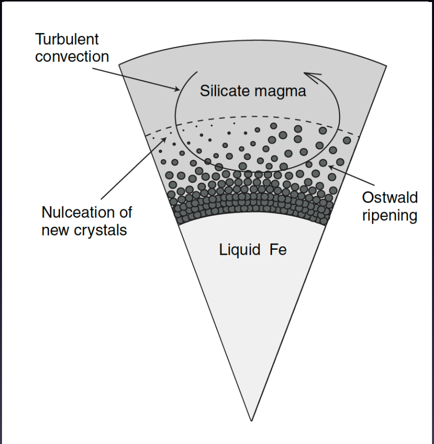
(Canup, Icarus, 2004)



Magma Oceans

Magma ocean in the early stages of crystallization. Nucleation occurs in the downgoing convective flow when it enters the two-phase region.

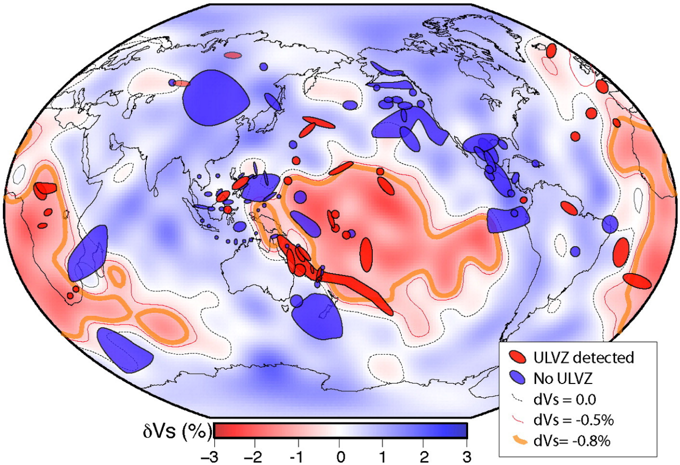
Crystals continue to growth because of Ostwald ripening-larger crystals grow at the expense of smaller ones. (Solomatov, ToG, 2007)



Ultra Low Velocity Zones ?

McNamara et al., EPSL, 2010

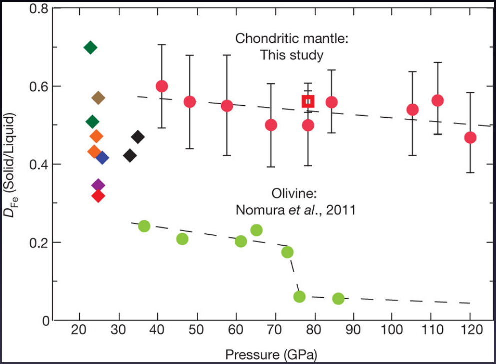
- Seismic velocity reduction $\delta v = 10 - 30\%$ -> partial melt
- Thickness $\sim$ 10 km
- High density $\delta \rho = 10\%$



Fe partition coefficient data

Fe partition coefficient (D_{Fe}) between silicate melt and the Mg-Pv liquidus phase.

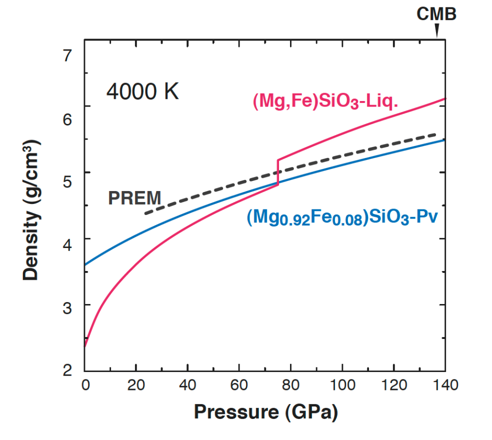
Determined using X-Ray Fluorescence analyses (red circles) and Electron-Probe Micro-Analyses (red square) by Andrault et al. (Nature, 2012).



Melt density data

Density of $(Mg,Fe)SiO_3$ liquid coexisting with $(Mg_{0.92}Fe_{0.08})SiO_3$ perovskite.

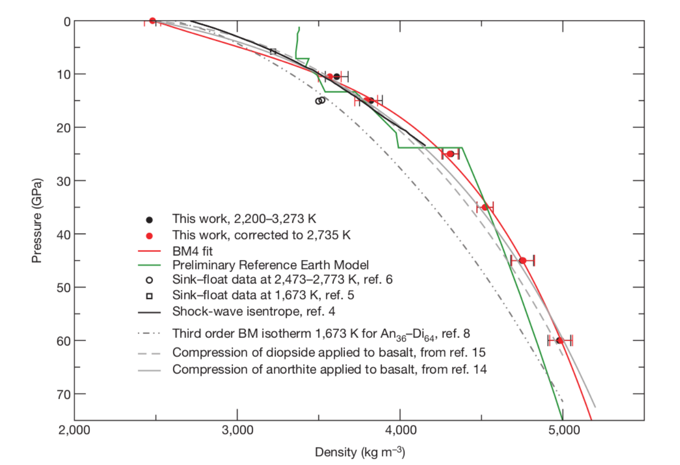
Calculated at 4000 K using Fe-Mg partitioning data obtained by Nomura et al., (Nature, 2010).



Melt density data

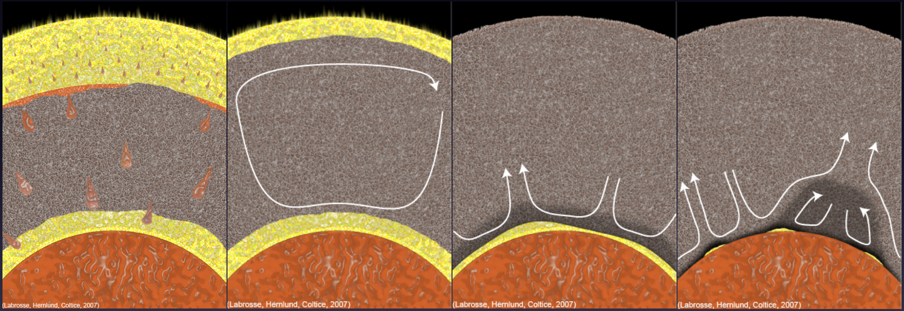
Density of molten basalt as a function of pressure

Calculated using in situ X-ray diffraction data obtained by Sanloup et al. (Nature, 2013).



The Basal Magma Ocean Hypothesis

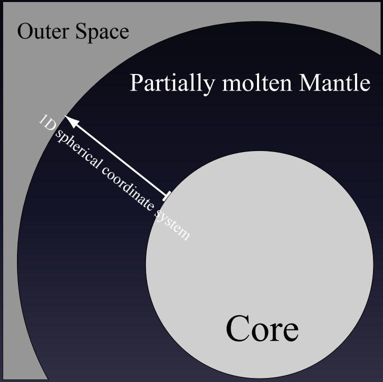
Labrosse et al., Nature, 2007



4.52 Gy | 4.50 Gy | 3.5 Gy | Today

Essence of the Model

- At the end of the Magma Ocean initial turbulent convective cooling, melt percolation takes place in a slowly convecting mantle and thus we neglect convective and diapiric advection.
- Melt and mantle densities encounters a crossover within the lower mantle.
- Melting and solidification are computed using enthalpy method
- Convective cooling of entirely molten shell is taken into account.



Two-phase flow formulation

From conservation of mass,

$$\frac{\partial \phi}{\partial t} + \nabla \cdot \mathbf{v}_f \phi = \frac{\dot{\Gamma}}{\rho_f}$$

$$\frac{\partial (1-\phi)}{\partial t} + \nabla \cdot \mathbf{v}_s (1-\phi) = -\frac{\dot{\Gamma}}{\rho_s}$$

From conservation of momentum,

$$\frac{\eta_f \phi^2}{k(\phi)} \delta \mathbf{v} + \phi \rho_f \mathbf{g} - \phi \nabla P_f + \nabla \cdot \phi \tau_f = 0$$

$$-\frac{\eta_f \phi^2}{k(\phi)} \delta \mathbf{v} + (1-\phi) \rho_s \mathbf{g} - (1-\phi) \nabla P_s + \nabla \cdot (1-\phi) \tau_s + \delta P \nabla \phi = 0$$

The indexes s and f hold for solid and fluid respectively and $\delta X = X_s - X_f$

Two-phase flow formulation

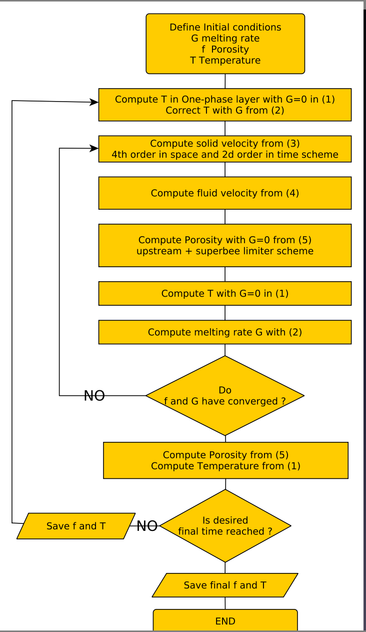
From the entropy production at the solid-fluid interface, by recognizing thermodynamic scalar forces and their conjugate fluxes (Sràmek et al., J.G.I.; Richard et al., E.P.S.L., 2007),

$$\delta P = -\frac{A\eta_s}{\phi}\nabla \cdot \mathbf{v}_s = -\frac{A\eta_s}{\phi}\left(\frac{D_s}{Dt}\phi - \frac{\dot{\Gamma}}{\rho_s}\right)$$

$$\dot{\Gamma} = L_{22}\left(\delta\epsilon - T\delta s - P_f\frac{\delta\rho}{\rho_f\rho_s}\right)$$

Spherical 1D non-dimensional Model

$$\bar{\rho}\frac{d}{dt}T^* + \cancel{\overline{\rho v}\frac{d}{dr}T^*} + \cancel{\frac{\phi_0 L}{C_P T_0}}\dot{\Gamma} =$$
$$\frac{k_T \eta_s}{\Delta\rho^2 C_P g \delta_c^3}\frac{1}{r^2}\frac{d^2}{dr^2}r^2 T^* + \frac{\delta_c g \phi_0}{C_P T_0}\phi^{2-n}\delta v^2$$
$$+ \frac{A\delta_c g}{C_P T_0}\frac{1-\phi_0\phi}{\phi_0\phi}\left(\frac{1}{r^2}\frac{d}{dr}r^2 v_s\right)^2 \qquad (1)$$

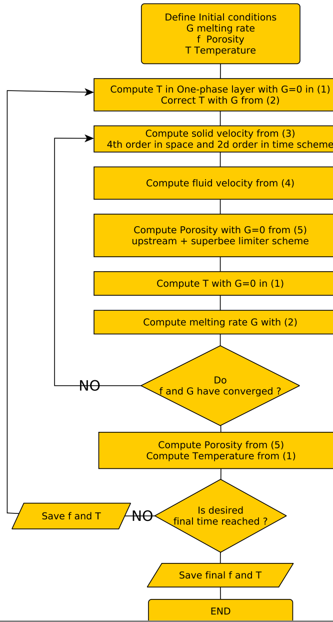


Spherical 1D non-dimensional Model

$$\dot{\Gamma} = -\bar{\rho}\frac{C_P T_0}{\phi_0 L}\Delta T$$

where $\Delta T = T^{melt} - T^*$

$$\dot{\Gamma} = \begin{cases} min(-\bar{\rho}\frac{C_P T_0}{\phi_0 L}\Delta T, \rho_s\frac{(1-\phi_0\phi)}{\phi_0}) & \text{if } \Delta T > 0 \\ -min(\ \bar{\rho}\frac{C_P T_0}{\phi_0 L}\Delta T, \rho_f\phi) & \text{if } \Delta T < 0 \end{cases} \quad (2)$$

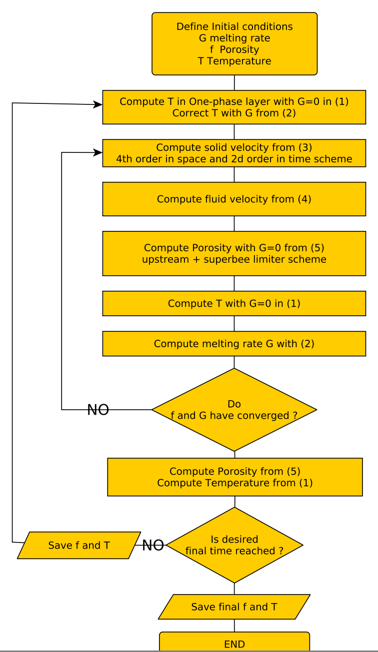


Spherical 1D non-dimensional Model

$$\frac{v_s}{\phi^n} - \frac{\partial}{\partial r}\left[\frac{1}{r^2}(1-\phi_0\phi)\left(\frac{4\phi_0}{3}+\frac{A}{\phi}\right)\frac{\partial}{\partial r} r^2 v_s\right] = -\phi_0(1-\phi_0\phi)\delta\rho + \frac{\phi_0}{\phi^n r^2}\int_{r_{CMB}}^{r} r'^2 \frac{\delta\rho}{\rho_s\rho_f}\dot{\Gamma}\,dr' \qquad (3)$$

$$v_f\phi_0\phi + v_s(1-\phi_0\phi) = \frac{\phi_0}{r^2}\int_{r_{CMB}}^{r} r'^2 \frac{\delta\rho}{\rho_s\rho_f}\dot{\Gamma}\,dr' \qquad (4)$$

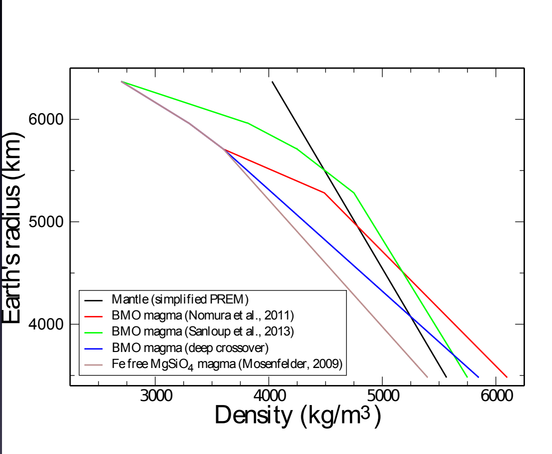
$$\frac{\partial\phi^*}{\partial t} + \frac{\partial}{\partial r}(v_f\phi^*) = \cancel{\frac{\dot{\Gamma}}{\rho_f}} = 0 \qquad (5)$$



Model Settings

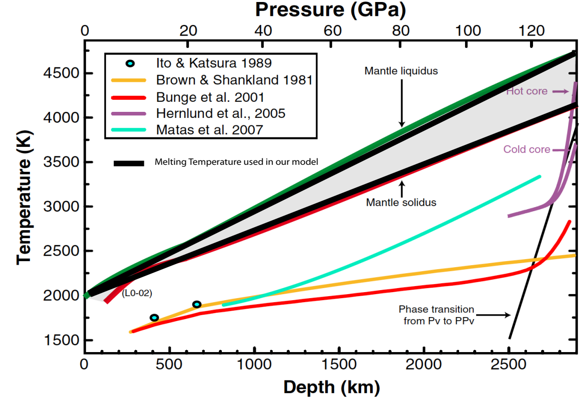
Evolution of melt density with depth in the mantle.
Solid phase (mantle) density from PREM and liquid phase adapted from Mosenfelder et al. (*J.Geophys.Res., 2009*), Nomura et al. (*Nature, 2010*) and Sanloup et al. (*Nature, 2013*).

Crossover takes place at 700 km of the Core Mantle Boundary



Temperature of melting

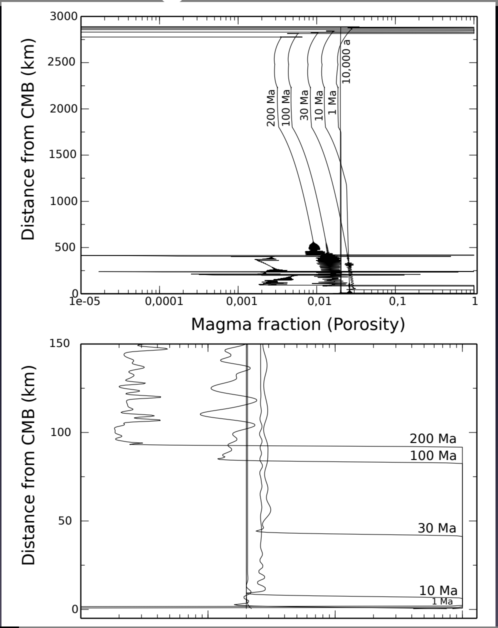
Melting curves of synthetic chondritic mantle and available estimates of the mantle geotherm.
(Andrault et al., EPSL, 2011)
In our model, mantle Solidus and Liquidus are assumed to be equal.
In the following numerical experiments, two melting temperature profiles have been used (thick black lines).



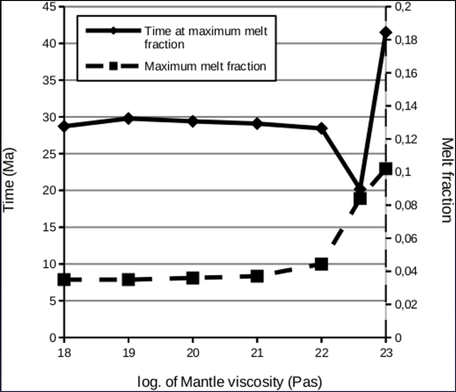
Formation of a Basal Magma Ocean

Temporal evolution of the fraction of magma (porosity) in a partially molten mantle.
$\eta_s = 10^{19}$ (Pa s), η_f=0.1 (Pa s),
k_0 =10^{-10} m^2, $\phi_0 = 0.02$,
$D_X = 2025$ km i.e. δ_c =2 km
fixed surface T, zero CMB flux

- The superficial one (SMO) reaches a thickness of 30 km before to slowly solidify and disappear after 160 Ma.
- After 100 millions years the BMO is 80 km thick and its lower boundary starts to move upward.

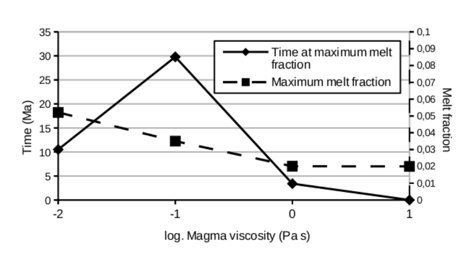


Time scale of BMO formation



η_f = 0.1 Pa s, $k_0 =10^{-10}$ m^2
($\phi_0 = 0.02$, $D_X = 2025$ km)
Time to reach the maximum magma fraction is weakly dependent of η_s

Influences of mantle and magma viscosities



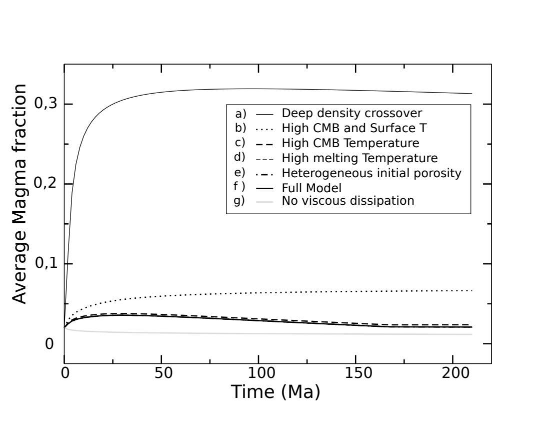
η_s = 10^{19} Pa s
Magma viscosity is strongly controlling the dynamics

δc **is not enough to describe the dynamics of the system.**

Re-melting & BMO formation

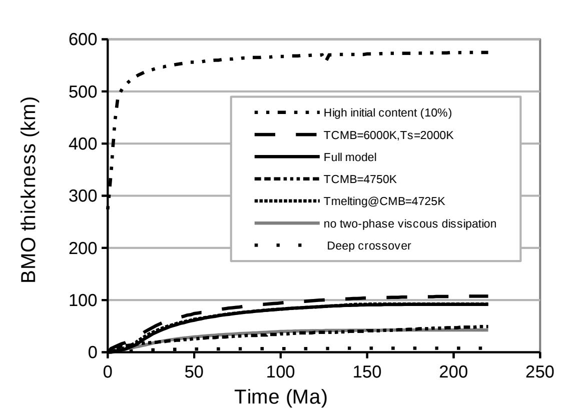
$\phi_0 = 0.02,$
$\eta_s = 10^{19}$ Pa s, η_f=0.1 Pa s

- the influences of the CMB temperature (6000 K), melting temperature (4725 K) and initial distribution are weak
- Deep density crossover provides more up going magma and then more remelting and higher average magma fraction (up to 30%)



BMO thickness

- The Depth of the crossover controls the BMO thickness
- Neglecting viscous dissipation makes the BMO thinner
- Surface Temperature does not constrain the thickness of BMO



Conclusions to take away

- A new pair of magma oceans can be reformed by percolation after the initial cooling of a global magma ocean
- The depth of the density crossover controls the thickness of the Basal Magma Ocean. $L_{BMO} \sim$ 10-100 km
- A thick BMO is observed for high boundary temperatures (T_{surf}=2000 ^oK and T_{CMB}=6000 ^oK), the strongest controlling parameter being the CMB temperature
- Two-phase viscous dissipation should be taken into account in models
- Presence of an early atmosphere is only weakly influencing the BMO magma dynamics *in our model*