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LETTERS

A crystallizing dense magma ocean at the base of the Earth's mantle

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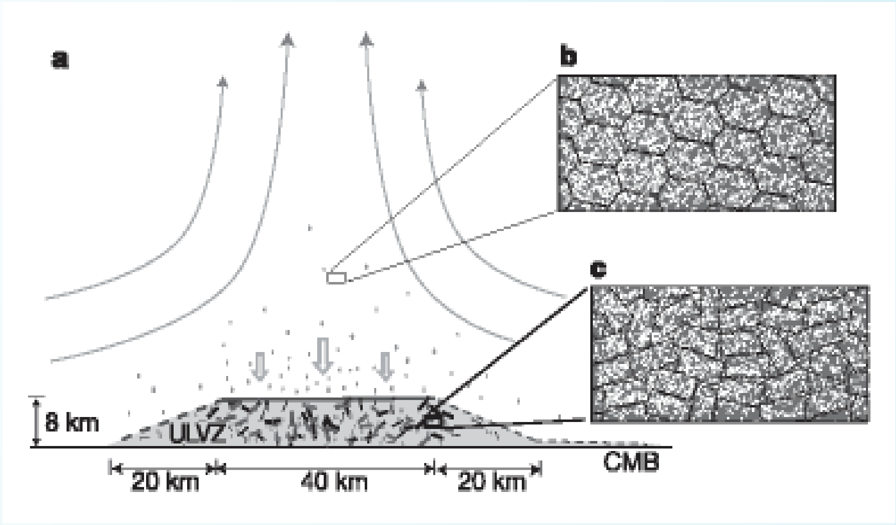
Partial melting at the core mantle boundary

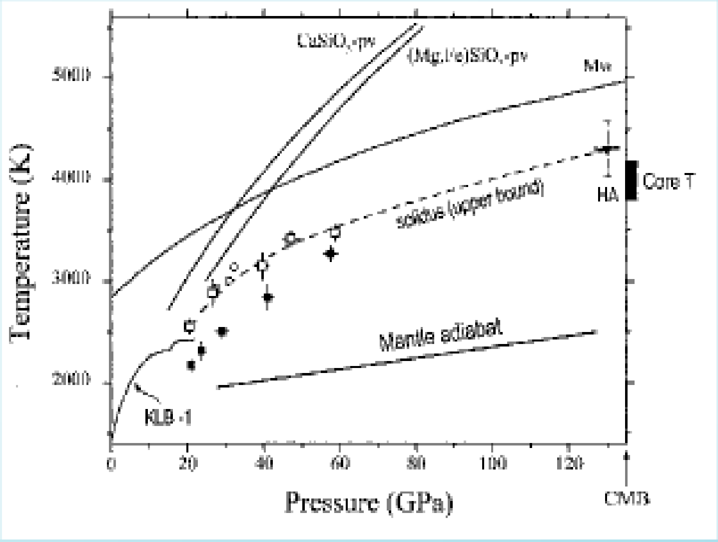


Detection of an ultra low velocity zone (ULVZ) at the plume root

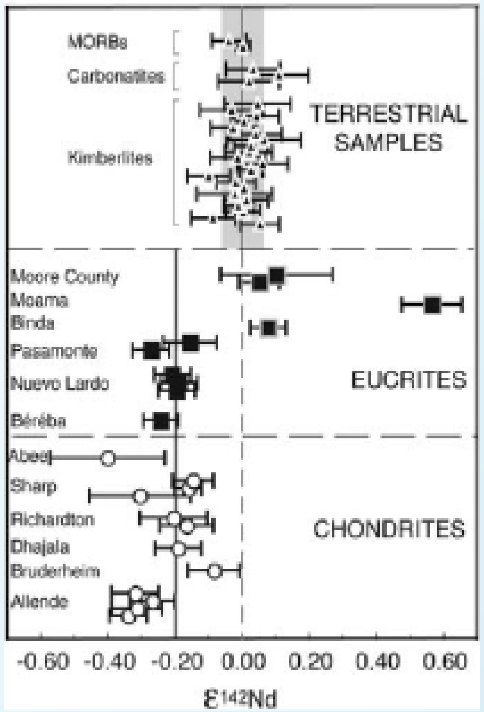
From Rost et al, 2005, Nature, **435**, 666.

Partial melting temperature of pyrolitic-like mixture

From Zerr et al, 1998, Science, **281**, 243



Early Earth differentiation



From Boyet et al, Science, 2005, **309**, 576

Radiogenic system ^{146}Sm- ^{142}Nd : τ=102 Ma

Lithophile element : tracers of mantle differentiation (inert concerning core formation)

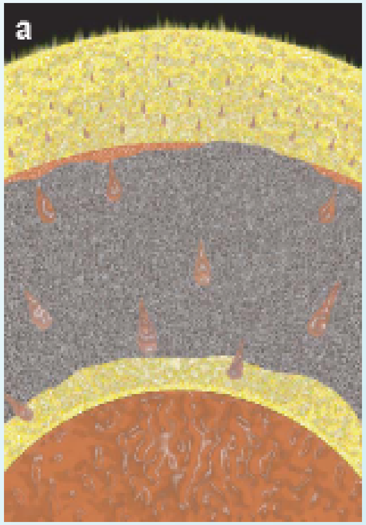
Existence of an hidden enriched reservoir !!!

20-30% of very incompatible elements (U, Th, K, ...)

20-60% of ^{40}Ar total budget

Magma ocean model

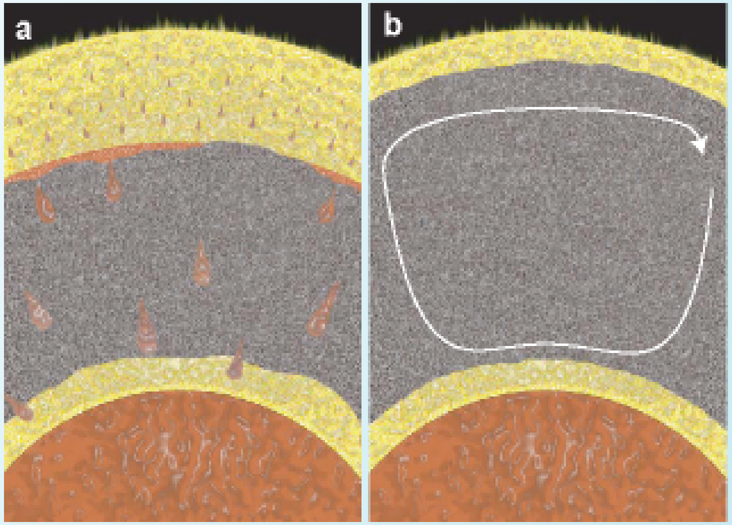
a: Percolation of iron by diapiric instabilities



Magma ocean model

a: Percolation of iron by diapiric instabilities

b: Crystallisation from up and bottom with different rates

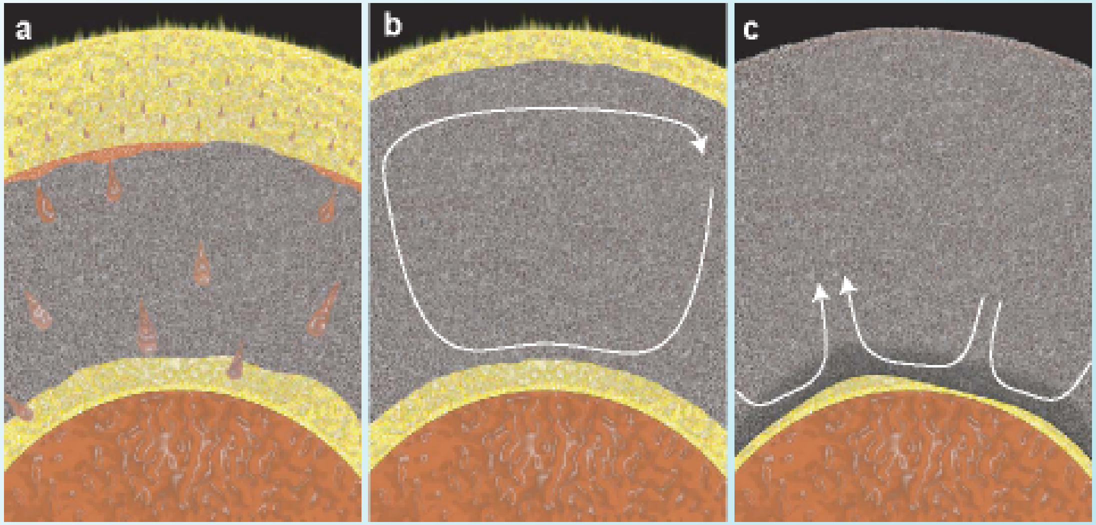


Magma ocean model

a: Percolation of iron by diapiric instabilities

b: Crystallisation from up and bottom with different rates

c: Crystallisation of Fe-enriched solids



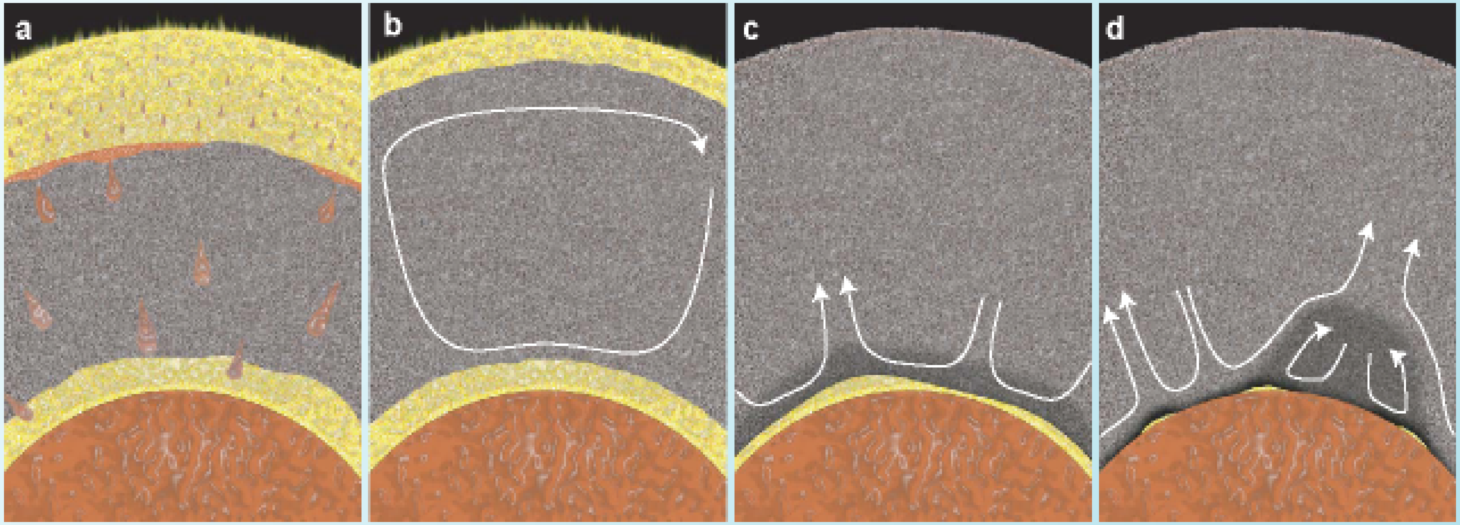
Magma ocean model

a: Percolation of iron by diapiric instabilities

b: Crystallisation from up and bottom with different rates

c: Crystallisation of Fe-enriched solids

d: Actual state with remaining mushy layer and partial melt



Stability of melt layer at the CMB

Gravitionnal stability :

-If enrichment in iron relative to magnesium

-If small or negative melting slope

Chemical stability :

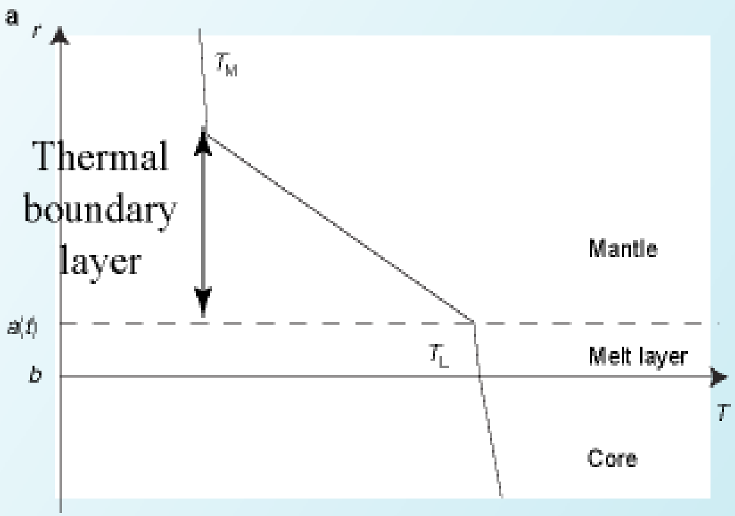
-If complete equilibrium with core, due to low viscosity

-Chemical interaction between core and mantle not well constrained

Evolution model of this melt layer

$$4\pi a^2 k \frac{T_L - T_M}{\delta} = -\ (M_m C_{pm} + M_C C_{pC}) \frac{dT_L}{dt} + H(t) - 4\pi a^2 \rho \Delta S T_L \frac{da}{dt}$$

Heat variation due to temperature variation in thermal boundary layer = - Specific heat production + Radiogenic heat production - Latent heat production

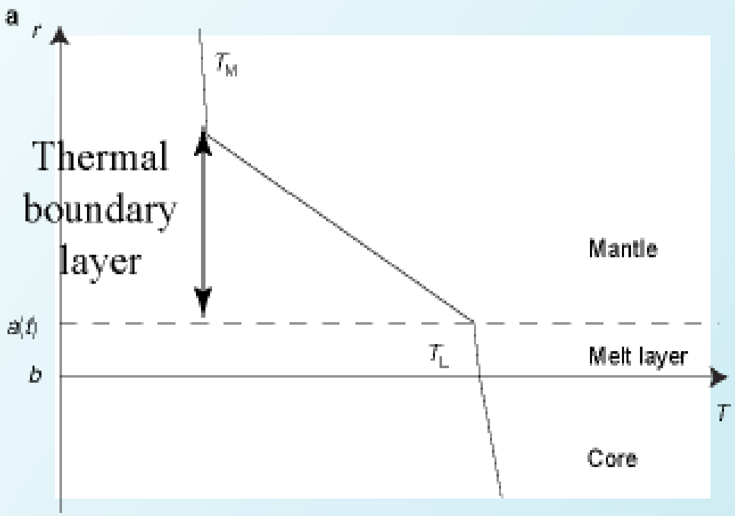


Adiabatic temperature gradient in melt layer and core

Evolution model of this melt layer

$$4\pi a^2 k \frac{T_L - T_M}{\delta} = -\left(M_m C_{pm} + M_C C_{pC}\right)\frac{dT_L}{dt} + H(\mathbf{t}) - 4\pi a^2 \rho \Delta S T_L \frac{da}{dt}$$

$$\frac{d\xi_L}{dt} = -\frac{3a^2\Delta\xi}{a^3 - b^3}\frac{da}{dt}$$



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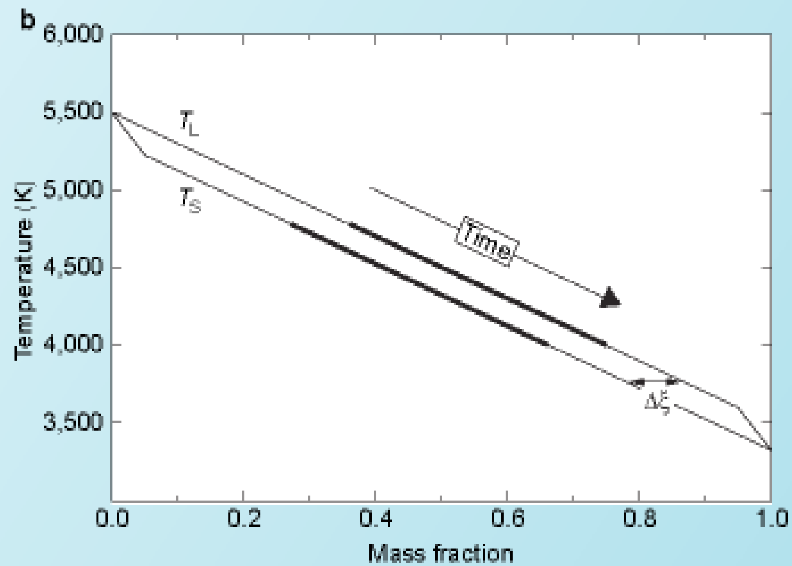

Idealized solid solution

Evolution model of this melt layer

$$4\pi a^2 k \frac{T_L - T_M}{\delta} = -\ (M_m C_{pm} + M_C C_{pC}) \frac{dT_L}{dt} + H(\mathbf{t}) - 4\pi a^2 \rho \Delta S T_L \frac{da}{dt}$$

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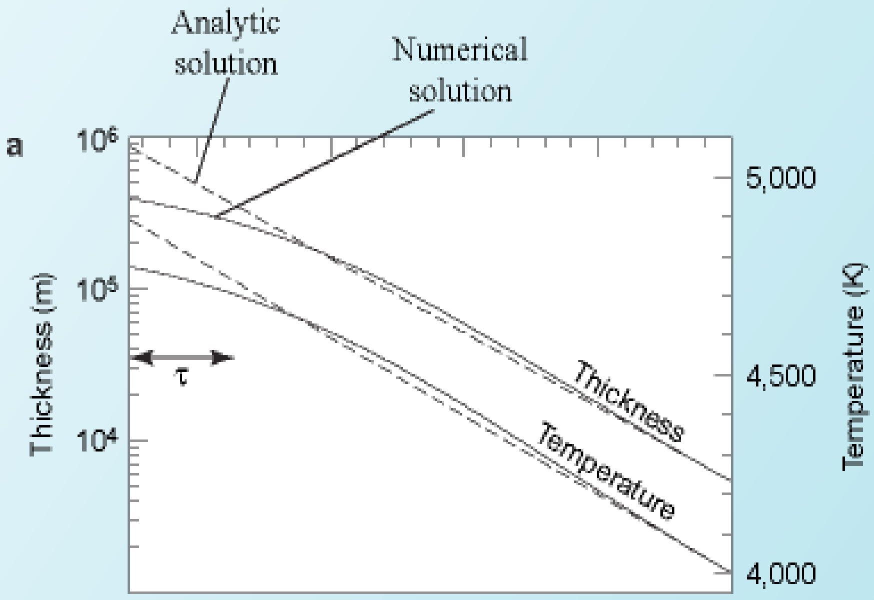

τ : e-fold time of decay of layer thickness : ~ 1 Gyr

Evolution model of this melt layer

$$4\pi a^2 k \frac{T_L - T_M}{\delta} = -\left(M_m C_{pm} + M_C C_{pC}\right)\frac{dT_L}{dt} + H(tt) - 4\pi a^2 \rho \Delta S T_L \frac{da}{dt}$$

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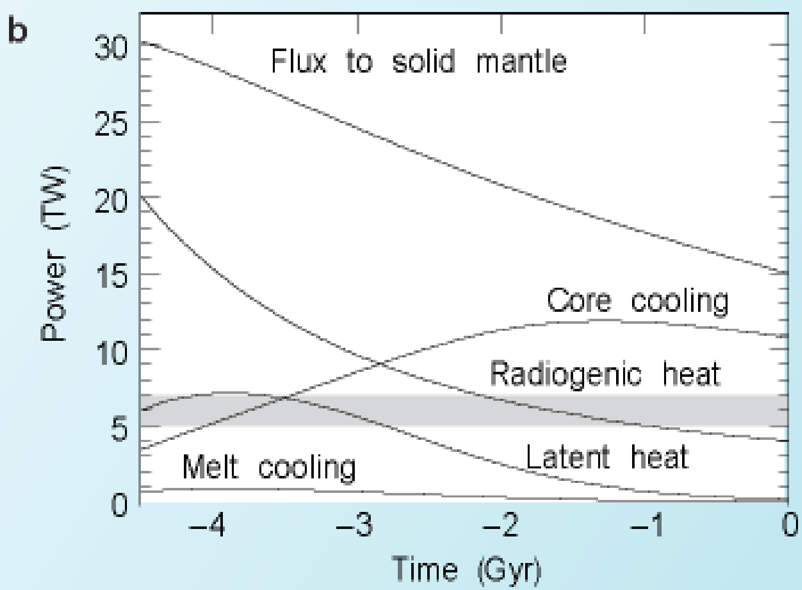

Evolution of heat production with time

Generation of geodynamo

→ Due to thermal convection

↓

No need of compositional convection for geodynamo

Melt layer at the CMB as hidden reservoir

Formed in the first 100 Myr of the Earth's history (as necessited by $\varepsilon^{142}Nd$)

Nb/Ta and Nb/La ratio of hidden reservoir must be higher than Earth

→ As Nb is more incompatible than Ta and La, hidden reservoir must be derived from melt.

Melt layer at the CMB as hidden reservoir

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Nb/Ta and Nb/La ratio of hidden reservoir must be higher than Earth

→ As Nb is more incompatible than Ta and La, hidden reservoir must be derived from melt.

So basal magma ocean is a good candidate for the hidden reservoir.

Evolution of isotopic composition of Earth and basal magma ocean

$$\frac{d}{dt}\,{}^{146}Sm_m = -\,{}^{146}Sm_m\lambda_{146} + {}^{146}Sm_m(D_{Sm} - 1)\frac{1}{M_m}\frac{dM_m}{dt}; \quad (7)$$

$$\frac{d}{dt}\,{}^{142}Nd_m = {}^{146}Sm_m\lambda_{146} + {}^{142}Nd_m(D_{Nd} - 1)\frac{1}{M_m}\frac{dM_m}{dt} \quad (8)$$

$$\frac{d}{dt}\,{}^{147}Sm_m = -\,{}^{147}Sm_m\lambda_{147} + {}^{147}Sm_m(D_{Sm} - 1)\frac{1}{M_m}\frac{dM_m}{dt} \quad (9)$$

$$\frac{d}{dt}\,{}^{143}Nd_m = {}^{147}Sm_m\lambda_{147} + {}^{143}Nd_m(D_{Nd} - 1)\frac{1}{M_m}\frac{dM_m}{dt} \quad (10)$$

$$\frac{d}{dt}\,{}^{144}Nd_m = {}^{144}Nd_m(D_{Nd} - 1)\frac{1}{M_m}\frac{dM_m}{dt} \quad (11)$$

$$\frac{d}{dt}\,{}^{146}Sm_s = -\,{}^{146}Sm_s\lambda_{146} + ({}^{146}Sm_s - {}^{146}Sm_m D_{Sm})\frac{1}{M_s}\frac{dM_m}{dt}; \quad (12)$$

$$\frac{d}{dt}\,{}^{142}Nd_s = {}^{146}Sm_s\lambda_{146} + ({}^{142}Nd_s - {}^{142}Nd_m D_{Nd})\frac{1}{M_s}\frac{dM_m}{dt} \quad (13)$$

$$\frac{d}{dt}\,{}^{147}Sm_s = -\,{}^{147}Sm_s\lambda_{147} + ({}^{147}Sm_s - {}^{147}Sm_m D_{Sm})\frac{1}{M_s}\frac{dM_m}{dt} \quad (14)$$

$$\frac{d}{dt}\,{}^{143}Nd_s = {}^{147}Sm_s\lambda_{147} + ({}^{143}Nd_s - {}^{143}Nd_m D_{Nd})\frac{1}{M_s}\frac{dM_m}{dt} \quad (15)$$

$$\frac{d}{dt}\,{}^{144}Nd_s = ({}^{144}Nd_s - {}^{144}Nd_m D_{Nd})\frac{1}{M_s}\frac{dM_m}{dt}; \quad (16)$$

Mass balance equations for each isotopes

$$\frac{{}^{146}Sm_{st}}{{}^{144}Nd} = \frac{{}^{146}Sm_0}{{}^{144}Nd}e^{-\lambda_{146}t}; \quad (17)$$

$$\frac{{}^{147}Sm_{st}}{{}^{144}Nd} = \frac{{}^{147}Sm_0}{{}^{144}Nd}e^{-\lambda_{147}t}; \quad (18)$$

$$\frac{{}^{142}Nd_{st}}{{}^{144}Nd} = \frac{{}^{142}Nd_0}{{}^{144}Nd} - \frac{{}^{146}Sm_0}{{}^{144}Nd}e^{-\lambda_{146}t}; \quad (19)$$

$$\frac{{}^{143}Nd_{st}}{{}^{144}Nd} = \frac{{}^{143}Nd_0}{{}^{144}Nd} - \frac{{}^{147}Sm_0}{{}^{144}Nd}e^{-\lambda_{147}t}; \quad (20)$$

Evolution of not fractionnated standard

Evolution of isotopic composition of Earth and basal magma ocean

$$Nd_{mi} = \frac{Nd_i}{D_{Nd}(1 - F) + F} \quad (21)$$

$$Sm_{mi} = \frac{Sm_i}{D_{Sm}(1 - F) + F} \quad (22)$$

$$Nd_{si} = \frac{Nd_i(M_{si} + M_{mi}) - Nd_{mi}M_{mi}}{M_{si}} \quad (23)$$

$$Sm_{si} = \frac{Sm_i(M_{si} + M_{mi}) - Sm_{mi}M_{mi}}{M_{si}} \quad (24)$$

Initial chemical composition of each reservoir

$$M_m = M_{mi}e^{-(t - t_i)/\tau} \quad (25)$$

Exponential decrease of melt layer mass

Evolution of isotopic composition of Earth and basal magma ocean

$$^{146}Sm_m = {}^{146}Sm_{mi}\, e^{[\lambda_{146} + (D_{Sm} - 1)/\tau](t - t_i)}; \quad (26)$$

$$^{147}Sm_m = {}^{147}Sm_{mi}\, e^{[\lambda_{147} + (D_{Sm} - 1)/\tau](t - t_i)}; \quad (27)$$

$$^{144}Nd_m = {}^{144}Nd_{mi}\, e^{(1 - D_{Nd})(t - t_i)/\tau} \quad (28)$$

$$^{142}Nd_m = {}^{142}Nd_{mi}\, e^{(1 - D_{Nd})(t - t_i)/\tau} \left[1 + \frac{^{146}Sm_{mi}}{^{142}Nd_{mi}} \frac{\lambda_{146} \quad e^{(D_{Nd} - D_{Sm} \quad _{146})(t - t_i)/\tau} \quad 1}{D_{Nd} - D_{Sm} \quad 146} \right]; \quad (29)$$

$$^{143}Nd_m = {}^{143}Nd_{mi}\, e^{(1 - D_{Nd})(t - t_i)/\tau} \left[1 + \frac{^{147}Sm_{mi}}{^{143}Nd_{mi}} \frac{\lambda_{147} \quad e^{(D_{Nd} - D_{Sm} \quad _{147})(t - t_i)/\tau} \quad 1}{D_{Nd} - D_{Sm} \quad 147} \right]; \quad (30)$$

$$^{146}Sm_s = \frac{e^{-\lambda_{146}(t - t_i)}}{M_s} \left[{}^{146}Sm_i M_{tot} - {}^{146}Sm_i M_m e^{(1 - D_{Sm})(t - t_i)/\tau} \right]; \quad (31)$$

$$^{147}Sm_s = \frac{e^{-\lambda_{147}(t - t_i)}}{M_s} \left[{}^{147}Sm_i M_{tot} - {}^{147}Sm_i M_m e^{(1 - D_{Sm})(t - t_i)/\tau} \right]; \quad (32)$$

$$^{142}Nd_s = \frac{M_{tot}}{M_s} \left[{}^{142}Nd_i + {}^{146}Sm_i \quad 1 - e^{-\lambda_{146}(t - t_i)} \right] \quad \frac{M_m}{M_s}\, {}^{142}Nd_m \quad (33)$$

$$^{143}Nd_s = \frac{M_{tot}}{M_s} \left[{}^{143}Nd_i + {}^{147}Sm_i \quad 1 - e^{-\lambda_{147}(t - t_i)} \right] \quad \frac{M_m}{M_s}\, {}^{143}Nd_m; \quad (34)$$

$$^{144}Nd_s = \frac{1}{M_s} \quad {}^{144}Nd_i M_{tot} - {}^{144}Nd_m M_m : \quad (35)$$

Final mass balances equations

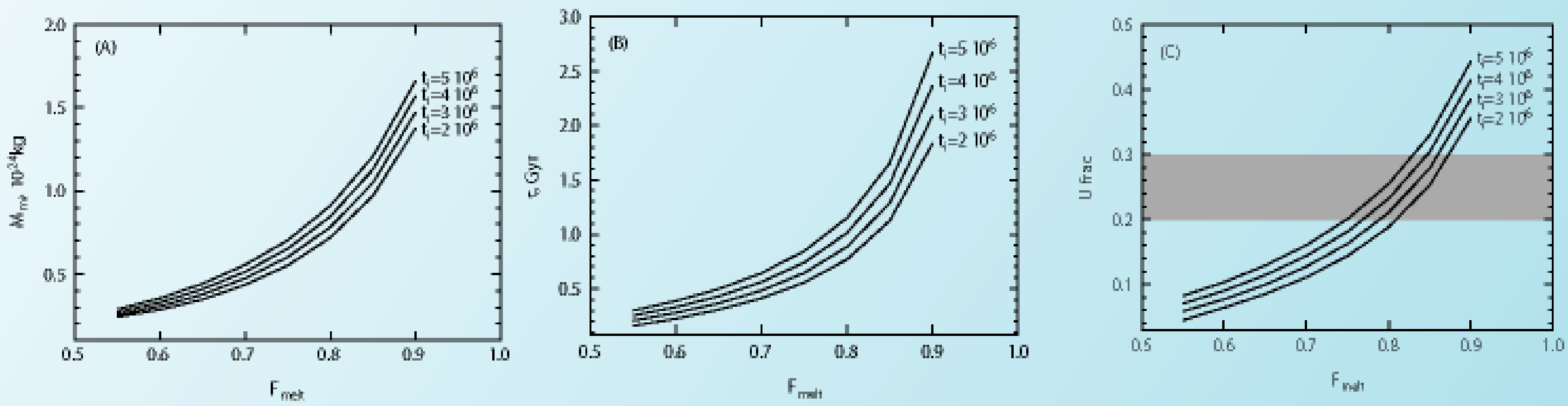
Evolution of isotopic composition of Earth and basal magma ocean

Four independant parameters : -Initial mass of melt layer M_{mi}

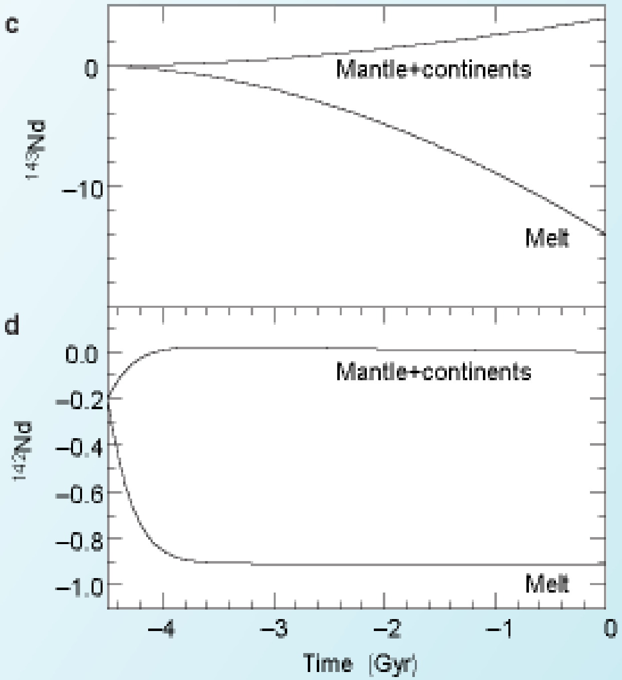
-Its crystallisation time τ

-Its time of formation t_i

-Its melt fraction F



Evolution of isotopic composition of Earth and basal magma ocean



F=80 % (corresponds to ~850 km thick)

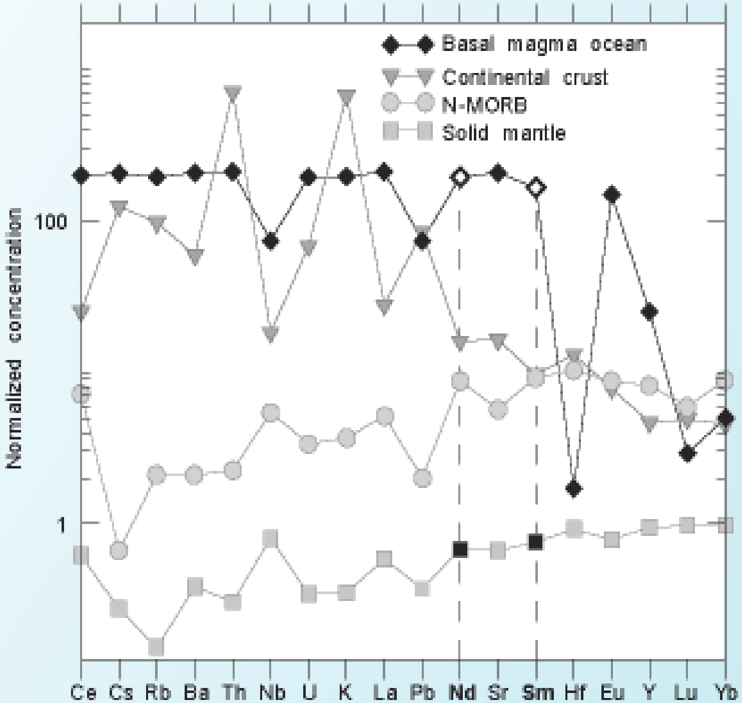
M_{mi} = 0.78 10^{24} kg

τ = 887 Myr

t_i = 30 Myr

Good agreement with observed values

Predicted element concentration in present-day mantle and basal magma ocean



Calculation made by applying a mass balance between continental crust and remaining melt.

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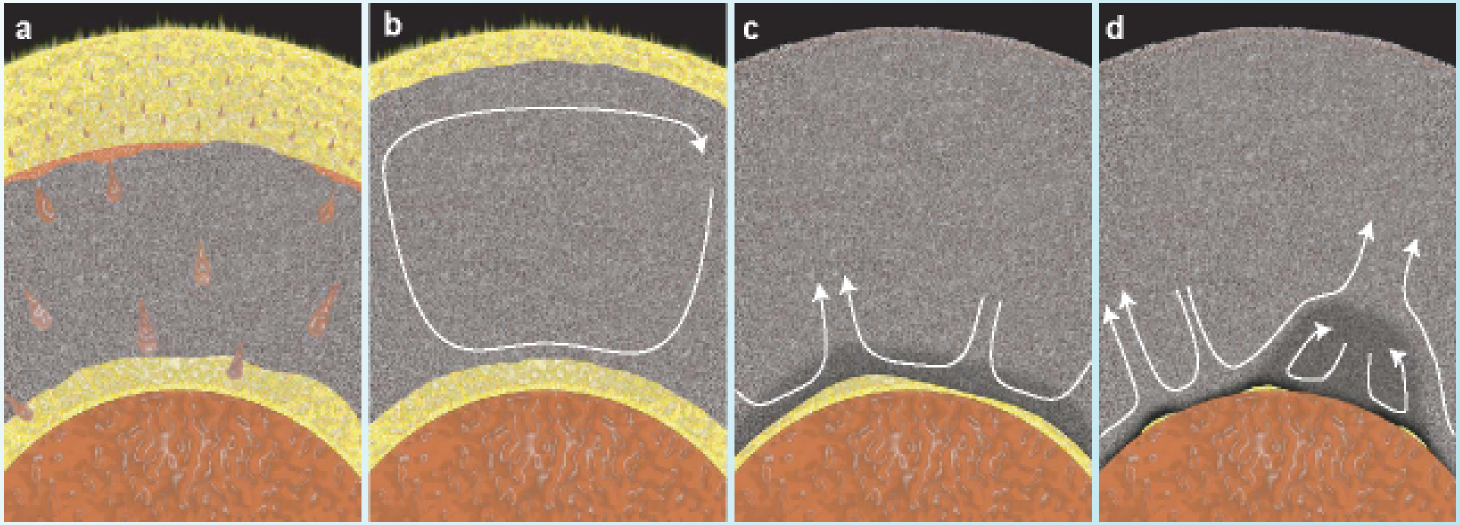
A "continental crust-like" at the top of the Earth's core

Magma ocean model



a : 850 km thick layer extracted by 80% of melting of lower mantle

b-c: Increasing Fe/Mg ratio with time in crystallising material due to magma differentiation

d: Denser piles accumulate under plume roots and incompatible elements are trapped in remaining melt