Evolution of the basal magma ocean (BMO) through Earth history

Does the present state of the Earth tell us anything on its formation?

The MOB (as suggested by Ben Phillips for a new acronym):
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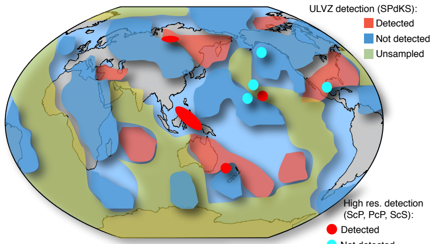
Introduction

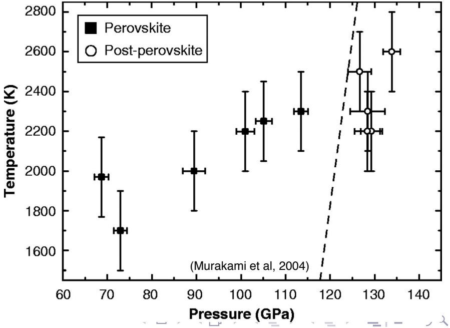
Our views on the lowermost mantle have largely changed over the last ∼12 years:

- Discovery of the ULVZ (Garnero & Helmberger ∼1996).
- Recognition of dense thermo-chemical piles (∼1999).
- Discovery of the post-perovskite (Murakami, et al. 2004).

What are the implications for the evolution of the deep Earth?

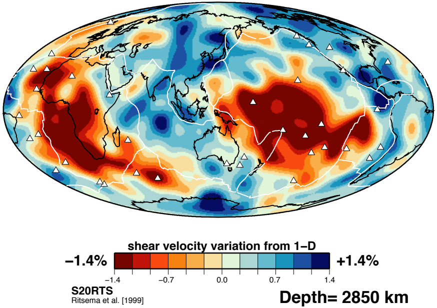


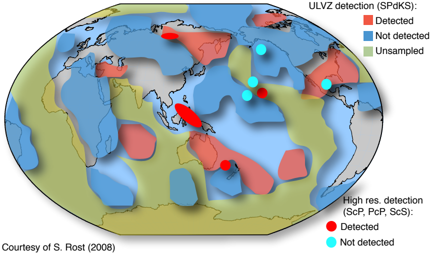
Courtesy of S. Rost (2008)



Global tomography and ULVZ

- Large V_S anomalies in the lower mantle $\rightarrow$ thermal and chemical heterogeneity.
- ULVZs at the edges of dense thermo-chemical piles.

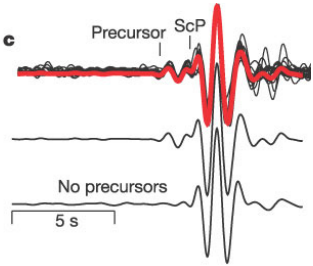


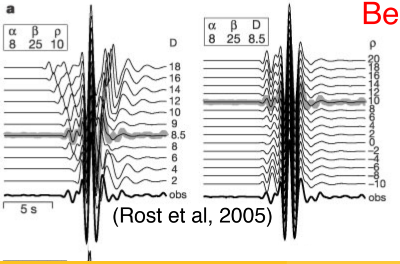


Physical properties of the ULVZ

Evidences for dense partial melt

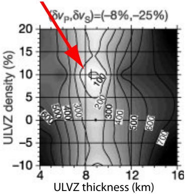
(Rost et al, 2005)





(Rost et al, 2005)

Best fit

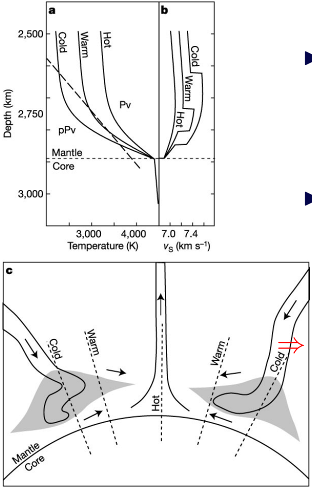


Inversion parameters:

- $\alpha = \delta V_P$
- $\beta = \delta V_S$
- $D =$ ULVZ thickness
- $\rho =$ ULVZ density

The double crossing model

Hernlund et al (2005), Nature.

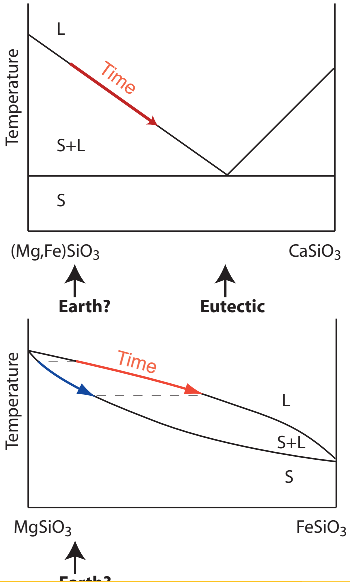


- Double seismic discontinuities explained if
  - the core temperature is high enough,
  - the temperature gradient is larger than the Clapeyron slope.
- Important geophysical implications
  - Direct measure of the thermal structure of the lower mantle.
  - Estimate of heat flux from the core 7–15 TW.

$\Rightarrow$ Core cooling over the age of the Earth:

$$\Delta T \sim \frac{Q_{CMB}\Delta t}{MC_p} \sim 1000K.$$

Ideas on melt processes



- For chemically complex systems, the composition of liquid and solid are different.
- In particular: Fe partitions preferentially in the liquid silicate rather than solid.
- Density change on melting: $\Delta\rho = \Delta\rho_\phi + \Delta\rho_\chi$.
  - $\Delta\rho_\phi$ decreases with pressure
  - $\Delta\rho_\chi < 0$

Density cross-over in the lower mantle

Ohtani (1983) :

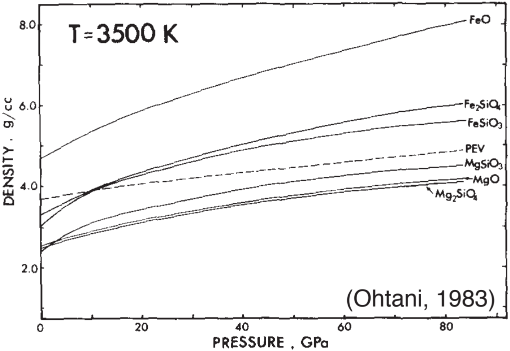
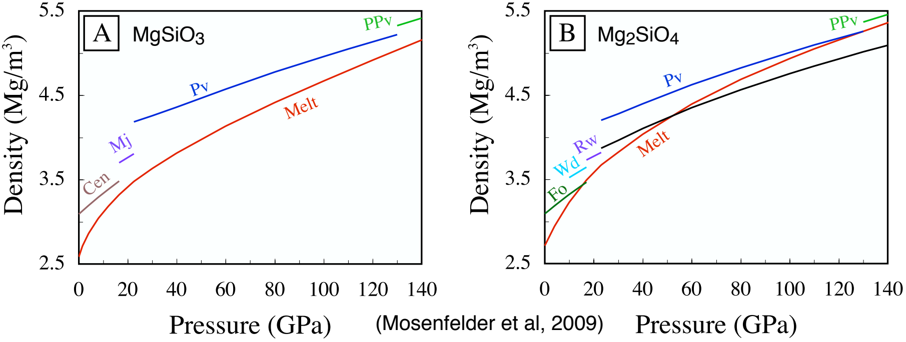


Fig. 5. Density of the melt with various compositions at 3500 K and high pressures. The density of perovskite $(Mg_{0.95-0.99}Fe_{0.05-0.01})SiO_3$ is also shown as a broken curve (PEV).

- Densities extrapolated from upper mantle values.
- Melt enrichment in FeO $\Rightarrow$ denser than solid.

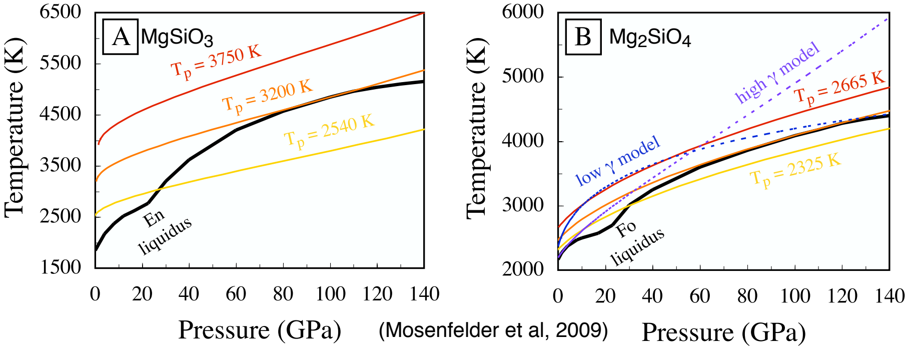
Shock experiments: Density



(Mosenfelder et al, 2009)

- At high pressure, the volume change upon melting is small ($MgSiO_3$) or even negative (Mg_2SiO_4).
- Partitioning of Fe in the melt ⇒ Liquid denser than solid with a realistic composition.

Shock experiments: Grüneisen parameter



(Mosenfelder et al, 2009)

- High Grüneisen parameter $\gamma \Rightarrow$ Crystallisation of the magma ocean from the centre of the mantle.

$$\frac{\partial T_{ad}}{\partial P} = \frac{\gamma T_{ad}}{K_S}$$

Arguments for a hot start in Earth history

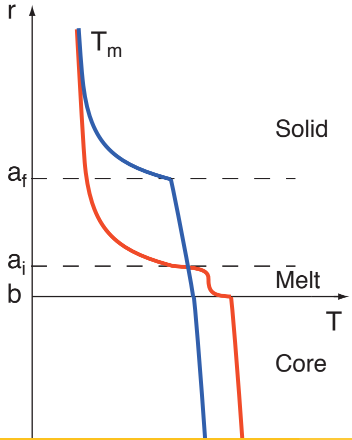
- Gravitational energy from Earth formation
  - Large impacts
  - Core segregation

  $\Rightarrow$ Enough energy to raise the average temperature by a few 1000 K. A large amount of melting!

- Runaway process: Iron melting $\rightarrow$ segregation $\rightarrow$ more melting (Ricard et al, in press, see movie of temperature).
- Partitioning of energy between the core and the mantle still uncertain.

Melting the mantle from below

$$q = Ck\frac{\Delta T}{h}\left(\frac{\alpha\rho g\Delta T h^3}{\kappa\mu}\right)^{1/3} \simeq 100\frac{\Delta T^{4/3}}{\mu^{1/3}}\mathrm{Wm}^{-2}$$



If the core starts superheated ($T >$ mantle solidus)

- heat transported by convection in the melt layer.
- melting front moves upward until all the initial superheat is consumed by heating and melting the lower mantle.

1000 K superheat $\rightarrow \sim$ 700 km mantle melting.

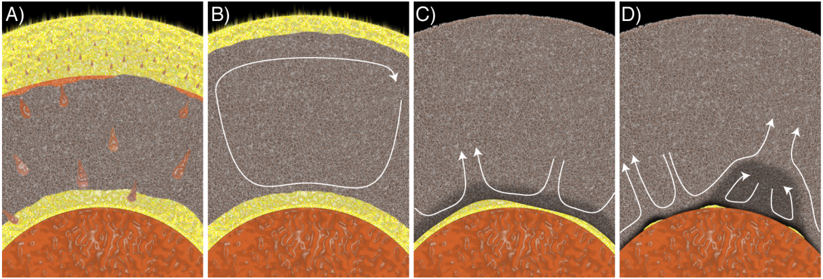
Importance of melting in the lowermost mantle

- Dense melt present now at the bottom of the mantle (ULVZ).
- The core has been cooling down as is evidenced by the maintenance of the geodynamo.

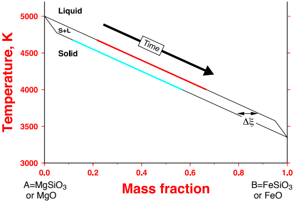
$\Rightarrow$ There should have been more melt in the past.

- This is also compatible with Earth forming scenarios.

Our cartoon view (Labrosse, Hernlund and Coltice, Nature 2007)



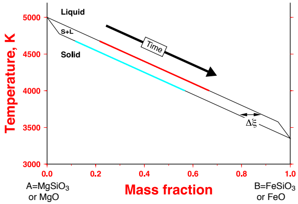
B Crystallisation of the magma ocean starting at mid-depth.



C Crystals formed at the base of the mantle entrained by convection in the solid mantle.

D Crystals too dense to be entrained and FeO rich magma lakes under chemical piles.

Time necessary for the crystallisation of the basal magma ocean



$$\tau = \frac{MC\Delta T}{Q} \sim 6\mathrm{Gyr}$$

$$M = 2\ 10^{24}\mathrm{kg},\ C \sim 1000\mathrm{JK}^{-1}\mathrm{kg}^{-1}$$
$$\Delta T \sim 1000\mathrm{K},\ Q \sim 10\mathrm{TW}.$$

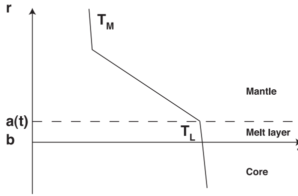
Time scale controlled by

- the heat flux taken up by convection in the solid mantle,
- the variation of the liquidus with chemical composition,
- the heat capacity of the core.

Conservation equations

Energy:

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



Mass fraction (ξ_L) of FeO:

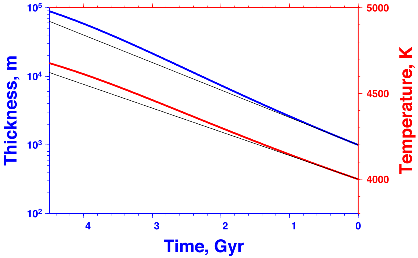
$$\frac{da}{dt} = \frac{a^3 - b^3}{3a^2 \Delta\xi} \frac{d\xi_L}{dT_L} \frac{dT_L}{dt}$$

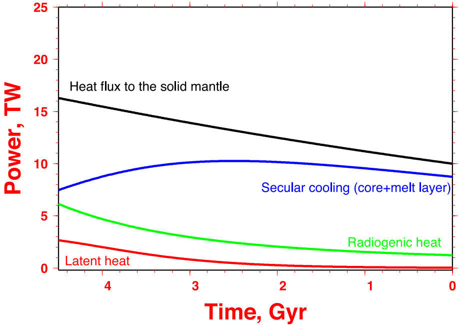
Approximate analytic solution:

$$\left.\begin{array}{l} a - b = (a_0 - b) e^{-t/\tau_C} \\ T_L = T_{L0} - \Delta\xi (T_A - T_B) \frac{t}{\tau_C} \end{array}\right\} \tau_C = \frac{M_C C_{pc} (T_A - T_B) \Delta\xi}{Q - H}$$

Long term evolution

Numerical solution of conservation equations:





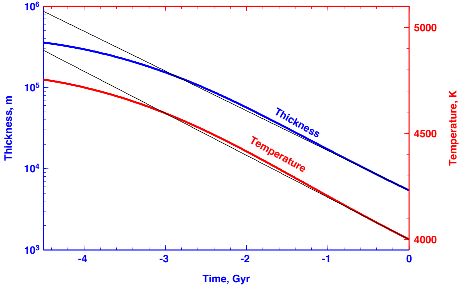
Earth budget in Uranium

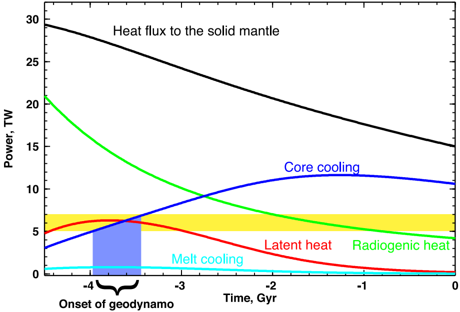
Box	[U]	Q (U+Th+K)
BSE (if CI)	20 ppb	20 TW
Continents (Rudnick & Gao, 2003)	1.3 ppm	7 TW
MORB source	8.3–11 ppb	7–9 TW

between 20 and 30% of the budget must be stored at depth!

- Classical solution: the whole lower mantle or thermochemical piles.
- Our solution: the melt at the base of the mantle.

Long term evolution: the preferred model





Important implication: delayed onset of the dynamo!

Tarduno et al (2006) : the earliest well established record is 3.2 Ga old.

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ARTICLES

Terrestrial nitrogen and noble gases in lunar soils

M. Ozima[1], K. Seki[2], N. Terada[2]†, Y. N. Miura[3], F. A. Podosek[4] & H. Shinagawa[2]†

The nitrogen in lunar soils is correlated to the surface and therefore clearly implanted from outside. The straightforward interpretation is that the nitrogen is implanted by the solar wind, but this explanation has difficulties accounting for both the abundance of nitrogen and a variation of the order of 30 per cent in the $^{15}N/^{14}N$ ratio. Here we propose that most of the nitrogen and some of the other volatile elements in lunar soils may actually have come from the Earth's atmosphere rather than the solar wind. We infer that this hypothesis is quantitatively reasonable if the escape of atmospheric gases, and implantation into lunar soil grains, occurred at a time when the Earth had essentially no geomagnetic field. Thus, evidence preserved in lunar soils might be useful in constraining when the geomagnetic field first appeared. This hypothesis could be tested by examination of lunar farside soils, which should lack the terrestrial component.

data at hand". Hence, it may be possible that the substantial fractions of ilmenite grains used in this study had a surface implantation age close to 3.8–3.9 Gyr ago, which is generally assigned to the formation age[29,30] of major impact basins from where the Apollo samples were collected. It is then tempting to speculate that the GMF was null or very weak before about 3.9 Gyr ago.

The delayed onset of the dynamo

Budget in incompatible elements:

- Radiogenic heating important in the basal magma ocean.
- Initial mass important rapidly decaying.

$\Rightarrow$ Latent and radiogenic heat important in the early BMO can prevent efficient (super-isentropic) core cooling.

Can we avoid the delayed onset by increasing the early CMB heat flow?

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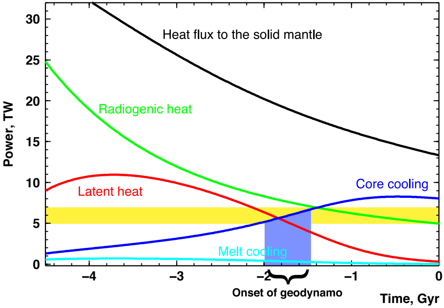
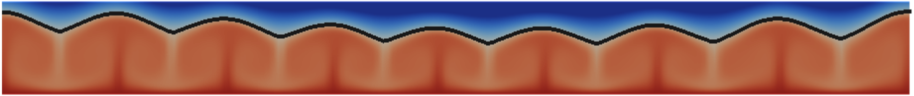
No! An initially higher temperature gives a more important latent heat.



Thermal convection and crystallisation
PhD work of Martina Ulvrova



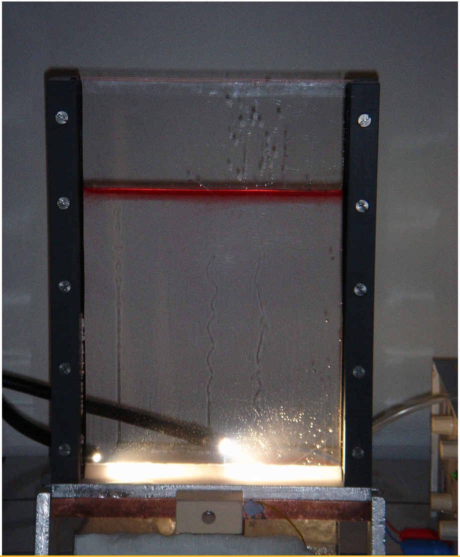
- Convection in the melt
- Diffusion in the solid
- Interface motion following Stefan's condition

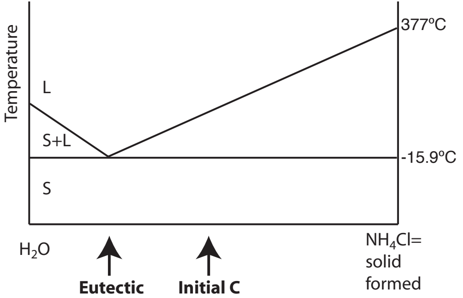
$$q = Ck\frac{\Delta T}{h}\left(\frac{\alpha\rho g\Delta T h^3}{\kappa\mu}\right)^{1/3}$$

- Small convection $\Rightarrow$ buffering the thermal coupling between the core and the mantle?

Composiotional convection

Internship of Nathanael Machicoane

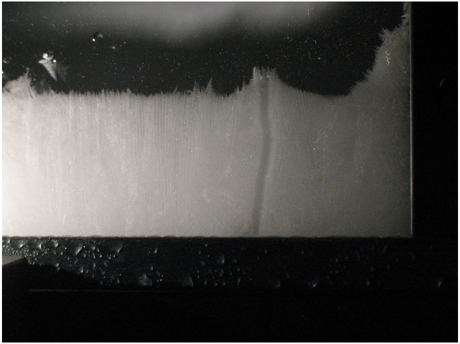




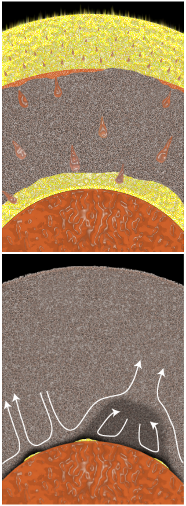
- Freezing from below a dense solid.
- Releasing a lighter fluid.

Composiotional convection

Internship of Nathanael Machicoane



Conclusions: Basal magma ocean and dynamo



Arguments in favor of the basal magma ocean:

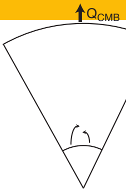
- ULVZs $\Rightarrow$ Presence of dense silicate melts.
- Evolution of the core: $\sim$ 1000 K cooling in 4.5 Ga $\Rightarrow$ Melt more important in the past.
- Conditions of Earth formation.

Early evolution of the BMO

- Large radiogenic and latent heat $\Rightarrow$ Delayed onset of the dynamo.
- Possible re-equilibration between the core and the mantle via the magma ocean at CMB pressure!

The end!

Conditions for a convective dynamo



Minimum necessary conditions for the geodynamo:

either an inner core crystallising fast enough.

$\Rightarrow$ Compositional convection driven by the release of light elements upon inner core growth.

or a heat flow larger than that conducted along core's isentrope.

$\Rightarrow$ Thermal convection.

$\Rightarrow$The present heat flow can be lower than the isentropic one (Q_i), provided it was larger before the inner core started to crystallise.

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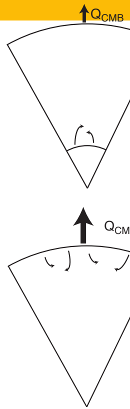

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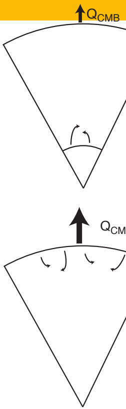


In addition:

- Thermal convection is necessary early in the history to reach the freezing point at the center.

⇒The present heat flow can be lower than the isentropic one (Q_i), provided it was larger before the inner core started to crystallise.

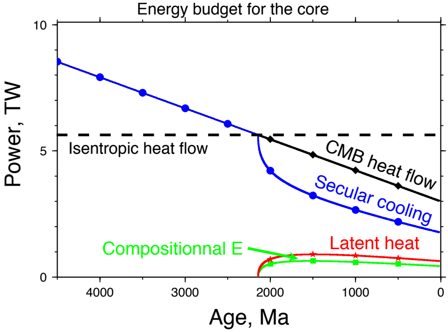
The cheapest dynamo

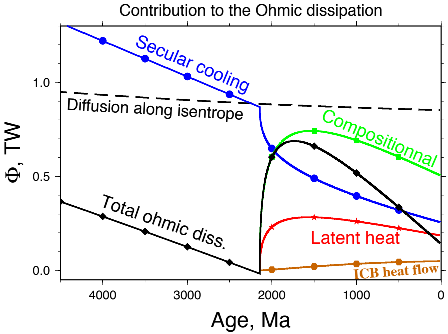
Take

$$Q(age) = Q_0 + B \times age$$

with

- $Q_0 < Q_i$
- $Q(IC\ age) = Q_i$.

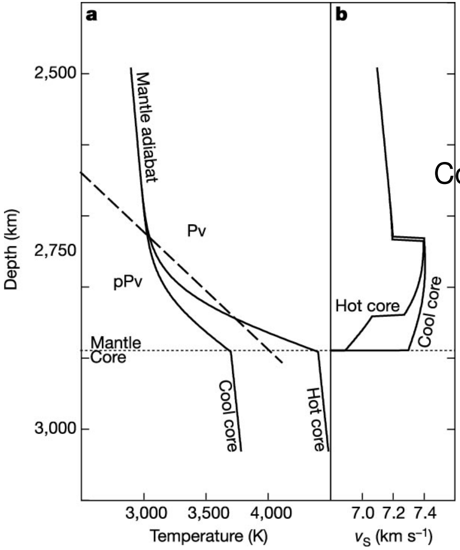




Note that the inner core is about 2.2 Gyr old!

Phase transitions and the thermal structure of D”

Hernlund et al (2005), Nature.



Core temperature uniform:

- Cool core: ubiquitous single discontinuity.
- Hot core: discontinuity is either absent (warm mantle) or double (cold mantle).