On the importance of lowermost mantle melt in the long term evolution of the Earth

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  - Paul Tackley - Zürich
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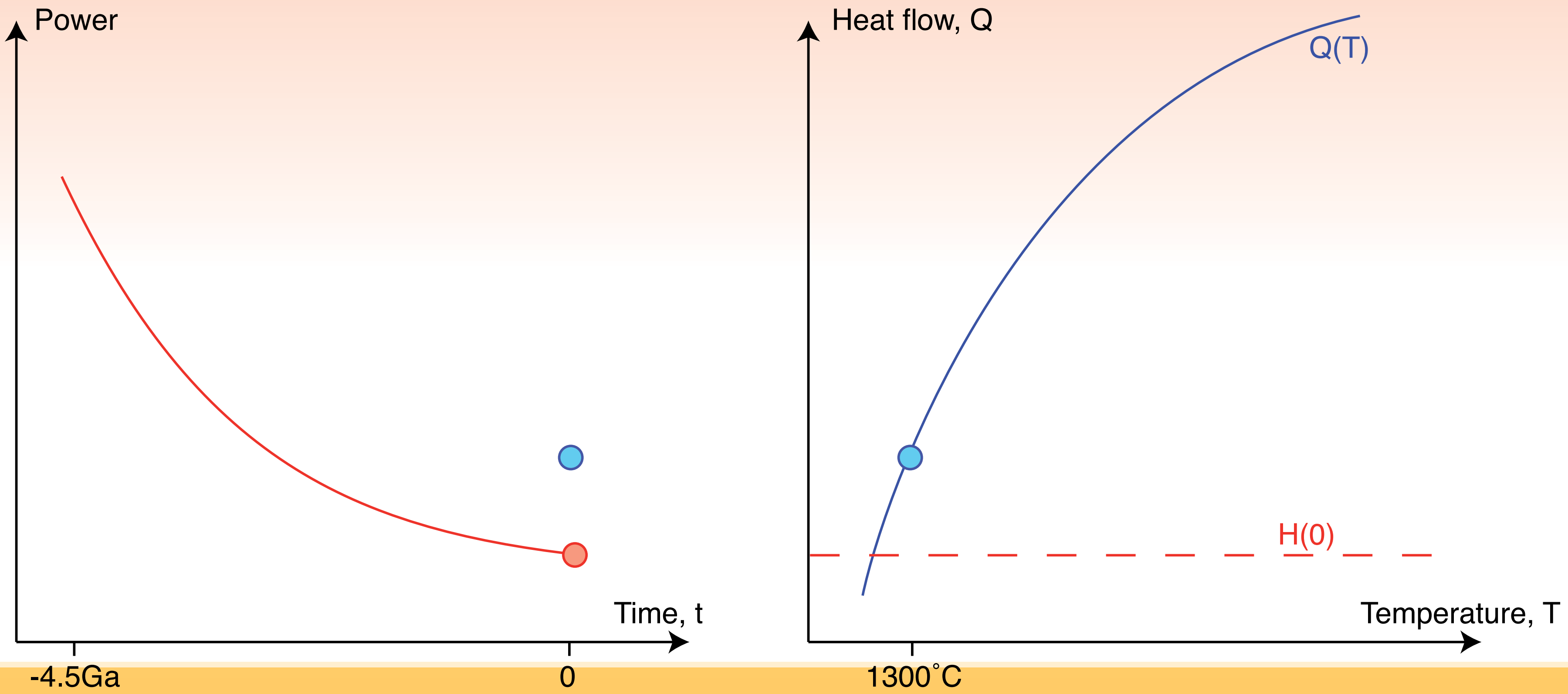
  - Institut Universitaire de France (IUF)

Outline

- Models for the thermal evolution of the Earth
- Constraints on q_{CMB} from the core side
- Evidence for partially molten regions at the bottom of the mantle
  - Solid ULVZ scenario
  - Partially molten ULVZs
- The basal magma ocean (BMO) and the thermal evolution of the Earth
- Formation of the basal magma ocean

The low Urey number "paradox"



$$MC\frac{dT}{dt} = H(t) - Q(T); \qquad Q(T) = Q_0 \left(\frac{T}{T_0}\right)^{4/3} \left(\frac{\eta(T)}{\eta_0}\right)^{-1/3}$$

Urey number : $Ur = H/Q * 100$

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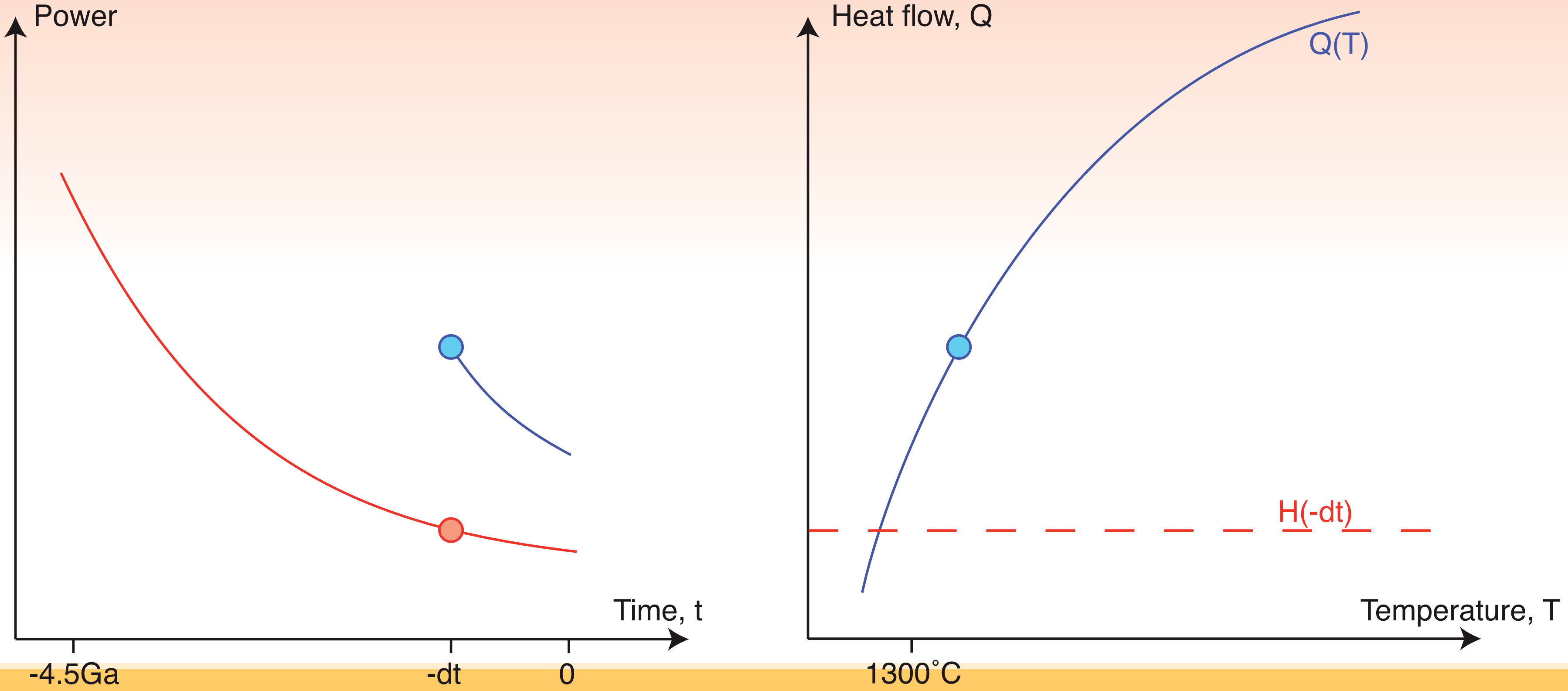

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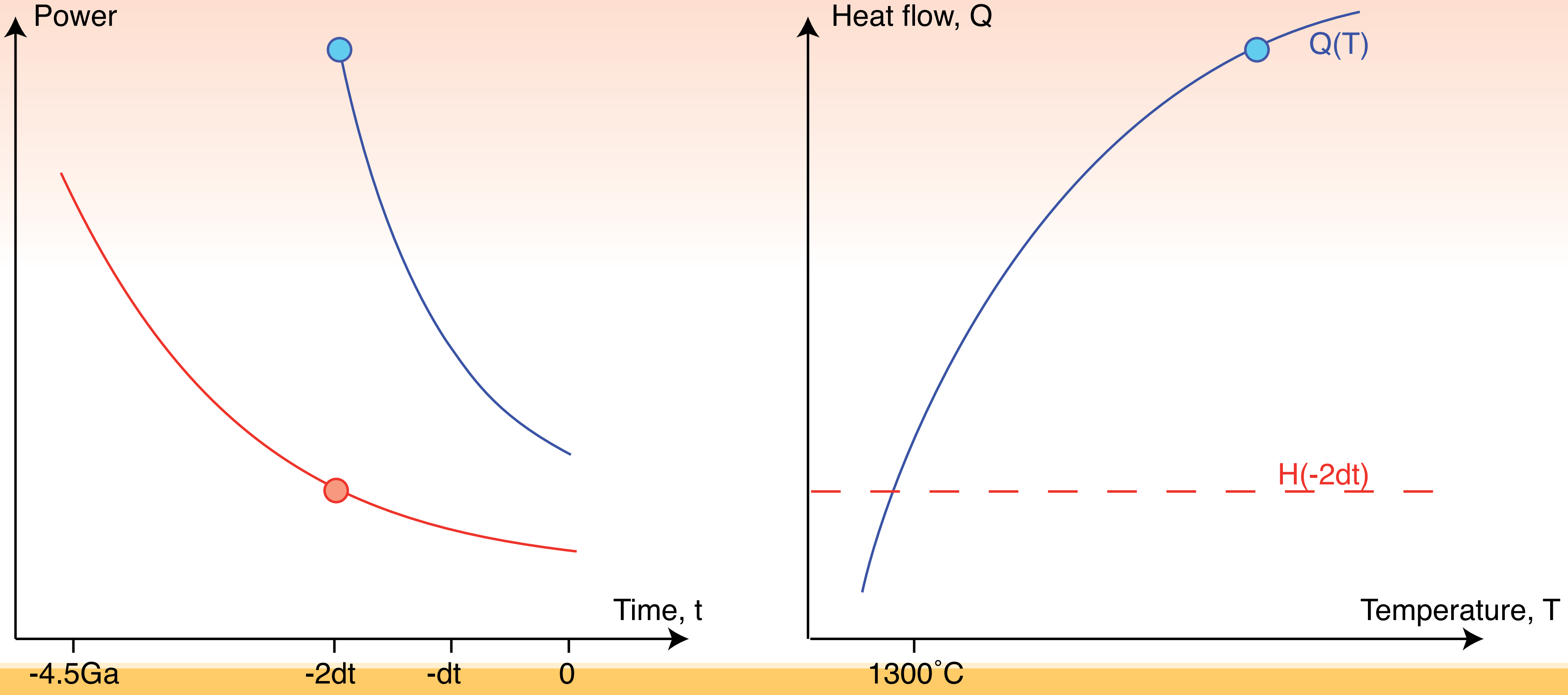

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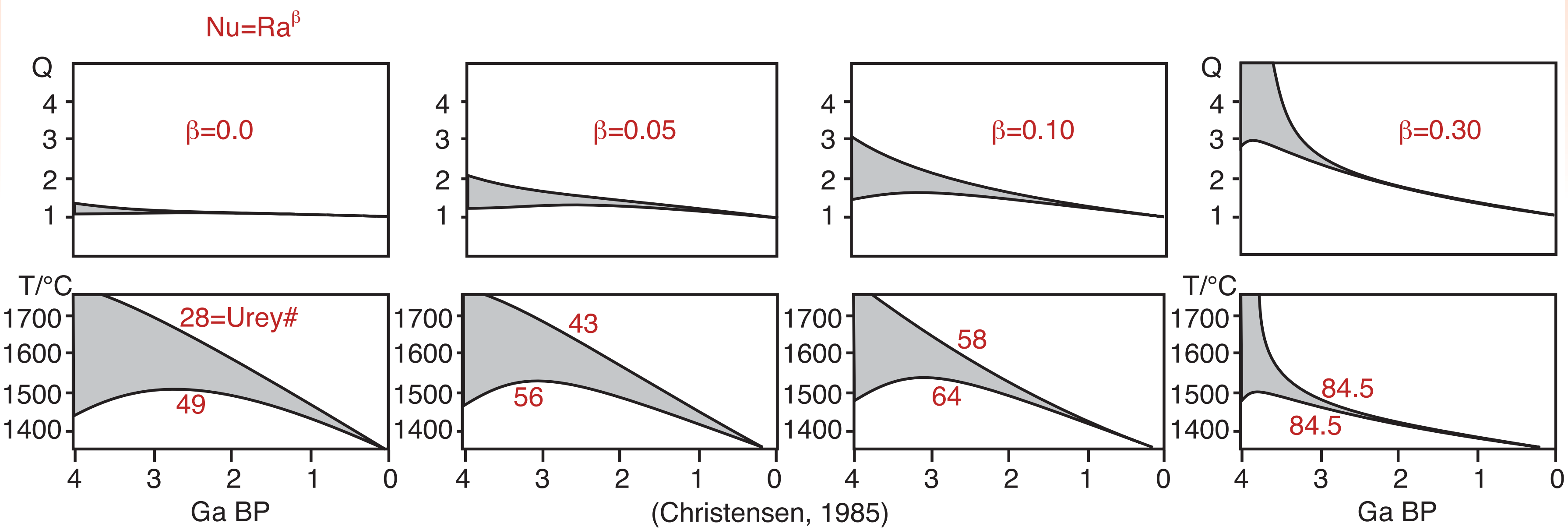
Lower β exponent to decrease the feedback ?



(Christensen, 1985)

$$Q(T) = Q_0 \left(\frac{T}{T_0}\right)^{1+\beta} \left(\frac{\eta(T)}{\eta_0}\right)^{-\beta}$$

Problem : No self-consistent dynamical model gives such low values of β

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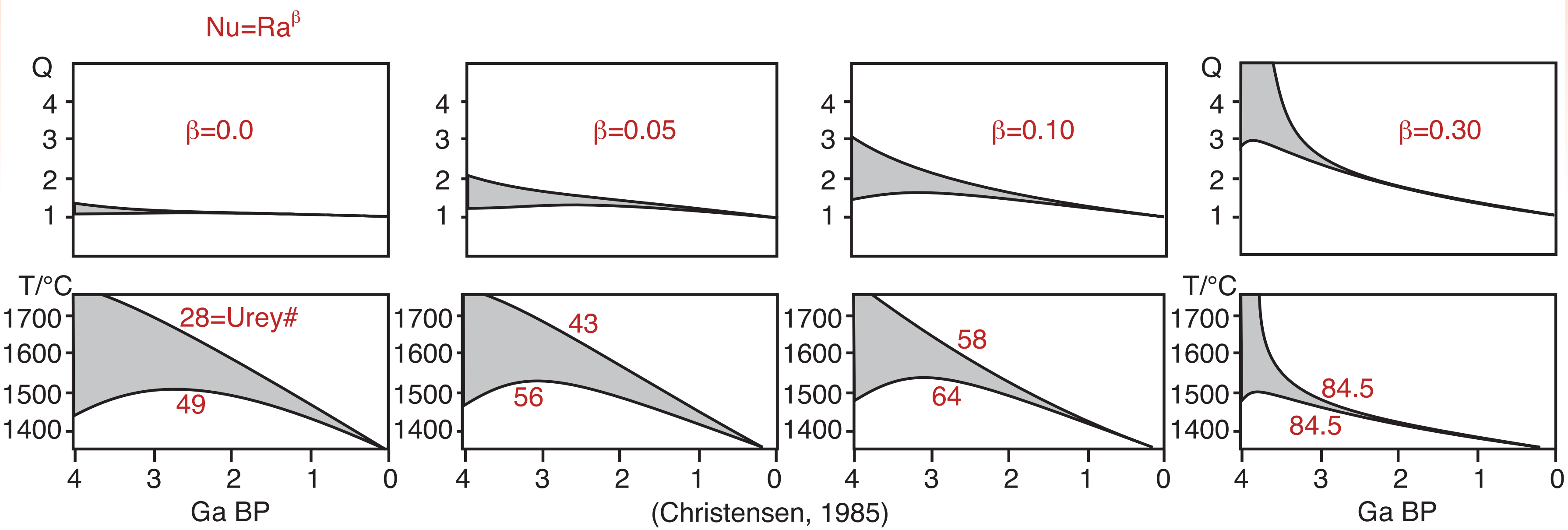

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Alternative scenario

- Standard approach :

$$MC\frac{dT}{dt} = H(t) - Q(T)$$

parameterised by the mantle potential temperature only.

⇒ Core and mantle assumed to cool at the same pace.

- Assume instead that the core is cooling and not the mantle :

⇒ No feedback from temperature dependence of the mantle viscosity !

$$M_M C_M \frac{dT_M}{dt} = H(t) - Q(T_M) + Q_{CMB}(T_M)$$

$$M_C C_C \frac{dT_C}{dt} = -Q_{CMB}(T_M)$$

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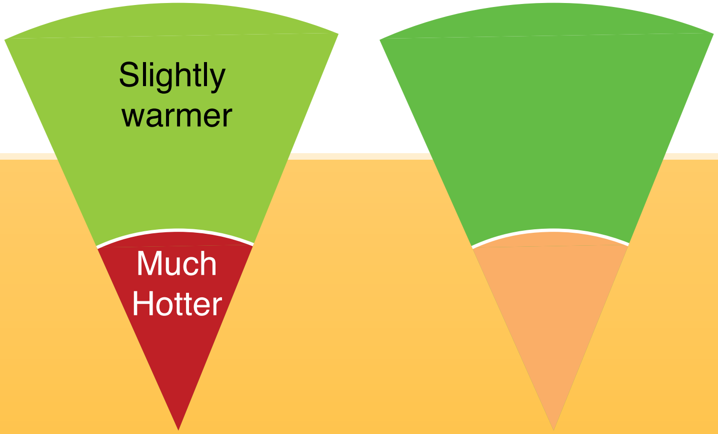

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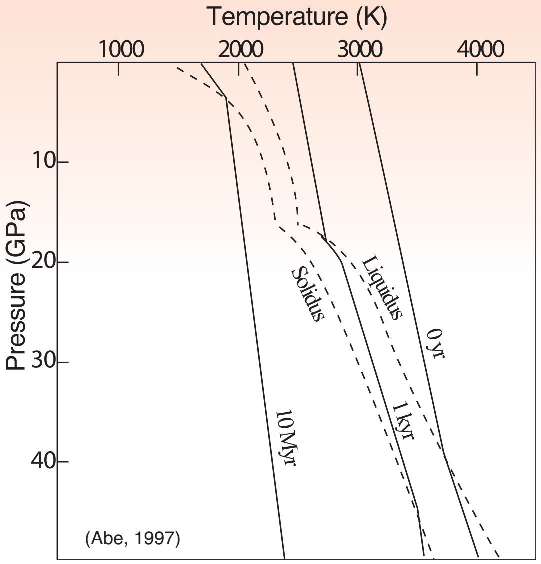
Evidences for the core cooling faster than the mantle



- Total mantle cooling in 4.5 Gyr constrained by the phase diagram of the upper mantle : $\Delta T_m < 200K$

- Core heat flow $> 10\mathrm{TW}$ constrained by
  - thermodynamics of the geodynamo with a large thermal conductivity $(> 90\mathrm{W/m/K})$.
  - double crossing of the Pv→PPv phase boundary.

$\Rightarrow \Delta T_c > 700\mathrm{K}$

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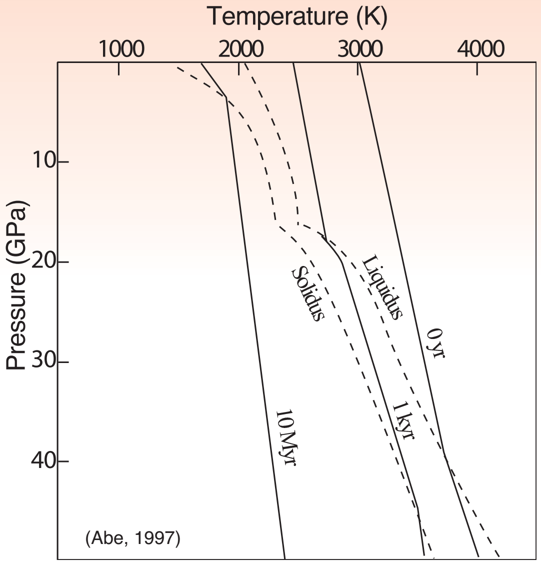

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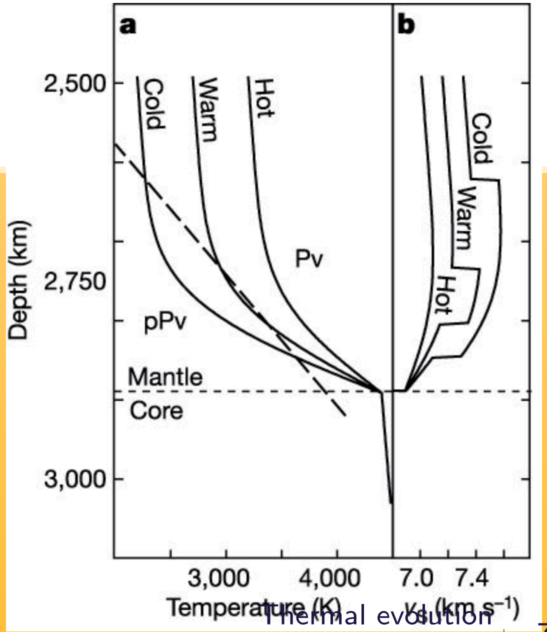

Outline

Models for the thermal evolution of the Earth

Constraints on q_{CMB} from the core side

Evidence for partially molten regions at the bottom of the mantle
  - Solid ULVZ scenario
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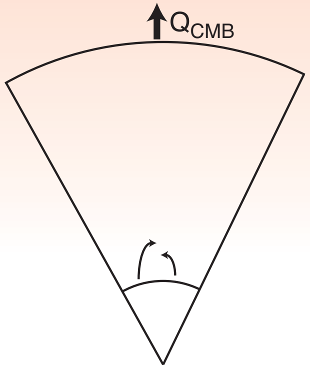
The basal magma ocean (BMO) and the thermal evolution of the Earth

Formation of the basal magma ocean

Conditions for a convective dynamo

Minimum necessary conditions for the geodynamo :



either an inner core crystallising fast enough.

⇒ 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.

⇒ Thermal convection.

Quantitatively : depends on the value of

- the thermal conductivity of the core
- the heat flow across the CMB

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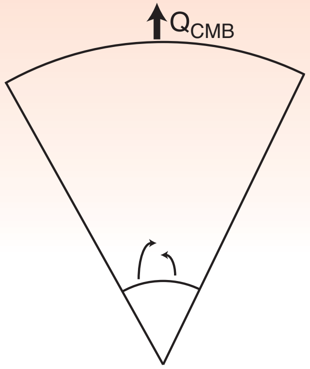

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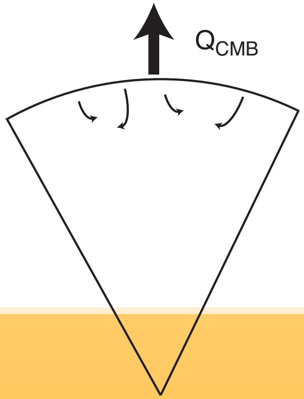

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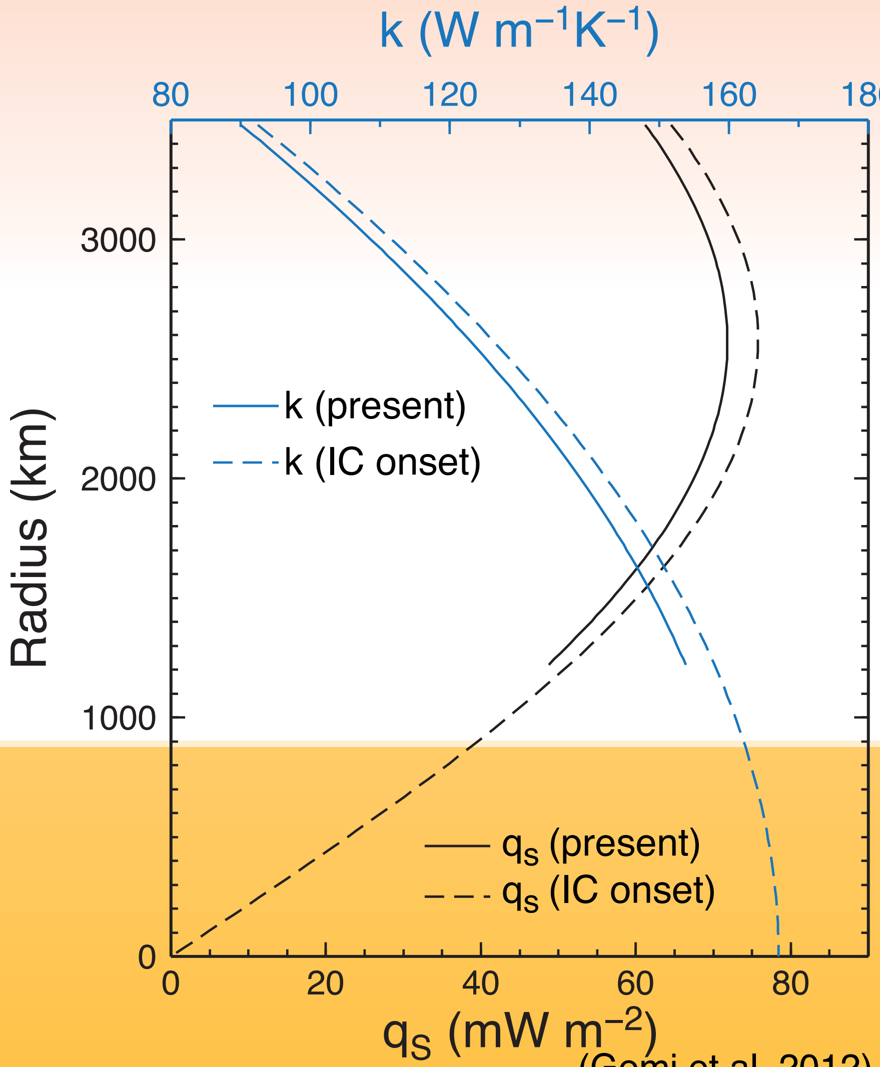
Thermal conductivity of the core

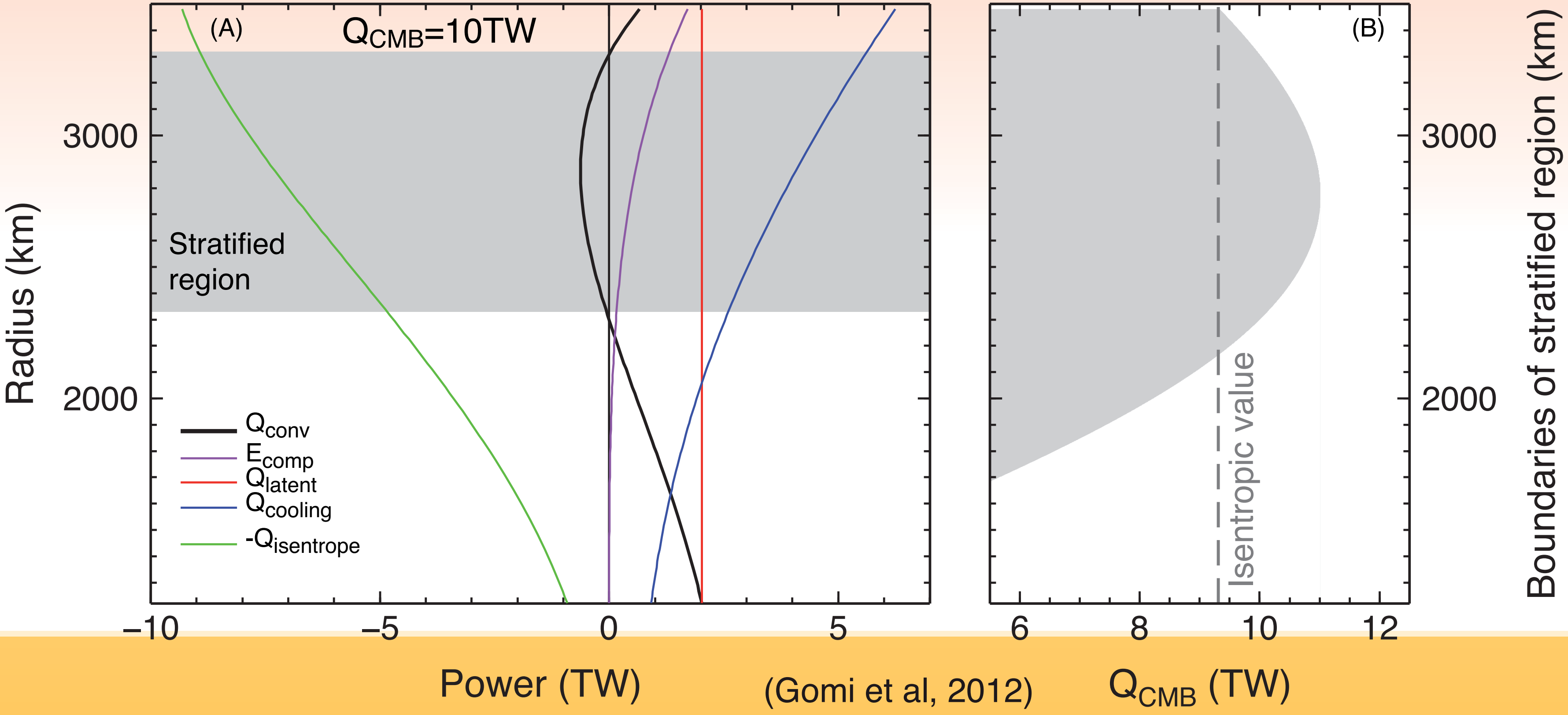


(Gomi et al, 2012)

- $k > 85 \mathrm{W/m/K}$ at CMB and $k > 150 \mathrm{W/m/K}$ at ICB conditions.
- Non-monotonous evolution of isentropic heat flux with depth.

⇒ A large heat CMB heat flow is necessary to avoid thermal stratification !

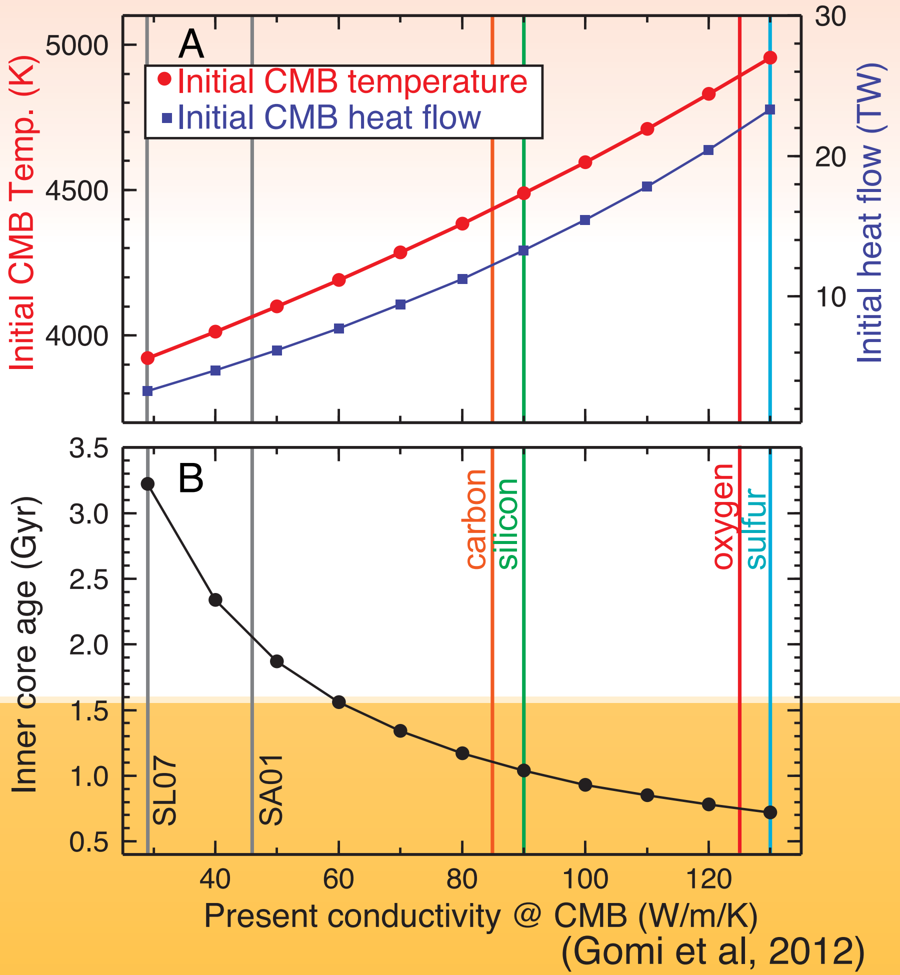
Thermal stratification from high thermal conductivity



(Gomi et al, 2012)

- Energy balance for sphere of radius r to compute the convective heat flow.
- $Q_{CMB} < Q_S \Rightarrow$ very thick stably stratified upper core.
- Unlikely because the magnetic field would probably be strongly damped by diffusion in the stable region.

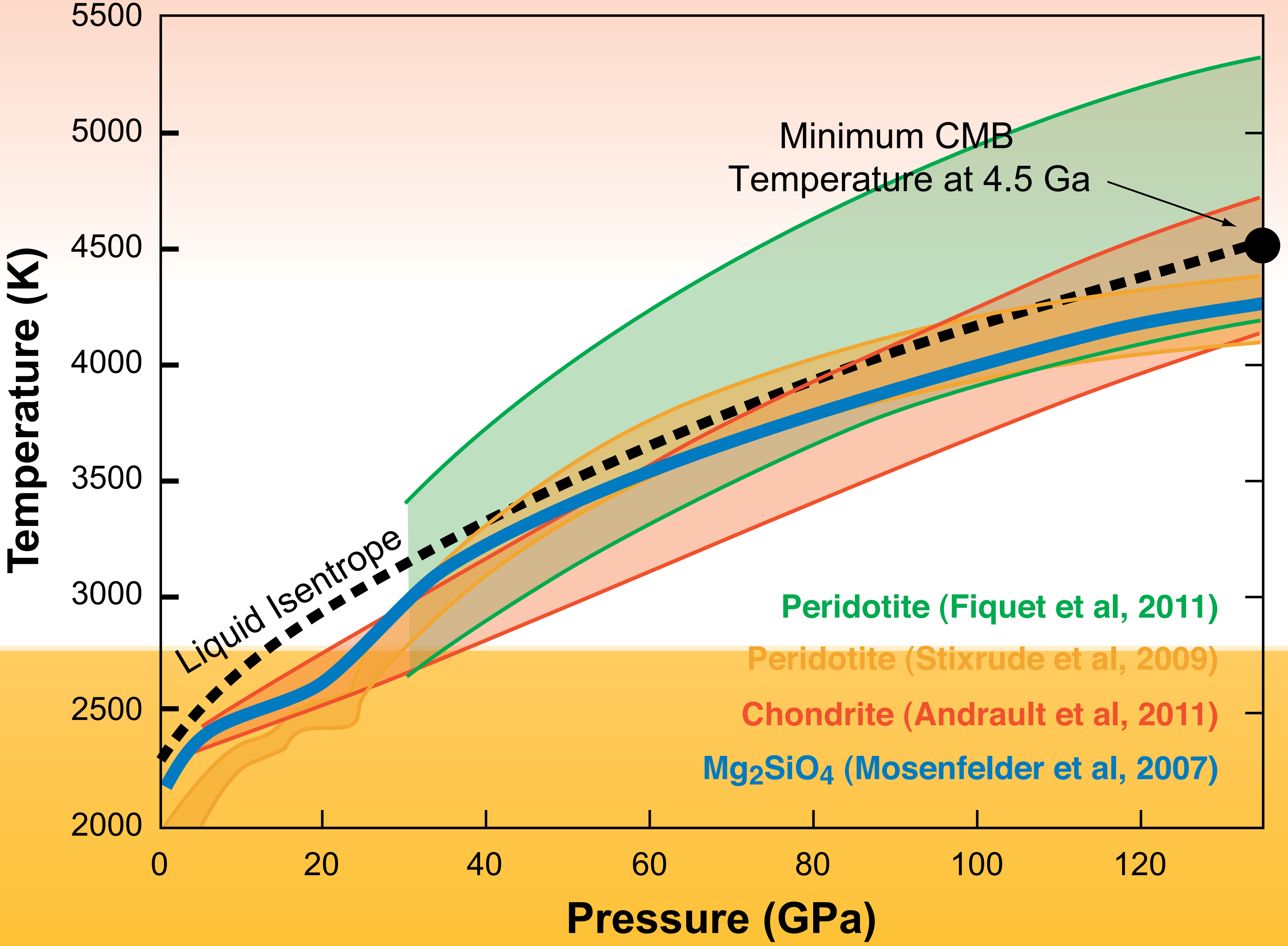
Implications of a large thermal conductivity



(Gomi et al, 2012)

- Use the core energy balance to compute the thermal evolution for $Q_{CMB} = Q_S$ at each time.
- Thermal conductivity depends on core composition.
- low IC age.
- High initial CMB heat flow and temperature.
- $T_{CMB}(4.5 Gyr) > 4500\mathrm{K} \Rightarrow$ melting of mantle minerals !

Mantle melting temperature



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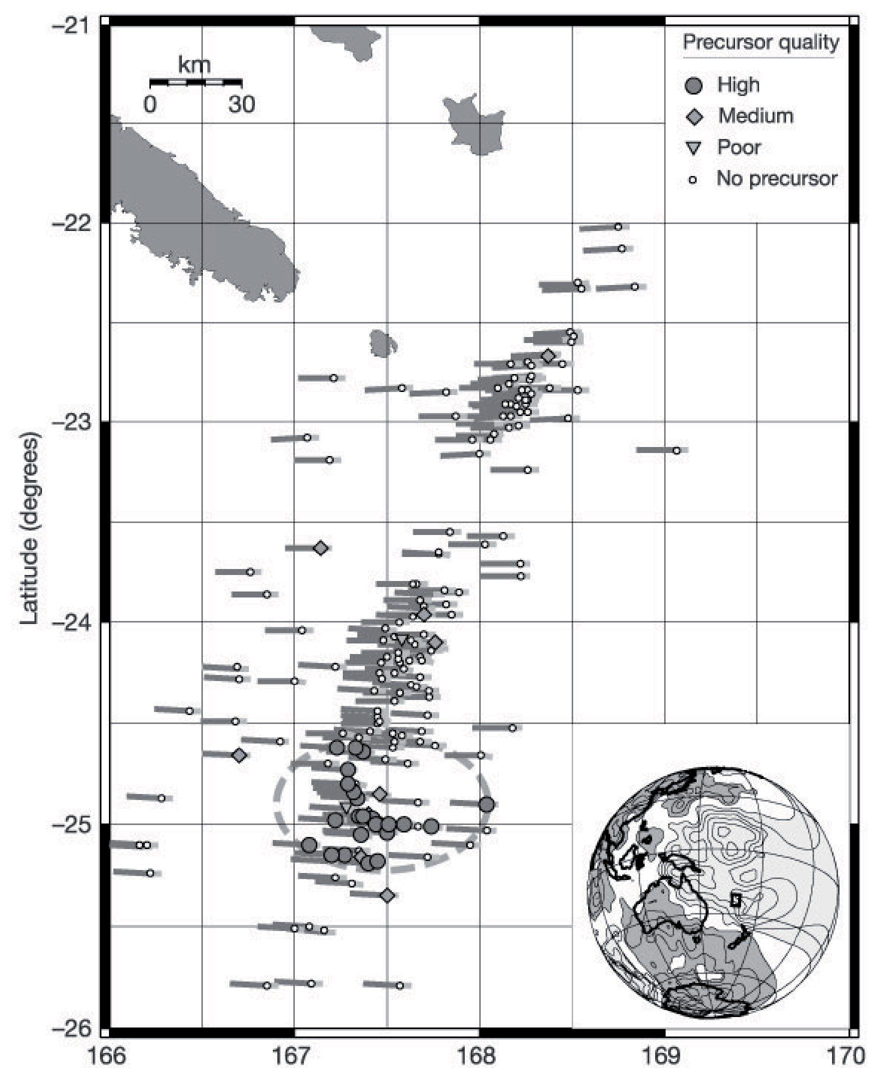
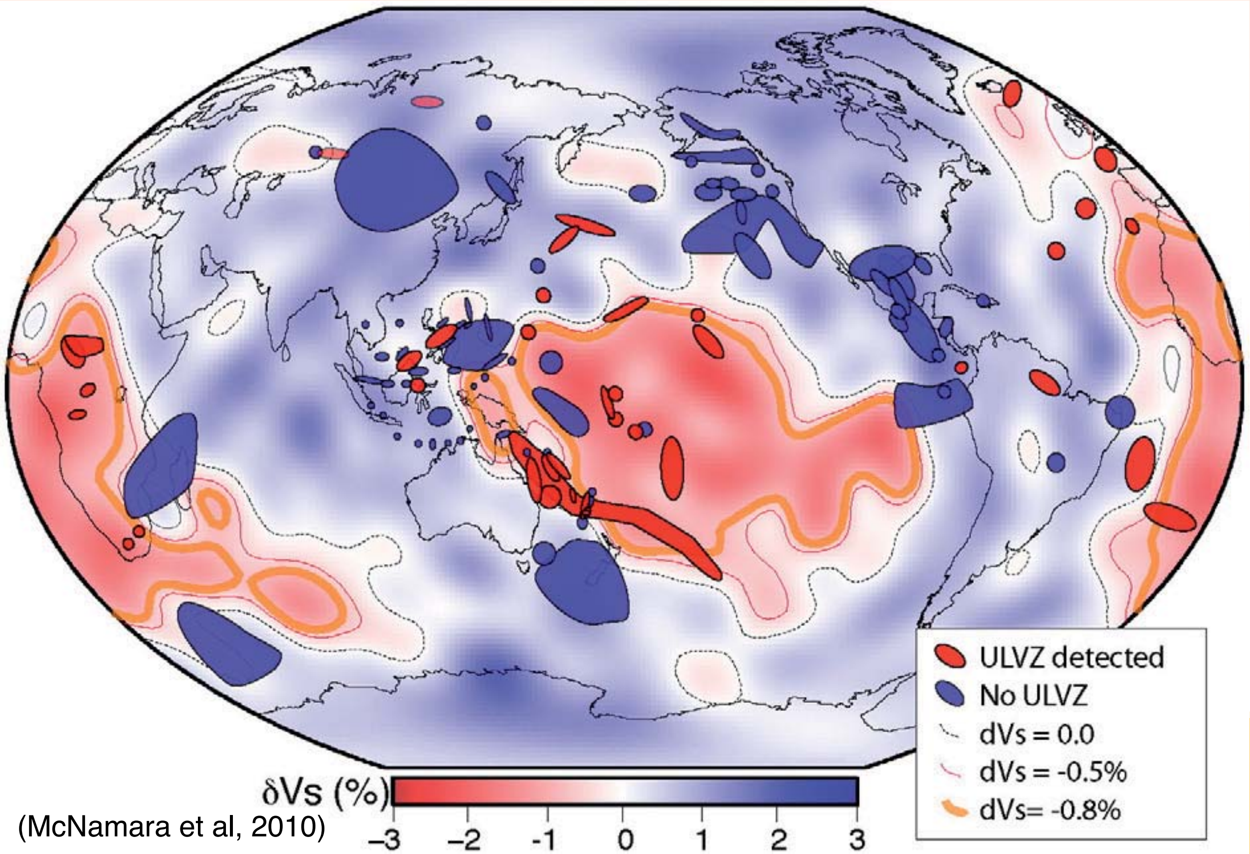
Ultra low velocity zones (ULVZ) : extremely localised anomalies !



(Rost et al, 2005)

About 100 km across !

Where do we see a ULVZ ?



(McNamara et al, 2010)

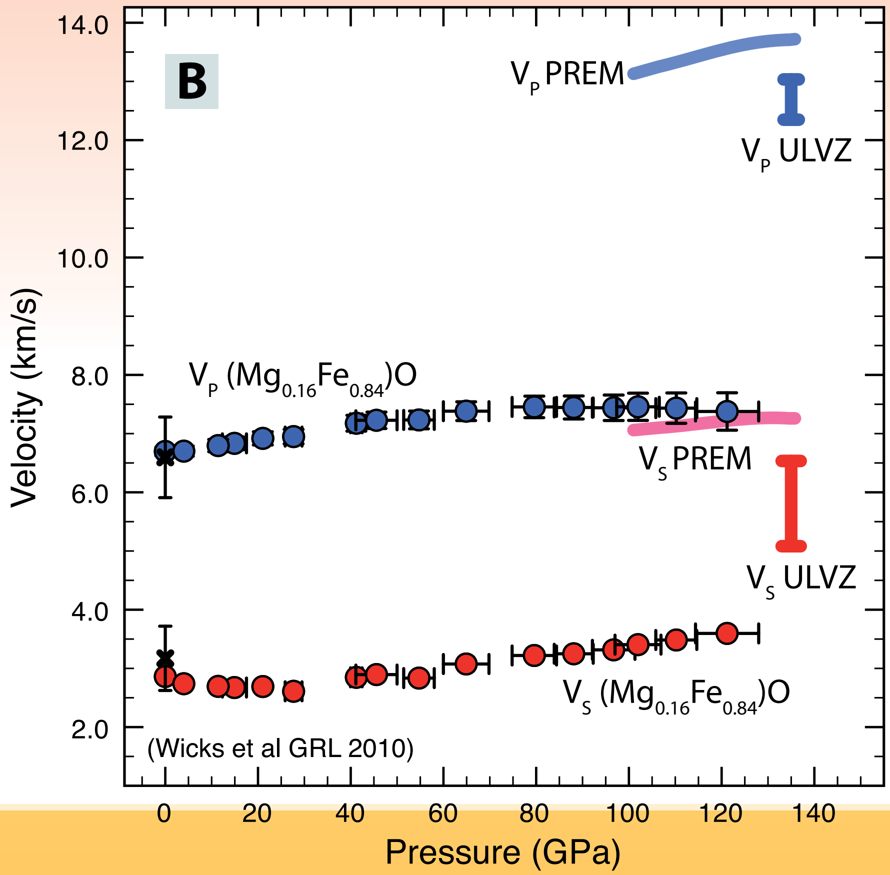
- ULVZs at the edges of the large low V_S regions (LLSVPs) ⇒ a link ?

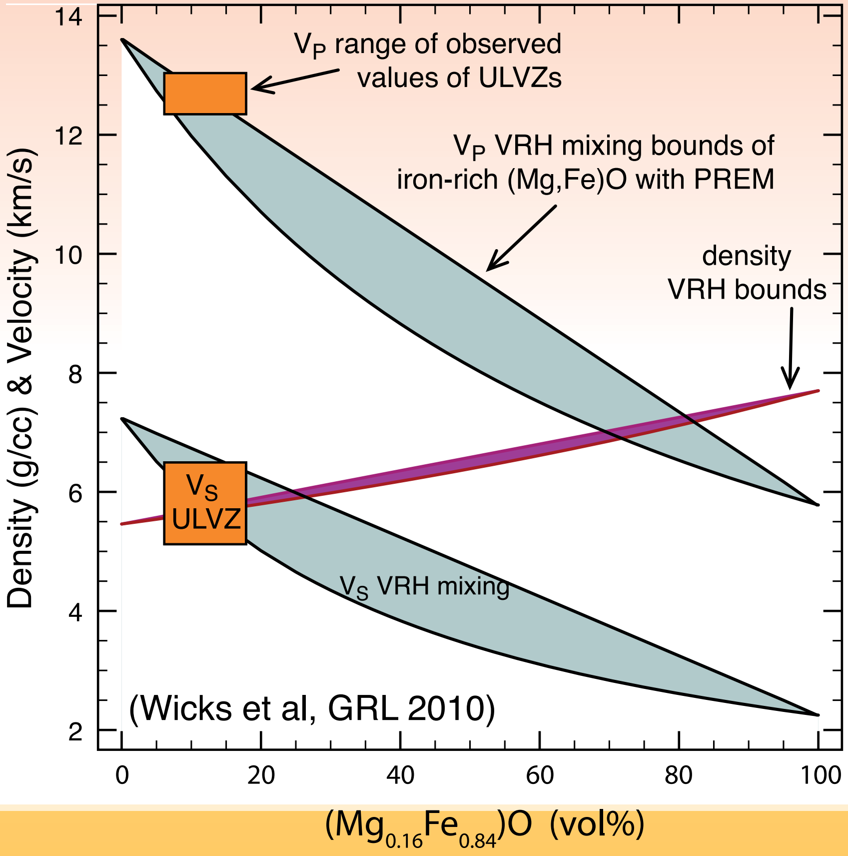
ULVZ properties

Observations :

- Ultra low velocity : $\delta V_P \sim -10\%$; $\delta V_S \sim -30\%$.
- High density : $\delta\rho \sim 10\%$.
- Thickness $\sim 10 - 40\ \mathrm{km}$.
- Two interpretations :
  - dense partial melt (Williams & Garnero, 1996, etc.)
  - Fe rich solid (Mao et al, 2006 ; Wicks et al, 2010)
- Both interpretations require lateral variations of composition.

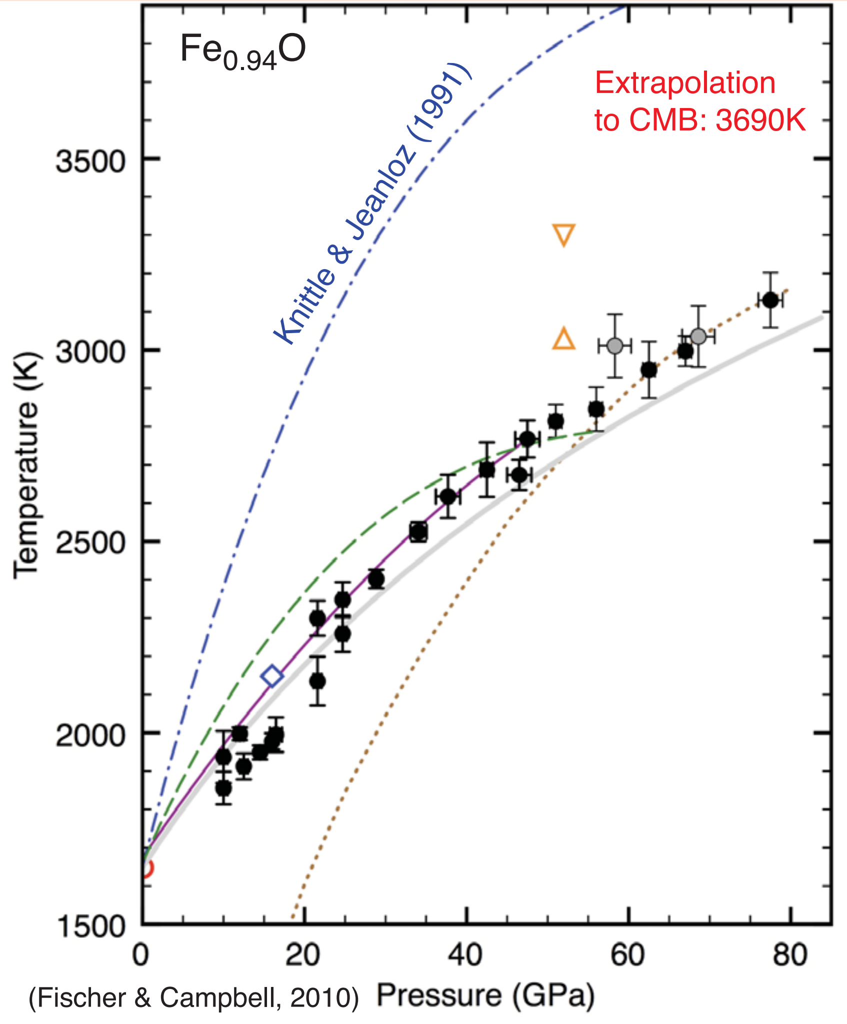
Fe-rich composition and seismic velocities





- A mixture of normal mantle with little Fe-rich (Mg,Fe)O can explain the ULVZs velocities.
- How are these Fe-rich patches formed ?
- Is this material solid at CMB conditions, anyway ?

Melting temperature of wüstite



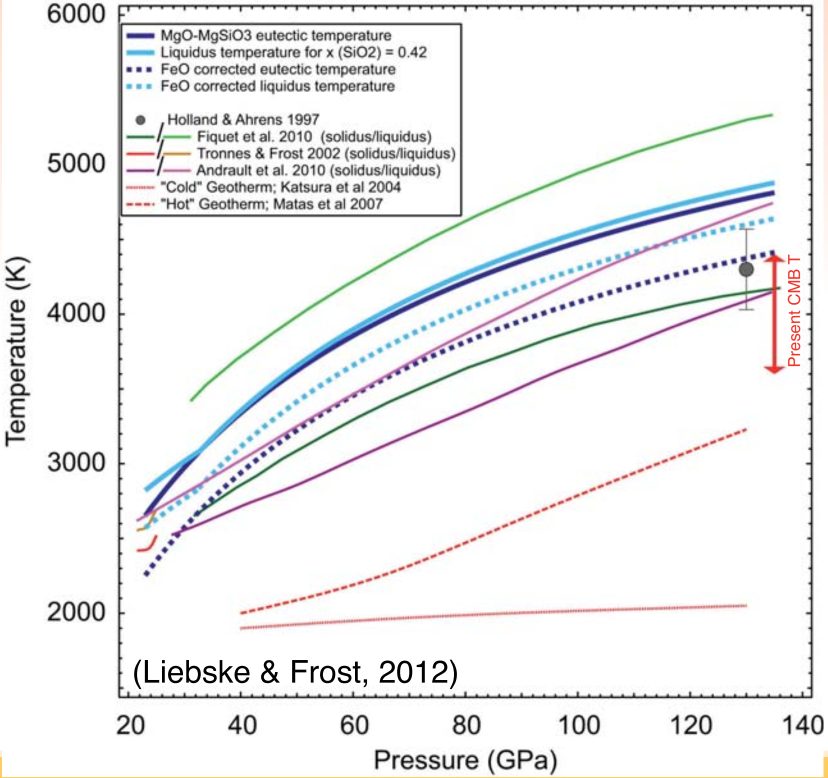
(Fischer & Campbell, 2010)

- Actual CMB temperature > 3500 K.

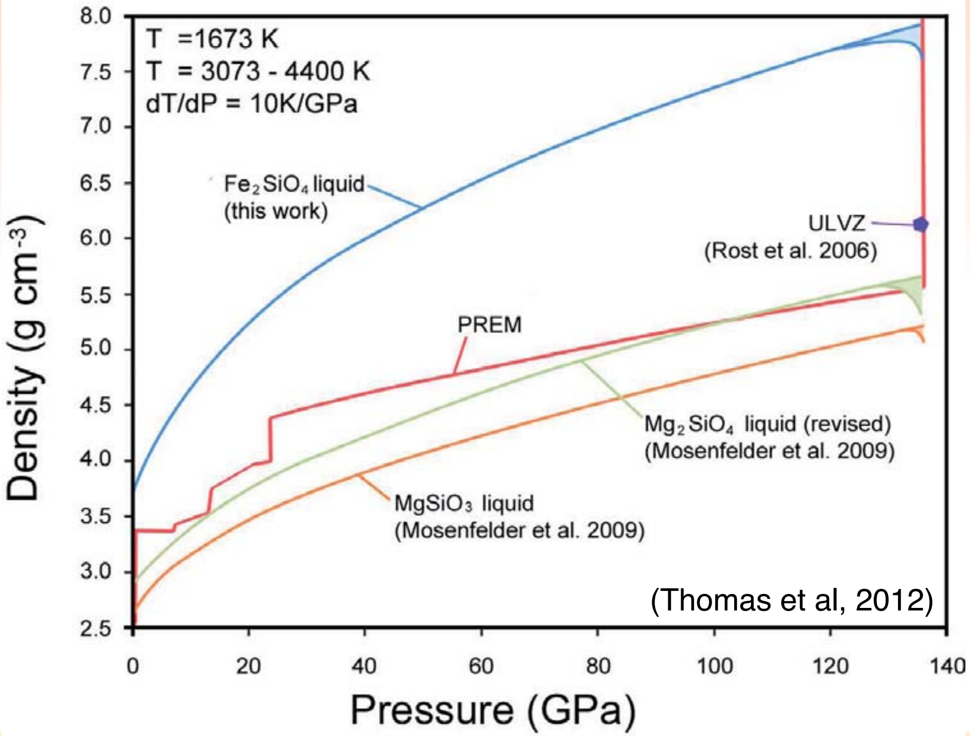
⇒ Wüstite possibly molten there at present and certainly in the recent past.

- This scenario requires large compositional variations in the lowermost mantle !

Temperature and density



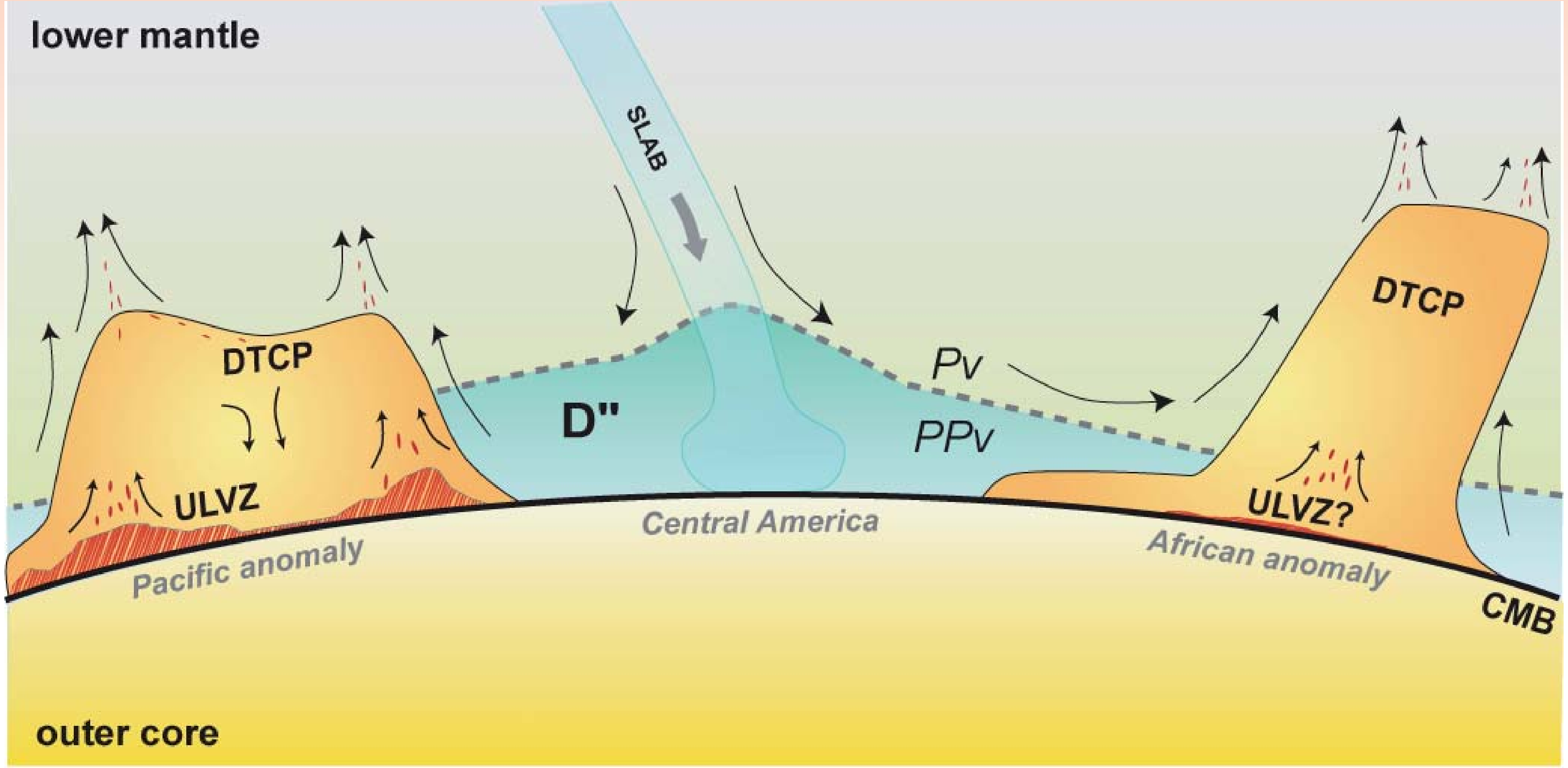
(Liebske & Frost, 2012)



(Thomas et al, 2012)

- ULVZs must be FeO rich compared to “normal mantle” to explain their high density and low solidus.
- Must also be in equilibrium with their environment ⇒ LLSVPs should be FeO rich, although less than ULVZs.

Summary cartoon for the structure of D”



[Garnero et al. [2006]

Whether solid or partially molten, ULVZs

- must be enriched in FeO compared to the average mantle,
- are most easily formed by fractional crystallisation.

Dense thermo-chemical piles (DTCP, LLSVP) most likely also rich in FeO (but less than ULVZs).

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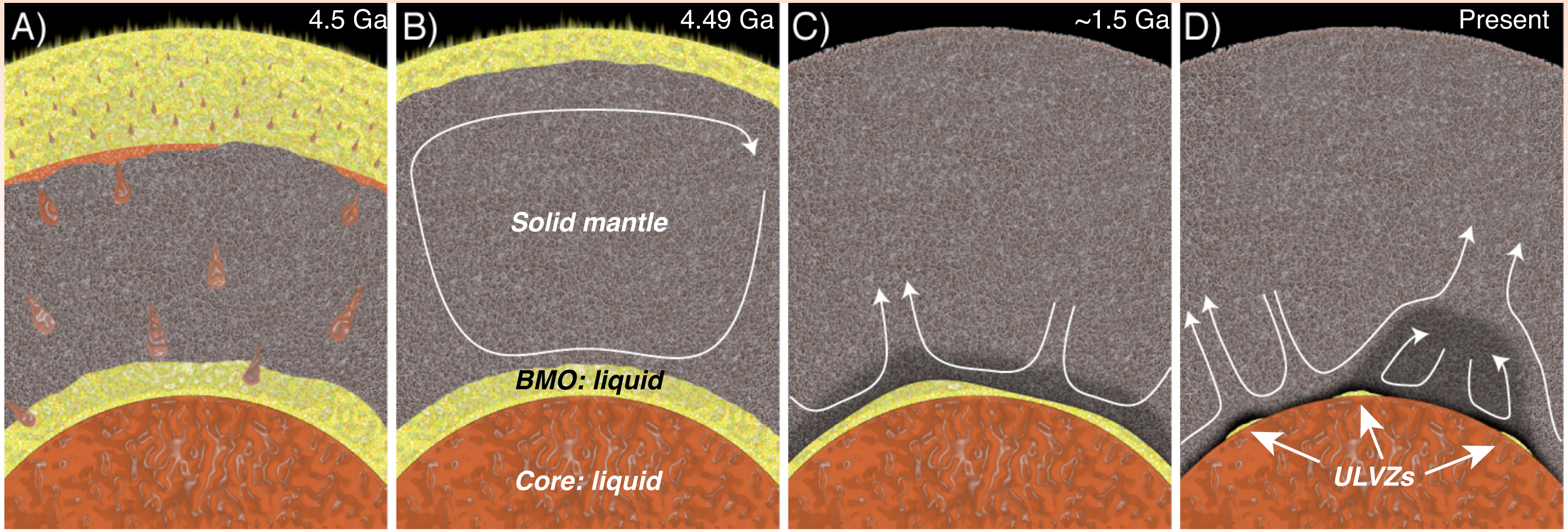
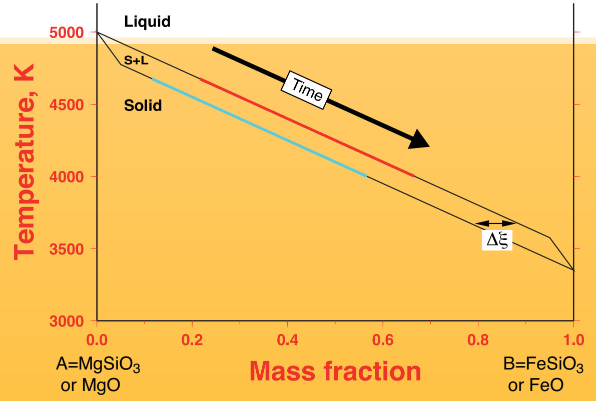
Our cartoon view



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.

Super-isentropic temperature difference across the melt layer

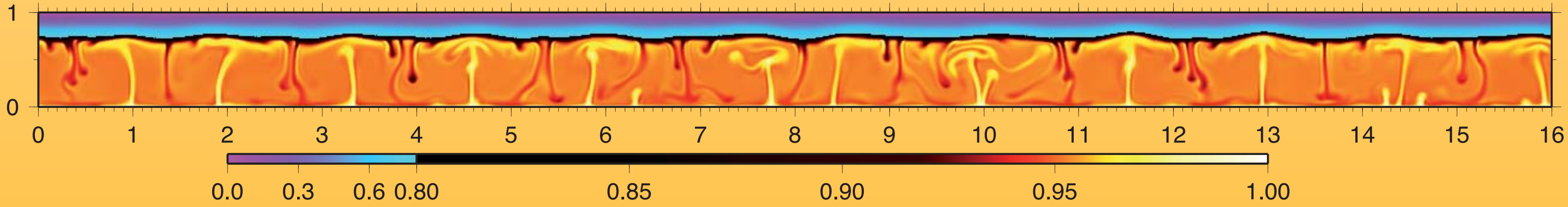
Convective heat flux :

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

Low viscosity magma :

⇒ Negligible super-isentropic temperature difference (ΔT).

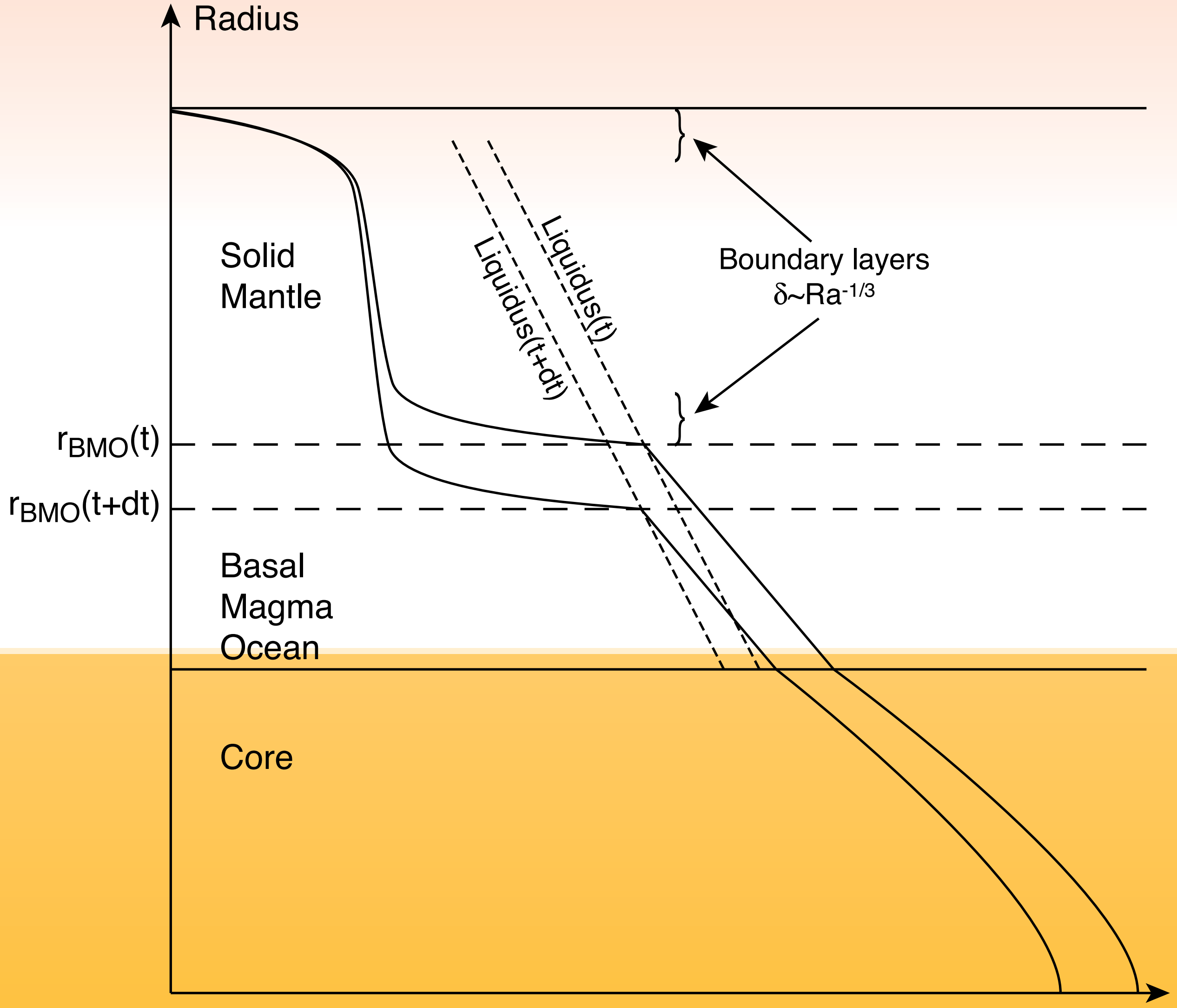
⇒ Core cooling must follow the evolution of the liquidus of the mantle.



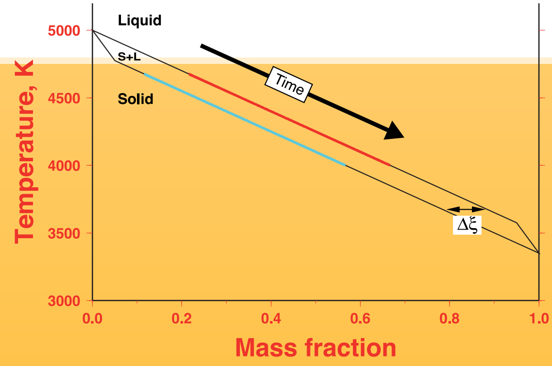
(Ulvrova et al, PEPI, 2012)

Thermal evolution of the Earth

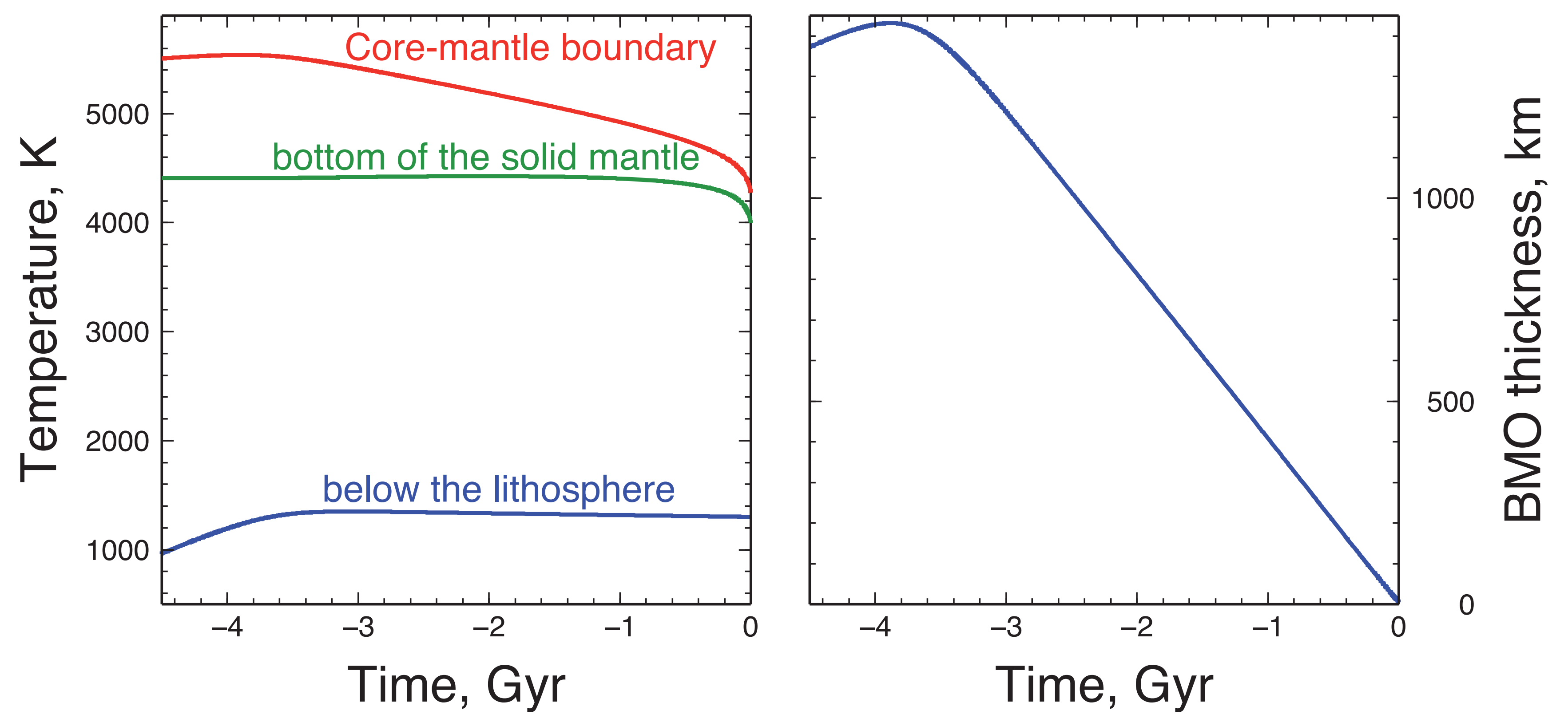
A coupled model :



- Energy balance for each shell
- Phase diagram including pressure and composition effects (Mg#).

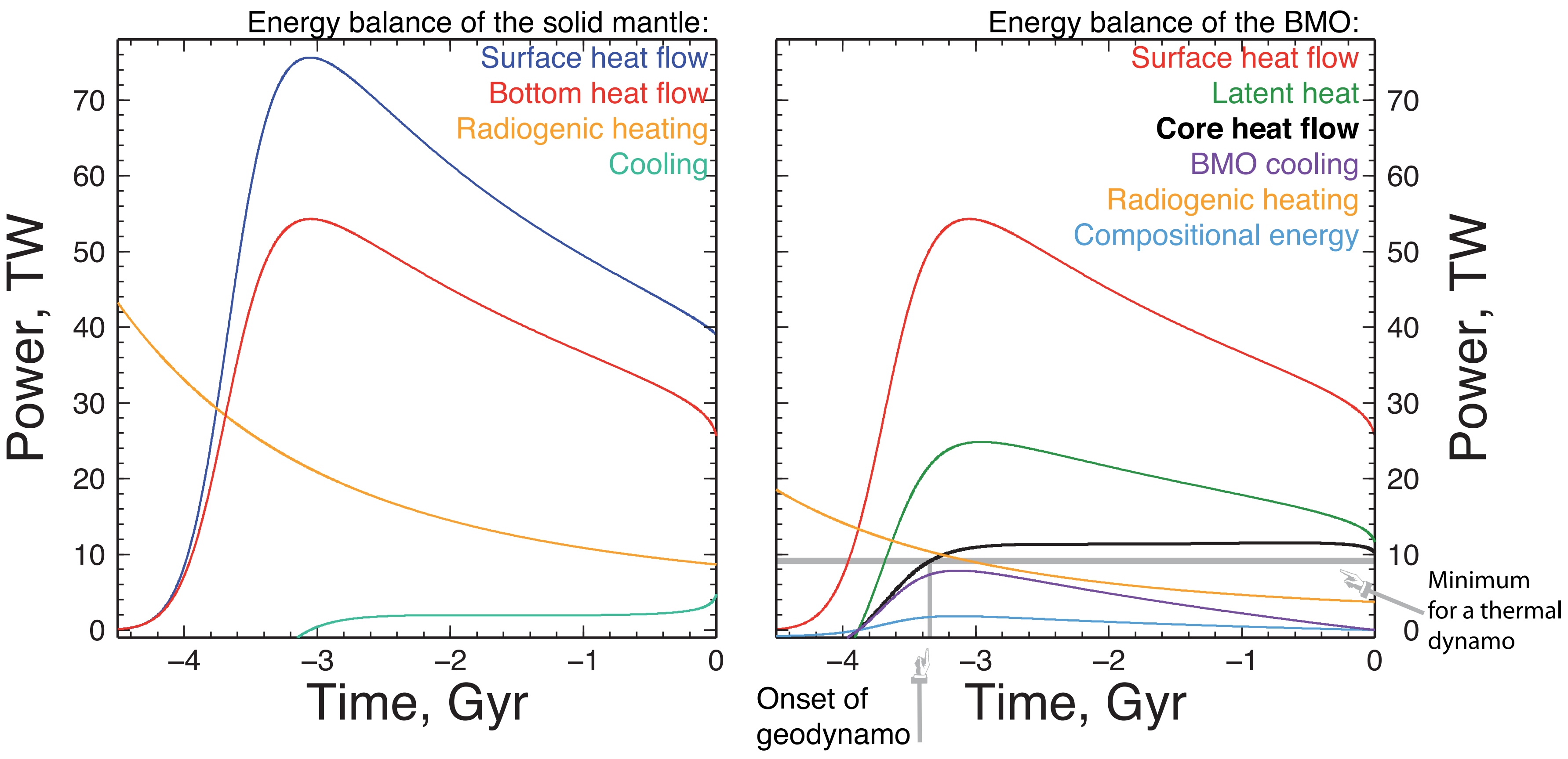


Results : thermal evolution and BMO thickness



- Mild thermal evolution of the mantle
- Large core cooling
- Thick initial basal magma ocean

Results : Energy balances



- Thermal catastrophe in the mantle avoided by a large heat flow at its base.
- Smaller heat flow from the core, sufficient to drive a thermal dynamo.

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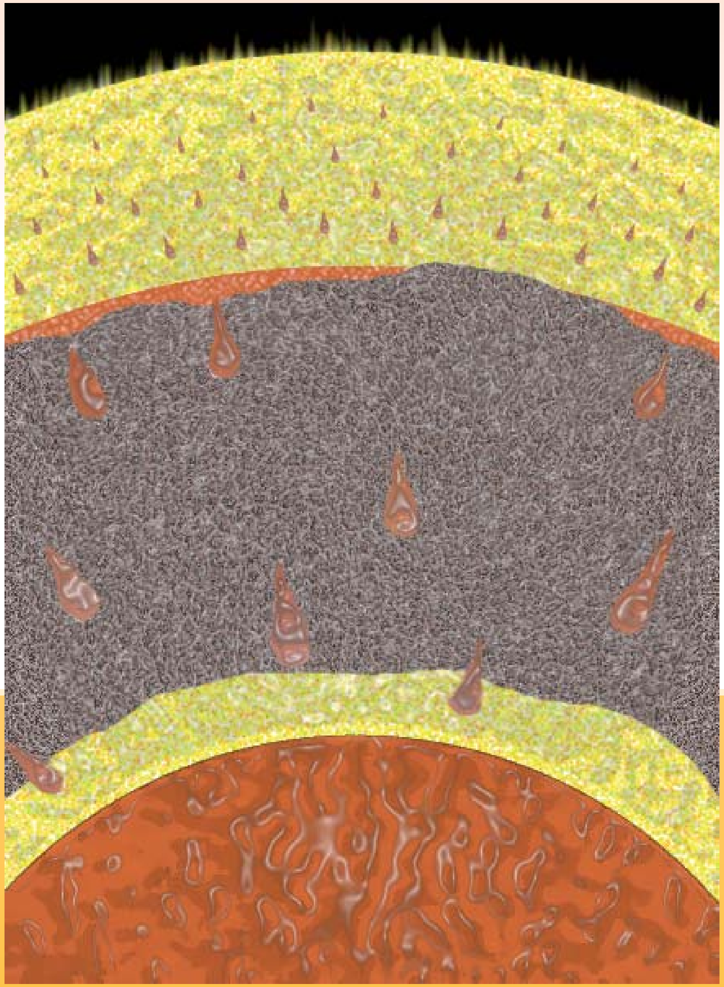
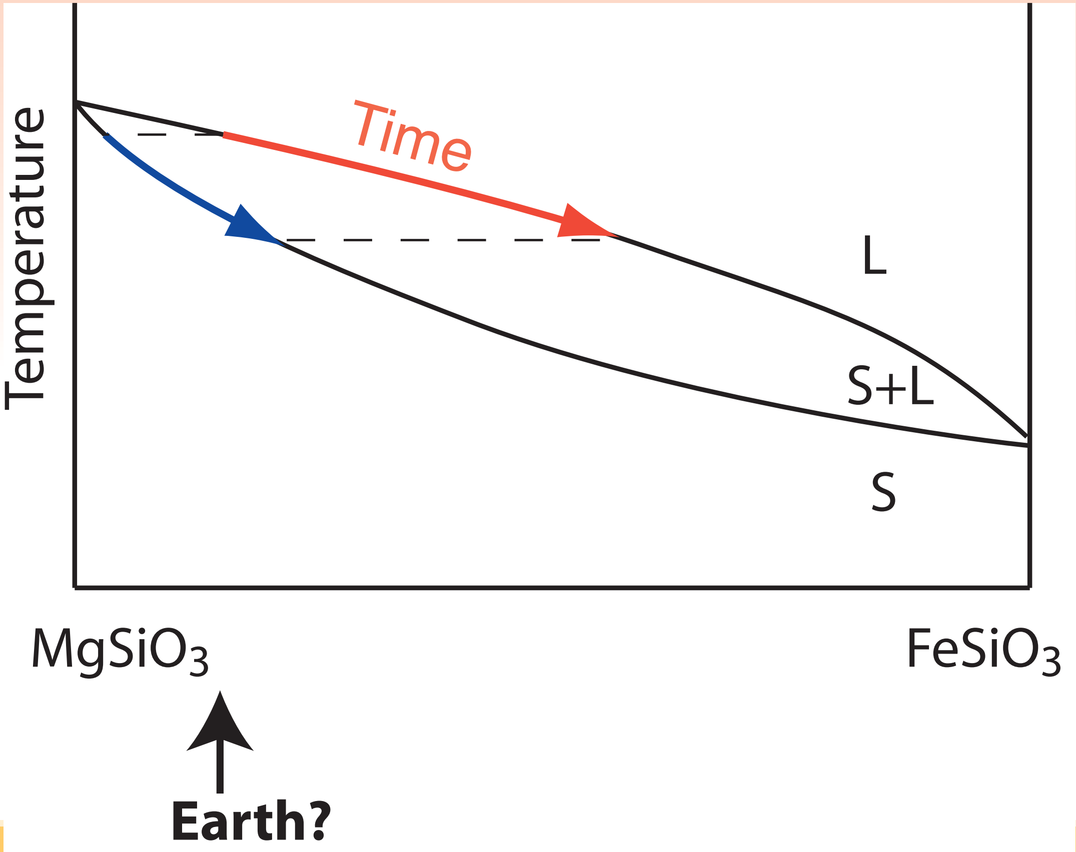
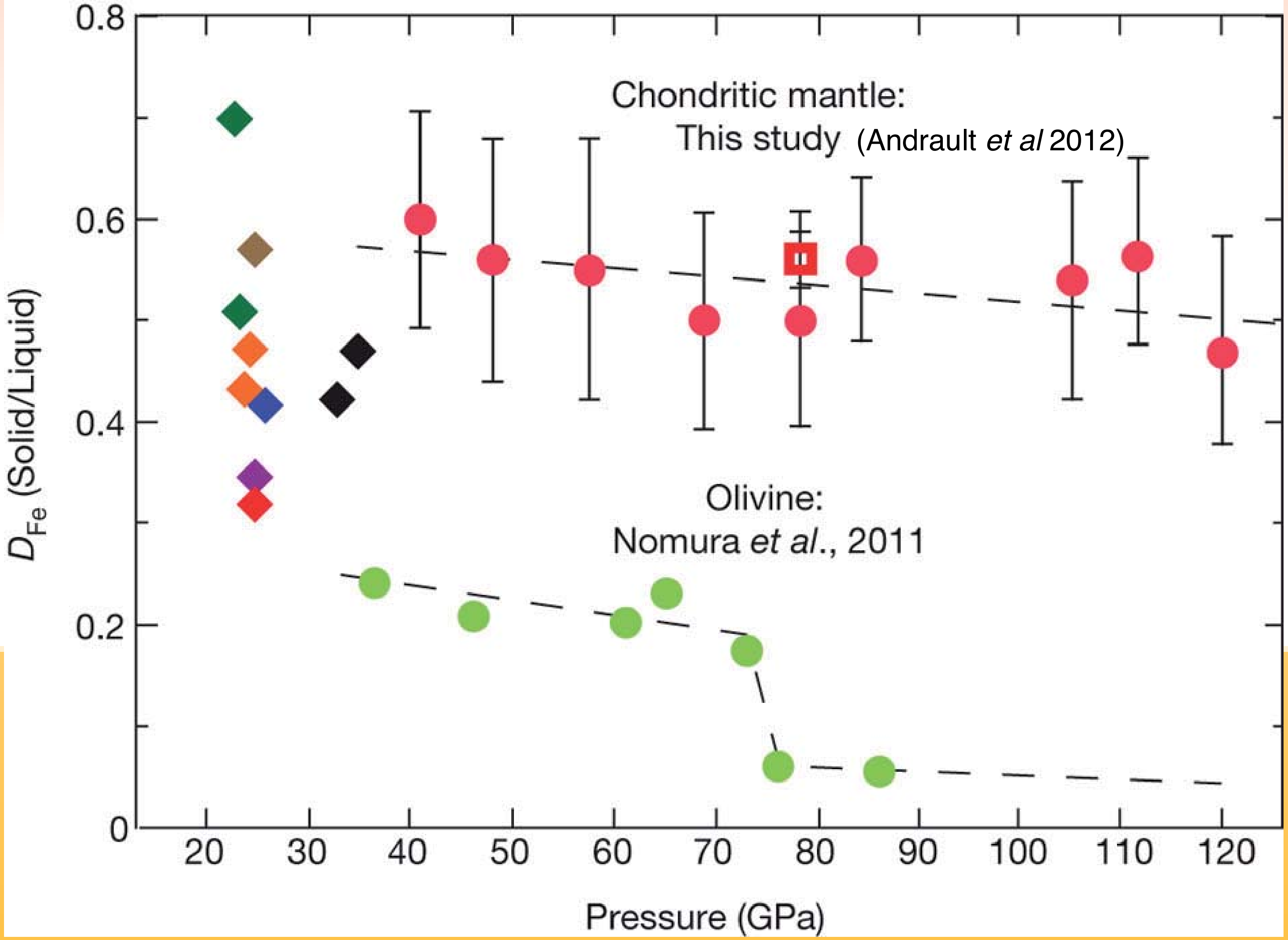
Original scenario



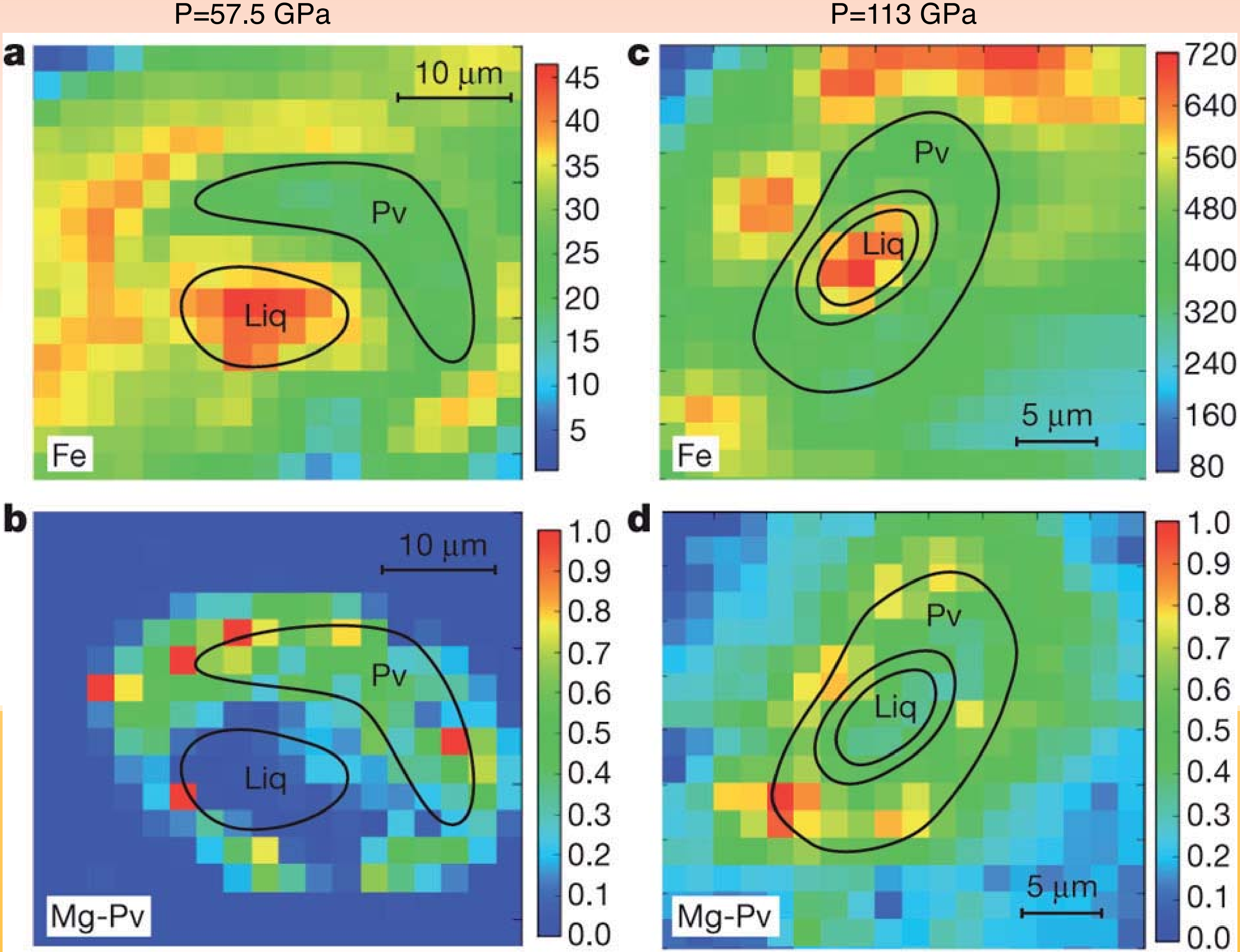


- Fractional crystallisation ⇒ liquid enriched in FeO compared to the solid.
- Crystals forming at the bottom of the mantle could float up and the mantle could crystallise from the middle.

Liquid-solid partition of FeO



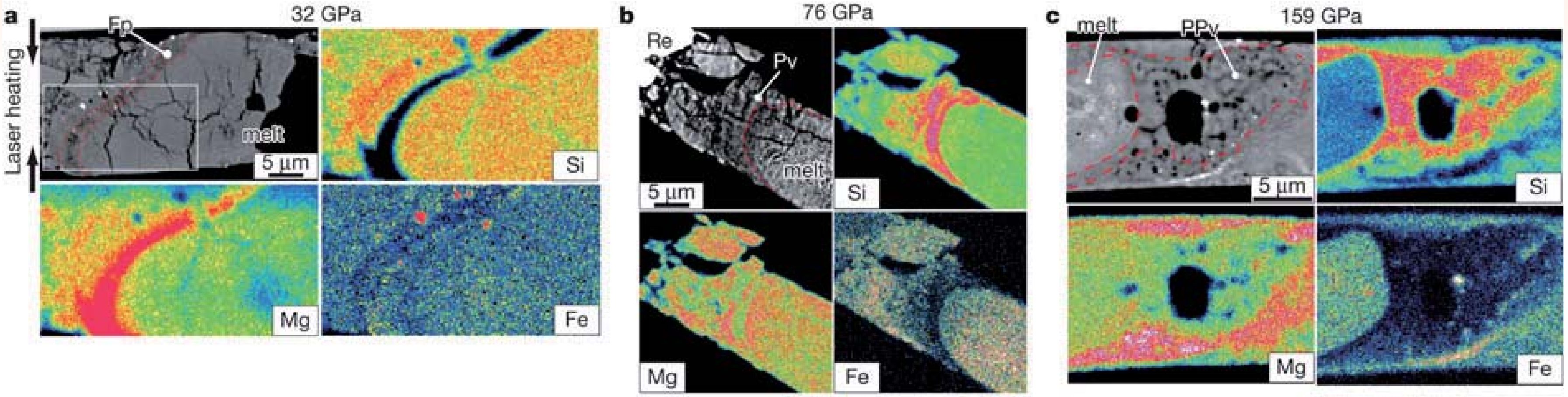
Analytical difficulties



(Andrault et al, 2012)

- Image resolution : liquid and solid measured not actually in contact.
- Soret diffusion : Fe driven toward the cold part, Pv.

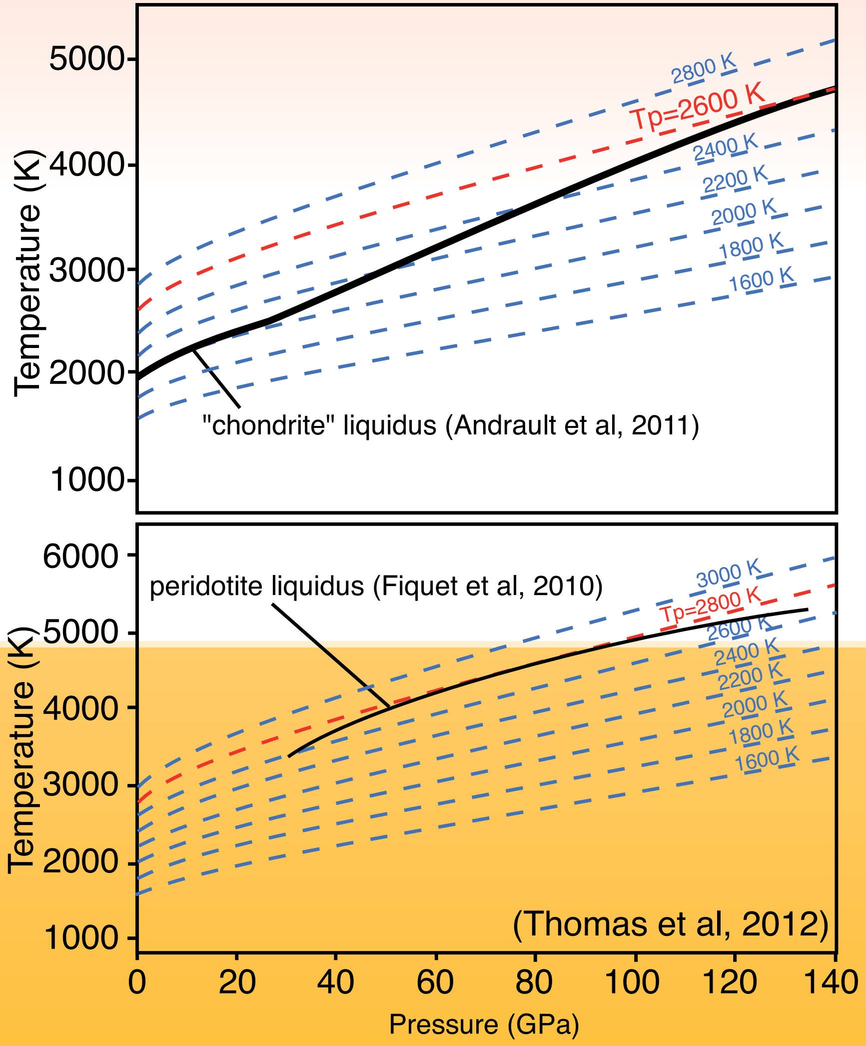
Analysis by Nomura et al (2011)



- Short heating duration to avoid Soret diffusion.
- High resolution images of the quenched samples.

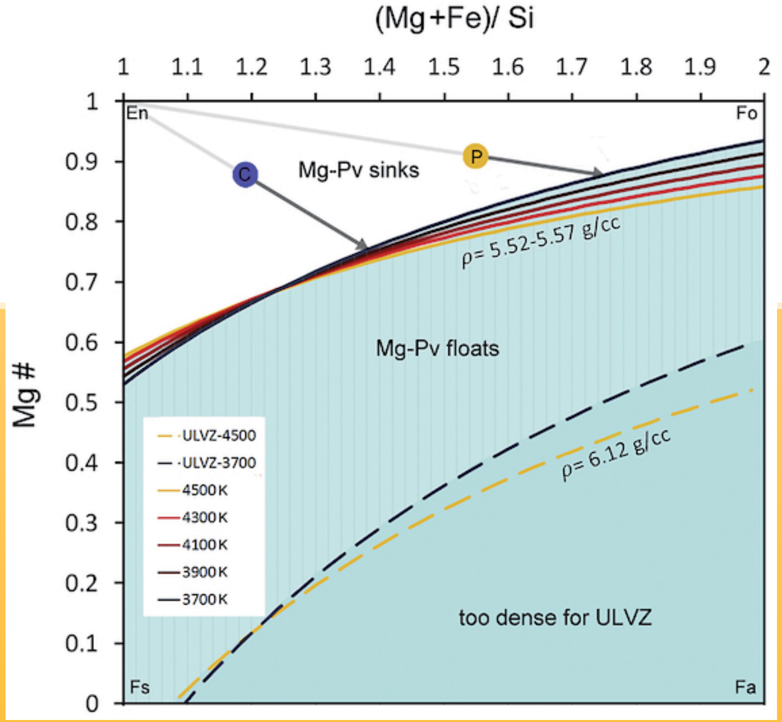
Freezing a global magma ocean

- Thomas et al (JGR 2012) : shock experiment on Fe_2SiO_4 and thermodynamic modeling.

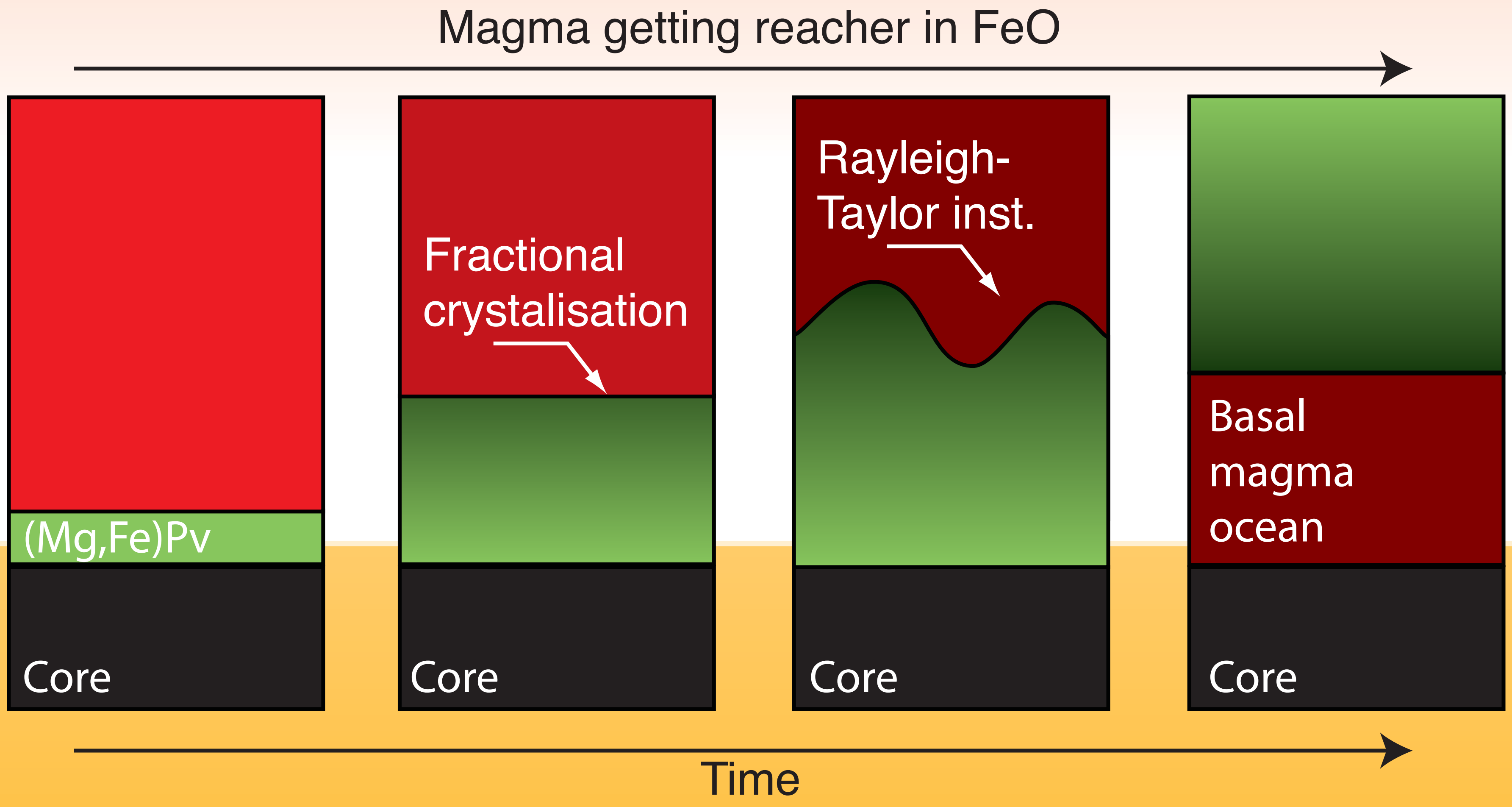


(Thomas et al, 2012)

- Freezing from the bottom or the mid-mantle.
- Mg-Pv denser than the liquid at CMB pressure.



Alternative scenario for the formation of the BMO

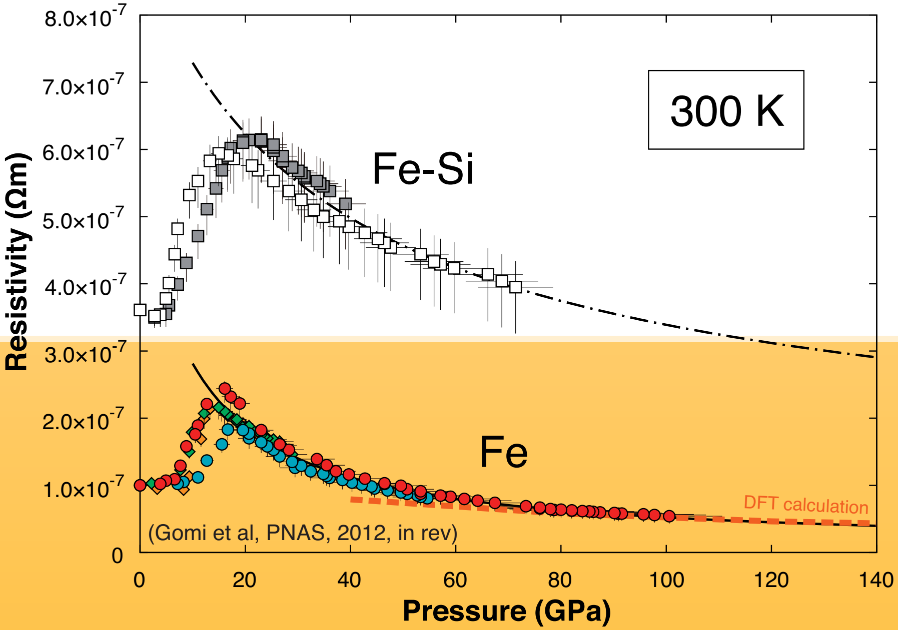


Conlusions

- The thermal evolution of the Earth can be reconciled with classical scalings of mantle convection ($Nu \propto Ra^{1/3}$) if the lowermost mantle was largely molten in the past.
- Whether solid or partially molten, ULVZs are best explained by fractional crystallisation of a dense magma trapped at the CMB.
- Formation scenarios for this basal magma ocean still need to be explored quantitatively using recent equations of state.

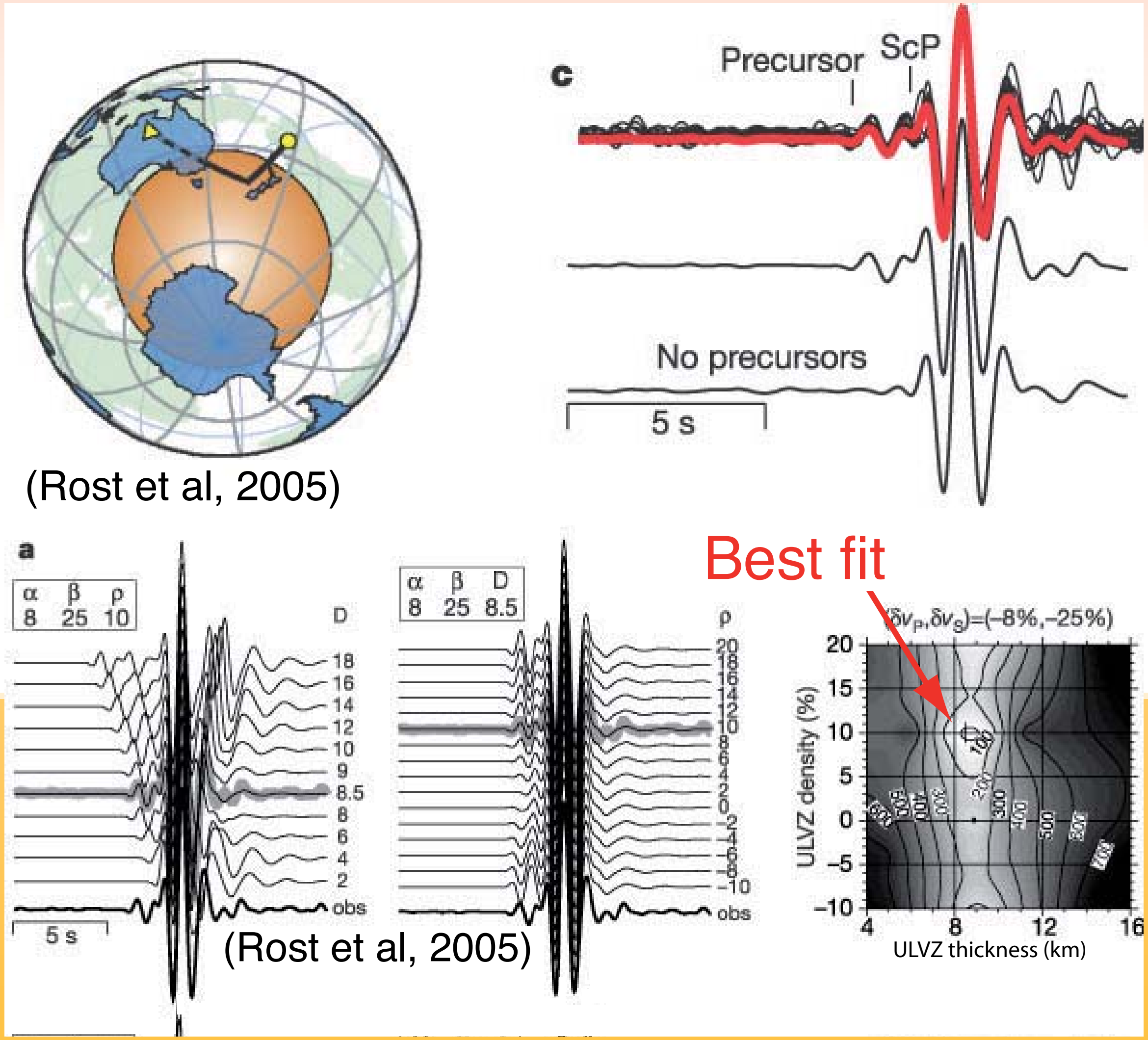
Thermal conductivity of the core -1

- Previous estimates : $28\mathrm{W/K/m}$ (Stacey & Loper, 2007) and $46\mathrm{W/K/m}$ (Stacey &Anderson, 2001).
- Recently revised upward by Hirose et al (2011), de Koker et al (2012), Pozzo et al (2012) and Gomi et al (2012).



- HP measurements and *ab initio* calculation of electrical resistivity.
- Use of the Wiedeman-Franz law to get thermal conductivity.
- HT extrapolation using Bloch-Grüneisen law and saturation effect.

Physical properties of the ULVZ



(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