The Moon plays a major role in maintaining the Earth's magnetic field

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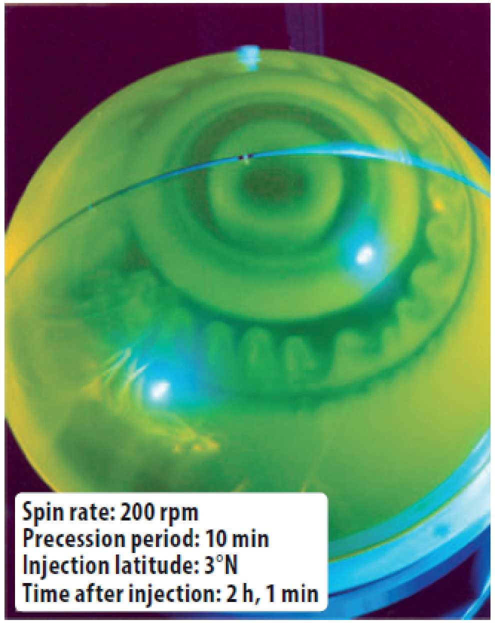


Fluid injection during precession (Vanyo, 2004)

This talk is divided in 4 parts:

1- Thermal state of the core: A puzzling paradox

2- Current core temperature : Still quite hot !

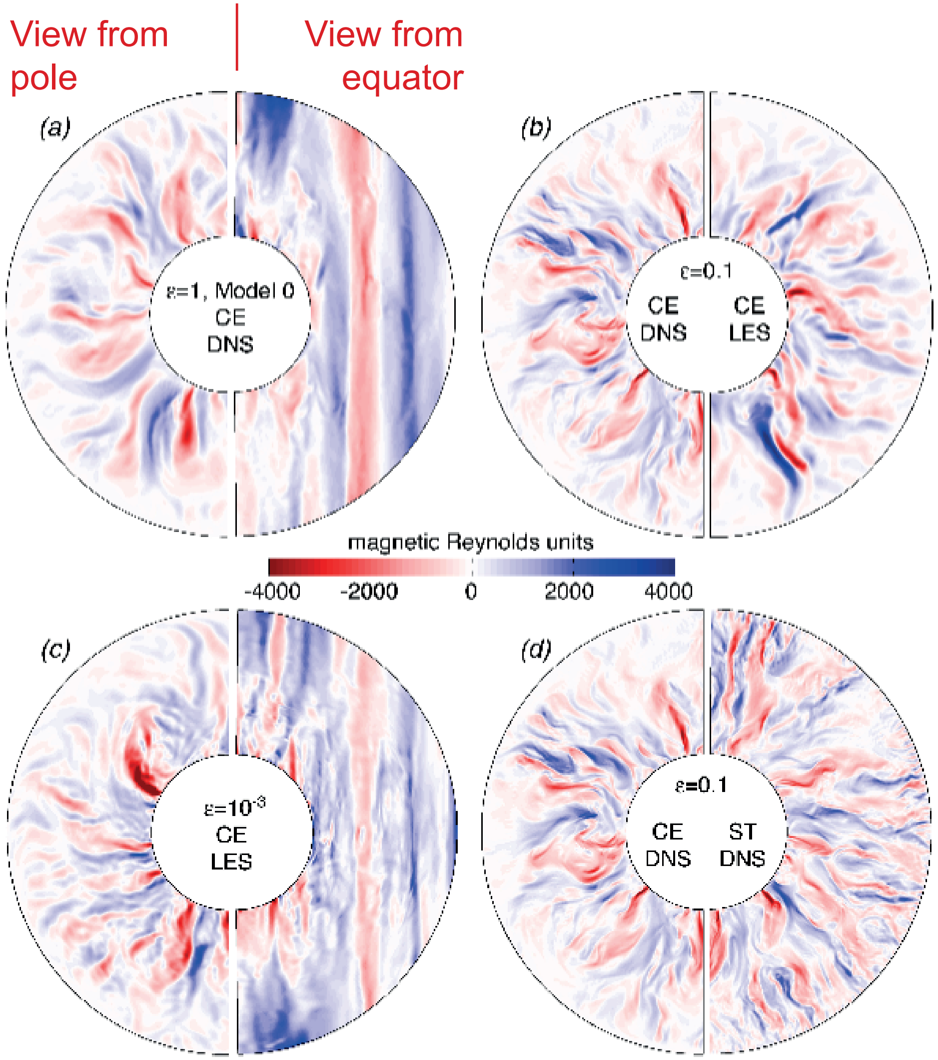
3- Early core temperature after crystallization of the magma ocean

4- Mechanical forcings are required to maintain the geodynamo alive

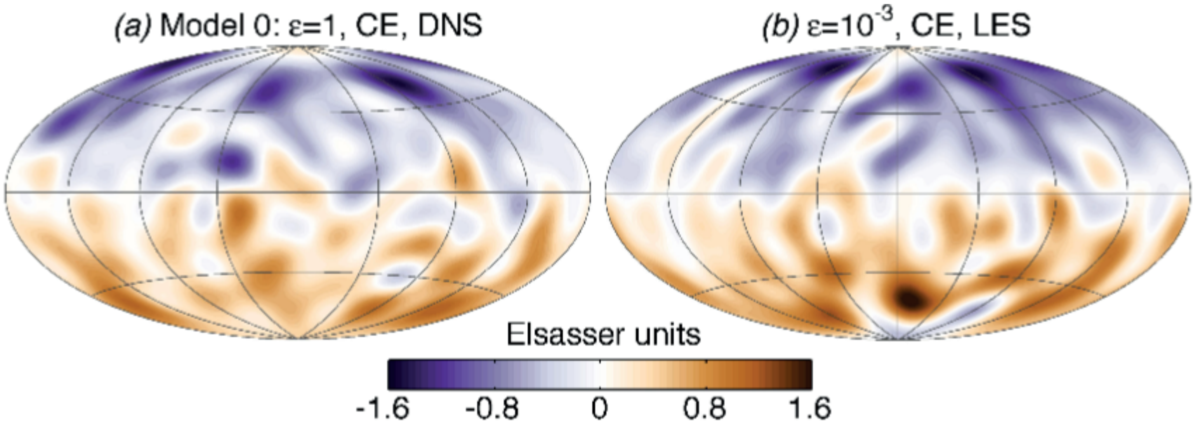
The Earth magnetic field is produced in the liquid outer core

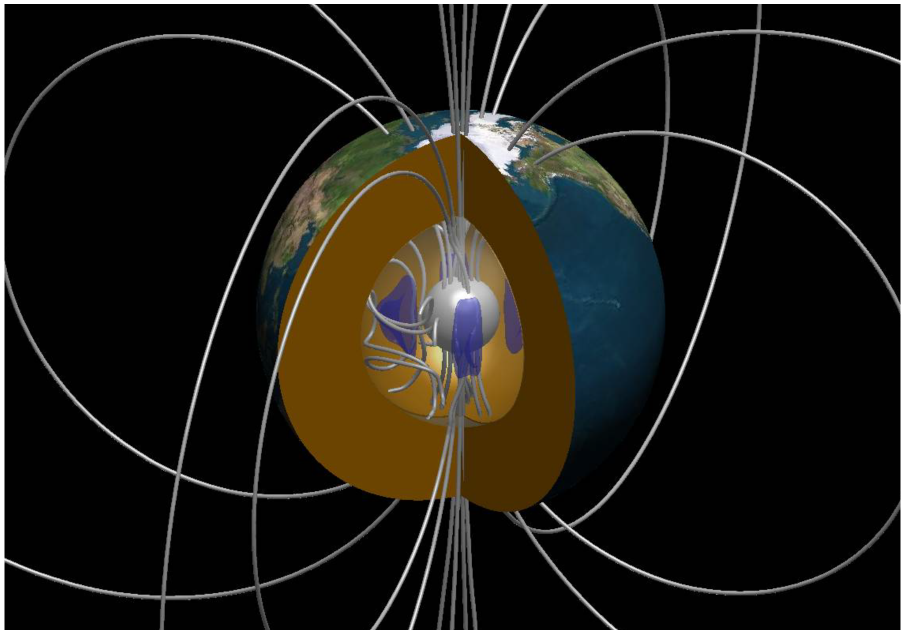
Aubert et al., 2017

Magnetic spectral energy density profiles



Radial magnetic field at core surface





What is the energy source to maintain the Geodynamo ?

Three possible mechanisms to produce motions in the core:

- **Thermal convection**
  Generated by a heat flux out of the core of 5 to 15 TW
  High thermal conductivity of the liquid Fe-alloy support high value (10-15 TW)

- **Solutale convection**
  Produced by growth of an inner core relatively depleted in light elements
  or by a flux of atoms at the core-mantle boundary

- **Mechanical forcing**
  Precession and tides at the CMB stir the outer core

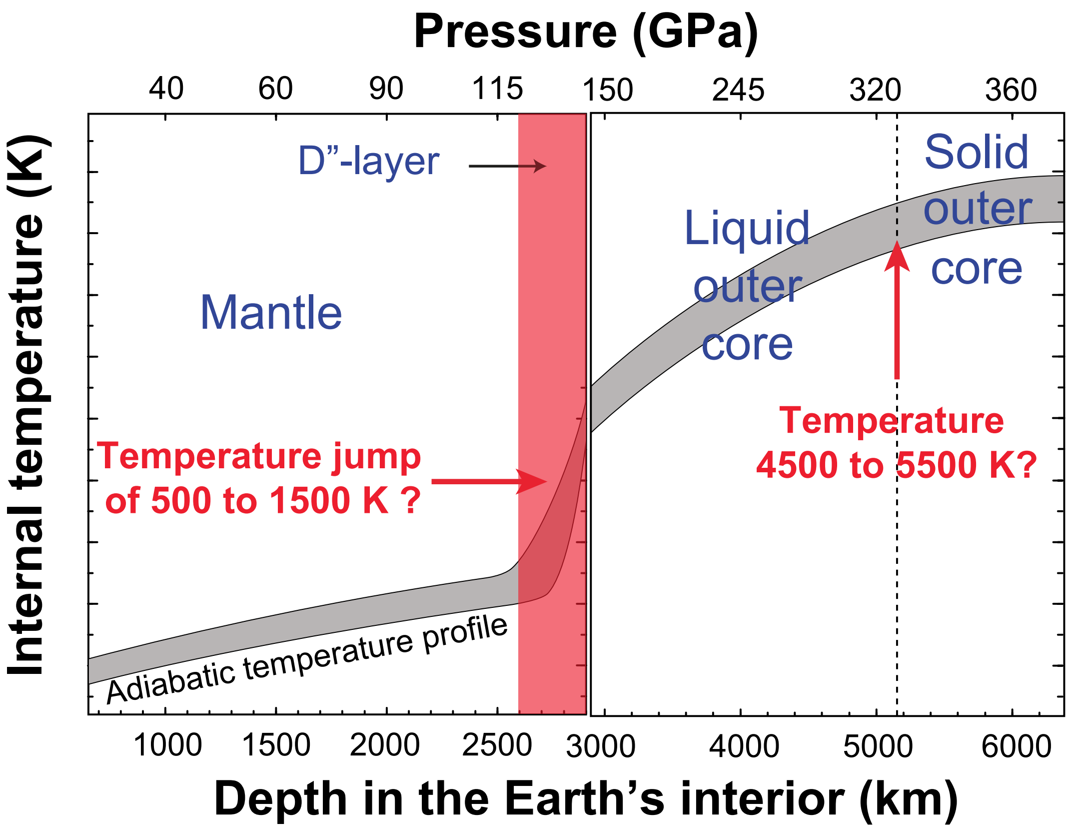
The classical model suggests:

- **Solutale convection**
  Seems reasonable, since the Earth's core is partially solidified

- **Thermal convection**
  The heat flux out of the core could help inducing mantle convection

- ~~**Mechanical forcing**~~
  ~~It may play a role, but appeared not necessary~~ => Discarded

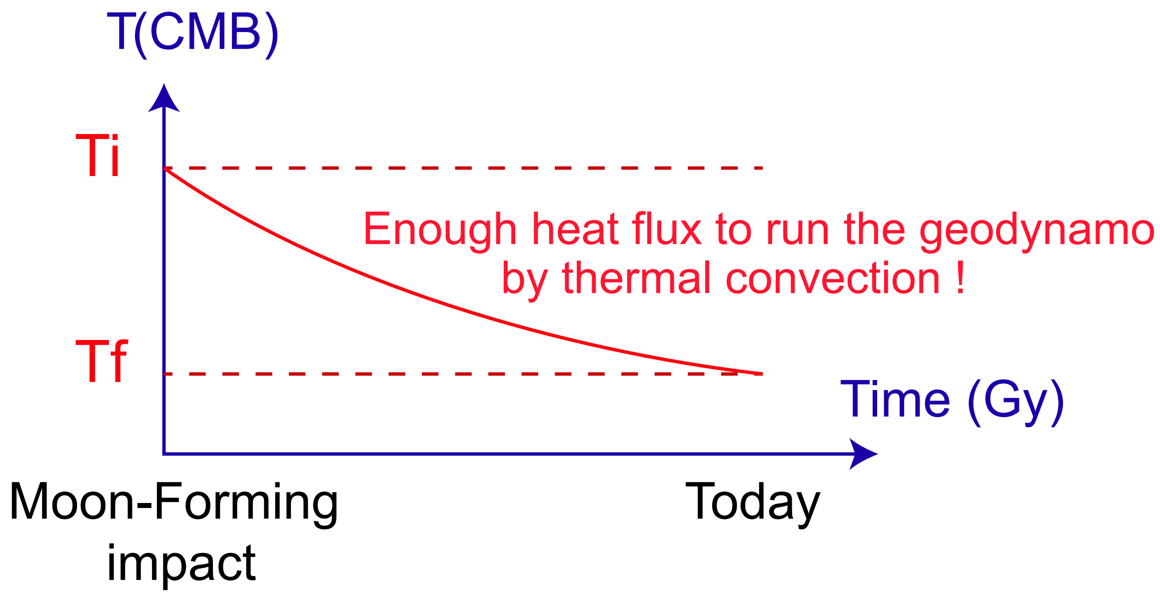
15 years ago, the thermal state of deep Earth was poorly constrained



Also k, thermal conductivity of the liquid Fe-alloy in the outer core, was poorly constrained

Evolution of temperature at the core-mantle boundary along the Earth's history

That was «happy days» !!!



Controversial value of k, thermal conductivity of the liquid outer core

LETTER

doi:10.1038/nature17957

High thermal conductivity, Nature, 2016

Experimental determination of the electrical resistivity of iron at Earth's core conditions

Kenji Ohta[1], Yasuhiro Kuwayama[2], Kei Hirose[3,4], Katsuya Shimizu[5] & Yasuo Ohishi[6]

LETTER

doi:10.1038/nature18009

Low thermal conductivity, Nature, 2016

Direct measurement of thermal conductivity in solid iron at planetary core conditions

Zuzana Konôpková[1]†, R. Stewart McWilliams[2], Natalia Gómez-Pérez[2,3] & Alexander F. Goncharov[4,5]

LETTER

doi:10.1038/nature11031

High thermal conductivity, Nature, 2014

Thermal and electrical conductivity of iron at Earth's core conditions

Monica Pozzo[1], Chris Davies[2], David Gubbins[2,3] & Dario Alfè[1,4]

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PHYSICS OF THE EARTH AND PLANETARY INTERIORS

High thermal conductivity, 2013

The high conductivity of iron and thermal evolution of the Earth's core

CrossMark

Hitoshi Gomi[a,*], Kenji Ohta[a,1], Kei Hirose[a,b,c,*], Stéphane Labrosse[d,e], Razvan Caracas[d], Matthieu J. Verstraete[f], John W. Hernlund[b,g]

With years, two major constraints arose...

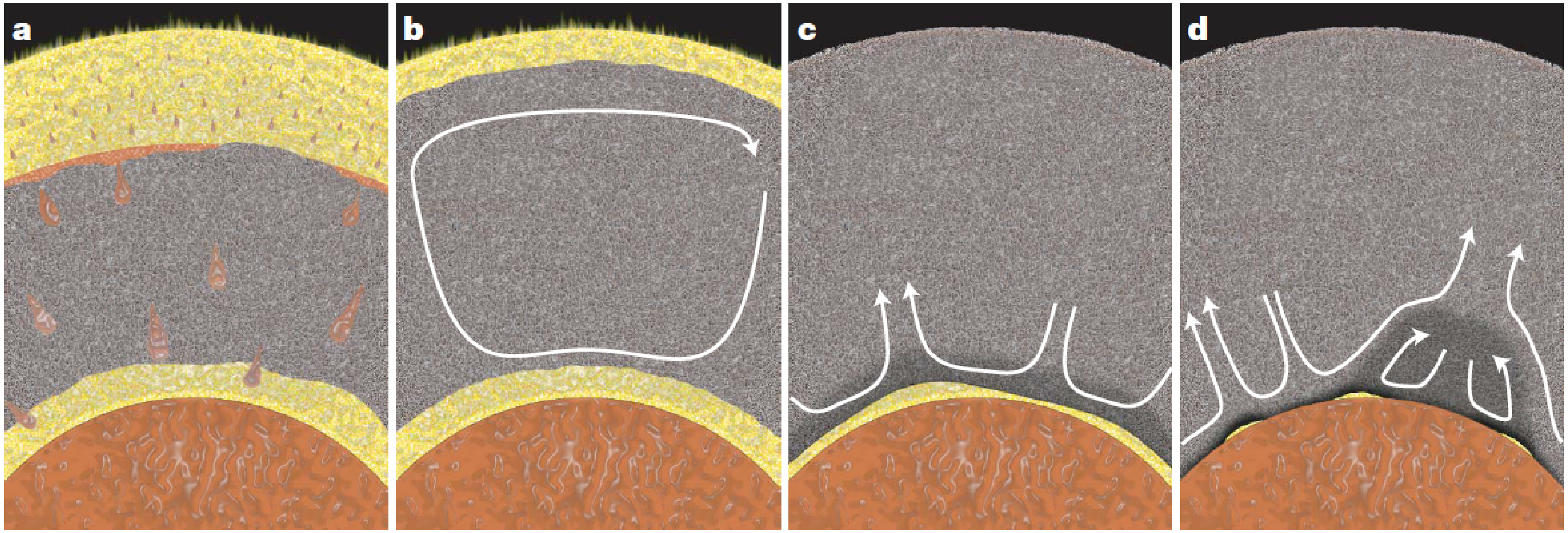
\# The thermal conductivity of the Fe-alloy in the outer core is at least twice than previously thougth.

=> A geodynamo maintained by thermal convection requires a large heat loss at the core-mantle boundary (10-15 TW)

\# The CMB temperature remains very high today. It is at ~4000 K, just below the mantle solidus

=> In the classical «cooling» scenario, the lowermost mantle should have been largely molten in the past !

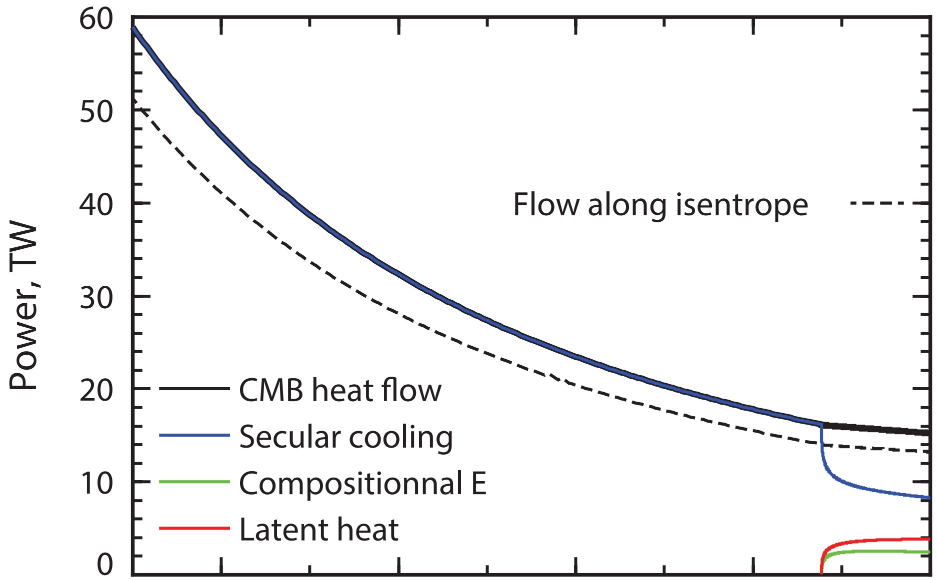
Labrosse et al., Nat. 2007

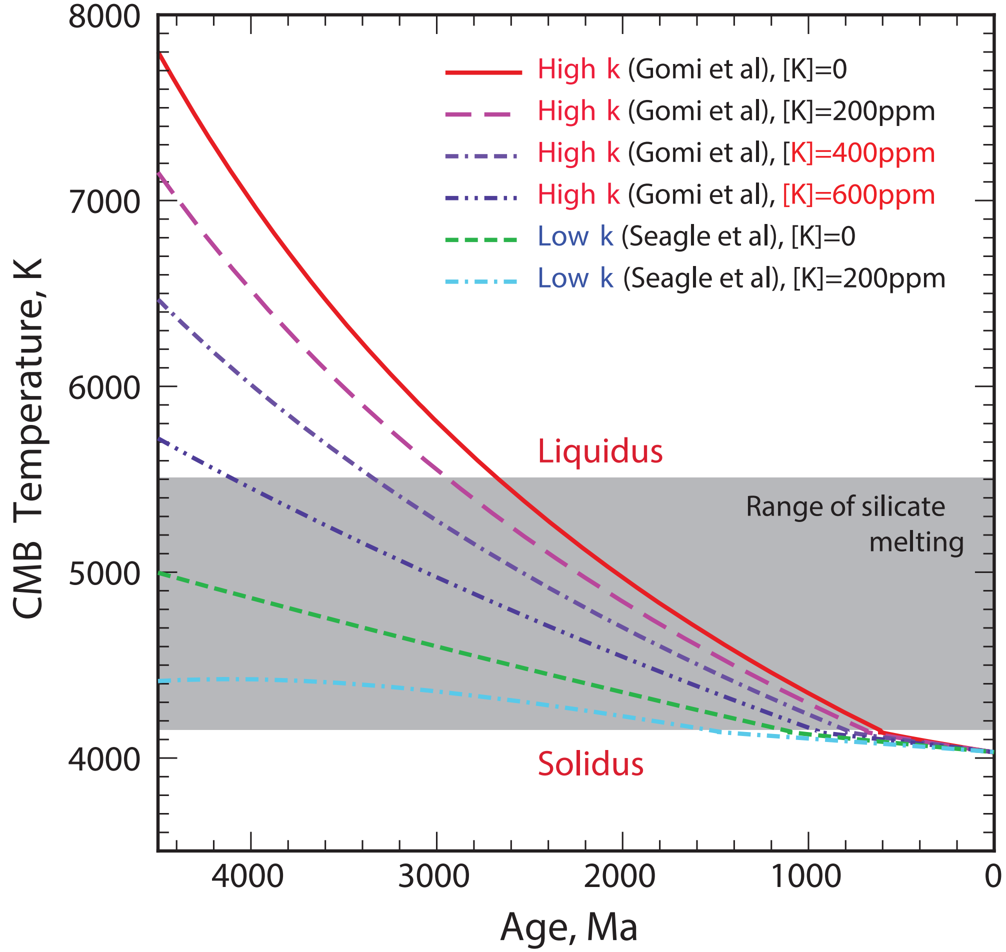


The newly revised «classical-like» model...

Labrosse, 2015, see also Davies et al., 2015

The model produces :
- Hot CMB today
- A current CMB heat flux of 15 TW

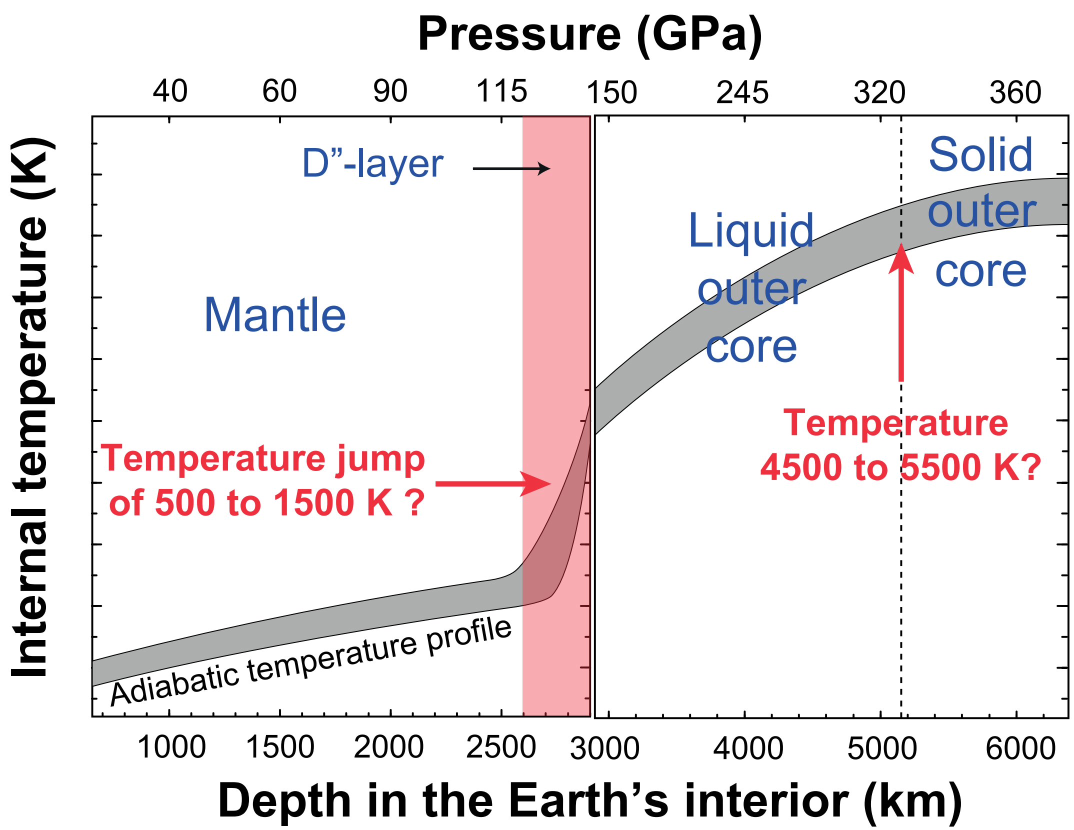




Implications :
- T(CMB) above the mantle liquidus for more than 1 Gy
- T(CMB) above the mantle solidus for up to 3.5 Gy
- Age of the inner core is less than 1 Gy

Also, the model predicts that the geodynamo should stop very soon: «Tomorrow», if 15 TW is the critical heat flux along the adiabat...

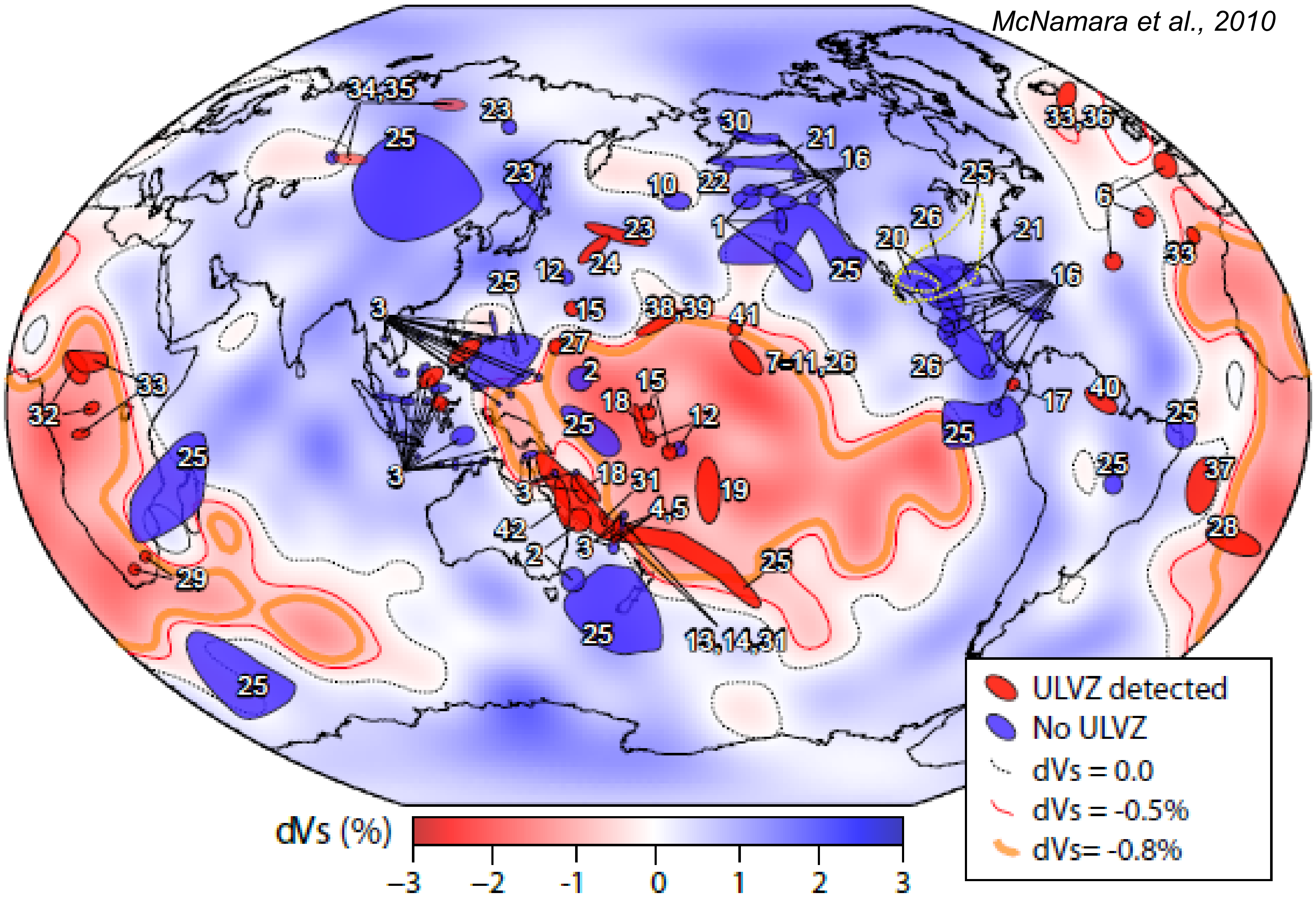
What is the current core temperature at the core mantle boundary ?



Ultra-low velocity zones

- ULVZs are small (~10 km tall, ~100 km across) dense (~10%), slow (>10% reduction) anomalies
- Might be preferrentially associated with the edges of the LLSVPs
- Different size / character than "Perm-type" anomaly.

McNamara et al., 2010



1. Rost et al. [2010, JGR]
2. Thomas et al. [2009, GJI]
3. Idehara et al. [2006, PEPI]
4 Rost et al. [2005, Nature]
5. Rost et al. [2006, JGR]
6. Rost and Garnero [2006, JGR]
7. Lay et al. [2006, Science]
8. Avants et al. [2006, GRL]
9. Mori and Helmberger [1995, JGR]
10. Kohler et al. [1997, GRL]
11. Revenaugh and Meyer [1997, Science]
12. Garnero and Vidale [1999, GRL]
13. Rost and Revenaugh [2001, Science]
14. Rost and Revenaugh [2003, JGR]
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16. Persh et al. [2001, GRL]
17. Niu and Wen [2001, GRL]
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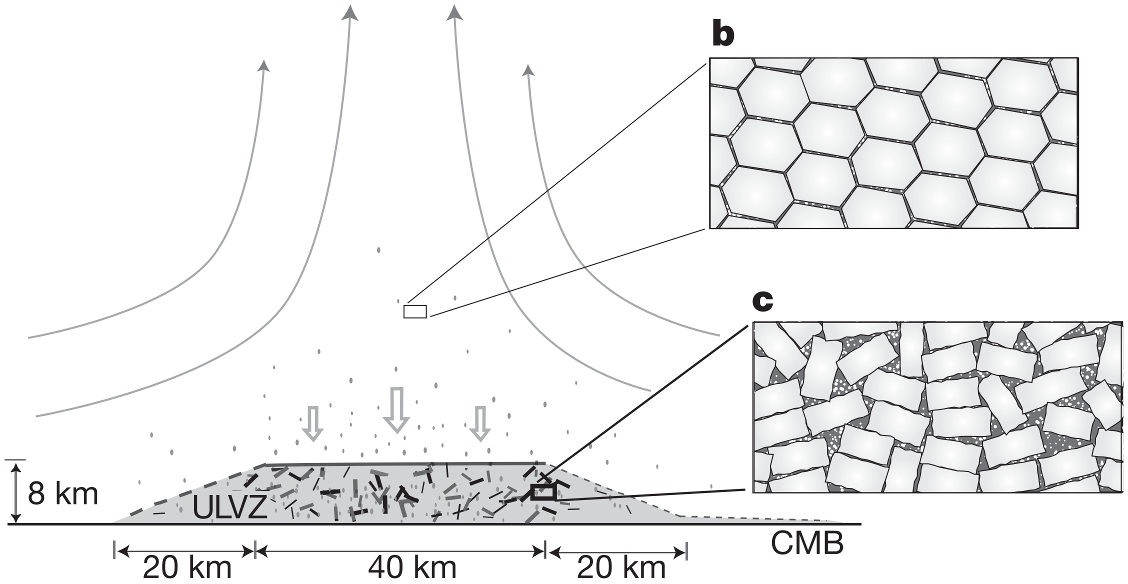
19. Wen and Helmberger [1998, JGR]
20. Havens and Revenaugh [2001, JGR]
21. Castle and van der Hilst [2001, EPSL]
22. Vidale and Benz [1992, Nature]
23. Xu and Koper [2009, GRL]
24. Rondenay and Fischer [2003, JGR]
25. Thorne and Garnero [2004, JGR]
26. Hutko et al. [2009, PEPI]
27. He and Wen [2009, JGR]
28. Wen [2002, JGR]
29. Sun et al. [2009, JGR]
30. Rost and Thomas [2009, PEPI]
31. Rost et al. [2010, JGR, in press]
32. Ni and Helmberger [2001, GRL]
33. Helmberger et al. [2000, JGR]
34. Ross et al. [2004, JGR]
35. Thybo et al. [2003, EPSL]
36. Helmberger et al. [1998, Nature]
37. Ni and Helmberger [2001b, EPSL]
38. Luo et al. [2001, EPSL]
39. Sun et al. [2007, PNAS]
40. Zou et al. [2006, GJI]
41. Courtier et al. [2007, GRL]
42. Koper and Pyle [2004, JGR]

Partial melting today in the lowermost mantle: Different models

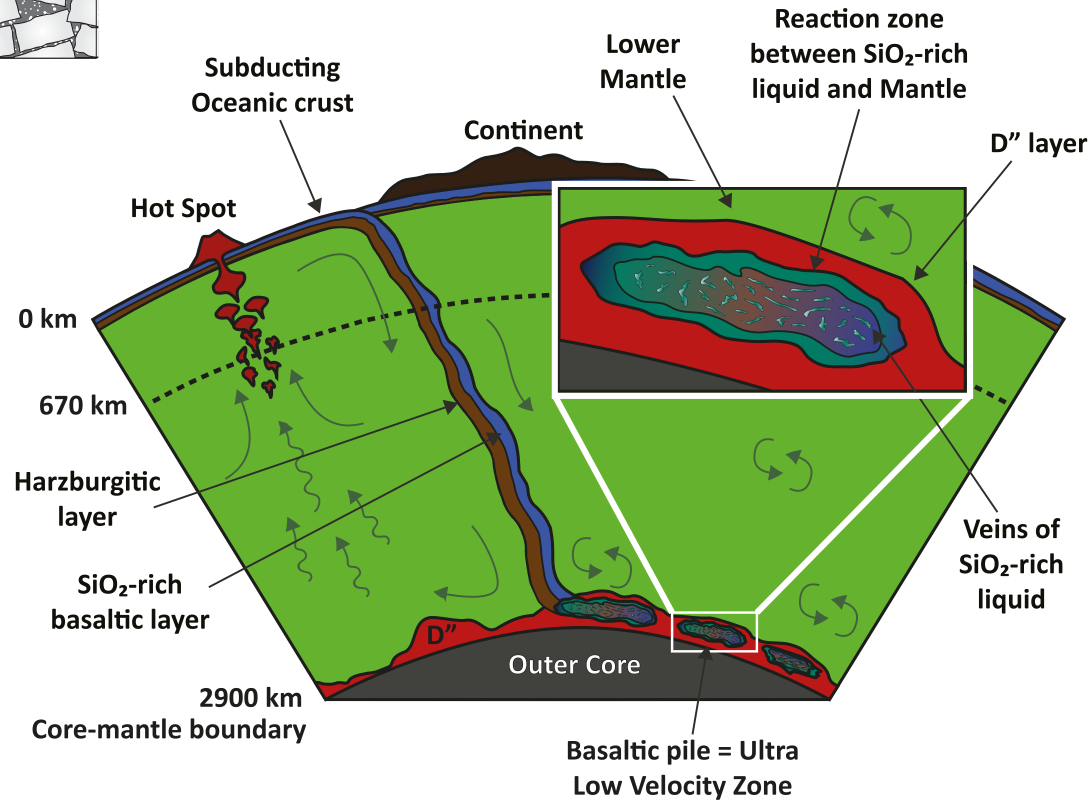


Melting of the mean mantle

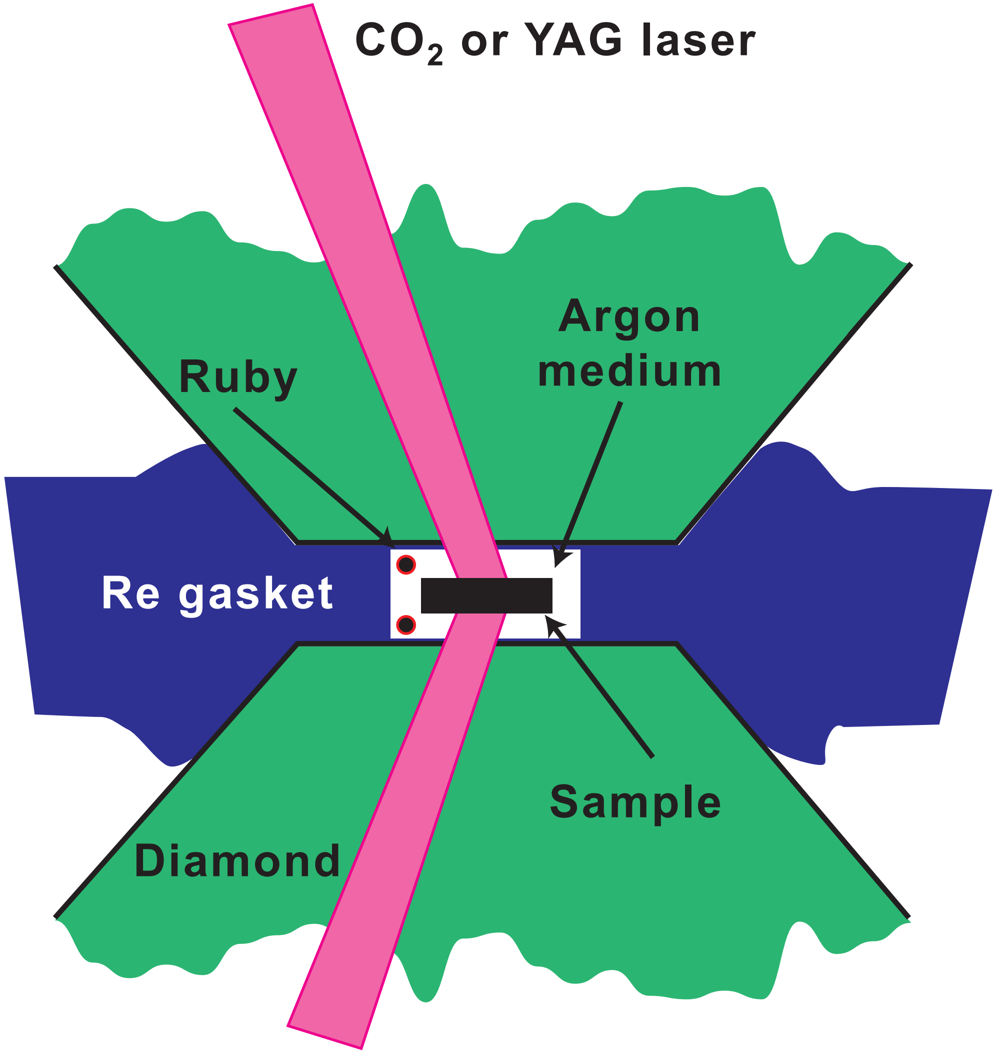
e.g. Rost et al., 2005

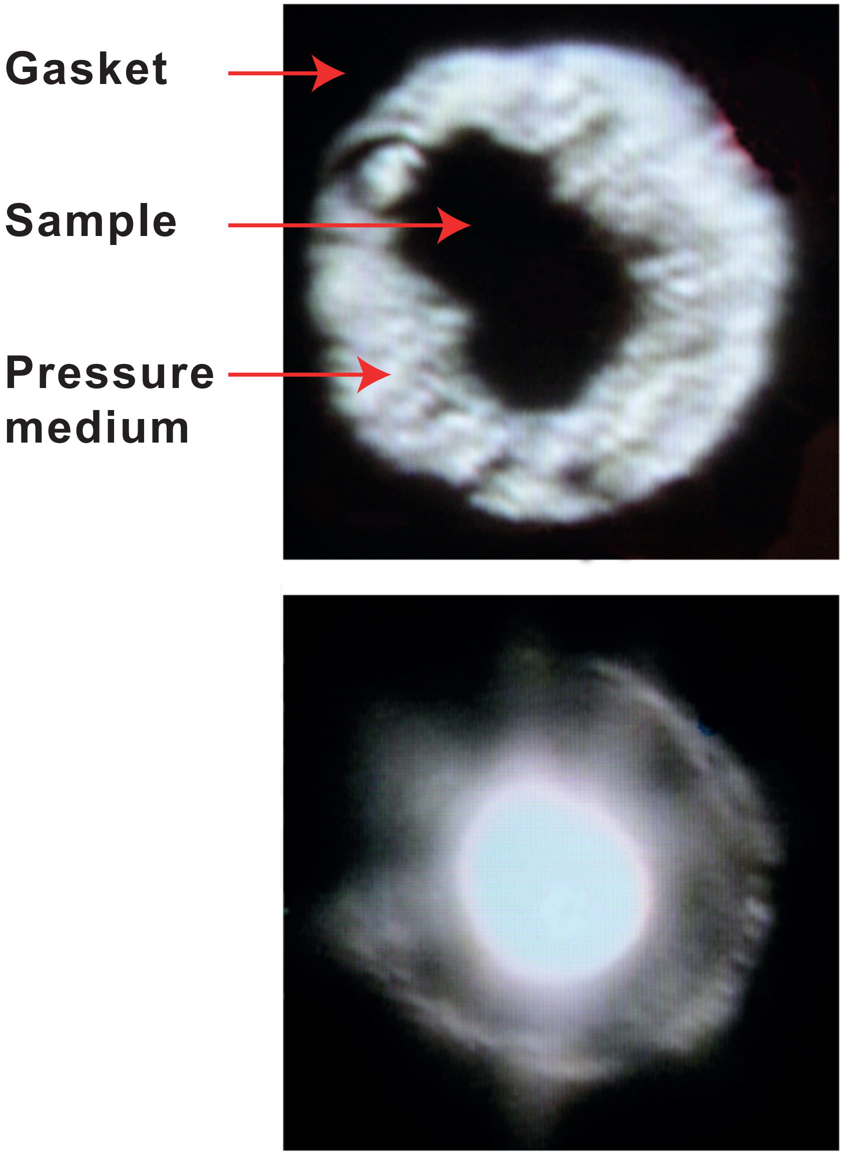
Melting of the subducted slabs

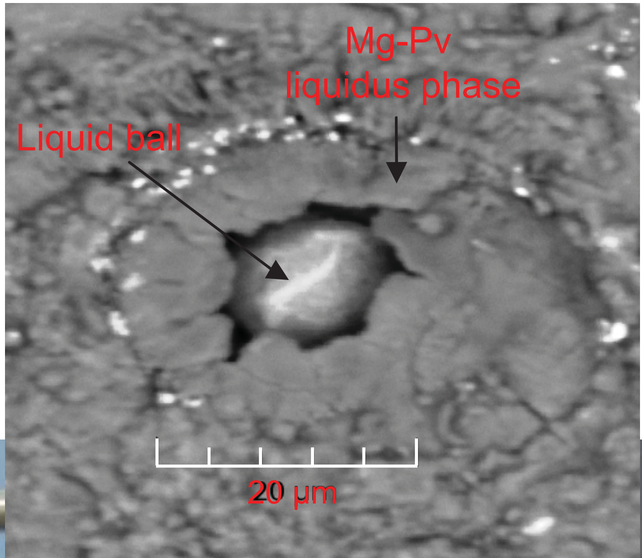
Andrault et al., 2014

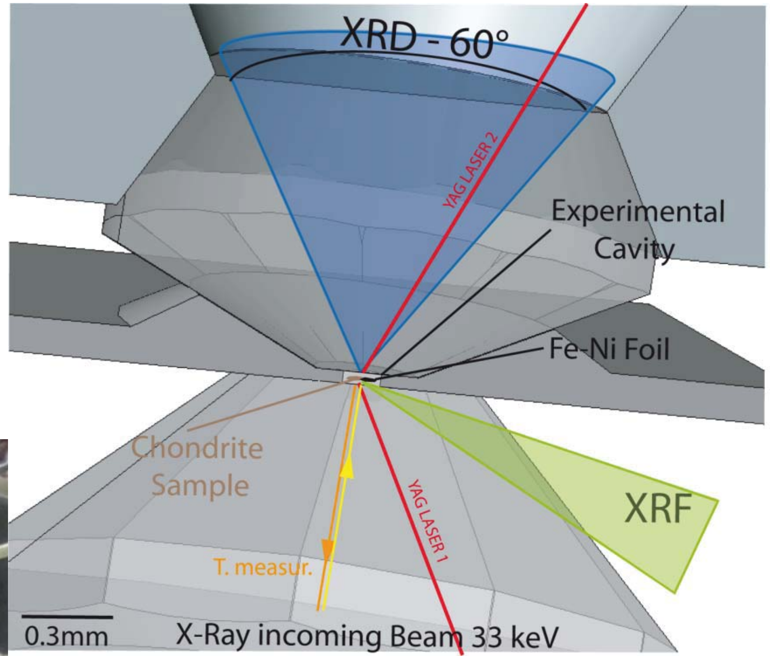


New melting curve determination using X-ray diffraction
=> using the diamond anvil cell



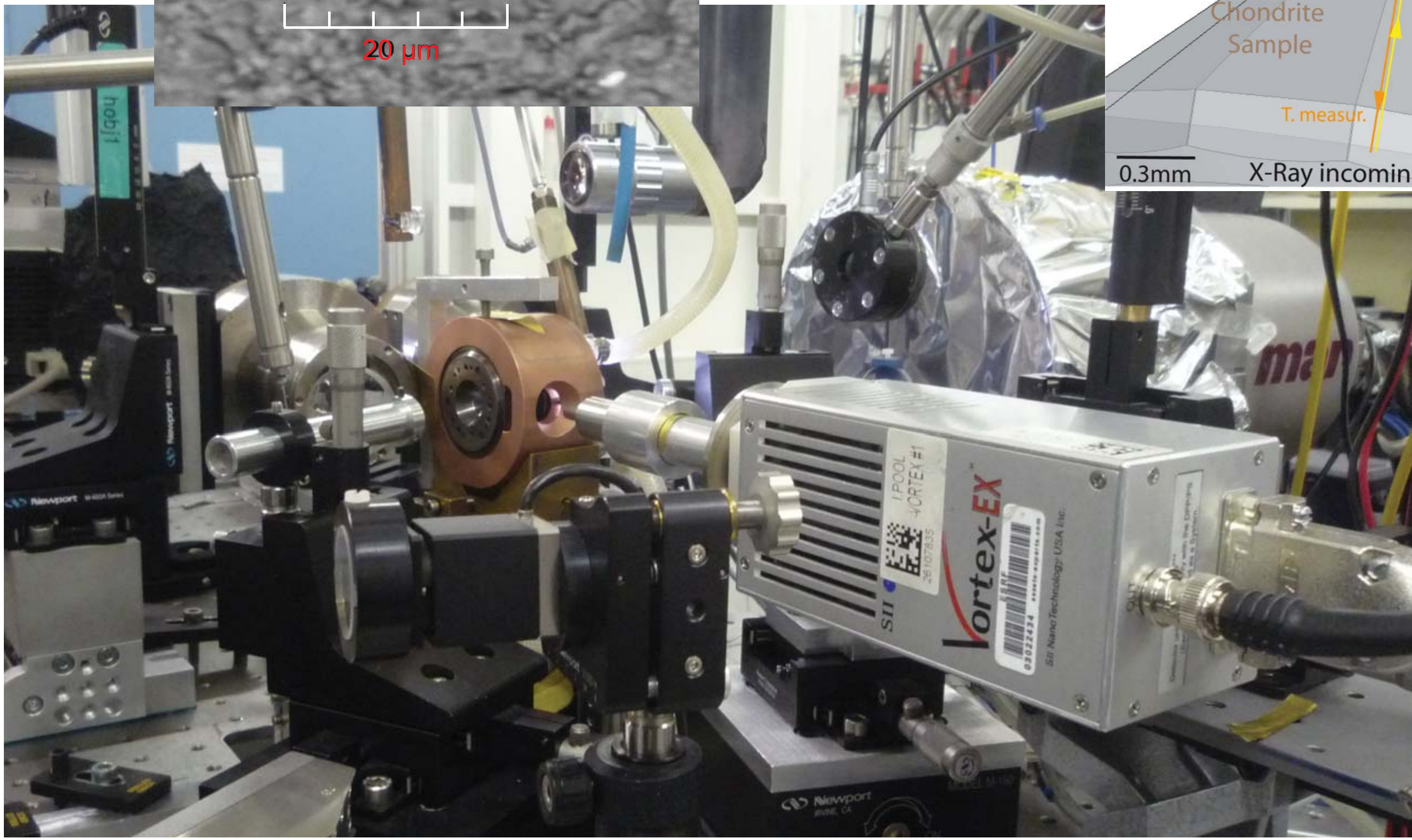






Special DAC design

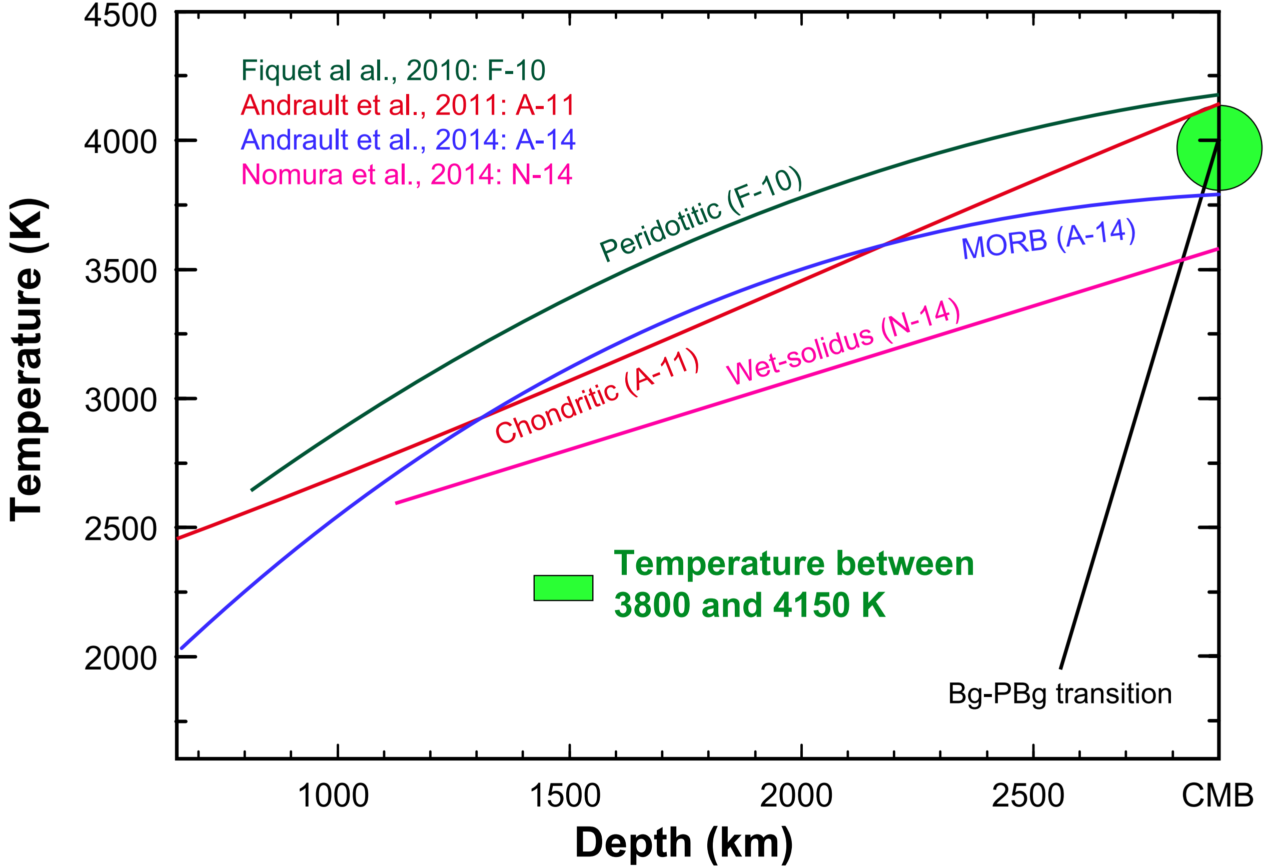
Petitgirard et al, RSI 2012



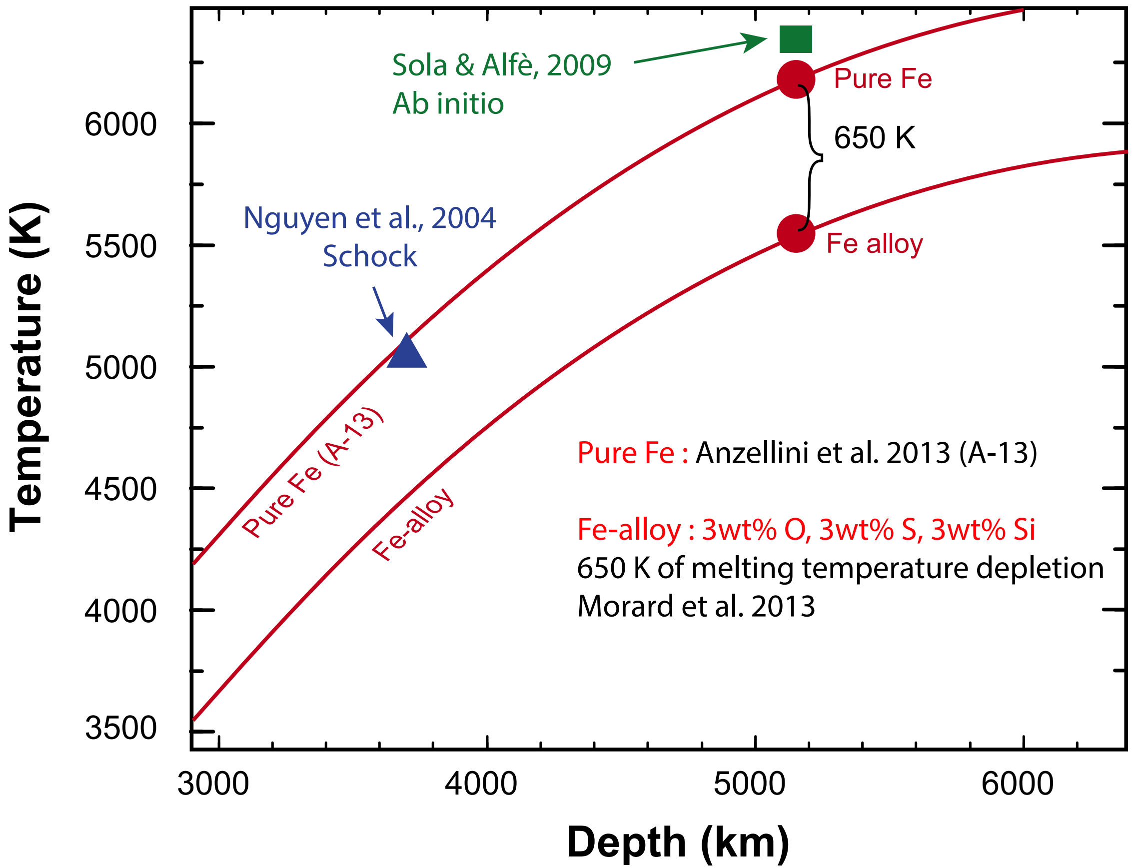
XRF Measurement
on ID27 (ESRF)

(Andrault et al., 2012)

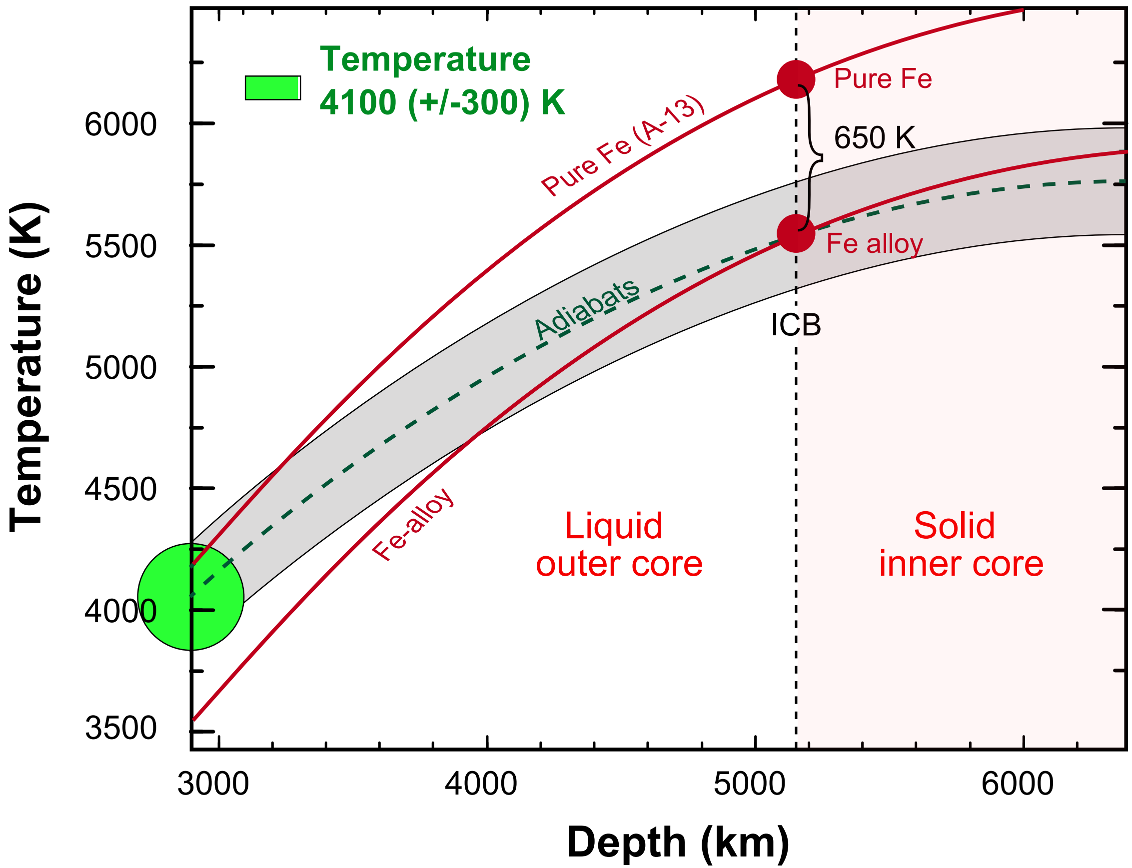
Melting curves (solidus) of various lower mantle materials



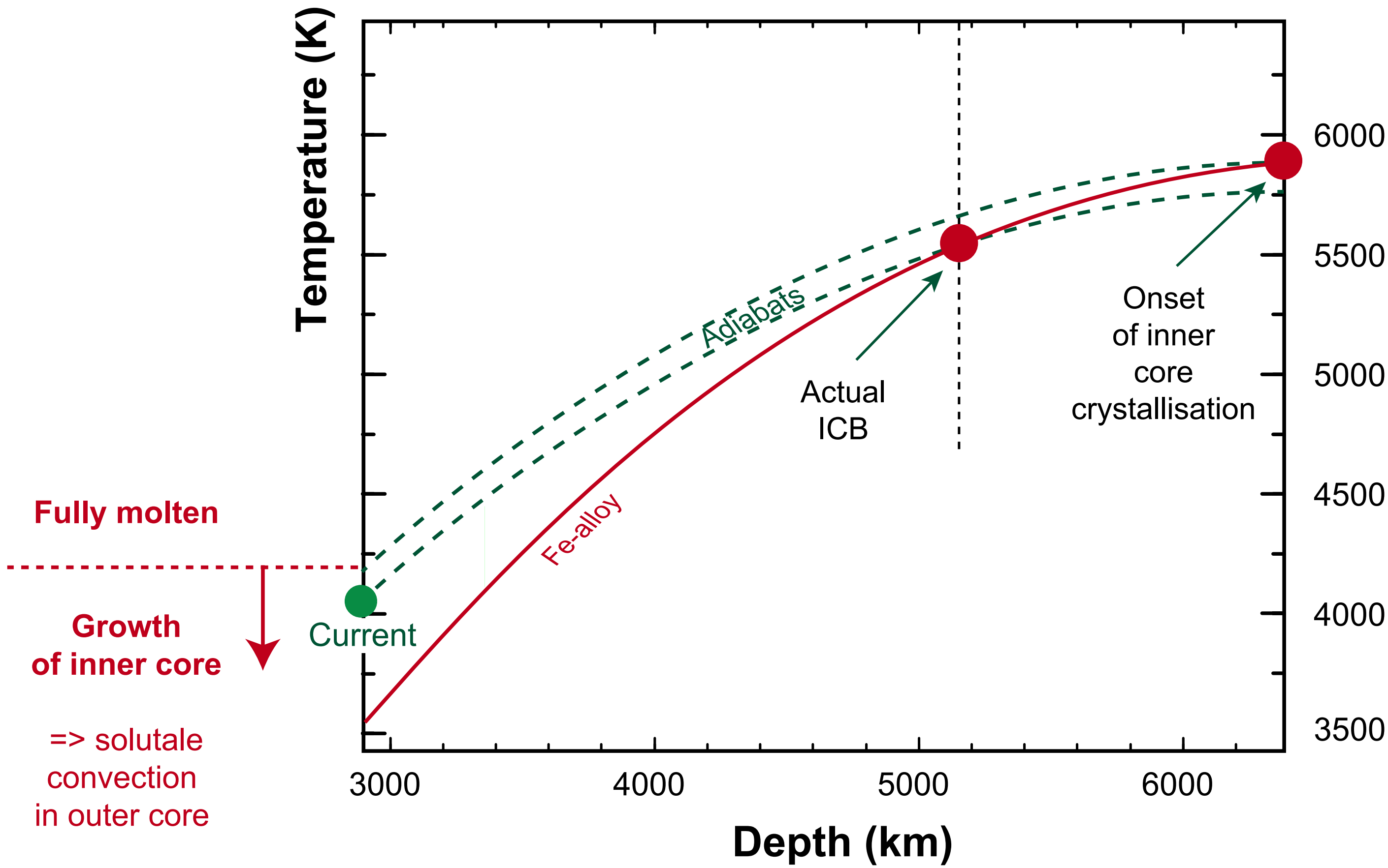
Melting curve of Fe and Fe-alloys



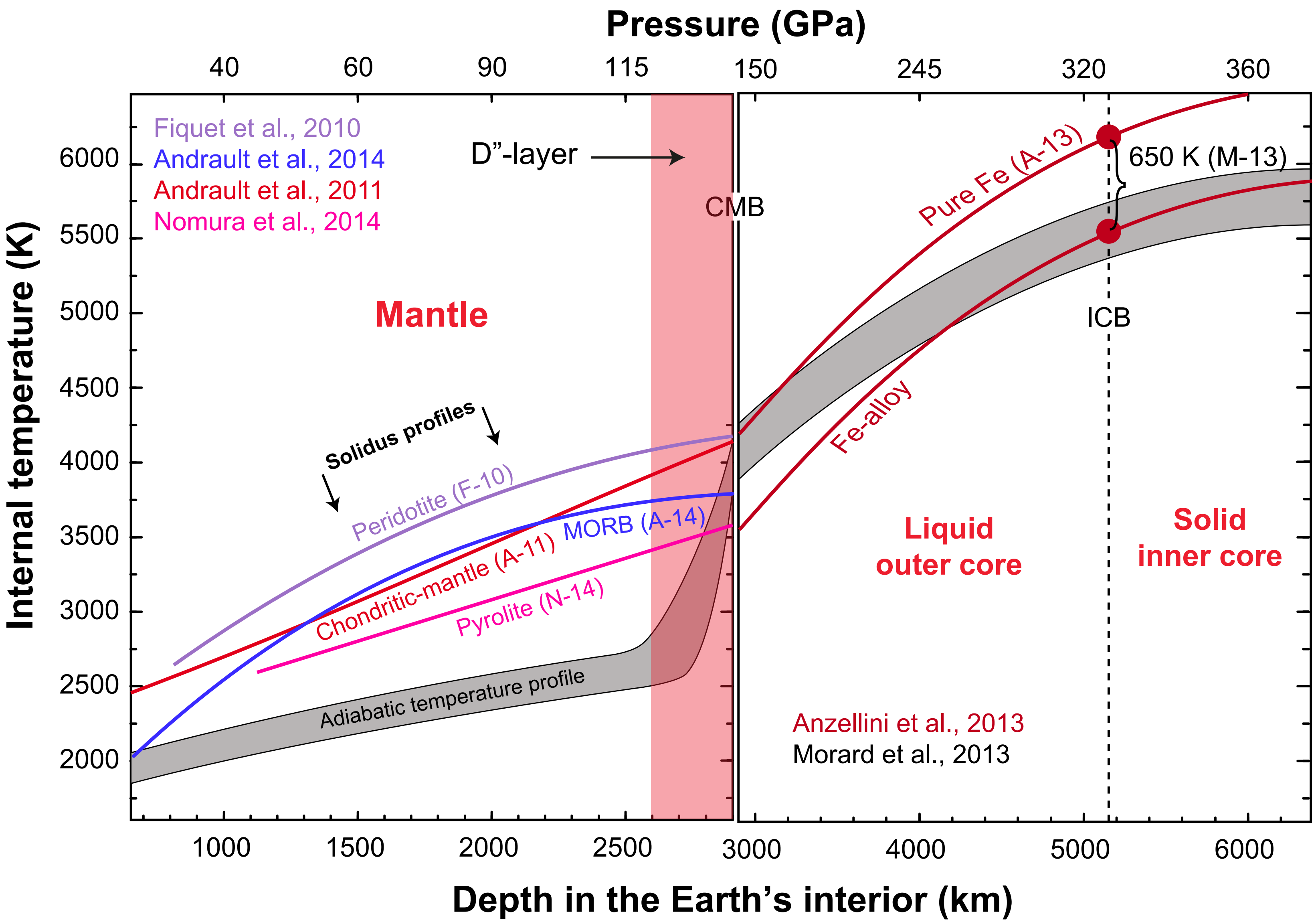
Temperature profile in the core



Behavior of the inner core upon fluctuation of the CMB temperature

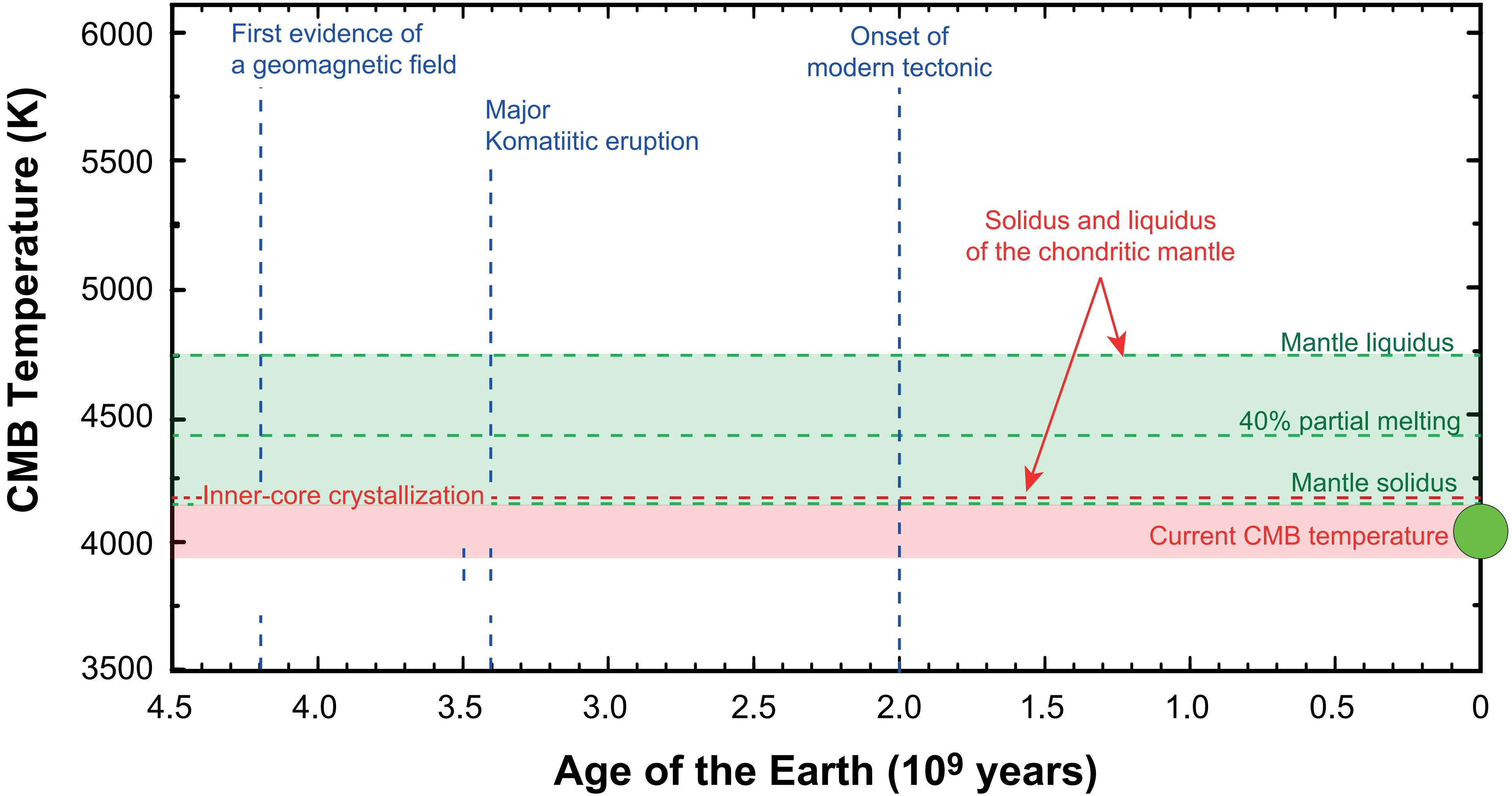


Current temperature profile in the deep Earth



The current temperature at the CMB is well constrained

Why does the CMB temperature is still ~at the mantle solidus after ~4.5 Gy ?
What has been its evolution along geological ages ?

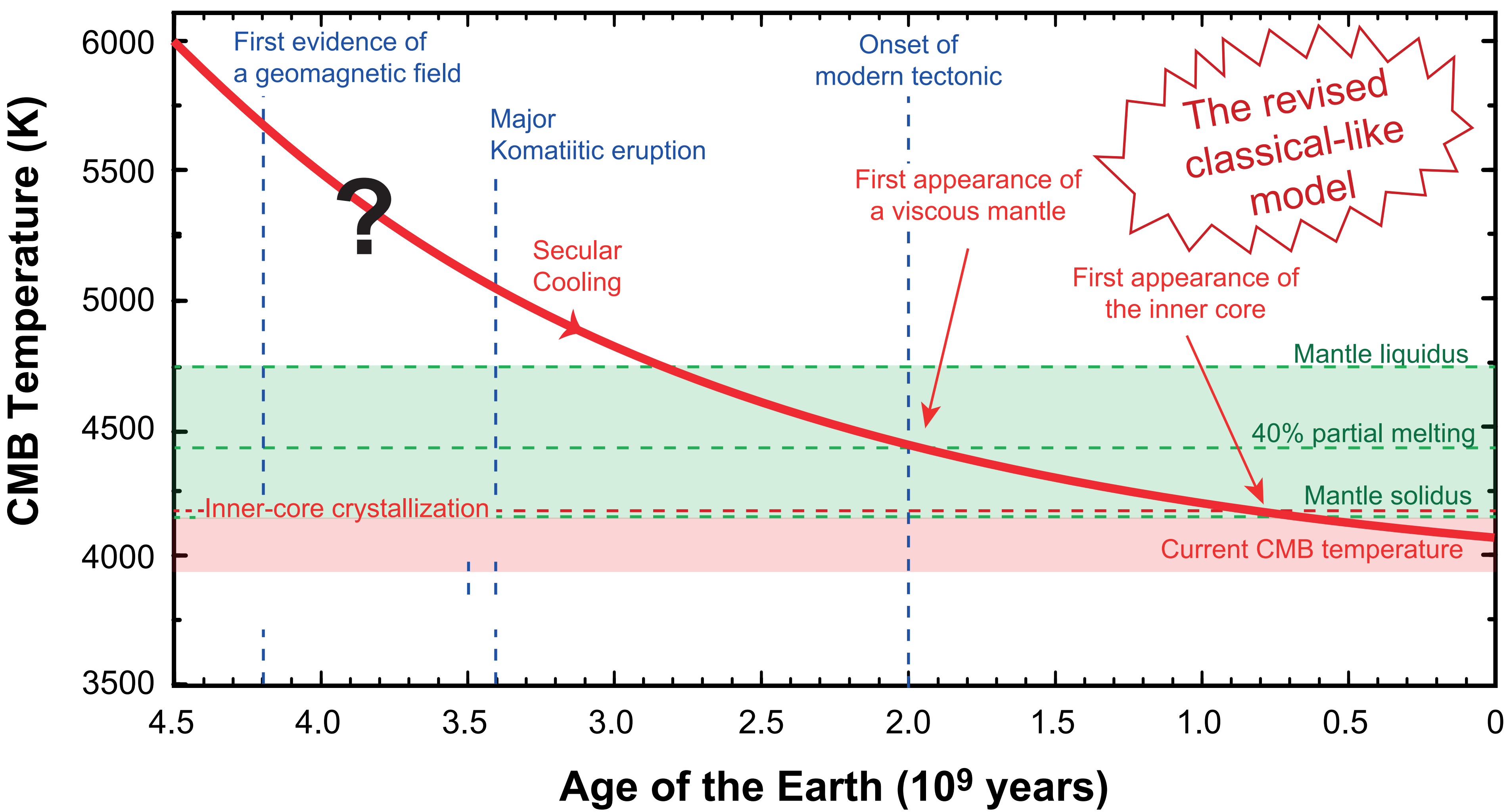


Secular cooling can produce thermal convection and core motions

It requires a CMB heat flux up to 10-15 TW

Which translates into an initial CMB temperature larger than 7000 K (Labrosse, 2015)

see also (Nakagawa & Tackley, 2005, 2010)



What was the early core temperature after the giant Moon-forming impact and the crystallization of the magma ocean ?

We modeled heat transfert in the primitive mantle

- Using a 1D model (i.e. lateraly averaged)
- Including the heat from the core

Heat transfer within a highly turbulent environment…

Heat conduction equation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla.(k\nabla T) + \rho H$$

$$k = k_c + k_v$$

$$k_v \propto (L, Ra^{\beta}, \Delta T)$$

$$Ra = \frac{\alpha g(r) C_p \rho^2 \Delta T L^3}{k_c \eta}$$

$$\eta = f(\phi)$$

$$\phi = \frac{T - T_{sol}}{T_{liq} - T_{sol}}$$

ρ = density
C_p=heat capacity
T=temperature
t=time
H=radiogenic heating

k=thermal conductivity
k_c=intrinsic conductivity
k_v=eddy conductivity

L=magma ocean thickness
Ra=Rayleigh number
β =turbulence power
$\Delta T = T - T_{ad}$

α = thermal expansioncoeff.
g=gravity
η =dynamic viscosity

ϕ =melt fraction

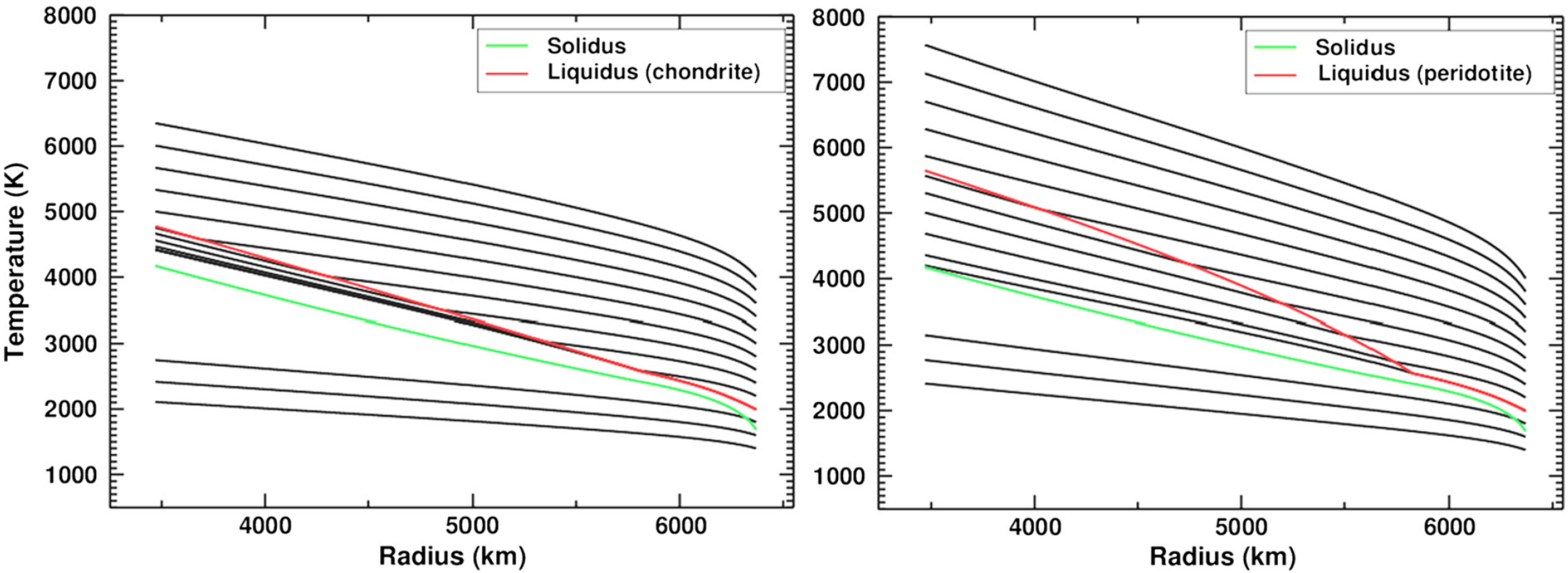
T_{sol}=solidus temperature
T_{liq}=liquidus temperature

Set of input parameters

Variable and non-dimensional parameter values for numerical models.

Melt density	ρ_m	A-model: 2684–5274 $kg\,m^{-3}$ F-model: 2679 – 5378 $kg\,m^{-3}$	Computed from Thomas and Asimow (2013)
Heat capacity	C_p	A-model: 1742 $J\,kg^{-1}\,K^{-1}$ F-model: 1800 $J\,kg^{-1}\,K^{-1}$	Computed from Thomas and Asimow (2013)
Thermal expansion coefficient	α	A-model: 1.3×10^{-5}–7.9×10^{-5} K^{-1} F-model: 2×10^{-5}–9.6×10^{-5} K^{-1}	Computed from Thomas and Asimow (2013)
Viscosity of solid phase	η_s		From Eq. (8) with $\eta_{s,0}$ = 256 Pa s and B = 25.17
Viscosity of the magma ocean	η	1–10^{21} Pa s	From Eq. (7)
Total conductivity	k	5–10^{7} $W\,m^{-1}\,K^{-1}$	$= k_c + k_v$
Rayleigh number	Ra	at t = 0: 1×10^{27}–3×10^{27}	Computed from Eq. (3)
Prandtl number	Pr	350–3.6×10^{24}	$= C_p\eta/k_c$
Reynolds number	Re	at t = 0: Re ~ 10^{9}	From Solomatov (2007)

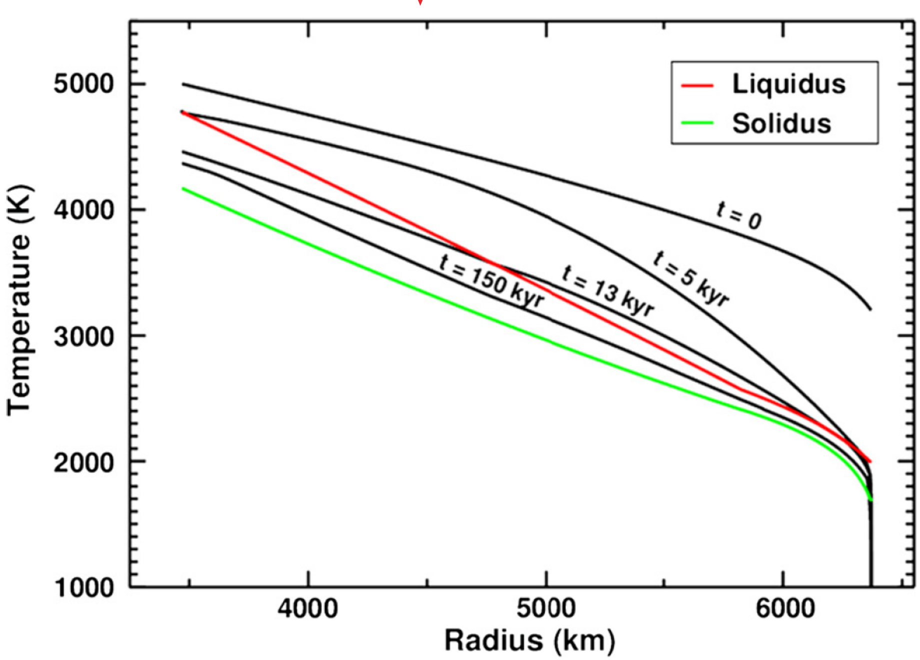
Computed adiabatic gradients compared with solidus and liquidus profiles



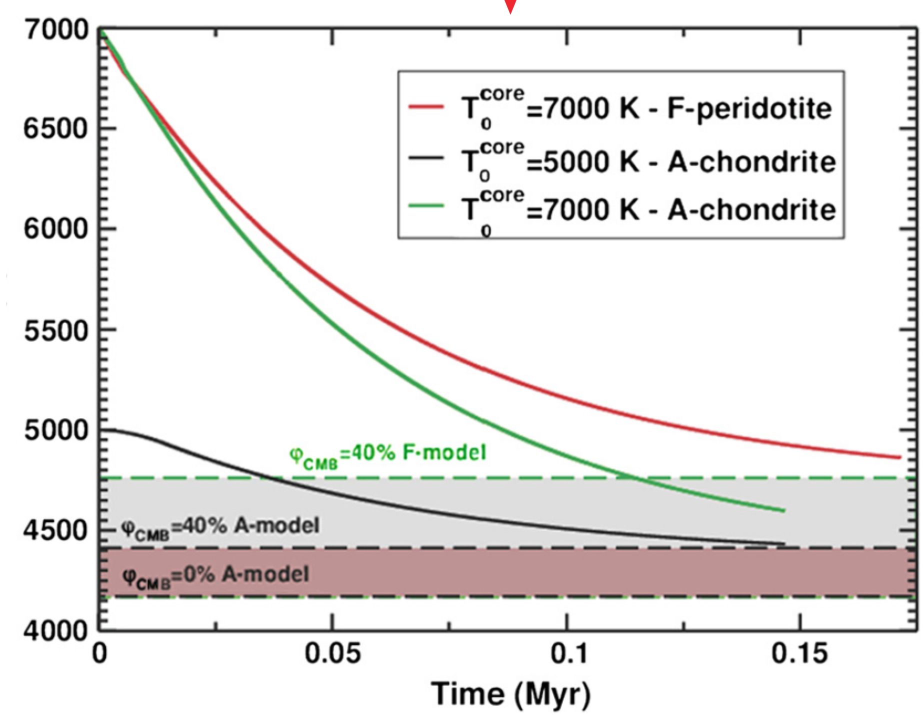
Rate of cooling after the Moon-forming impact

Rate of mantle cooling depends firstly on the viscosity of the magma ocean (through k_V)

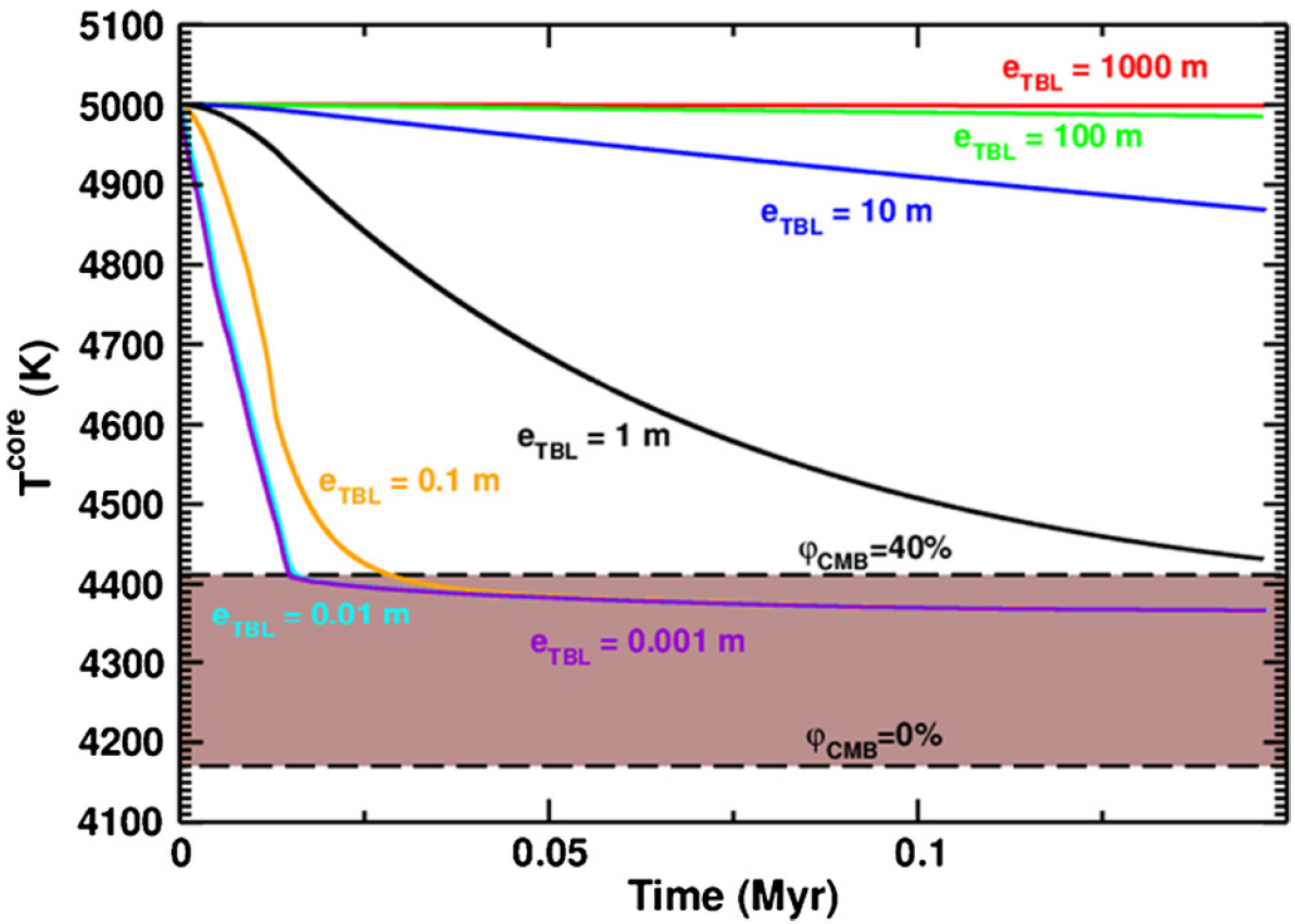
Temperature profile in the magma ocean



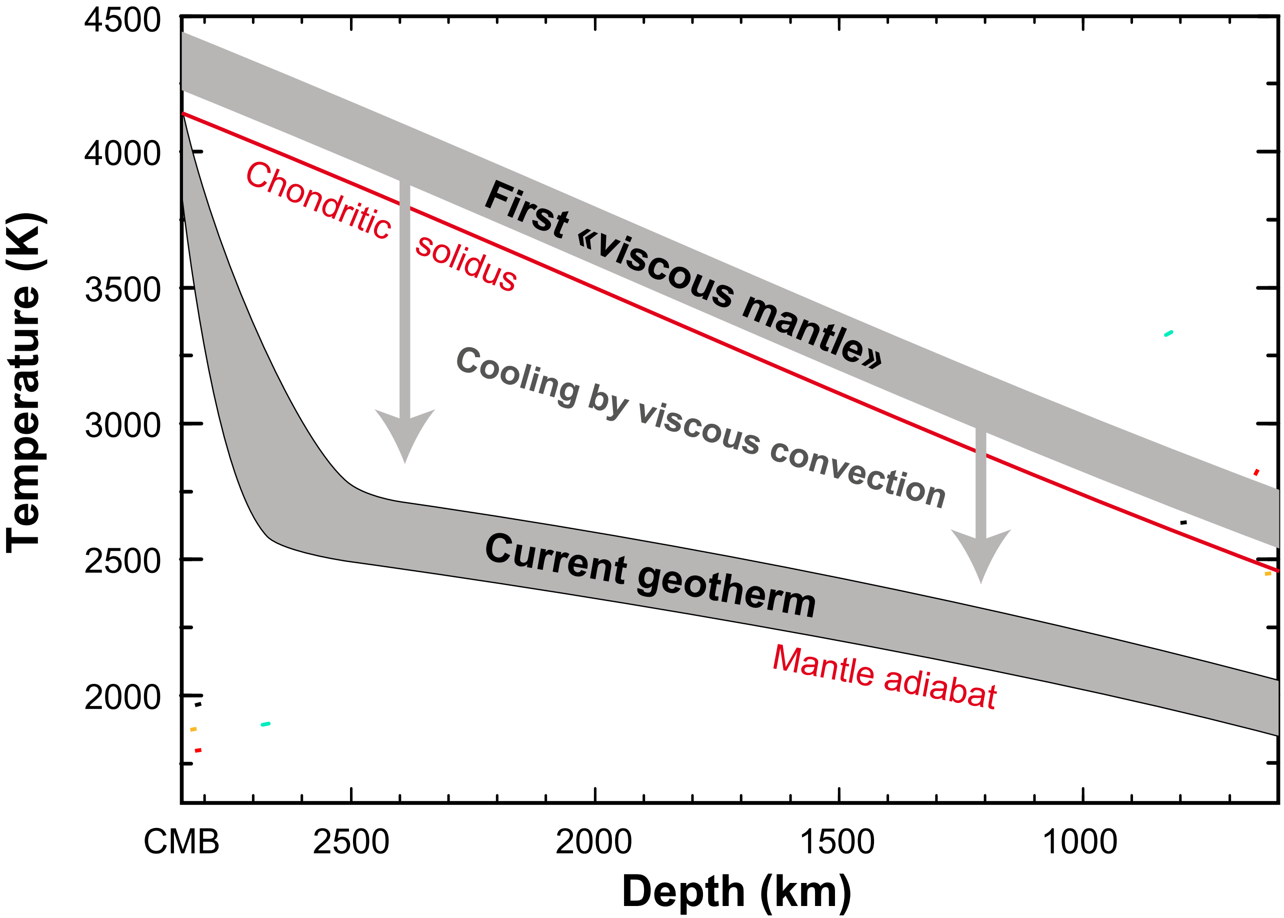
Core temperature as a function of time



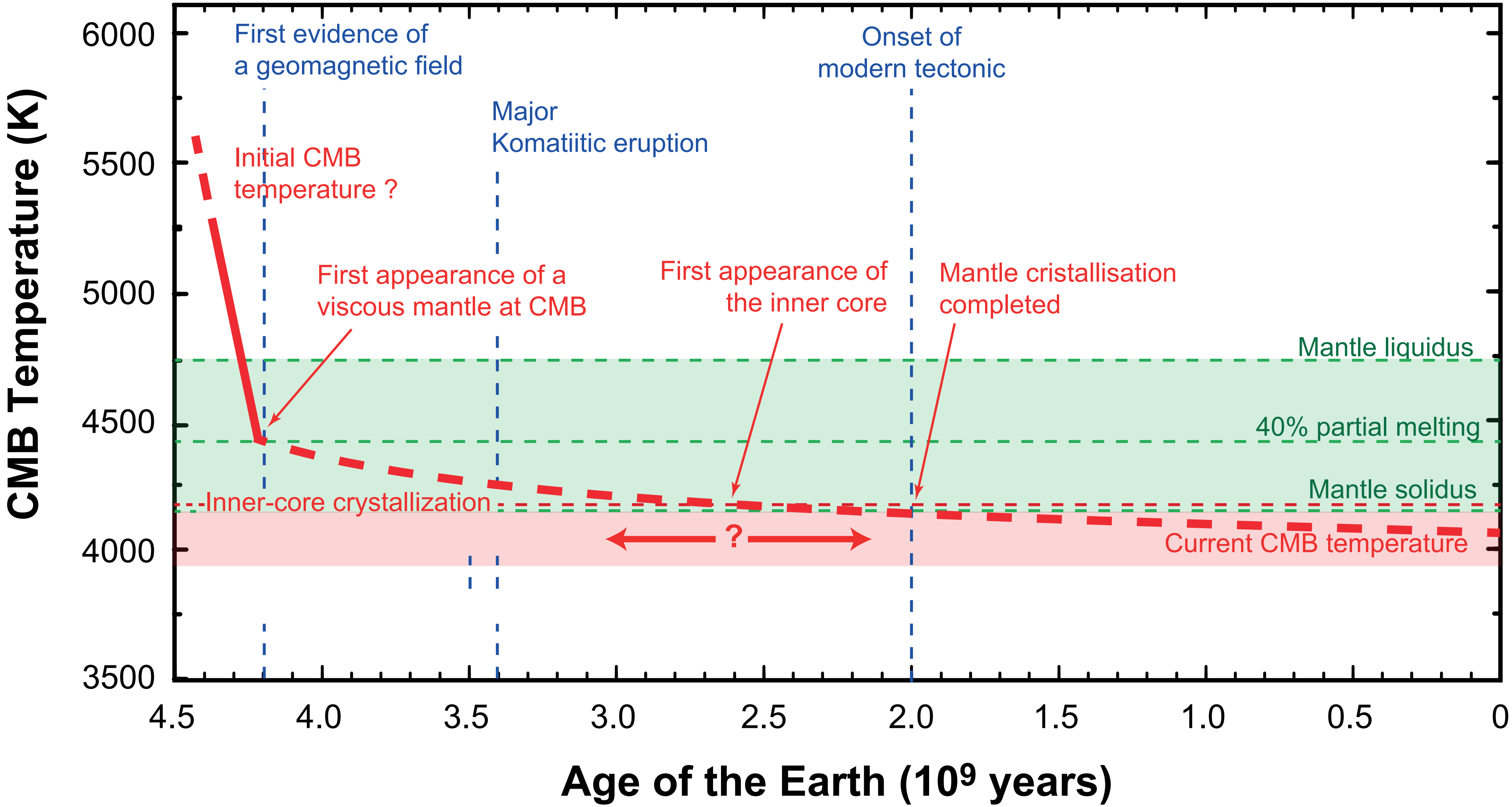
The rate of core cooling depends firstly on the thickness of the thermal boundary layer (e_{TBL}) located in the mantle, just above the core.



Settling of a stable mantle geotherm



“Rapid” cooling of the core until the lowermost mantle became viscous



What is the energy source to maintain the Geodynamo ?

Three possible mechanisms to produce motions in the core:

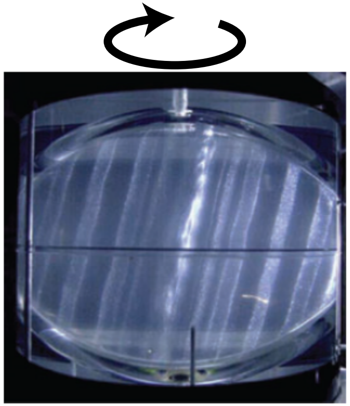
- **Thermal convection**
  Requires a heat flux of 5 to 15 TW out of the core
  High thermal conductivity of the liquid Fe-alloy support high thermal flux
  Not enough cooling

- **Solutale convection**
  Produced by growth of an inner core relatively depleted in light elements
  or by a flux of atoms at the core-mantle boundary
  Can contribute, but cannot do the job alone

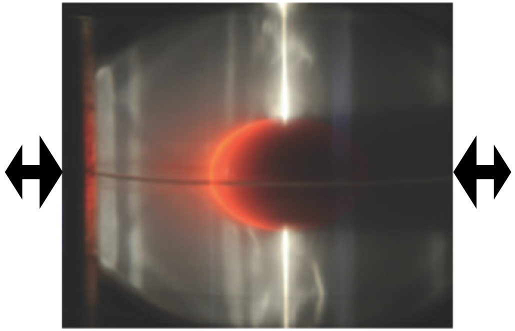
- **Mechanical forcing**
  Precession and tides at the CMB stir the outer core

This mechanism is required to explain:
- Early **Moon** and **Mars** magnetic fields
- Current magnetic field on **Ganymede**

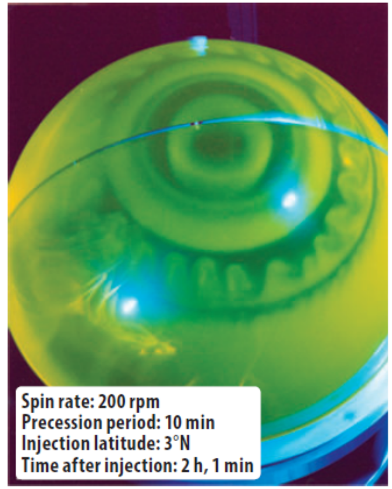
What is it ?
Does it brings enough energy ?



Precession (Noir, 2000)



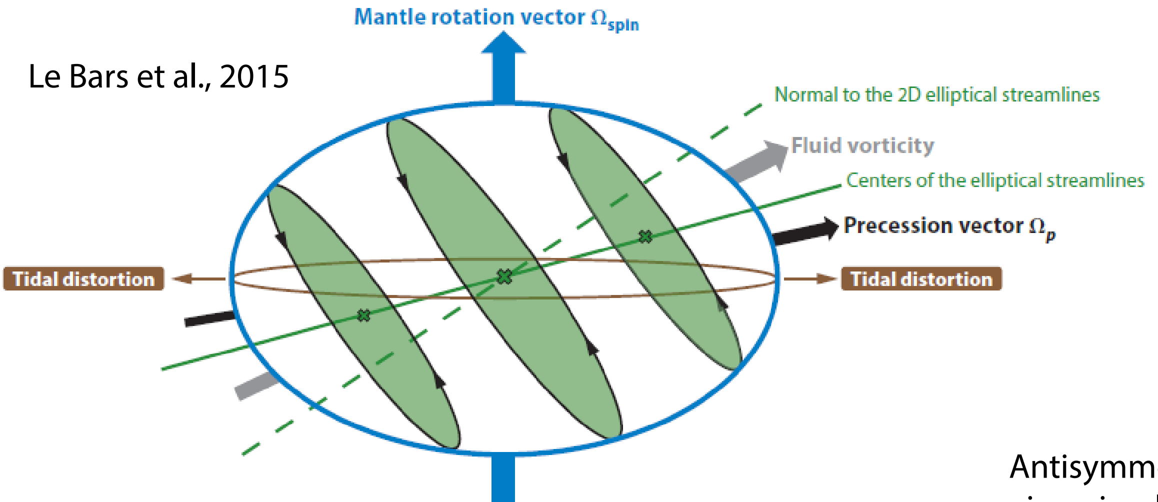
Tides (Sauret, 2013)

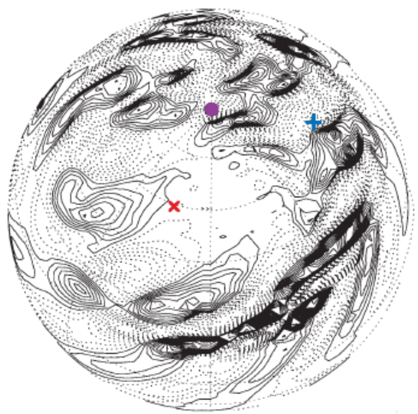


Fluid injection during precession (Vanyo, 2004)

Outer-core flows driven by mechanical forcings

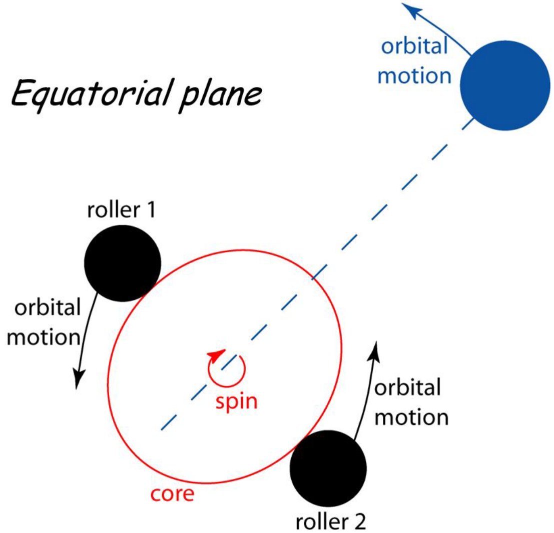
Le Bars et al., 2015





Antisymmetric component of radial velocity in a simulation (Lorenzani & Tilgner, 2001)

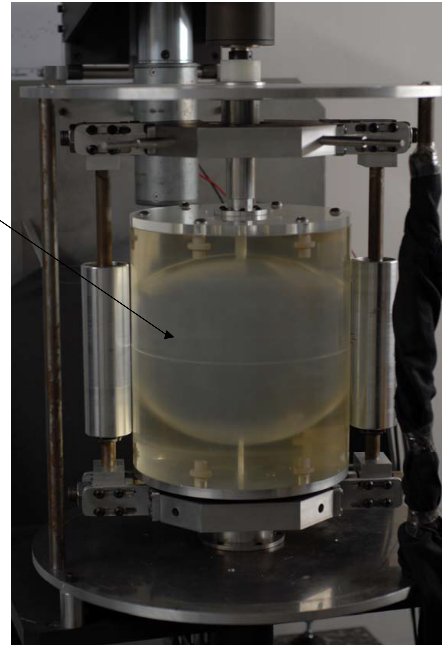
Role of tidal distorsion
Experimental set-up at IRPHE

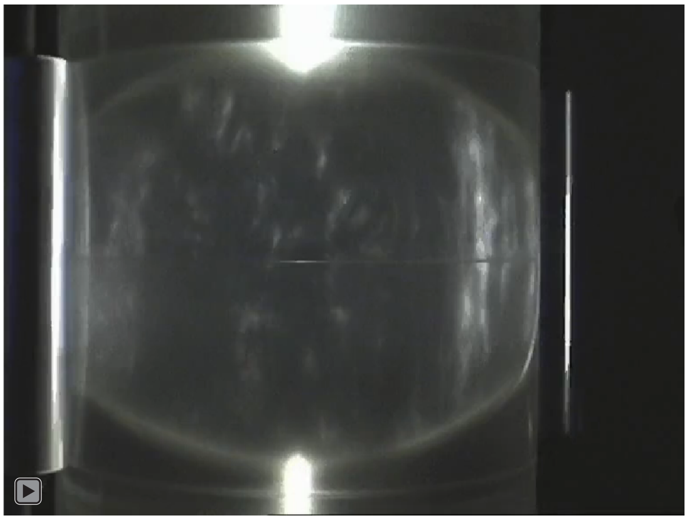


Working fluid = water

R=10cm

Rotation up
to +/-160rpm



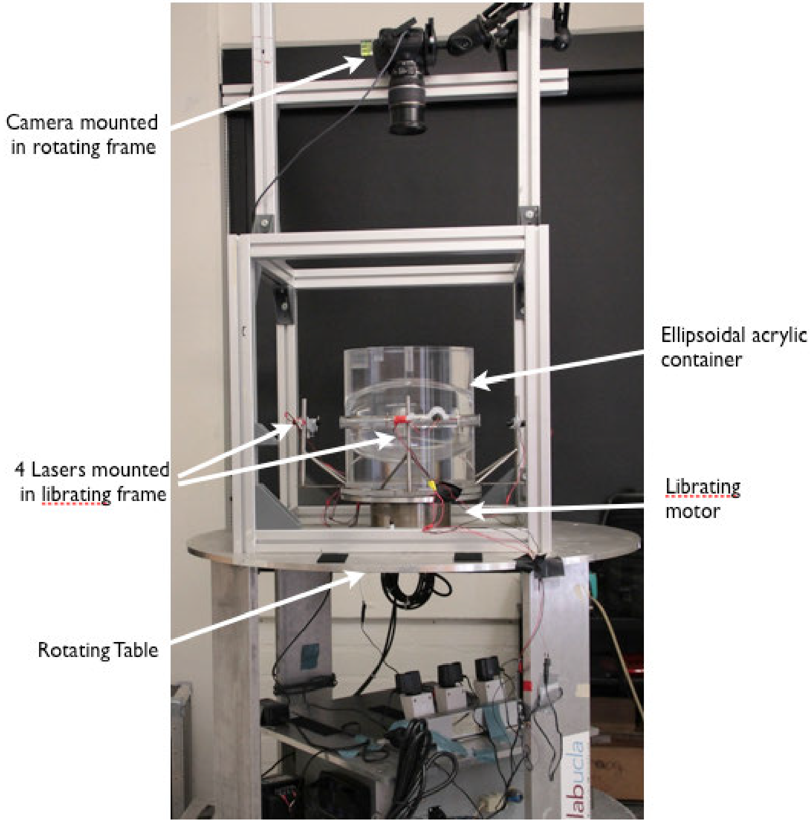


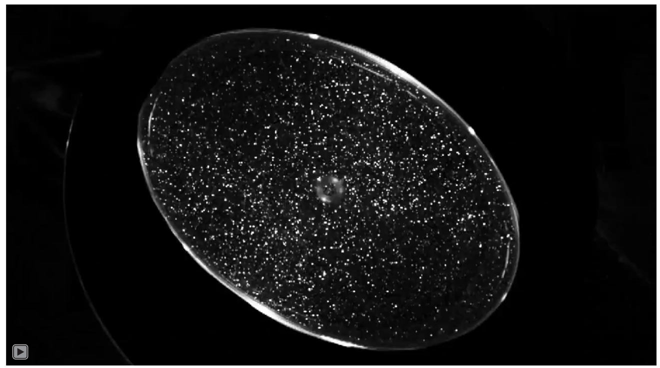
Sauret et al., 2014

3 dimensionless parameters

β= tidal bulge/radius = 0.09
Ω_{orbit}= orbital/spin rares = -0.053
E= Ekman number = 9.5 10^{-6}

Role of libration
Experimental set-up at spinlabucla





Grannan et al., 2014

Energy Budget: Running the Geodynamo by Mechanical forcings

3.7 TW is continuously injected into the Earthfrom Earth-Moon-Sun orbital system (Wunsch and Ferrari, 2004):

- 0.2 TW dissipated into Earth's atmosphere and mantle
- 1 TW is lost to the deep ocean
- Up to 2 TW additional tidal dissipation in shallow seas (Ferrari, 2015).

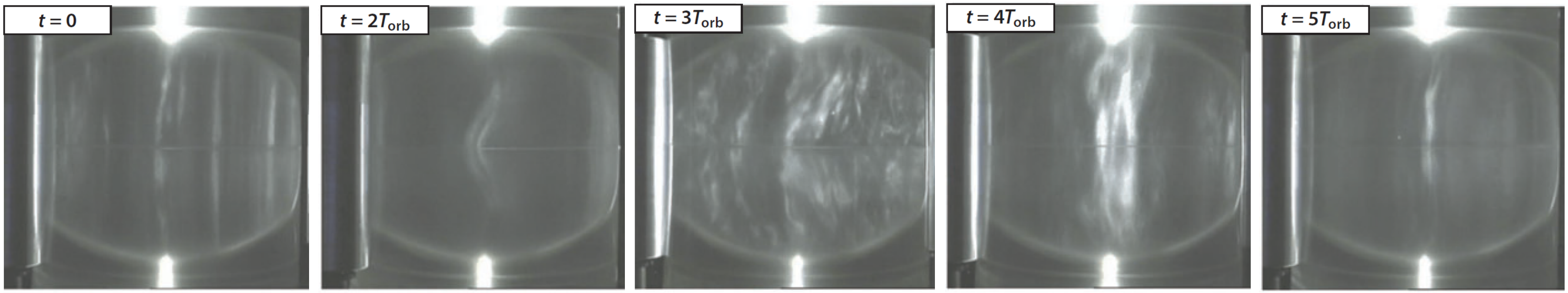
=> Hence, 0.5 to 1 TW, or even more (!) could be used to produce motions in the outer core

From 0.1 to 2 TW is required to induce a geodynamo in outer core (e.g. (Christensen and Tilgner, 2004)). This is related the amount of motion required in the outer core

Note : Significantly more energy was injected into the Earth in the past.

Mechanical forcing produces Instablities and turbulences

Time evolution during tidal distortion (Le bars et al., 2010)



Time evolution of the mean kinetic energy

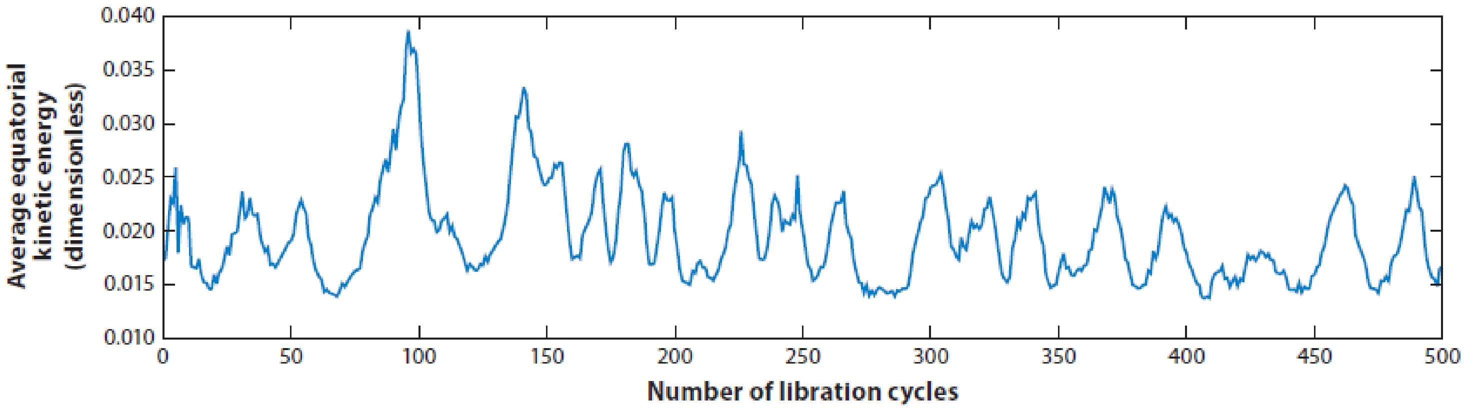
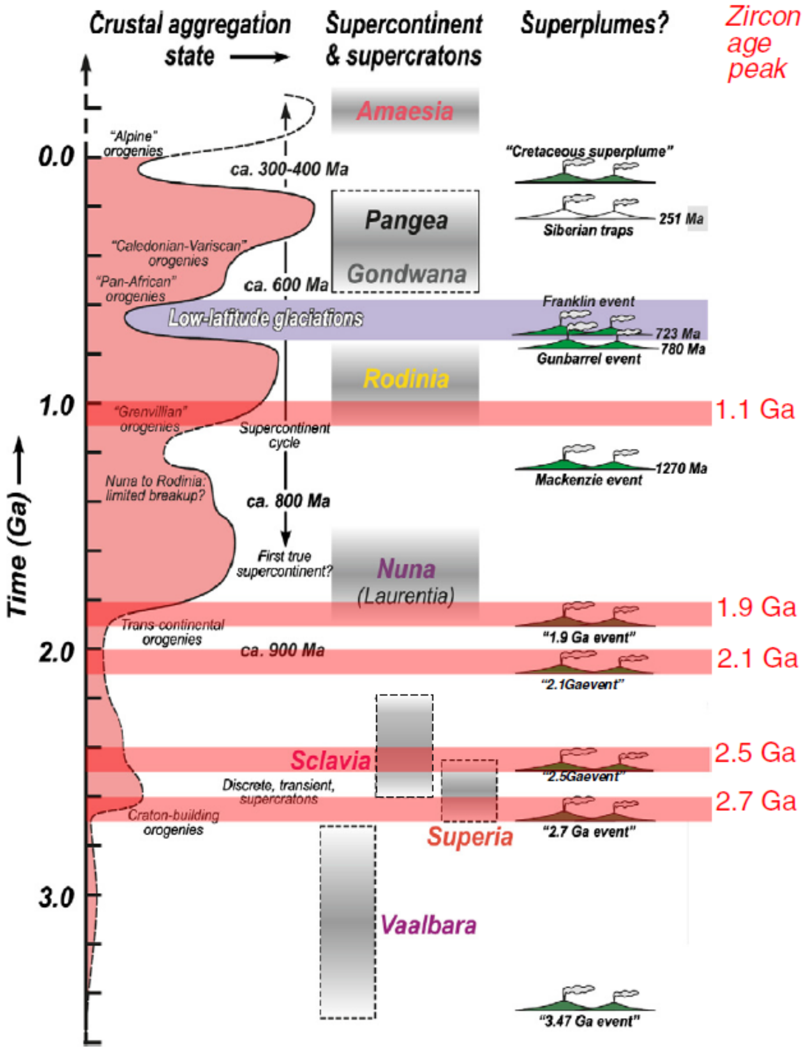
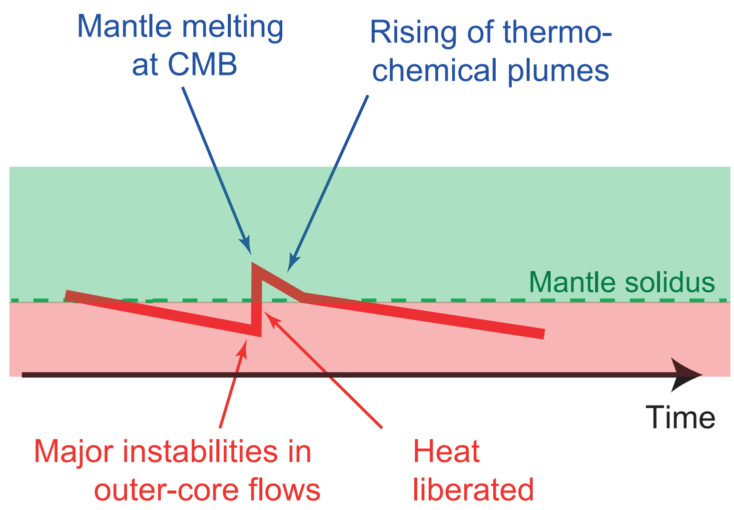


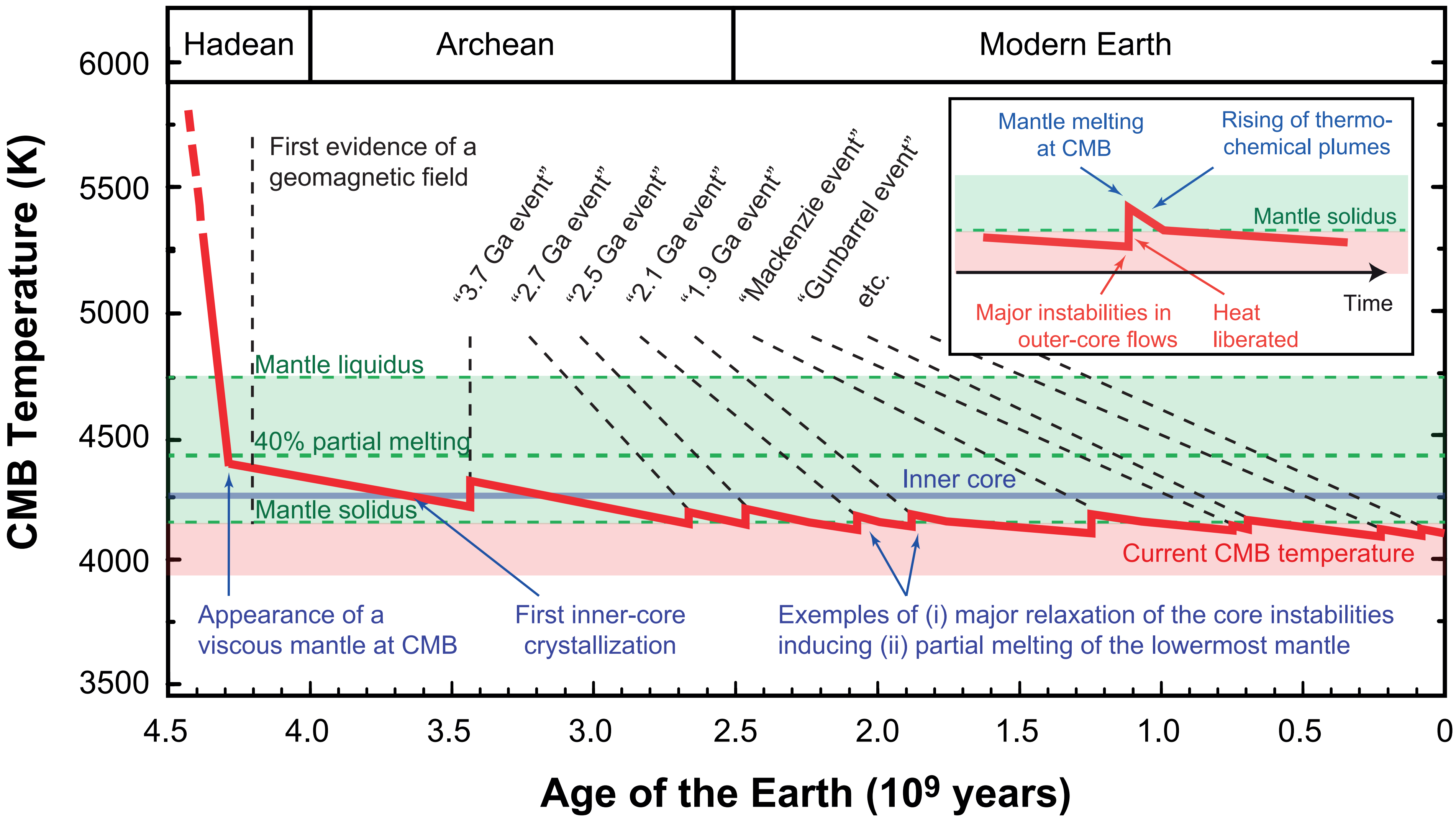
Figure courtesy of A. Grannan, SpinLab, UCLA

Ernst and Bleeker (2010)
Arndt and Davaille (2013)
Martin et al. (2014)



Speculative implications...




Hadean
Archean
Modern Earth
CMB Temperature (K)
6000
5500
5000
4500
4000
3500
First evidence of a geomagnetic field
"3.7 Ga event"
"2.7 Ga event"
"2.5 Ga event"
"2.1 Ga event"
"1.9 Ga event"
"Mackenzie event"
"Gunbarrel event"
etc.
Mantle melting at CMB
Rising of thermo-chemical plumes
Mantle solidus
Major instabilities in outer-core flows
Heat liberated
Time
Mantle liquidus
40% partial melting
Inner core
Mantle solidus
Current CMB temperature
Appearance of a viscous mantle at CMB
First inner-core crystallization
Exemples of (i) major relaxation of the core instabilities inducing (ii) partial melting of the lowermost mantle
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
Age of the Earth (10⁹ years)

SUMMARY:

The magma ocean solidification is achieved in 100-200 ky (viscous mantle at all depths)
After this delay, the maximum possible core temperature at CMB is ~4450K

Today, the core temperature at CMB is 4000-4150 K
Core cooling in ~4.4 Gy is insufficient to maintain geodynamo by thermal convection

Mechanical forcings may be a major ingredient to maintain the geodynamo
They are associated with secular changes of astronomical parameters in the Earth-Moon-Sun system

Even if (i) thermal convection and (ii) solutale convection still contribute today (?), the Geodynamo would have stopped earlier in absence of a Moon.

Searching for life on extrasolar planets ?
Favor planets with a satellite !

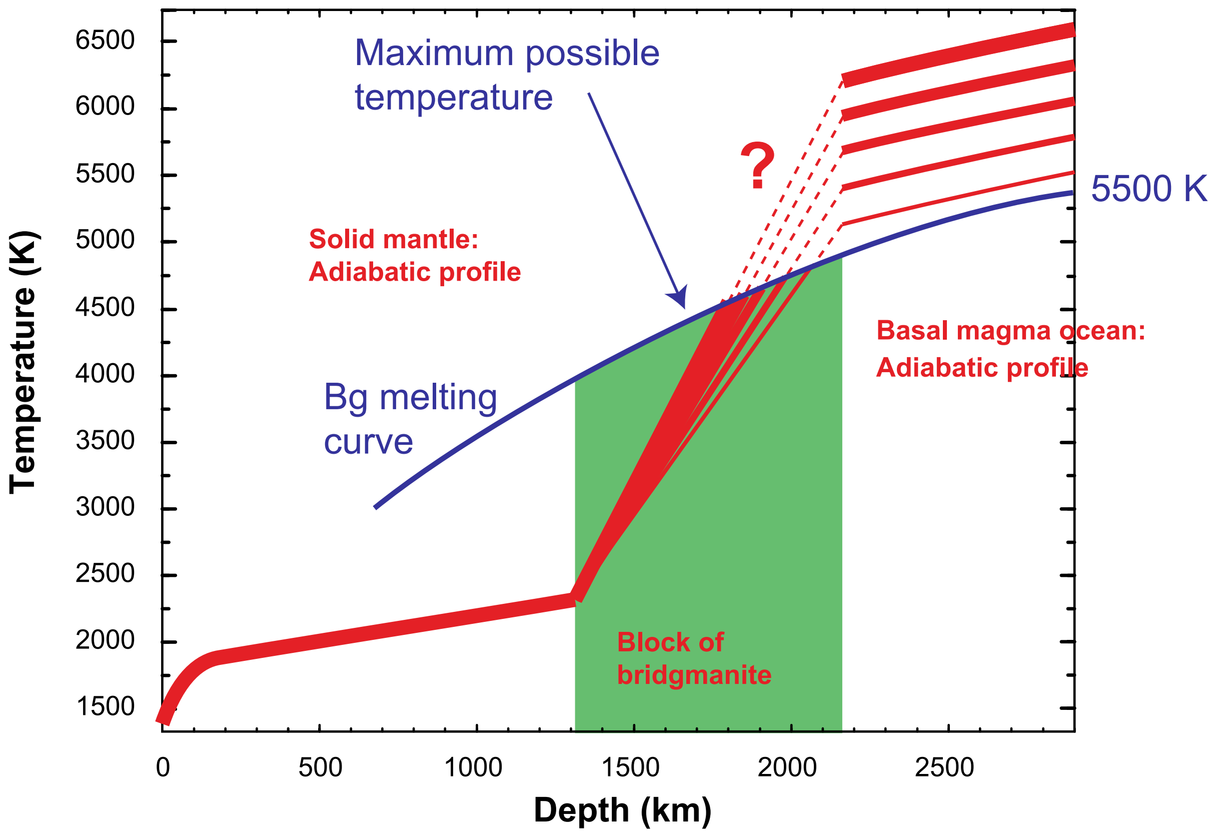
Already ~50 years ago...

W.V.R. Malkus, Science, 1968

Precession of the Earth as the Cause of Geomagnetism

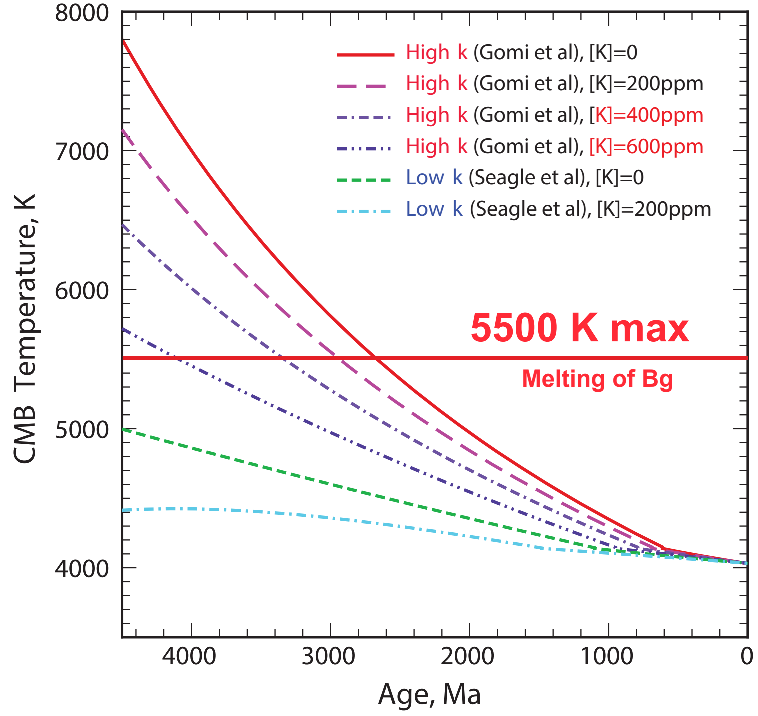
Experiments lend support to the proposal that precessional torques drive the earth's dynamo.

Presence of a thick refractory layer of bridgmanite at the center of the lower mantle ?

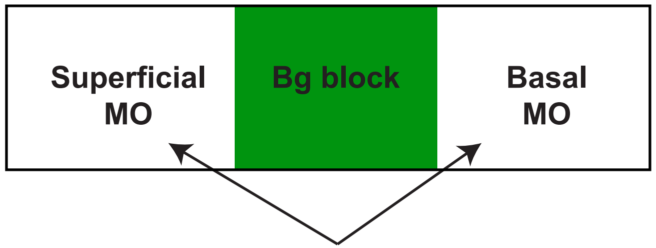


Implication: The core temperature after the Moon-Forming impact cannot be higher than ~5500 K

Labrosse, 2015



What if chemical segregation occurs?
Then, there would be reaction where Bg and the MOs are in contact !



The MOs should be enriched in incompatible elements