Institut des Sciences de la Terre

# La graine, Terra Incognita?

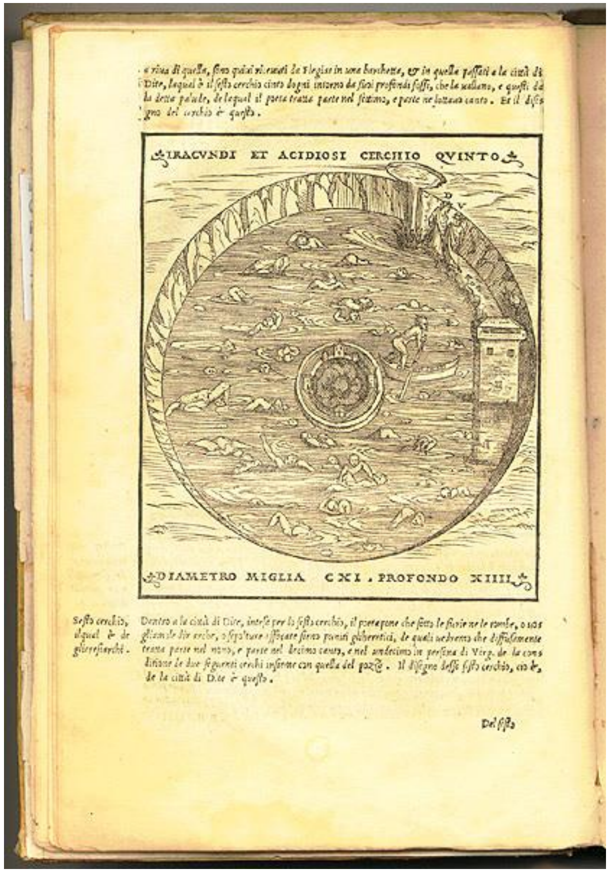
**L'impossible voyage au centre de la Terre ?**
**Reconstituer et enseigner l'inaccessible intérieur de la Terre.**


Philippe Cardin
Institut des Sciences de la Terre
Grenoble, France

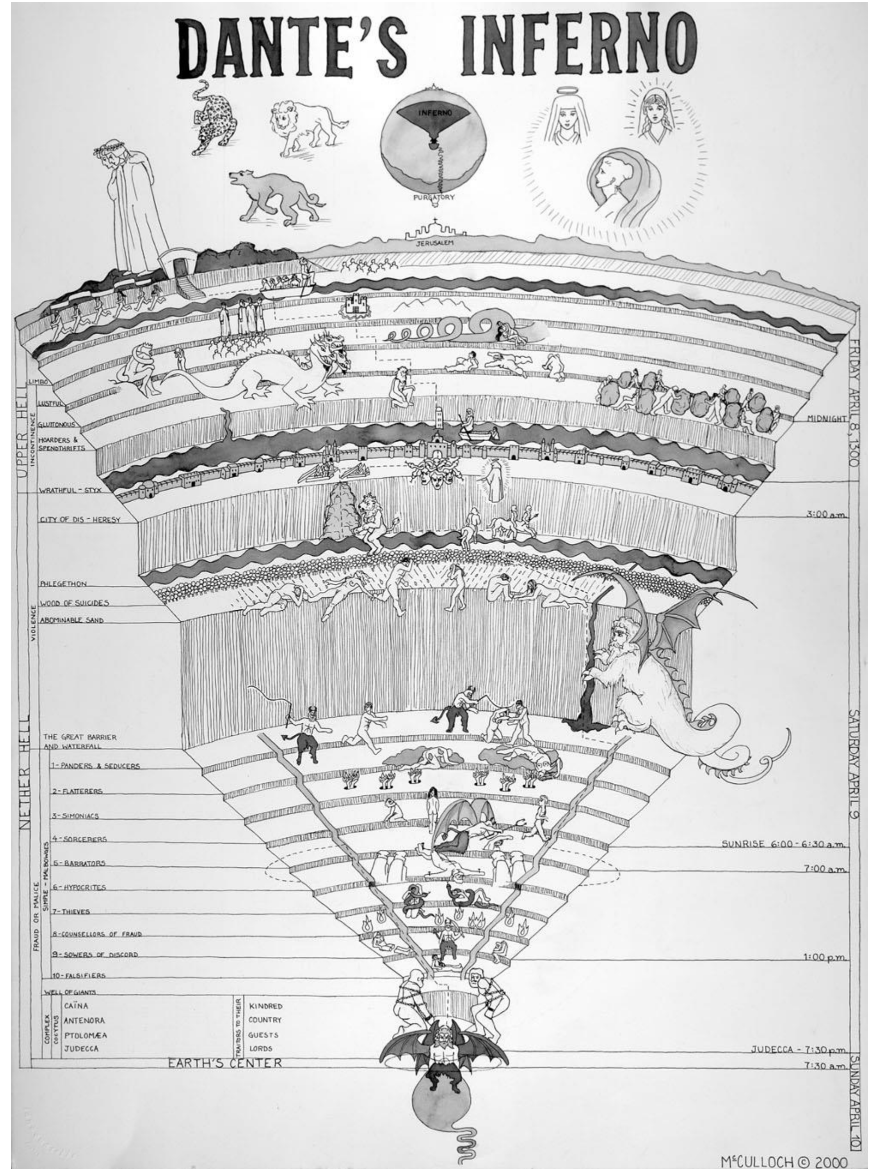

OSUG
Observatoire des Sciences de l'Univers de Grenoble

# Plan

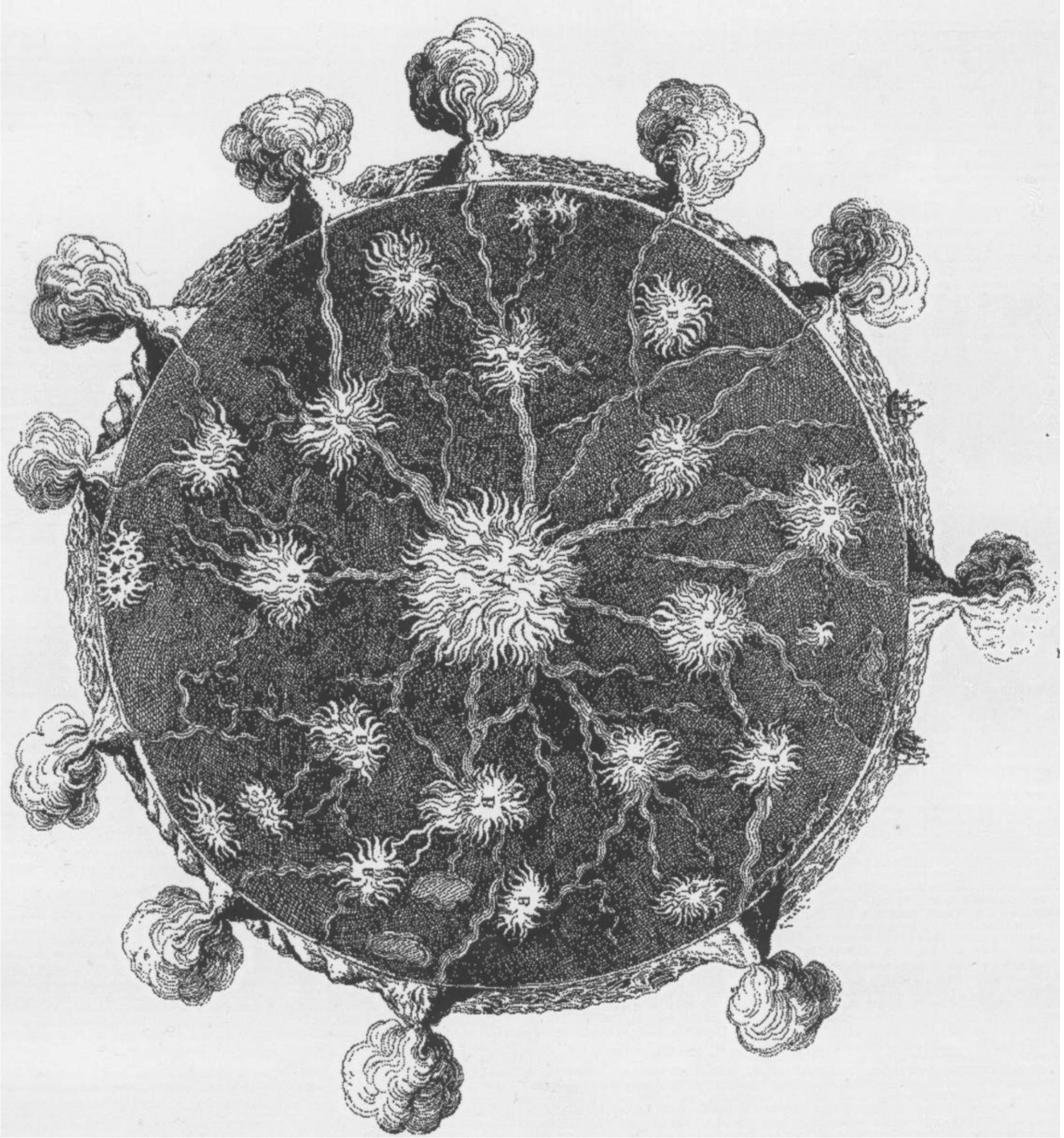
# L’intérieur de la Terre (1315)




Vellutello, 1544



# Le feu central

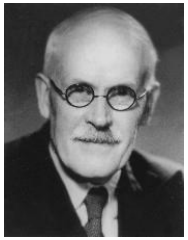


Kircher, 1678

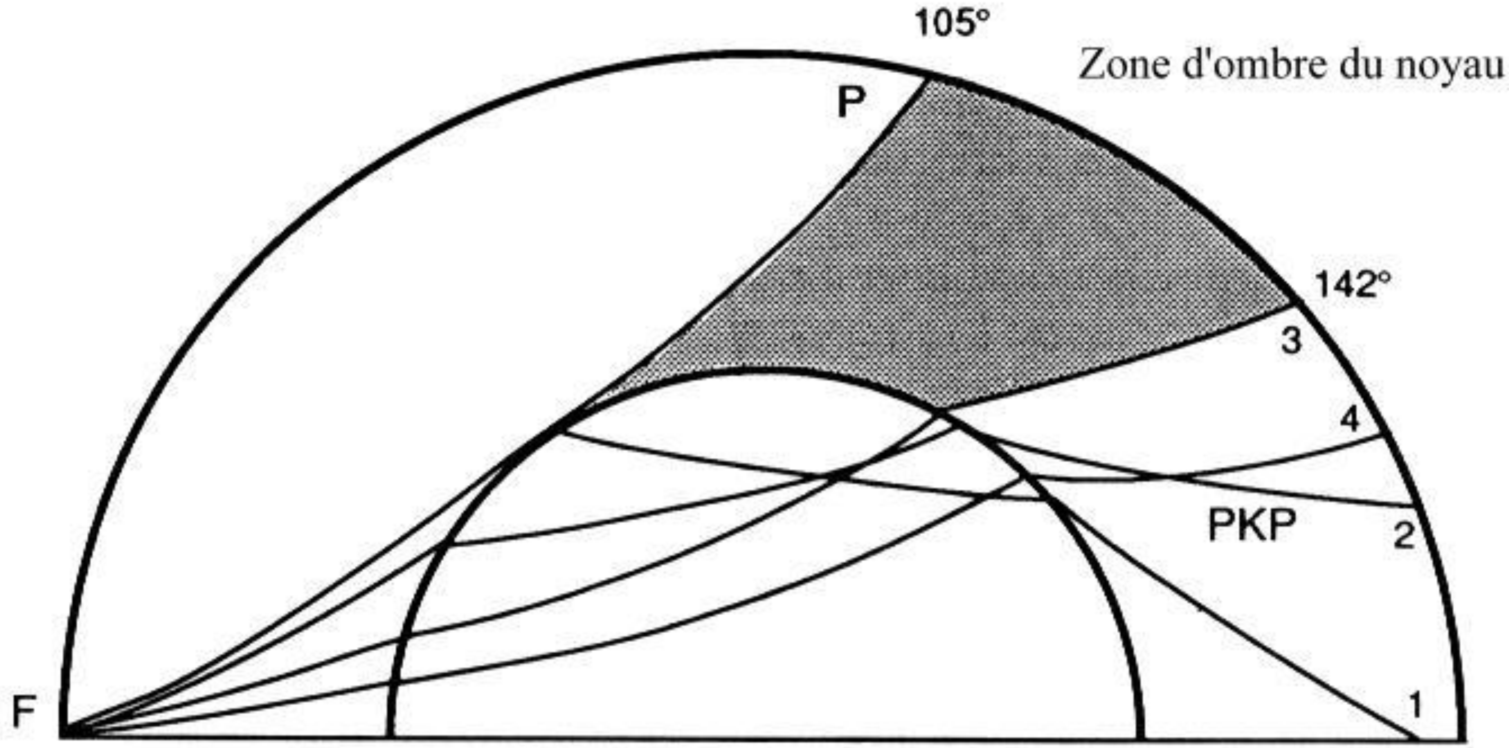
# Le noyau de la Terre

Oldham 1906


Gutemberg,1914



Jeffreys1926



# La découverte de la Graine – Inge Lehmann

(1888-1993)

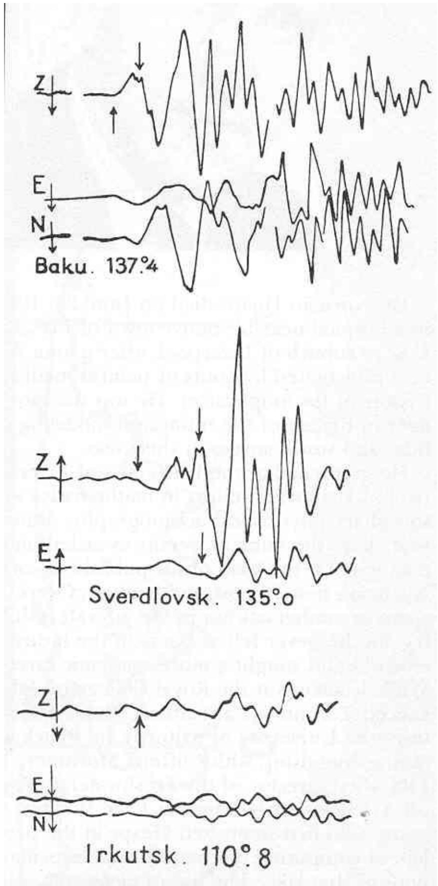



*Fig. 5.* Seismograms of the New Zealand earthquake of June 16, 1929, showing that the unexplained phases are well recorded on the vertical component [*Lehmann*, 1936].

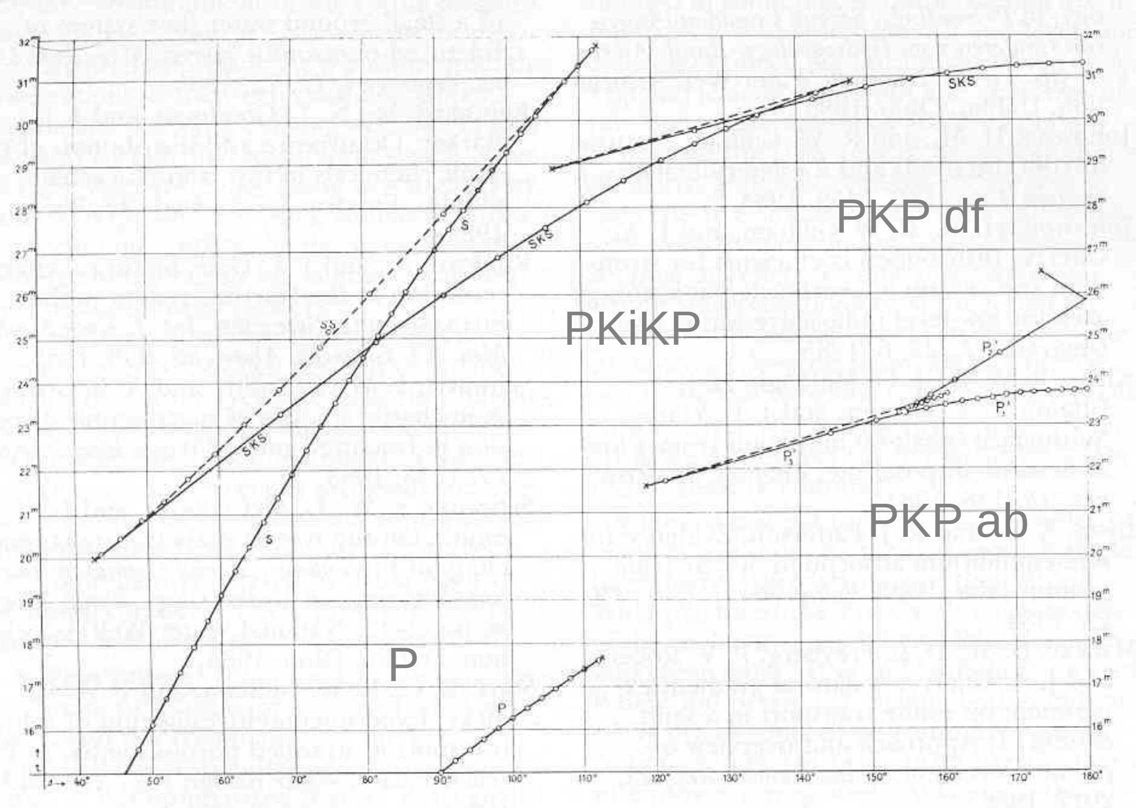



*Fig. 7.* Travel times for the earth model of Figure 6. The branch labeled $P_3'$ (now *PKIKP*) explains the phases in Figure 5 [*Lehmann*, 1936].

# La découverte de la Graine – Inge Lehmann

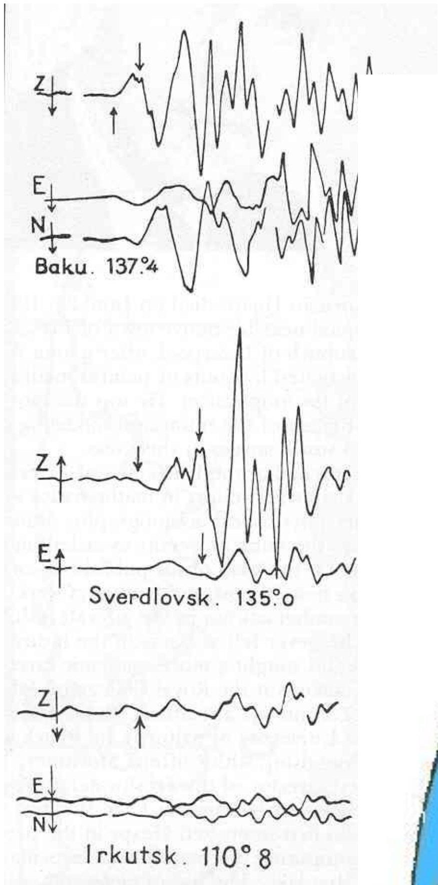
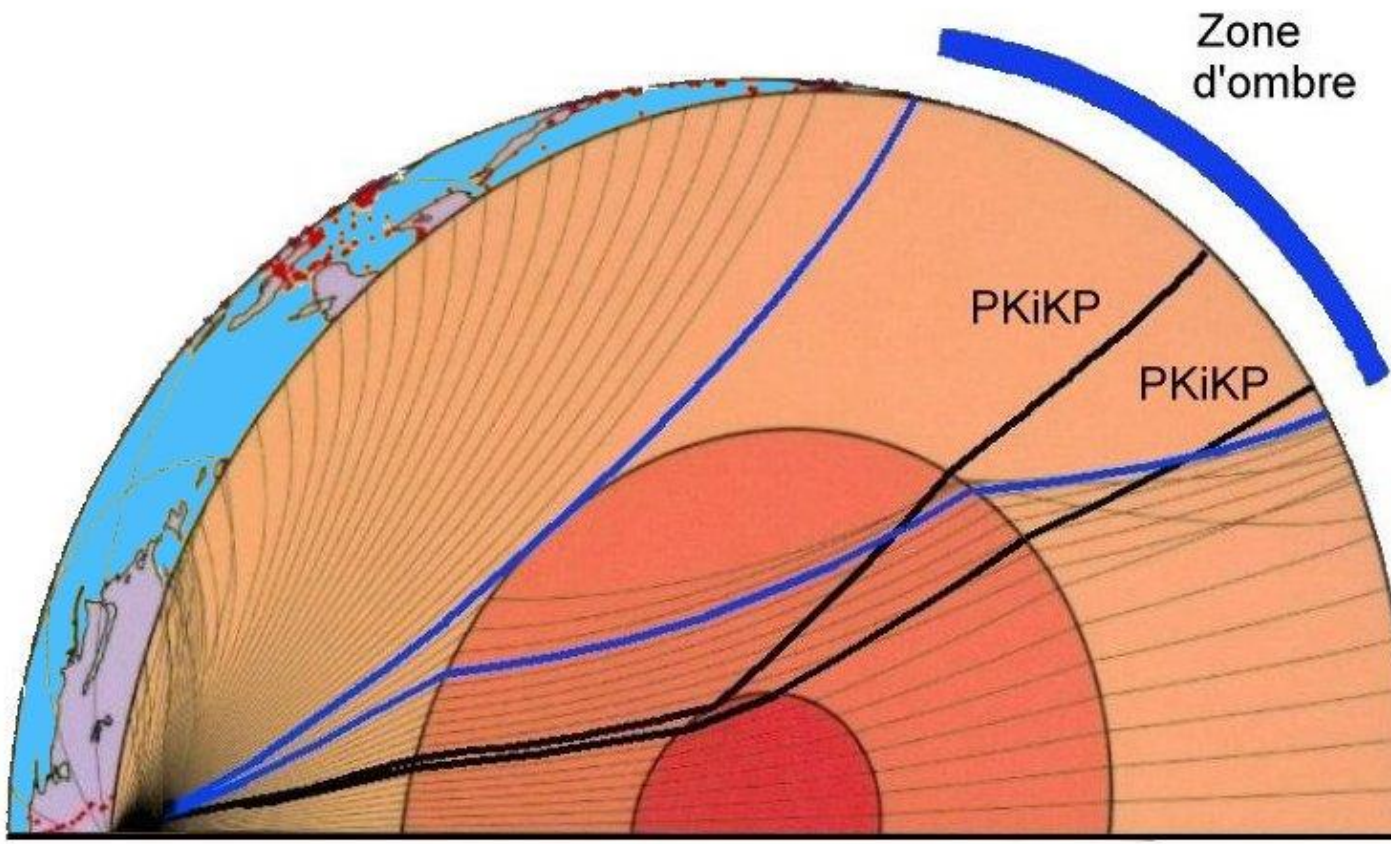
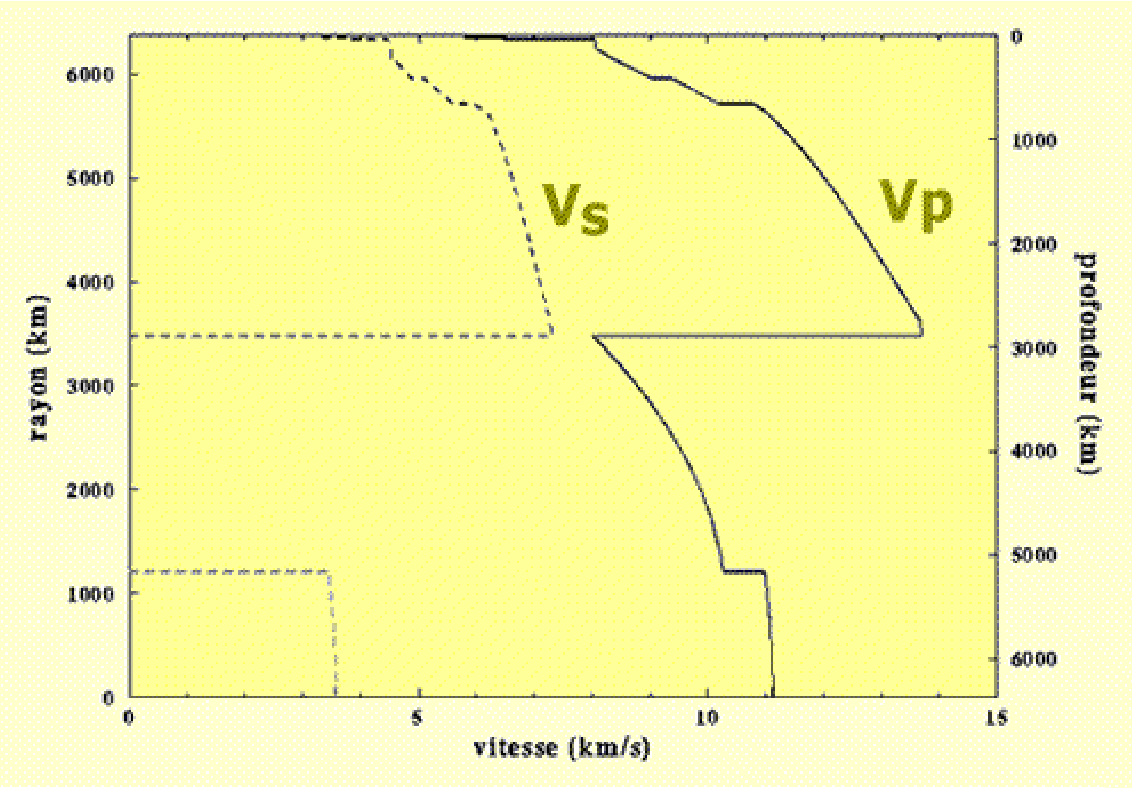
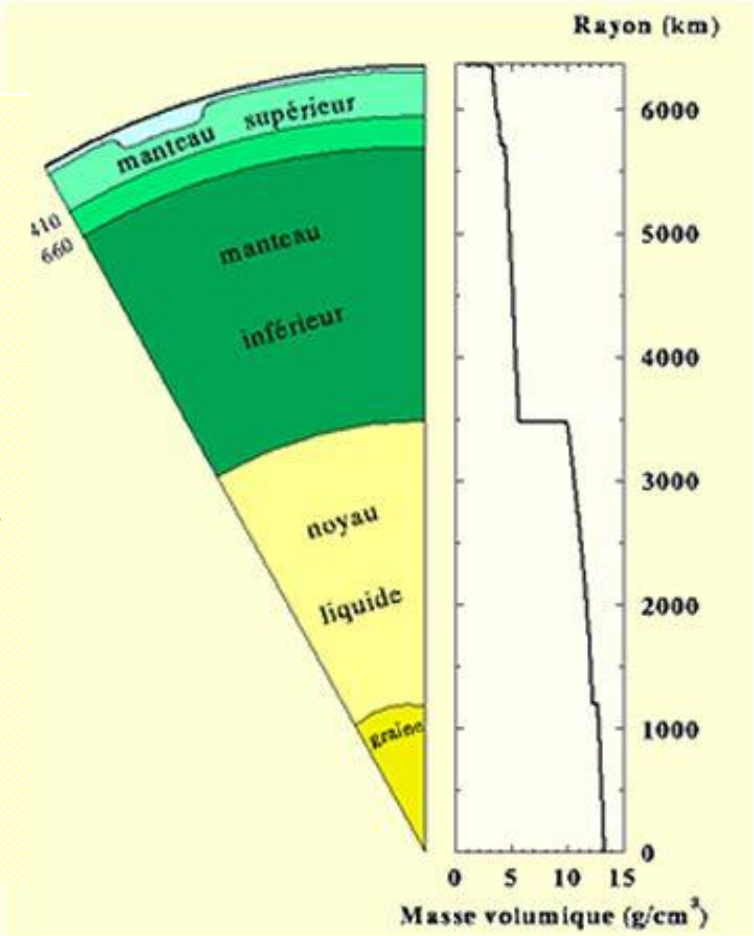



*Fig. 5.* Seismograms of the New land earthquake of June 16, 1929, s ing that the unexplained phases are recorded on the vertical component *mann,* 1936].



# Imagerie sismique




PREM 1981

# La graine est-elle solide?

PKJKP

**GEOPHYSICS**

## Shear properties of Earth's inner core constrained by a detect *J* waves in global correlation

**Hrvoje Tkalčić* and Thanh-Son Phạm**

Seismic *J* waves, shear waves that traverse Earth's inner core, provid the inner core's solidity and shear properties. However, these waves direct seismic wavefield because of their small amplitudes. We devis detect *J* waves in the earthquake coda correlation wavefield. They m similarity with other compressional core-sensitive signals. The inner c soft, with shear-wave speeds and shear moduli of 3.42 ± 0.02 kilome 149.0 ± 1.6 gigapascals (GPa) near the inner core boundary and 3.58 second and 167.4 ± 1.6 GPa in Earth's center. The values are 2.5% low used Preliminary Earth Reference Model. This provides new constrai interpretation of Earth's inner core.

Science - 2018

# Anisotropie sismique de la Graine

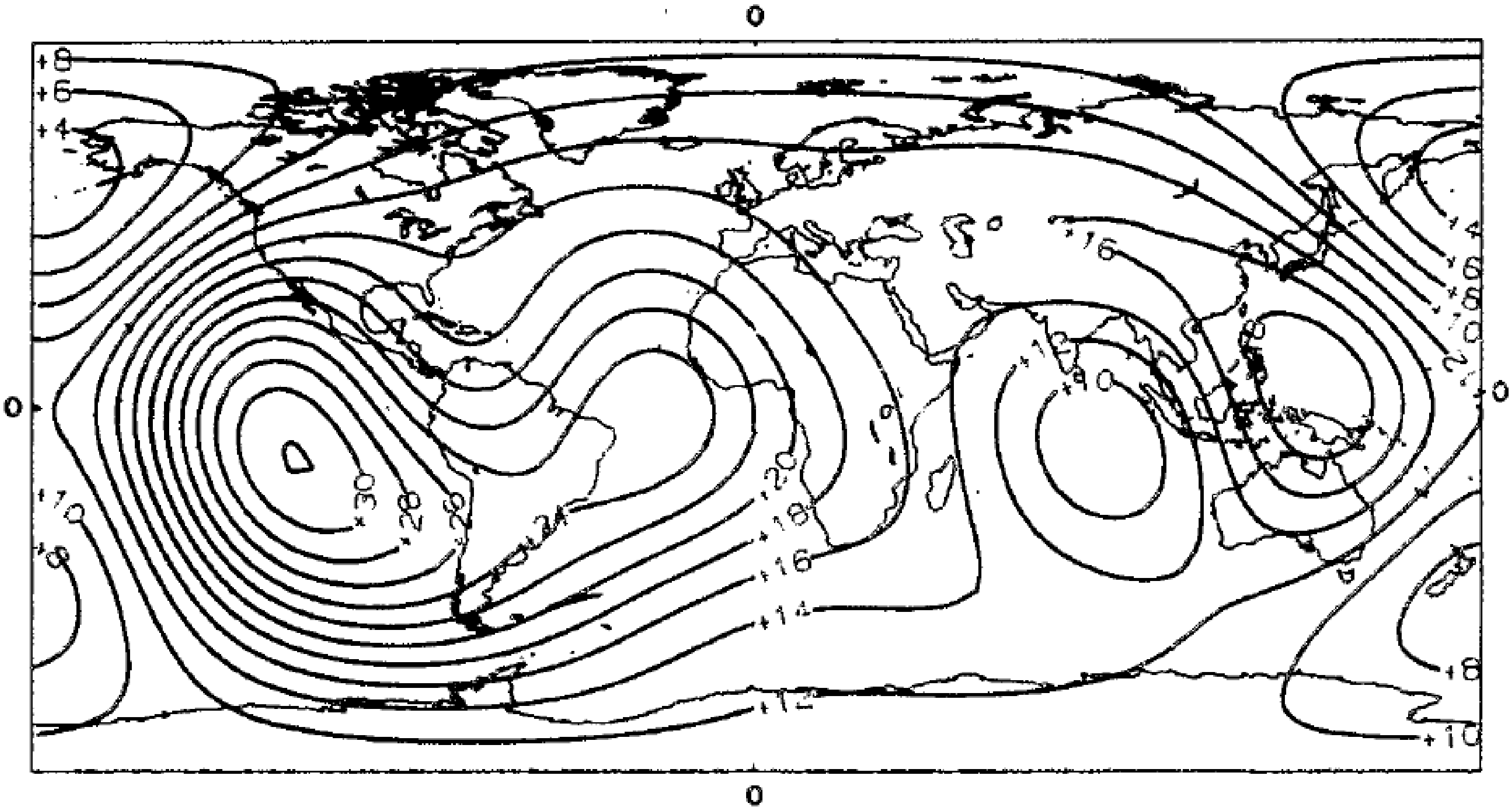
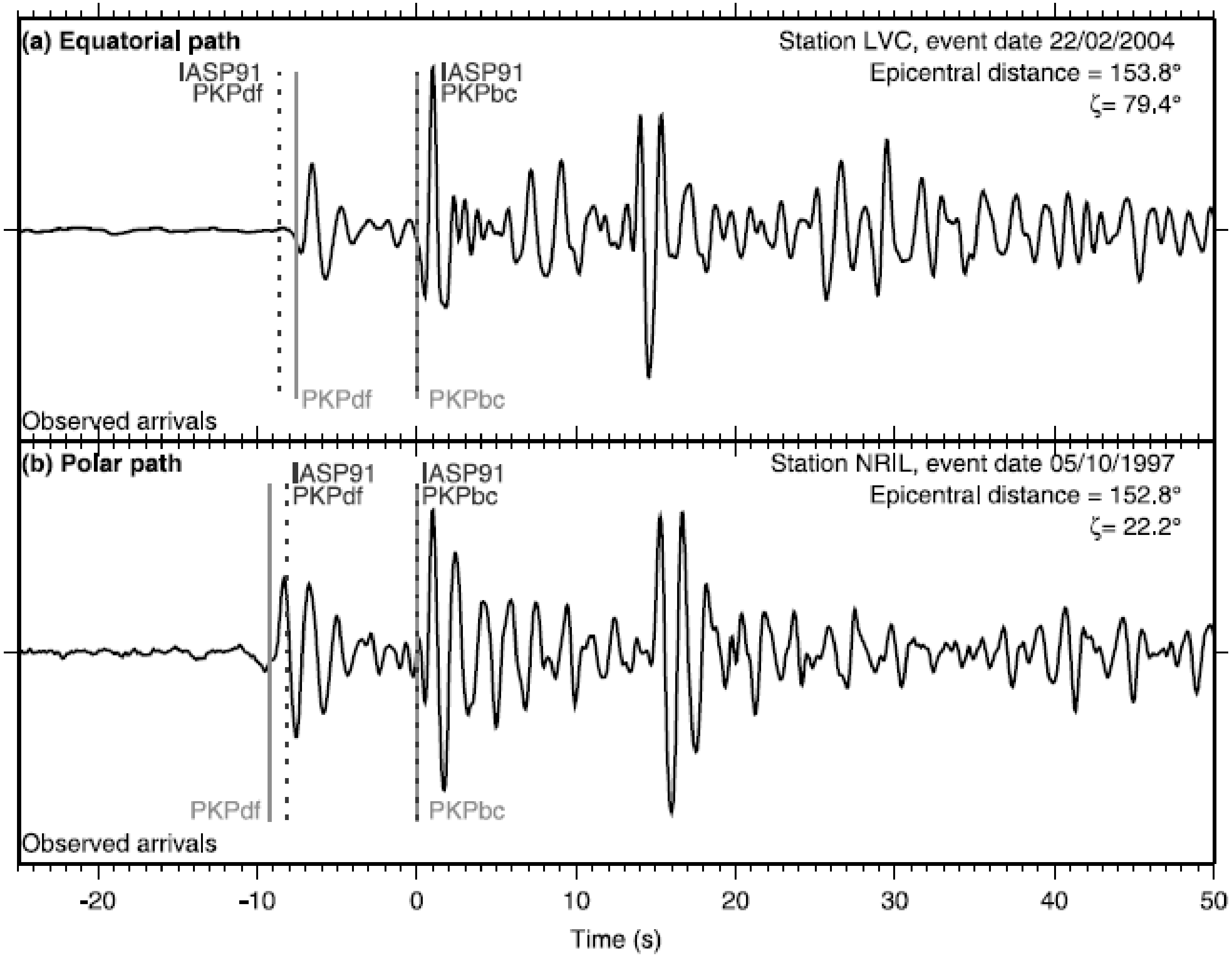



**Fig. 4** Spherical harmonics expansion up to a degree 4 of the PKIKP–P travel-time residual field. Values are in tenths of a second. A low number means a fast velocity in the core.

Poupinet et al, 1983

# Difference de temps d'arrivée




Annie Souriau
Georges Poupinet
ISTerre, oct 2013

Poupinet et al, nature 1983, Souriau 2008

ISTerre

# Séismologie différentielle

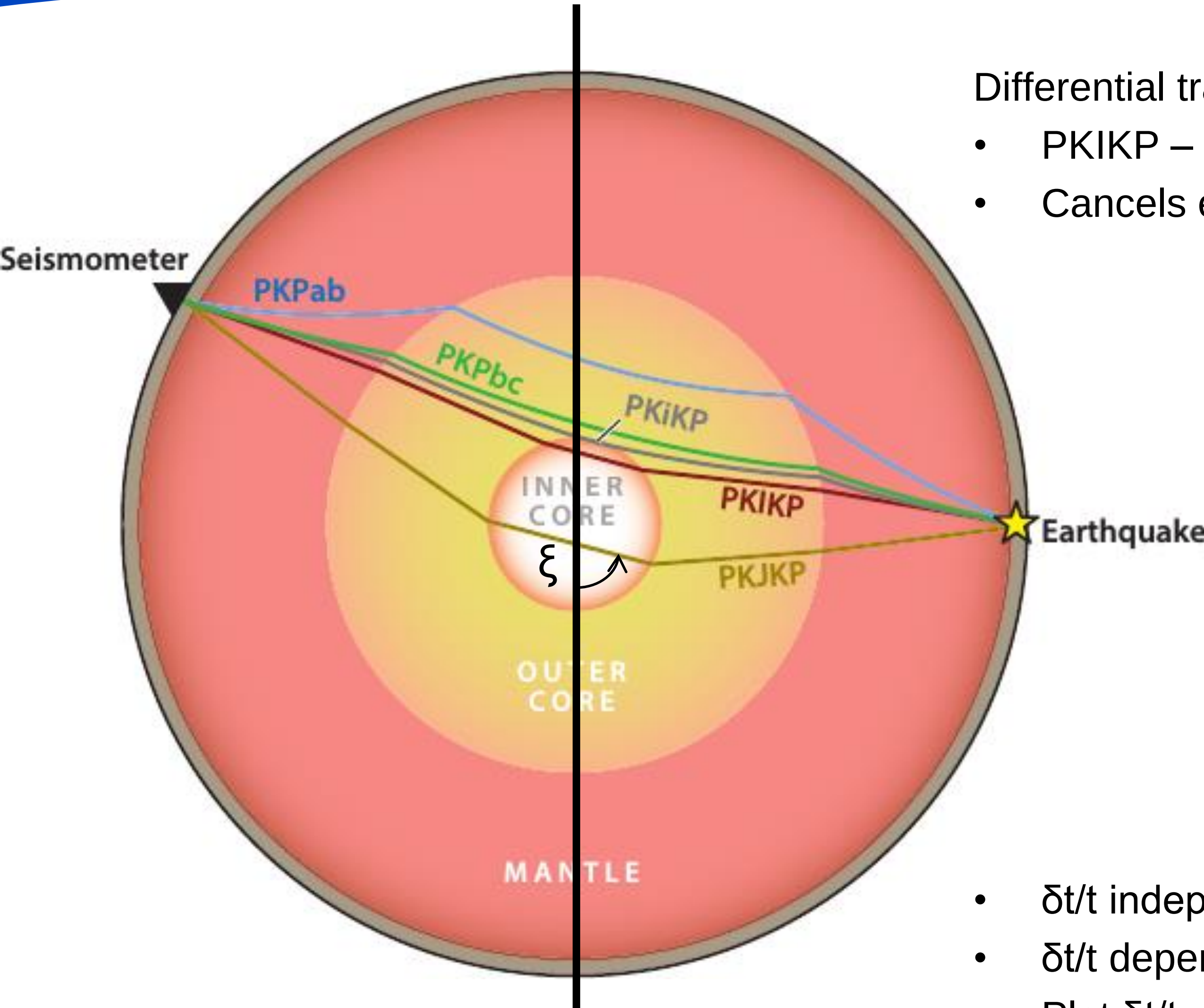


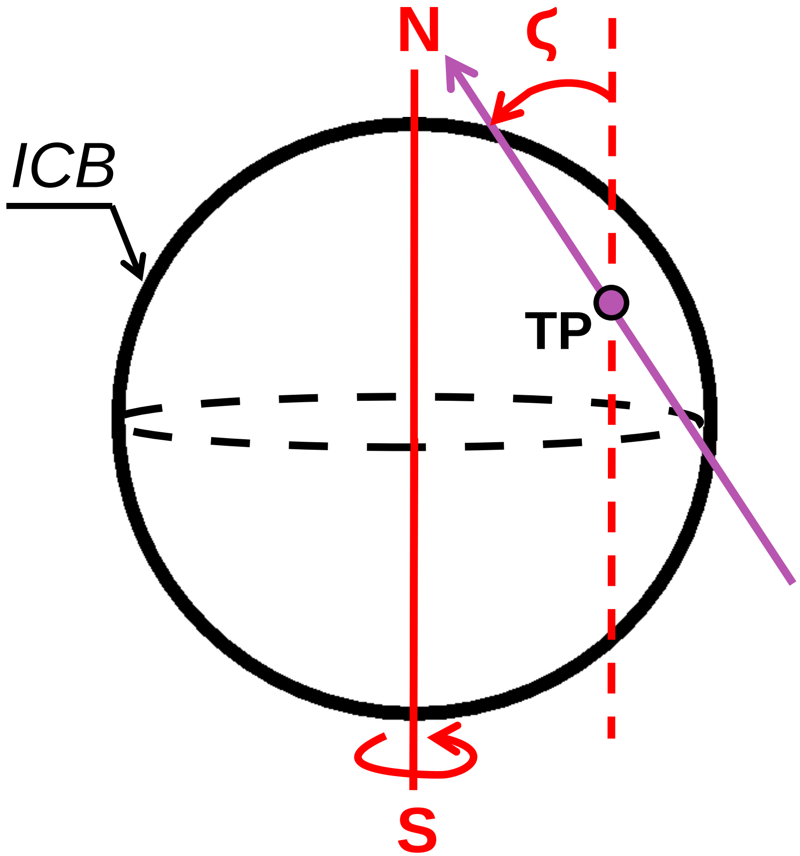

Illustration : Deuss, *Annu. Rev. Earth Planet. Sci.* 2015

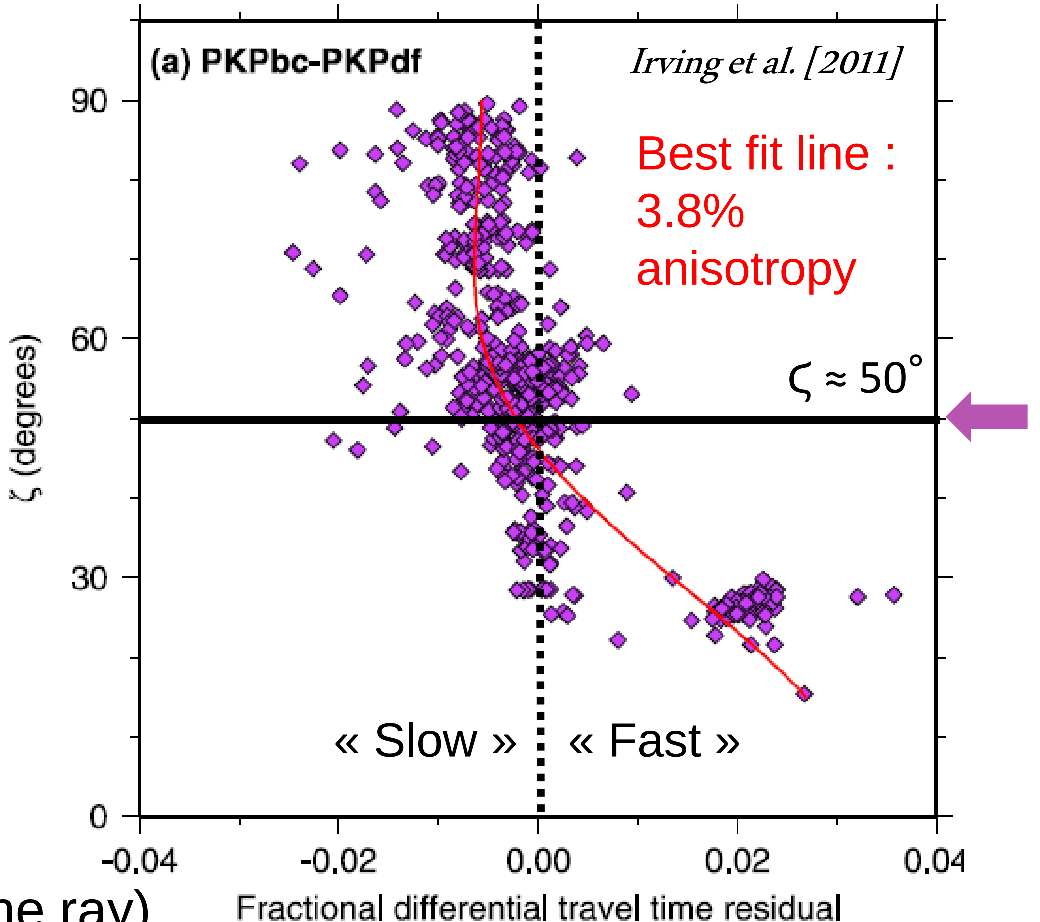
Differential travel time δt:

- PKIKP – PKiKP, or other combinations
- Cancels effects of mantle and crust

- δt/t independent of ξ: no anisotropy
- δt/t depends on ξ: anisotropy
- Plot δt/t vs. ξ, angle to Earth rotation axis

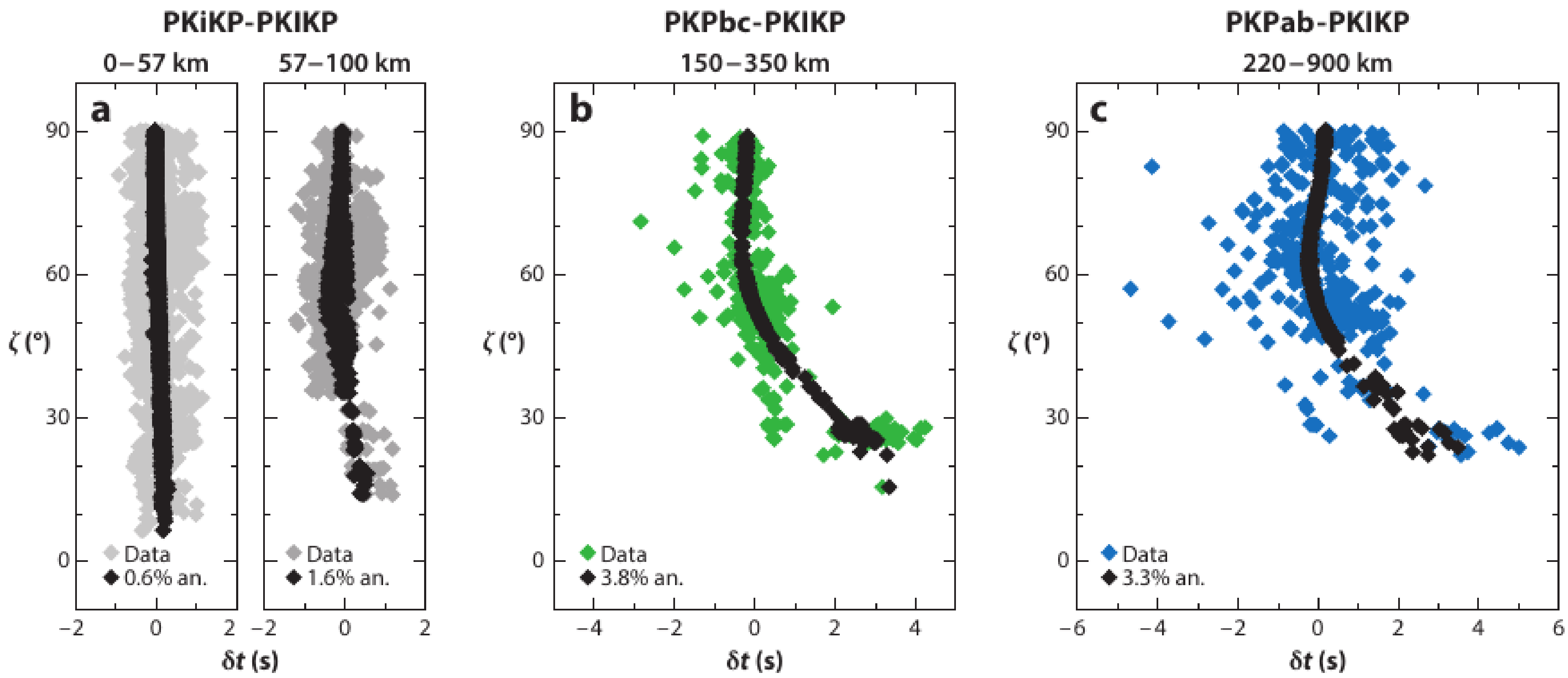
# La graine est anisotrope!




**TP** : turning point (deepest point of the ray)

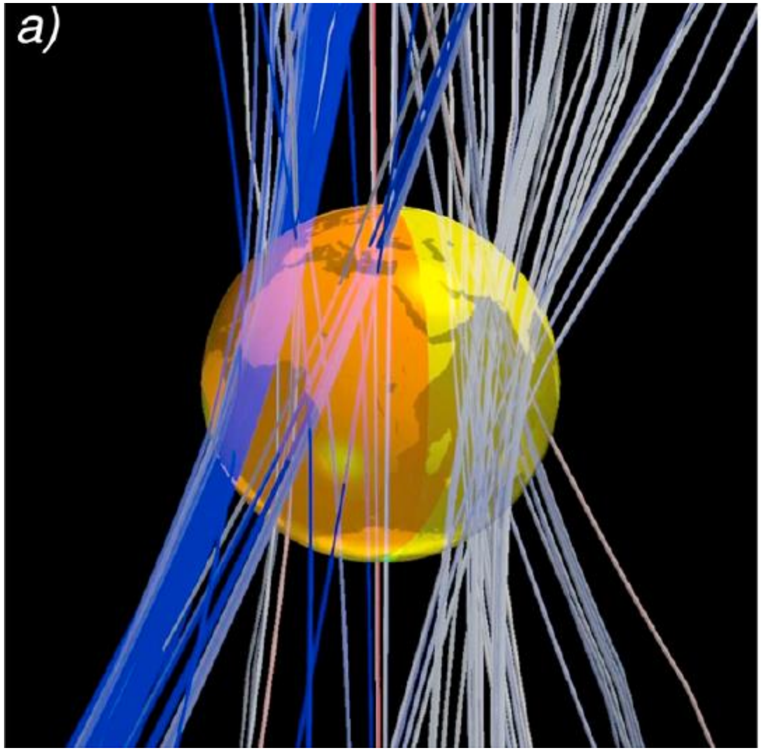
# L’anisotropie dépend de la profondeur



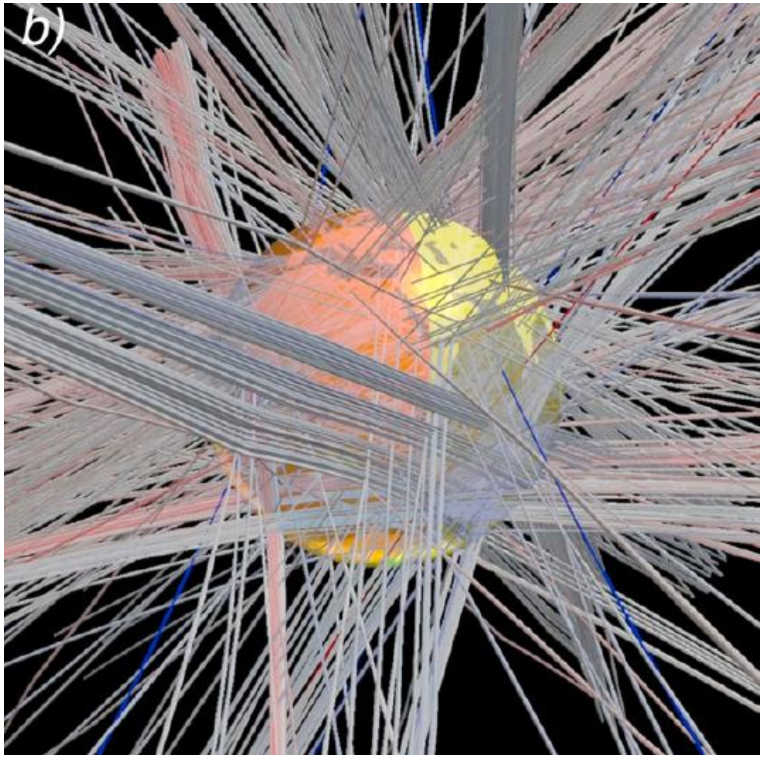

Deuss, *Annu. Rev. Earth Planet. Sci.* 2014
Data are from Irving & Deuss (2011a) and Waszek & Deuss (2011)

# Très peu de rais sismiques…

Quasi-polar PKIKP raypaths
ξ ≤ 35°




Quasi-equatorial PKIKP raypaths
ξ > 35°




1- Very incomplete coverage (N-S path particularly)
2- Waves go through the whole inner core

Illustration : Tkalčić, *Rev Geophys*. 2015

# Plan

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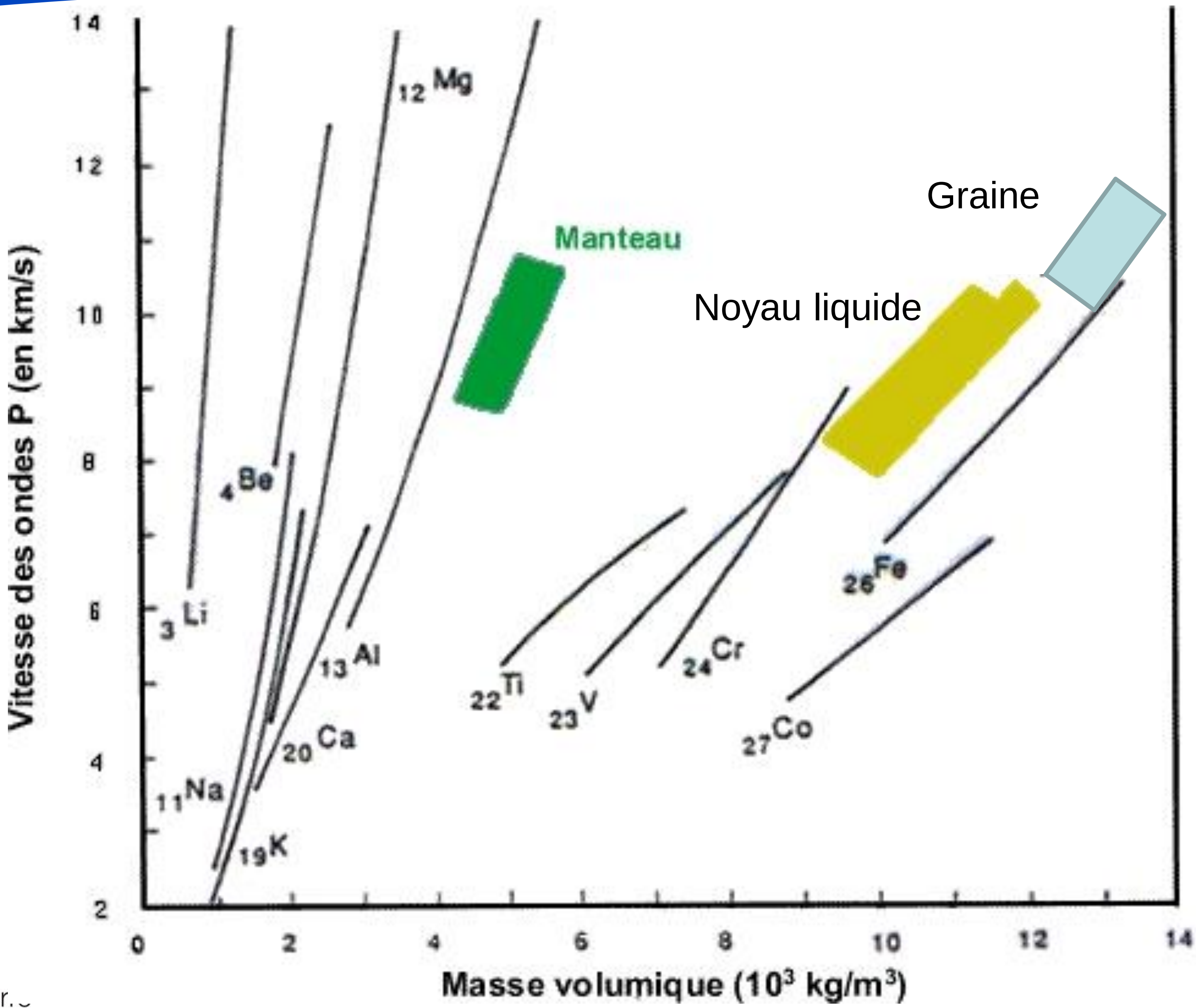
2. Une graine en Fer ?
3. Formation de la graine
4. Dynamique de la graine
5. L'anisotropie de la graine

# Loi de Birch



Vitesse des ondes P (en km/s)
Masse volumique (10³ kg/m³)
Manteau
Graine
Noyau liquide
3 Li
4 Be
12 Mg
13 Al
11 Na
19 K
20 Ca
22 Ti
23 V
24 Cr
26 Fe
27 Co

# Géochimie du noyau

Terre = $\sum$ météorites chondritiques

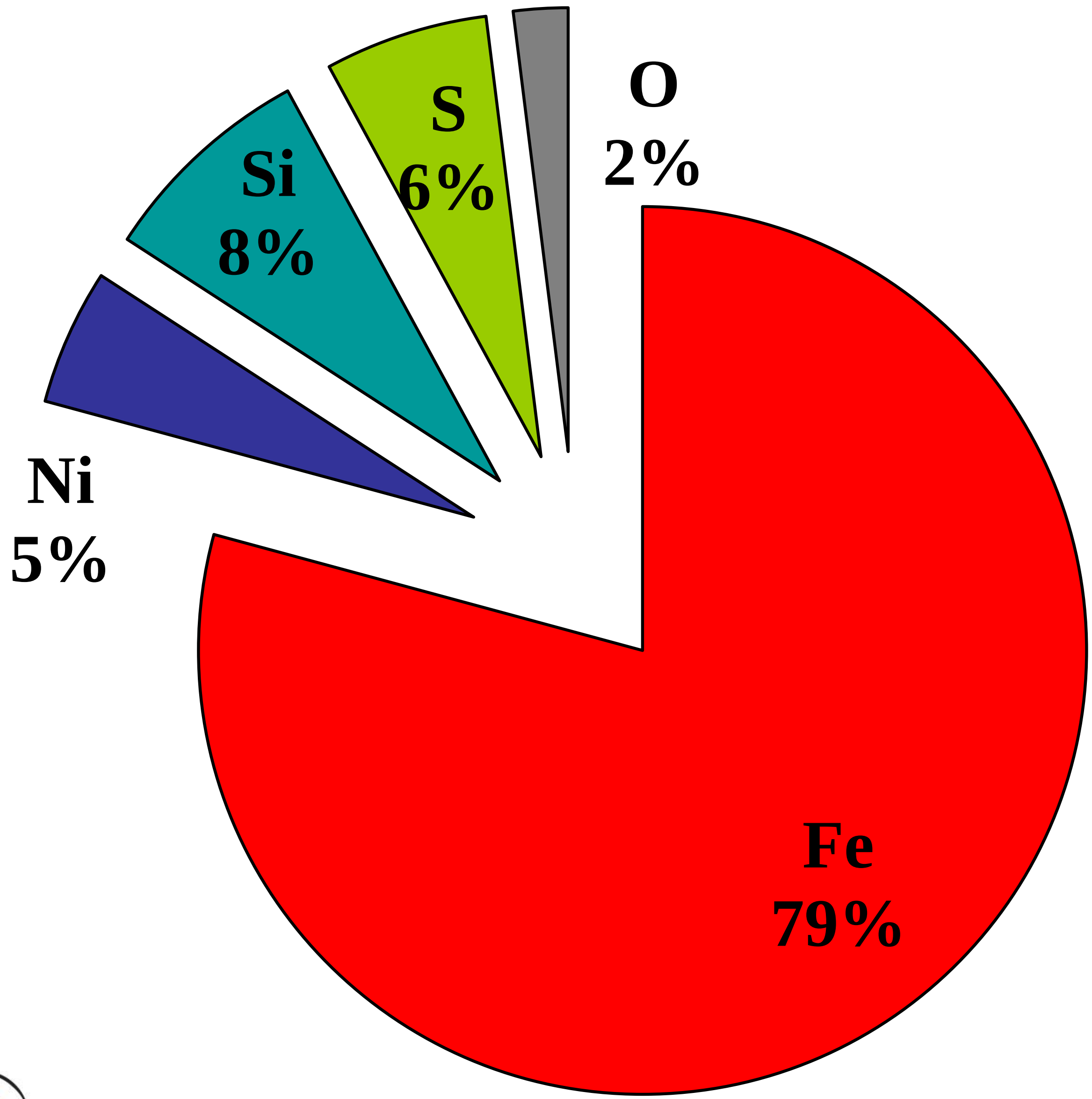
Noyau = Terre - croute - manteau

Chondrite

Météorite de Fer

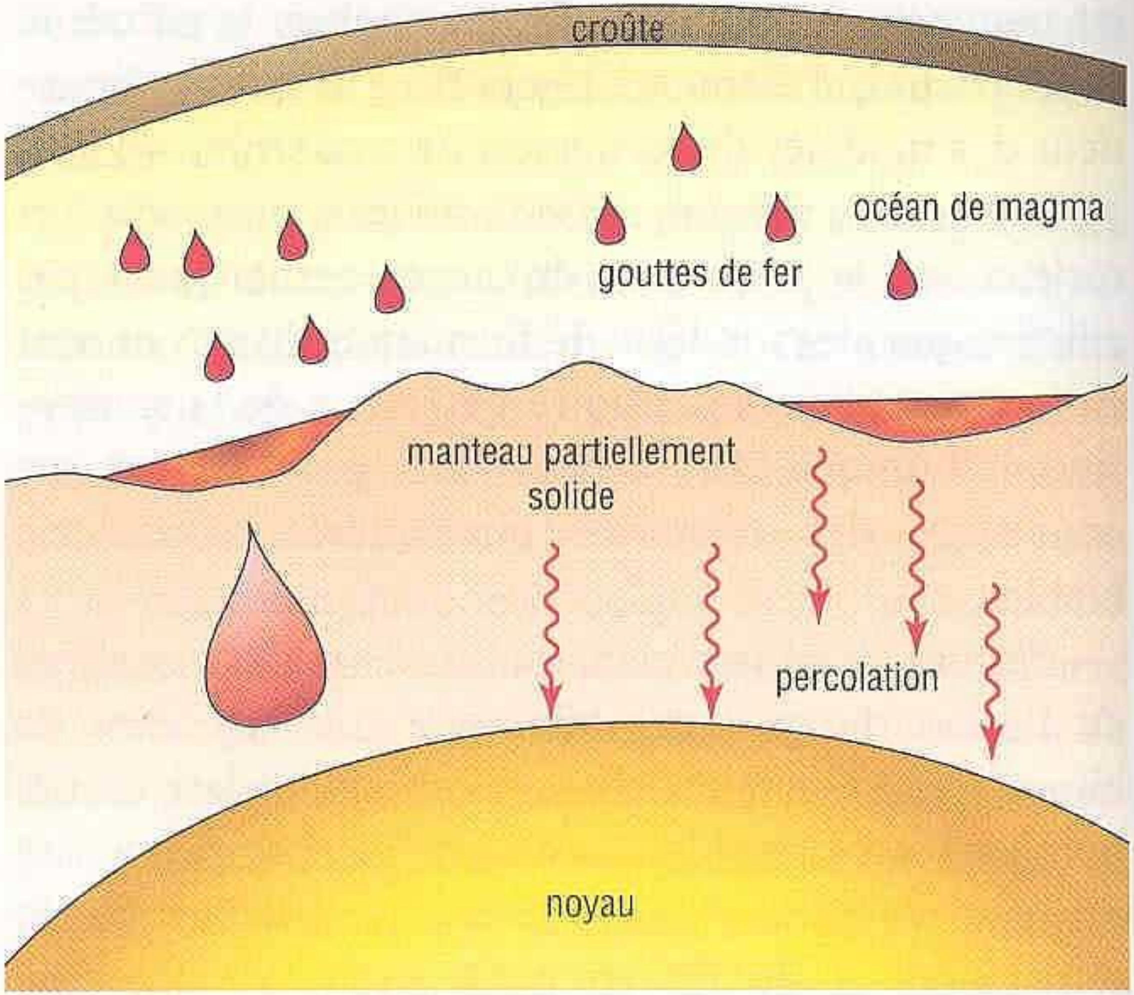
Pallasite

# Composition géochimique du noyau



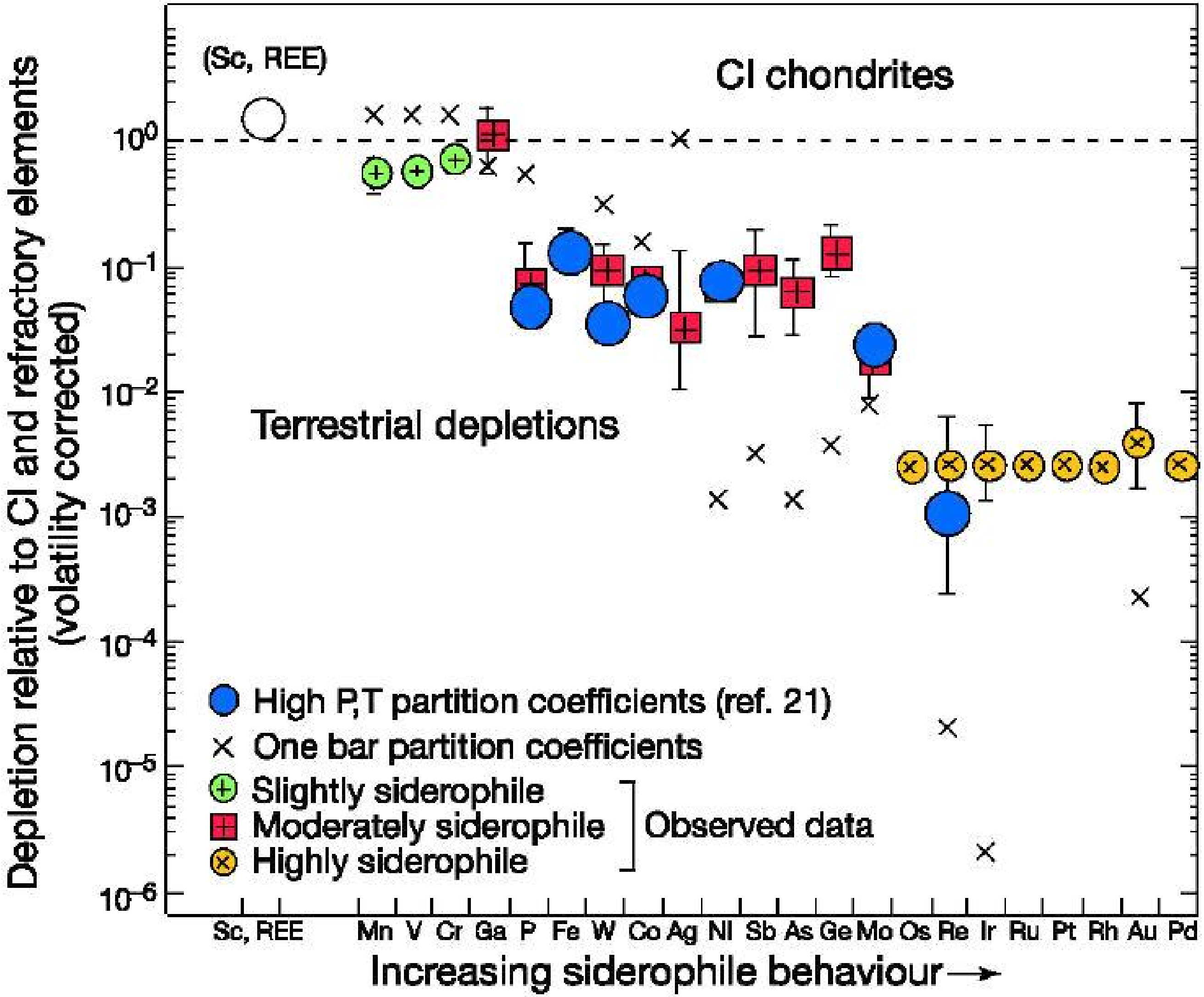

Allegre et al, 1995

# Formation du noyau




Source : D. J. Stevenson, *Science*, 1981.

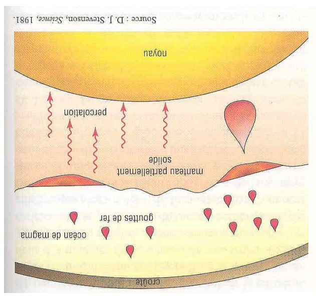
# Sidérophile/lithophile

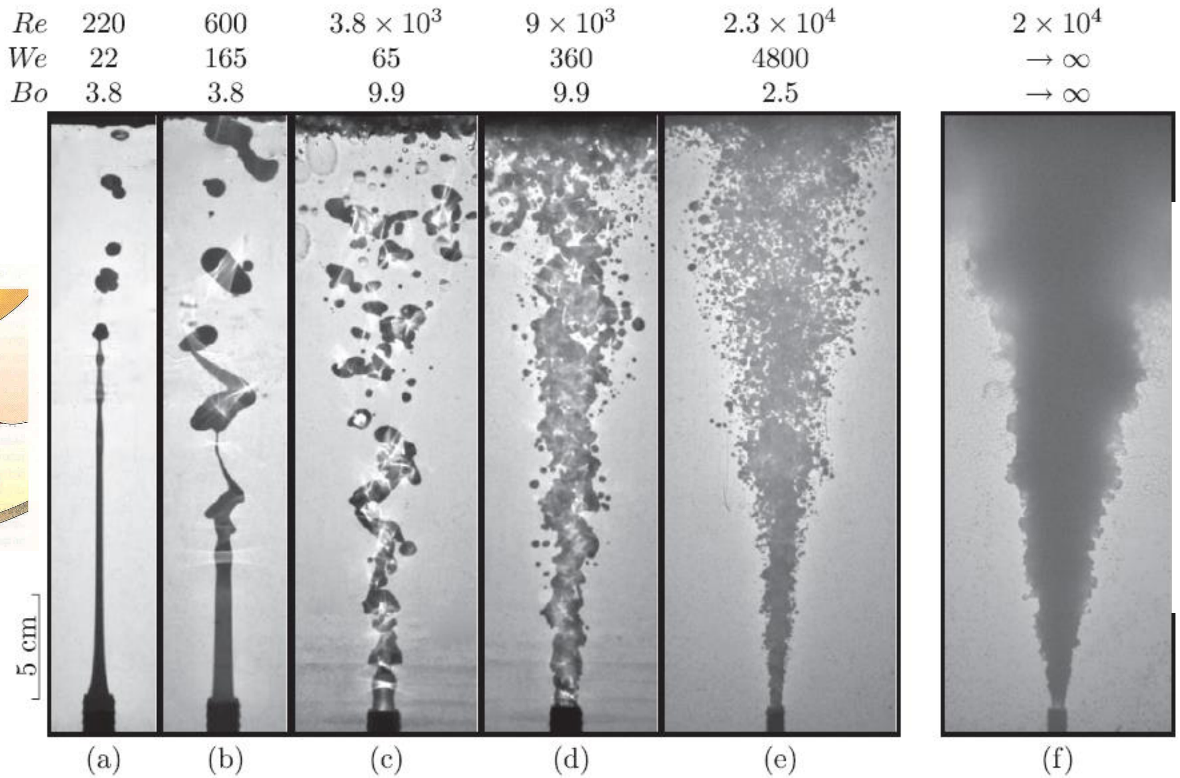



Drake et al, 2002

# Mélange turbulent métal/sillicates

306 R. Deguen et al. / Earth and Planetary Science Letters 310 (2011) 303–313



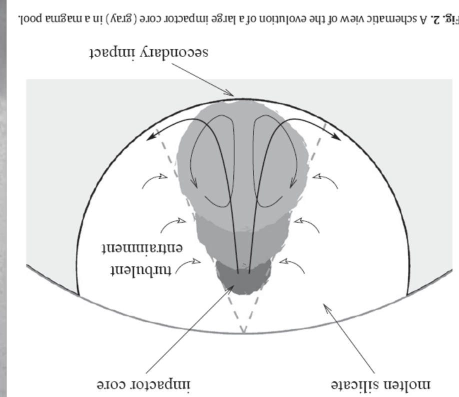
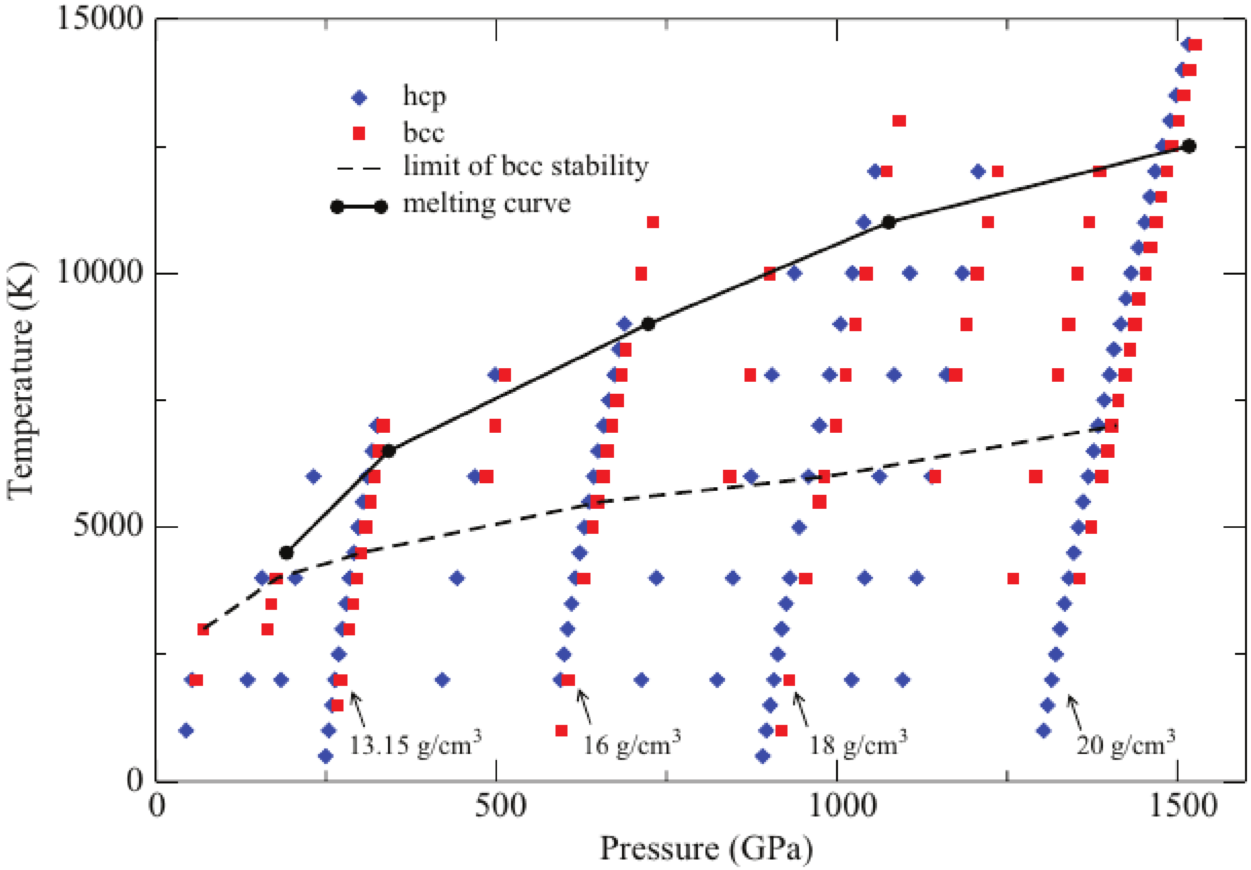




**Fig. 1.** Forced plumes in water. Canola oil is used in the experiments shown in a) and b) ($\lambda=0.1$, $\Delta\rho/\rho_w=0.08$), and a low viscosity silicone oil is used in the experiments shown in c) to e) ($\lambda=1.2$, $\Delta\rho/\rho_w=0.18$). f): forced plume of a water–alcohol mixture (density $\rho=810$ kg·m$^{-3}$) in cold water. In a), disruption is due to the Rayleigh-Plateau capillarity instability; fragmentation is due mainly to shear instabilities in d) and e). See text for dimensional parameters values.

# Diagramme de phase « théorique » du Fe

PHYSICAL REVIEW B **87**, 094102 (2013)

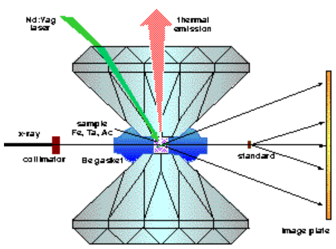
**_Ab initio_ equation of state of iron up to 1500 GPa**

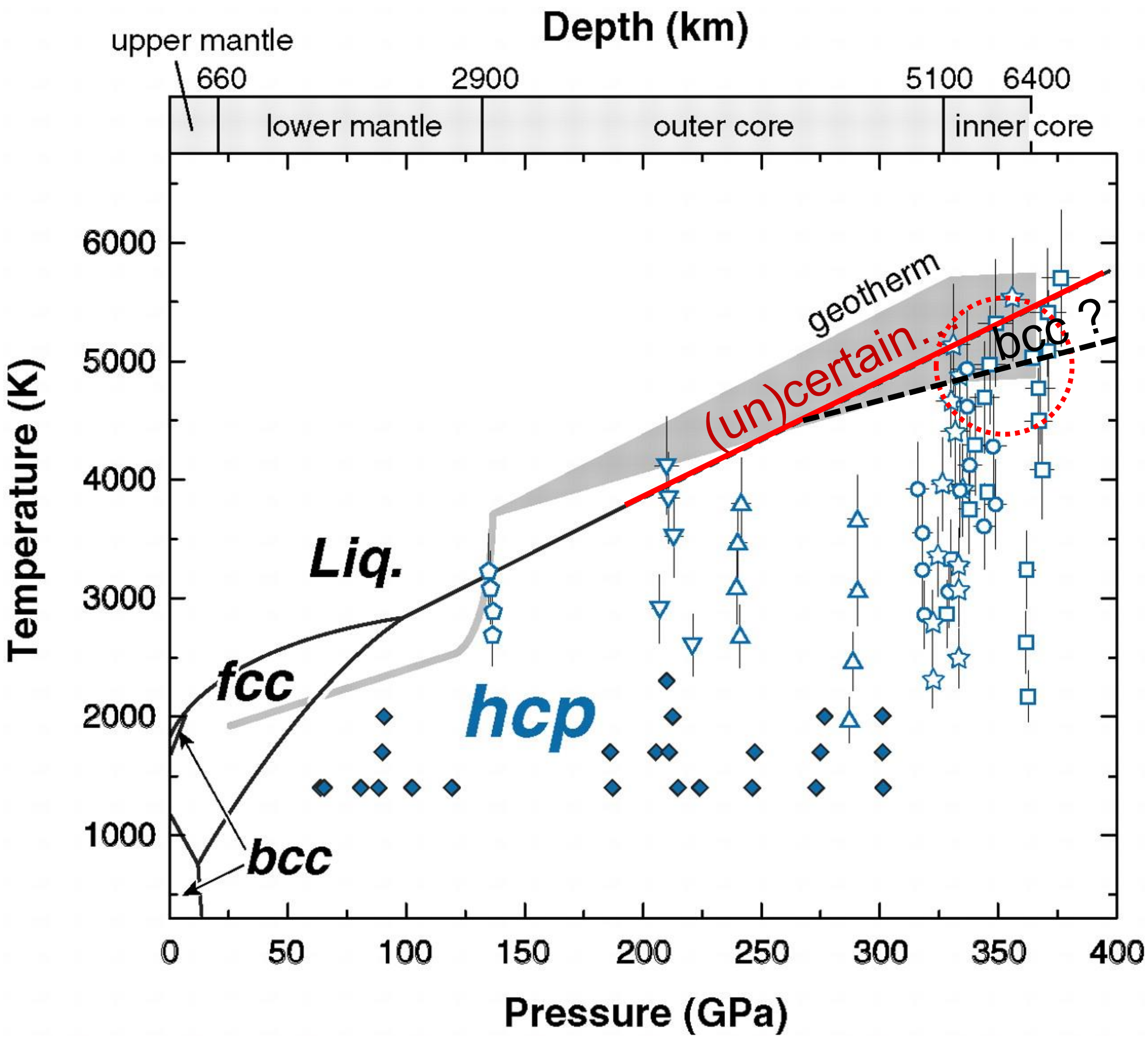



Bouchet et al

# Diagramme de phase « expé » du Fe

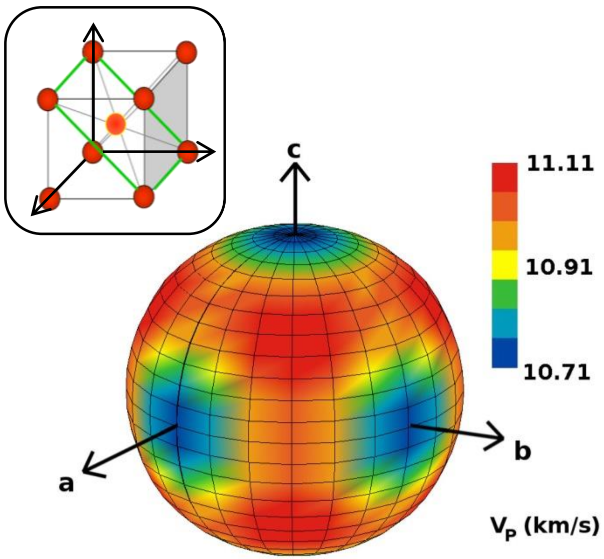
*Tateno et al. [2010]*



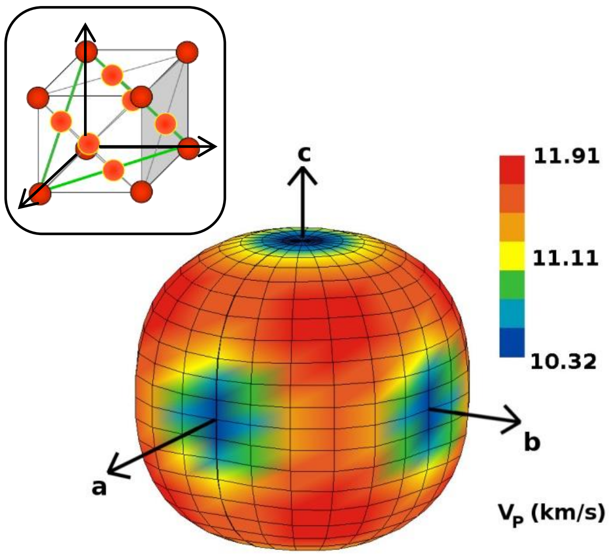
# Anisotropie cristaline

3 possible cristallographic phases for Fe at the inner core conditions



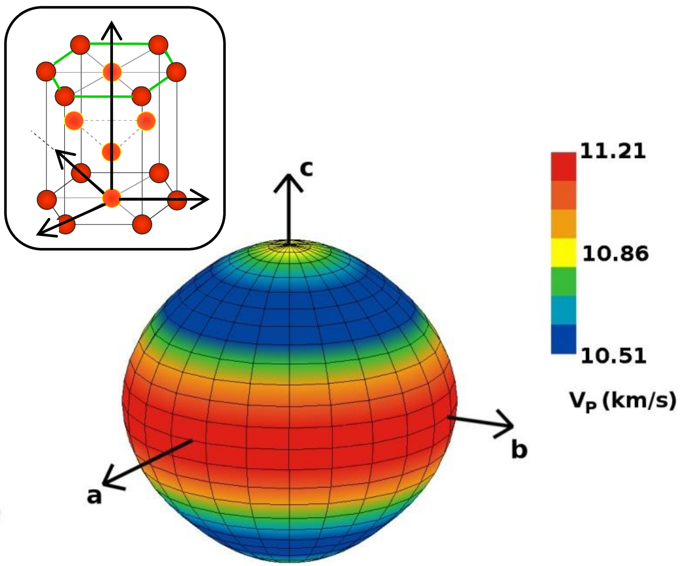

*Base centered cubic (bcc)*

Vocadlo, 2007




*Face centered cubic (fcc)*

Vocadlo, 2008

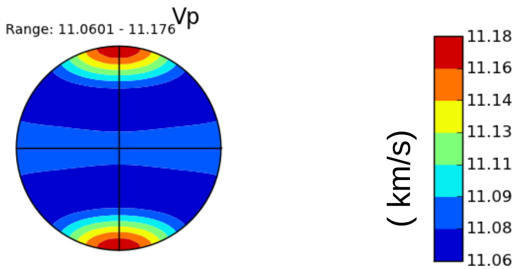


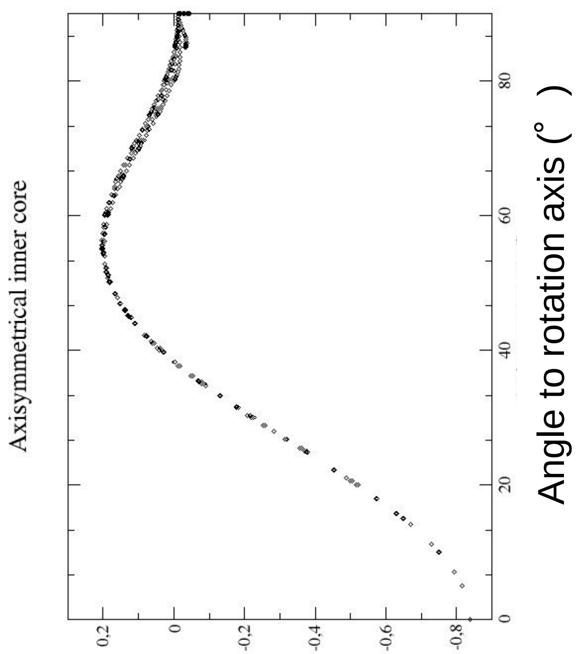

*Hexagonal compact (hcp)*

Vocadlo, 2009

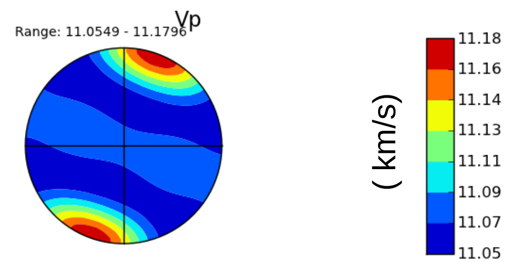
# La graine: un monocristal?

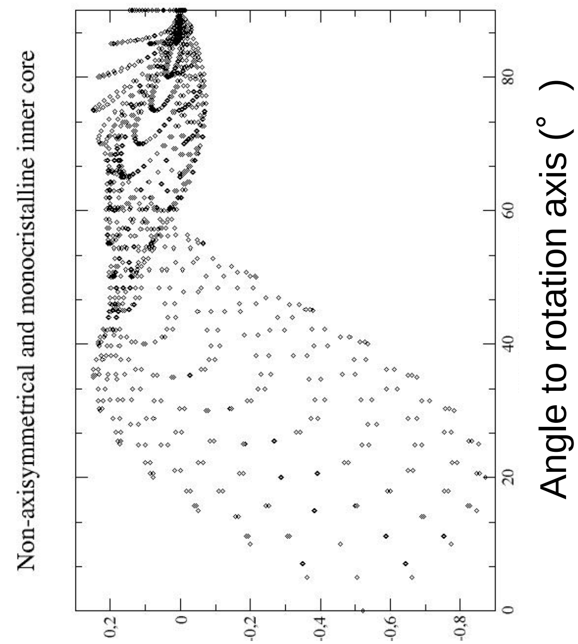
## Axisymmetric single cristal inner core

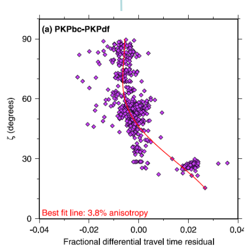



## Non-axisymmetric single cristal inner core



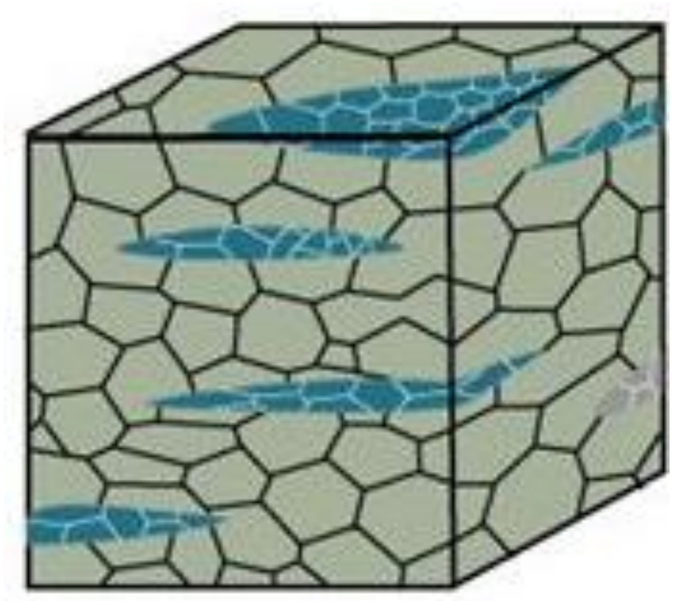



# Source d'anisotropie polycristalline

Shape preferred orientation

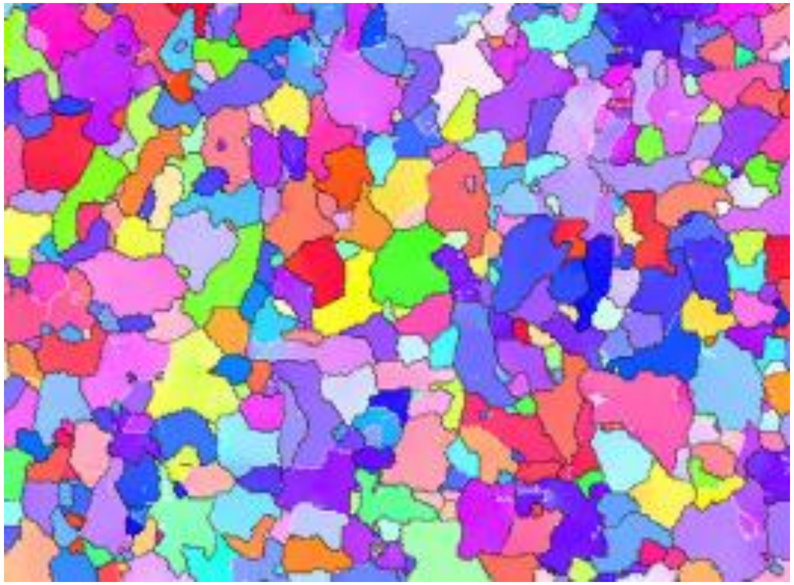
- Aligned grain shapes
- Aligned melt pockets



SPO in the inner core
"Structural anisotropy"
How were the SPO generated?

Lattice preferred orientations

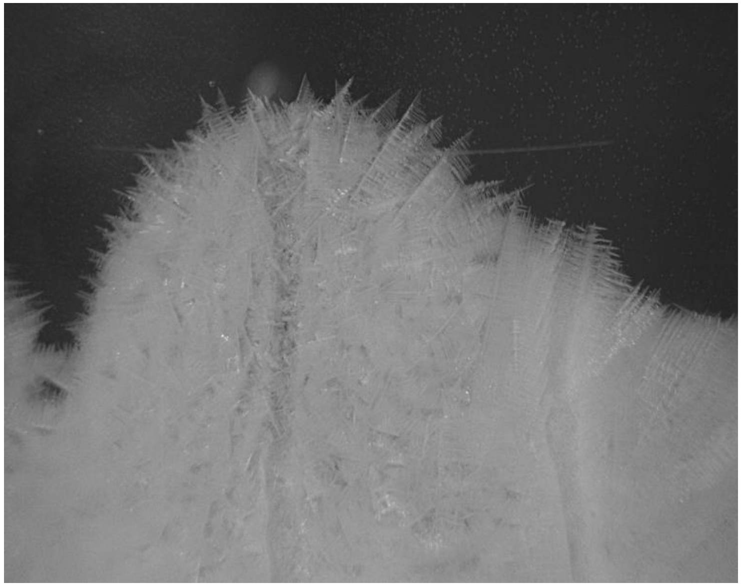
- Crystallization
- Plastic deformation



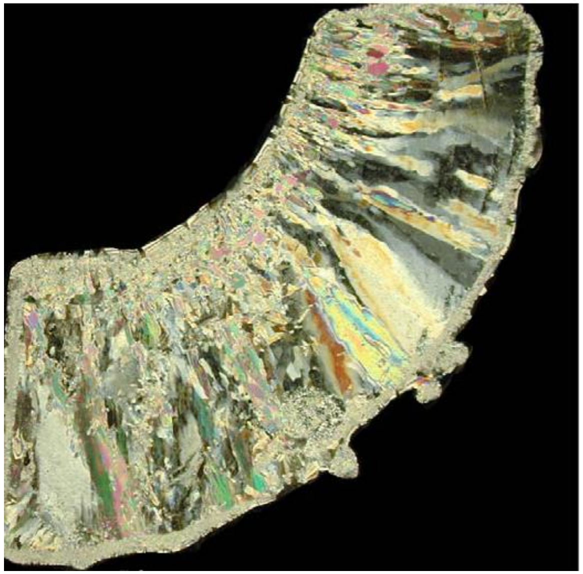
LPO in the inner core
"Deformation anisotropy"
Coupling of IC dynamics and anisotropy

# Solidification de cristaux

Cristallographic Preferred Orientation CPO

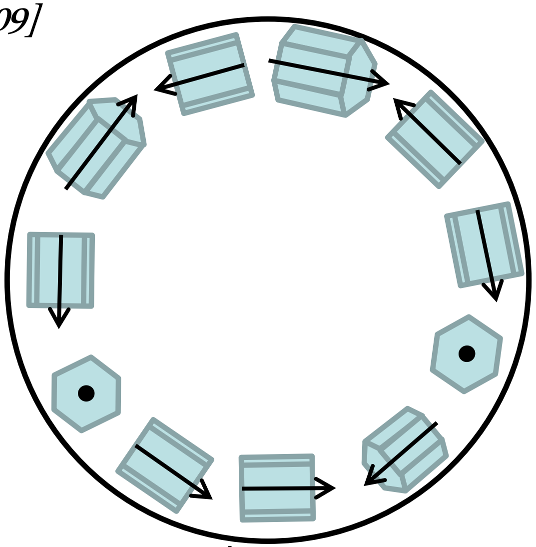


*Deguen [2009]*



*Bergman [2005]*

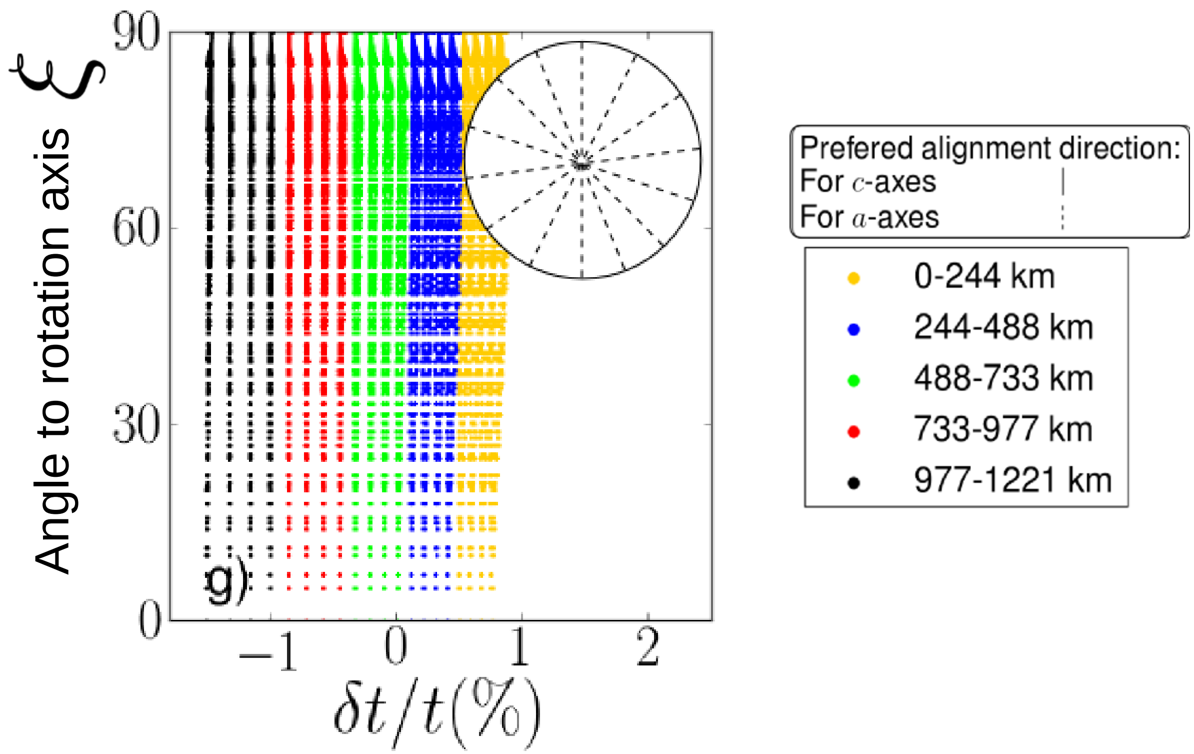
Spherical cristalisation



La graine terrestre

# Graine cristalisée sphérique

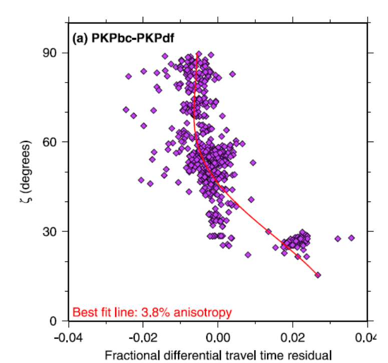
300 000 synthetic rais probing the inner core



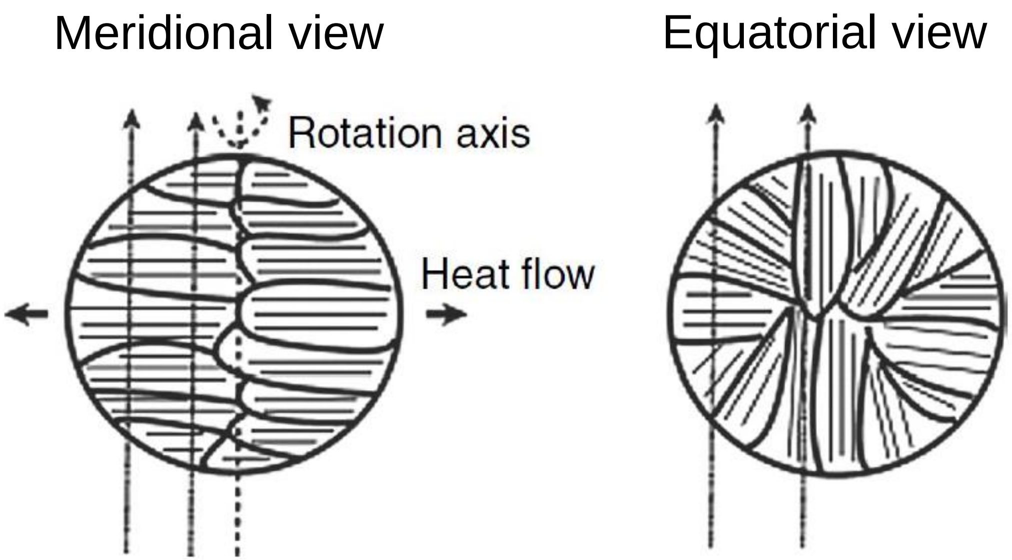

**Seismic residuals**

$$\frac{\delta t}{t} = \frac{s_{ray} - s_0}{s_0}$$

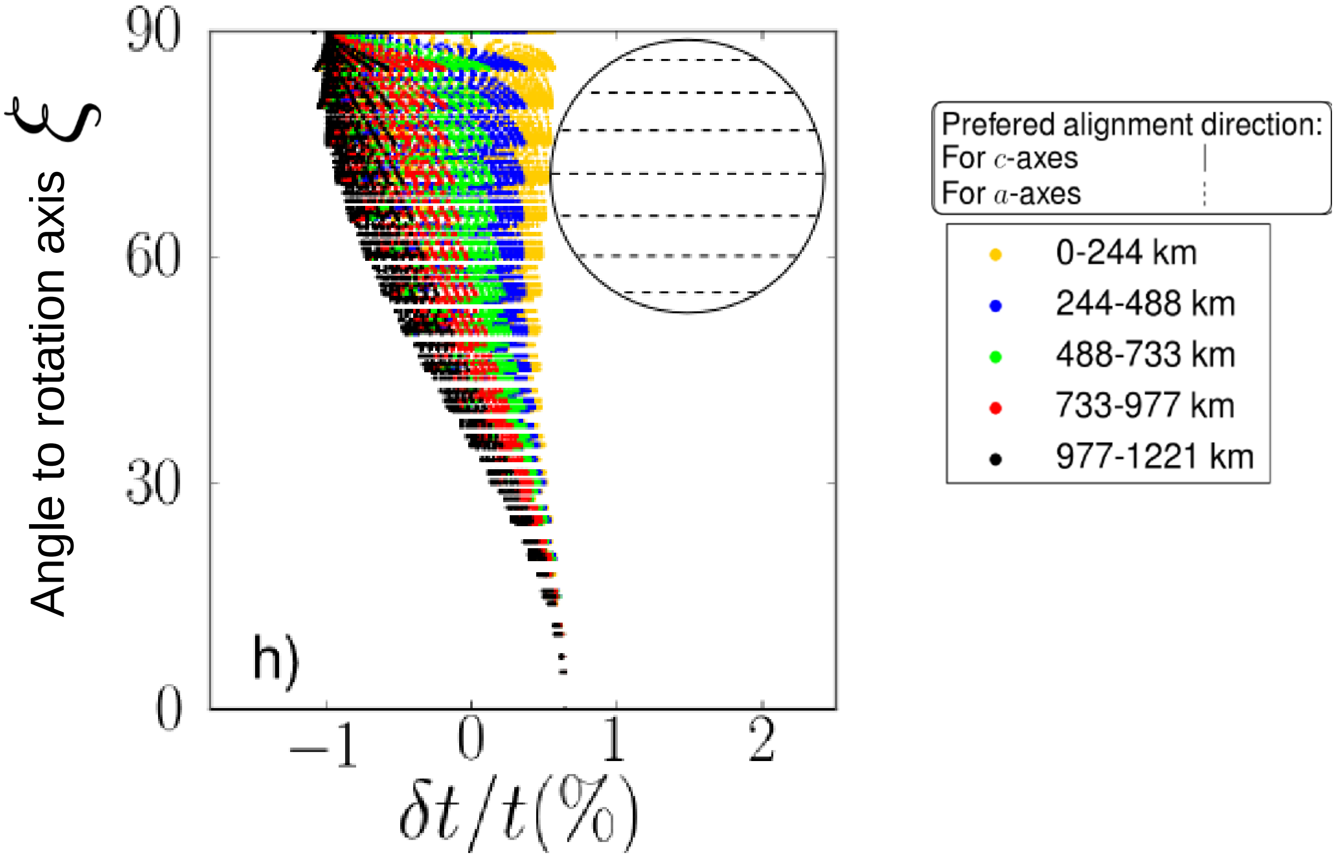
Where $s_0$ = average slowness in IC

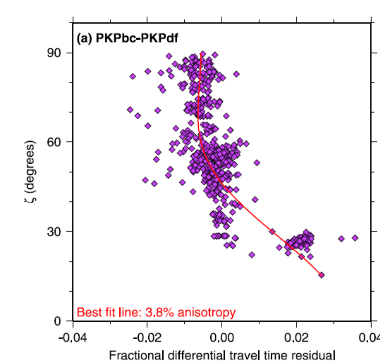


# Graine cristalisée cylindrique




*Bergman [1997], Sumita [2007]*


Angle to rotation axis $\xi$
90
60
30
0
h)
−1
0
1
2
$\delta t/t(\%)$
Prefered alignment direction:
For $c$-axes
For $a$-axes
0-244 km
244-488 km
488-733 km
733-977 km
977-1221 km


(a) PKPbc-PKPdf
ζ (degrees)
90
60
30
0
Best fit line: 3.8% anisotropy
-0.04
-0.02
0.00
0.02
Fractional differential travel time residual

# Plan

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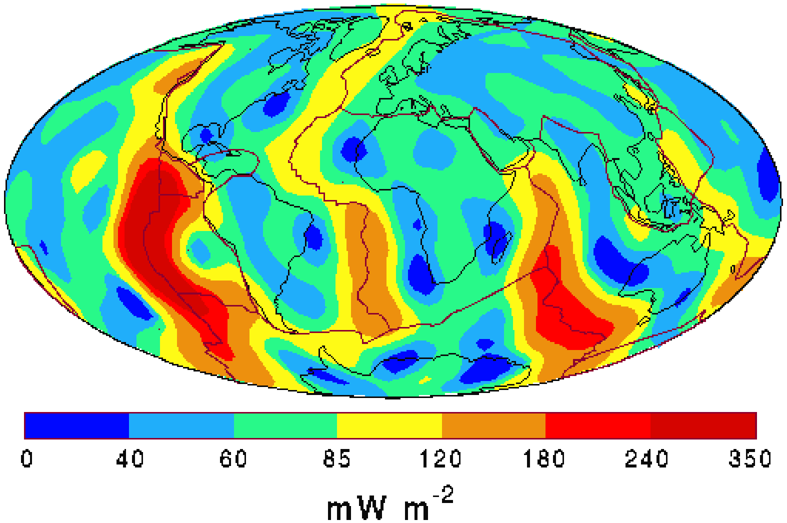
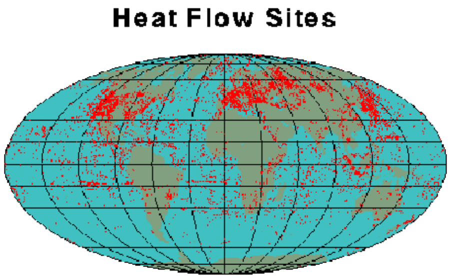
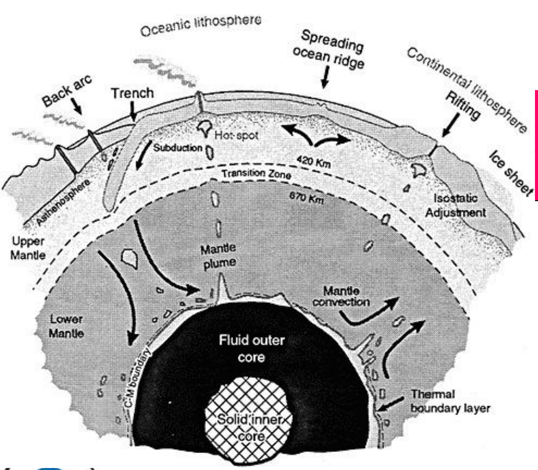
# Et la Terre se refroidit…




Flux de chaleur

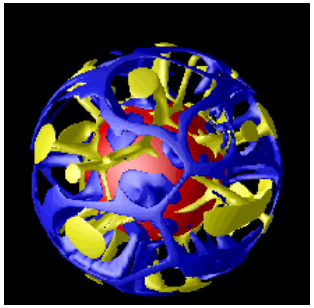
40 TW (± 5) = 5 TW (± 5) + 25 TW (± 5) + 10 TW (?)



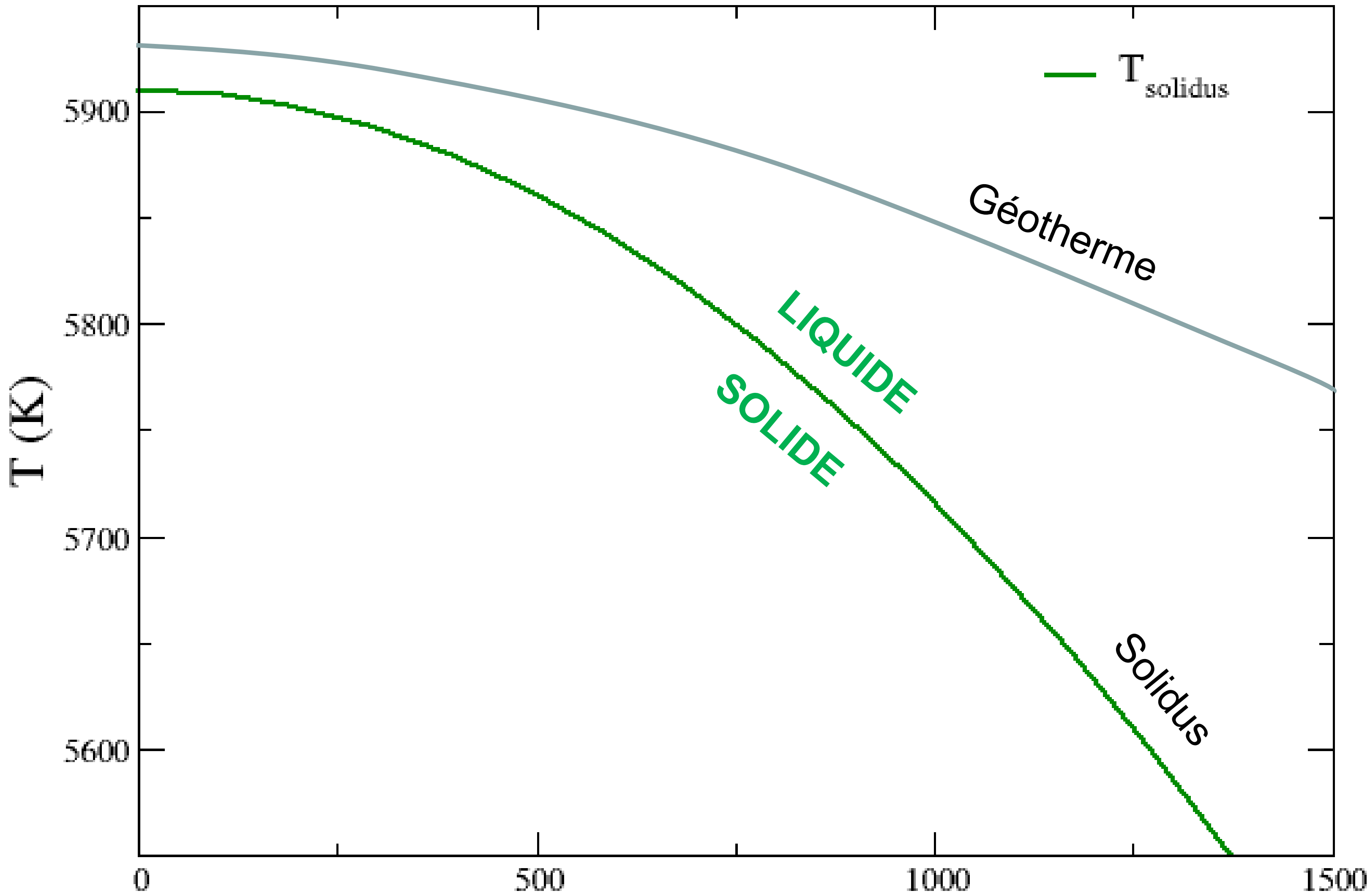

Noyau

Radioactivité

Refroidissement..

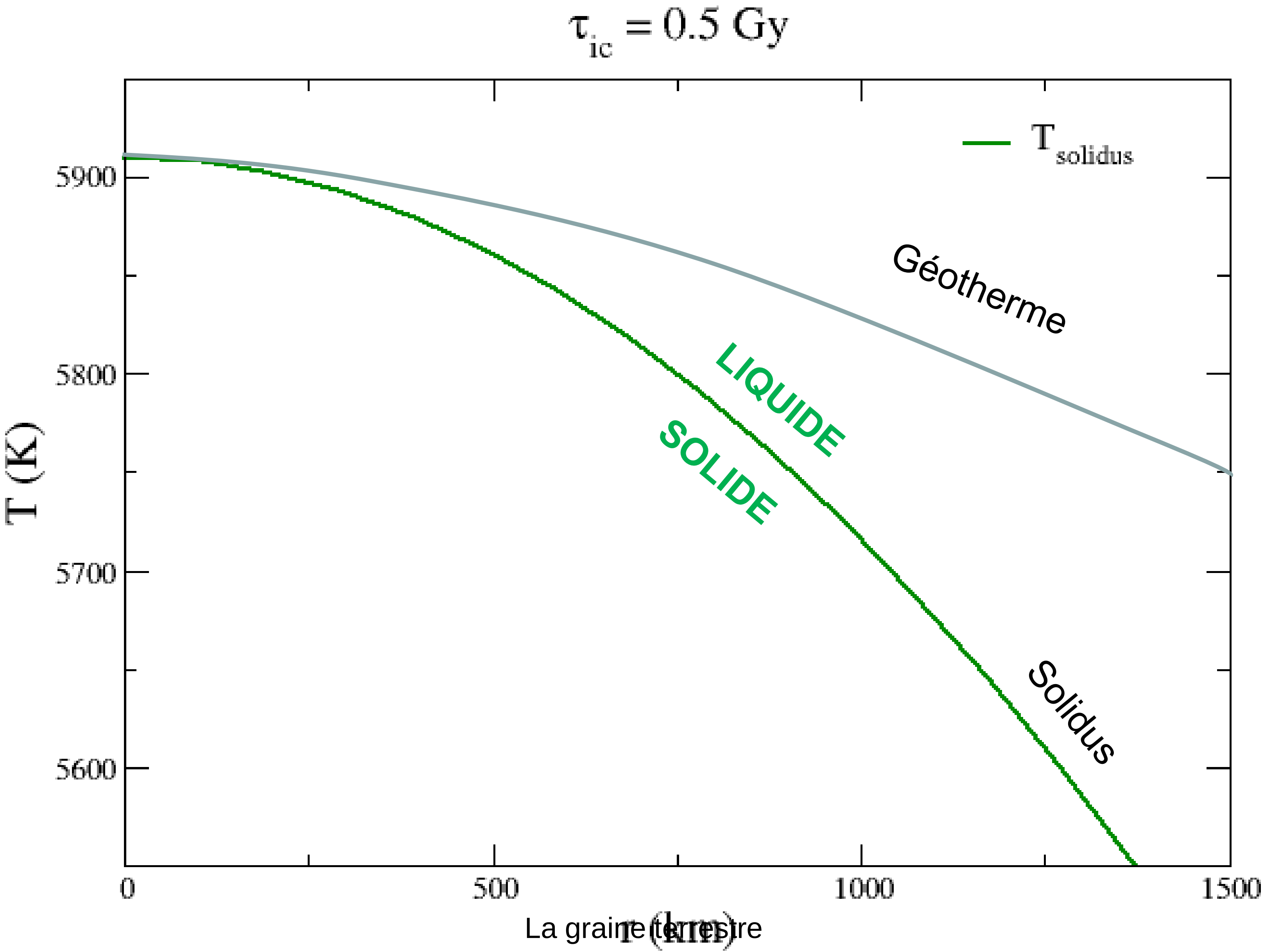


# Evolution thermique de la graine

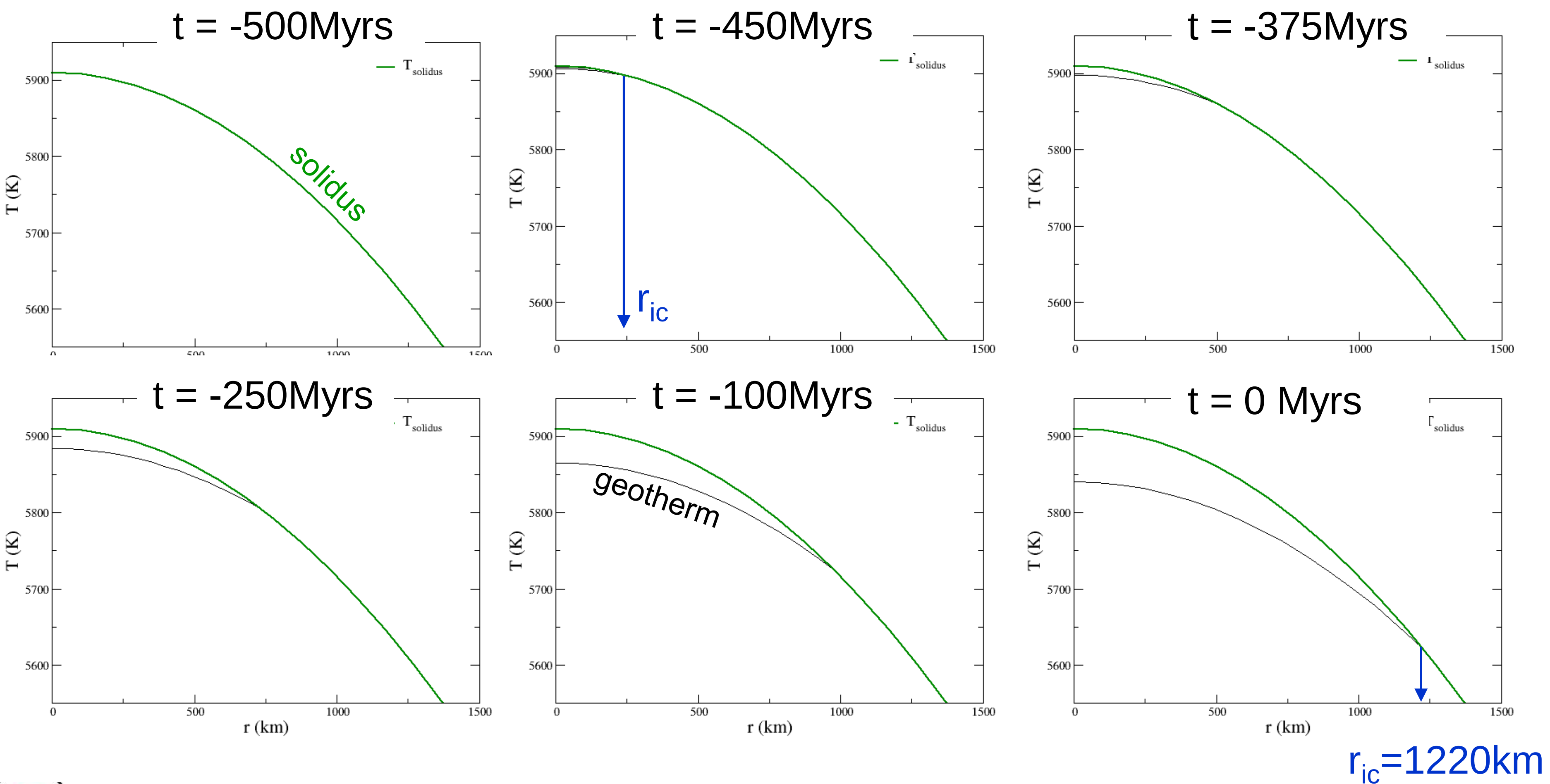


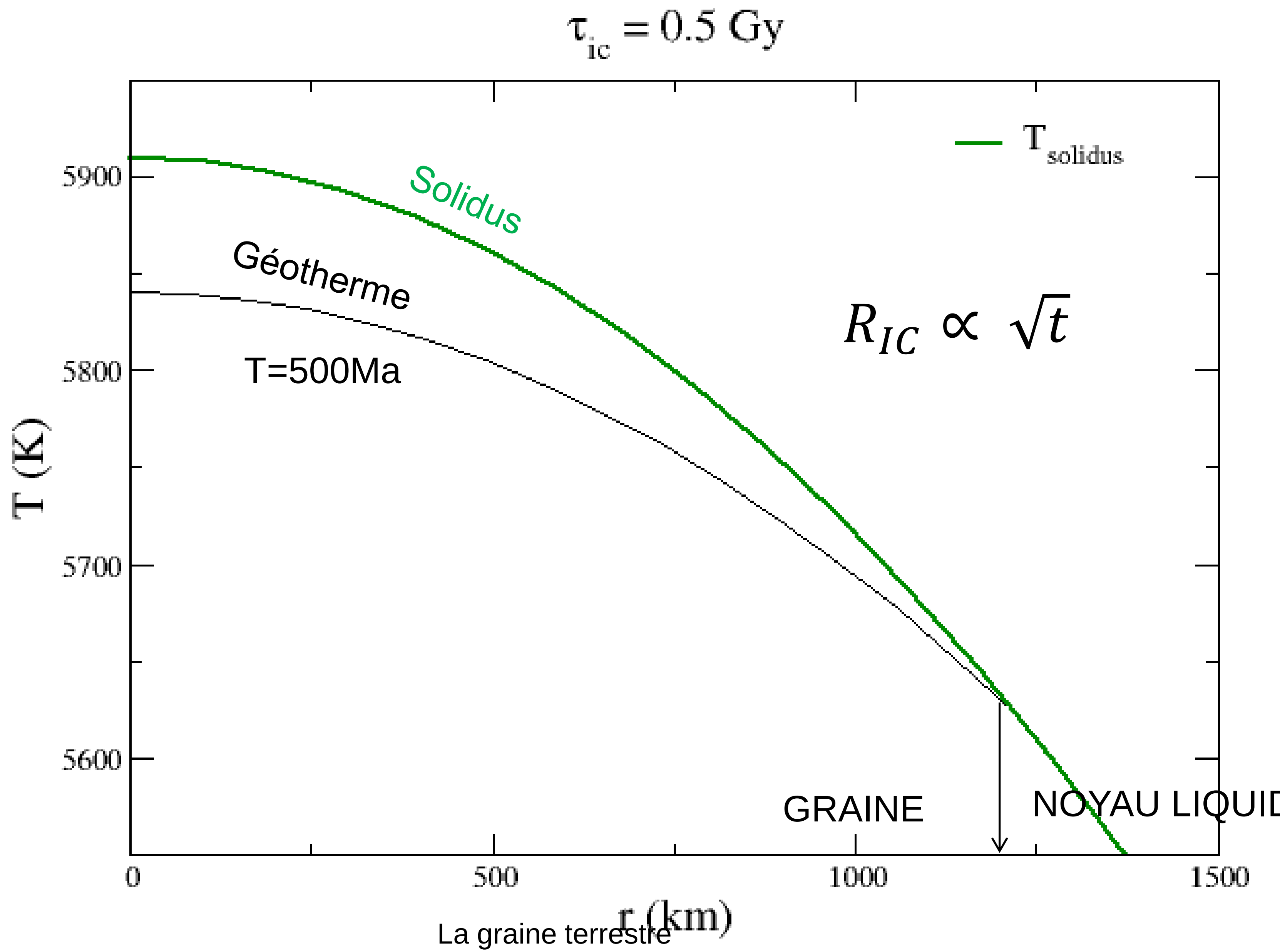

La graine terrestre

# Evolution thermique de la graine

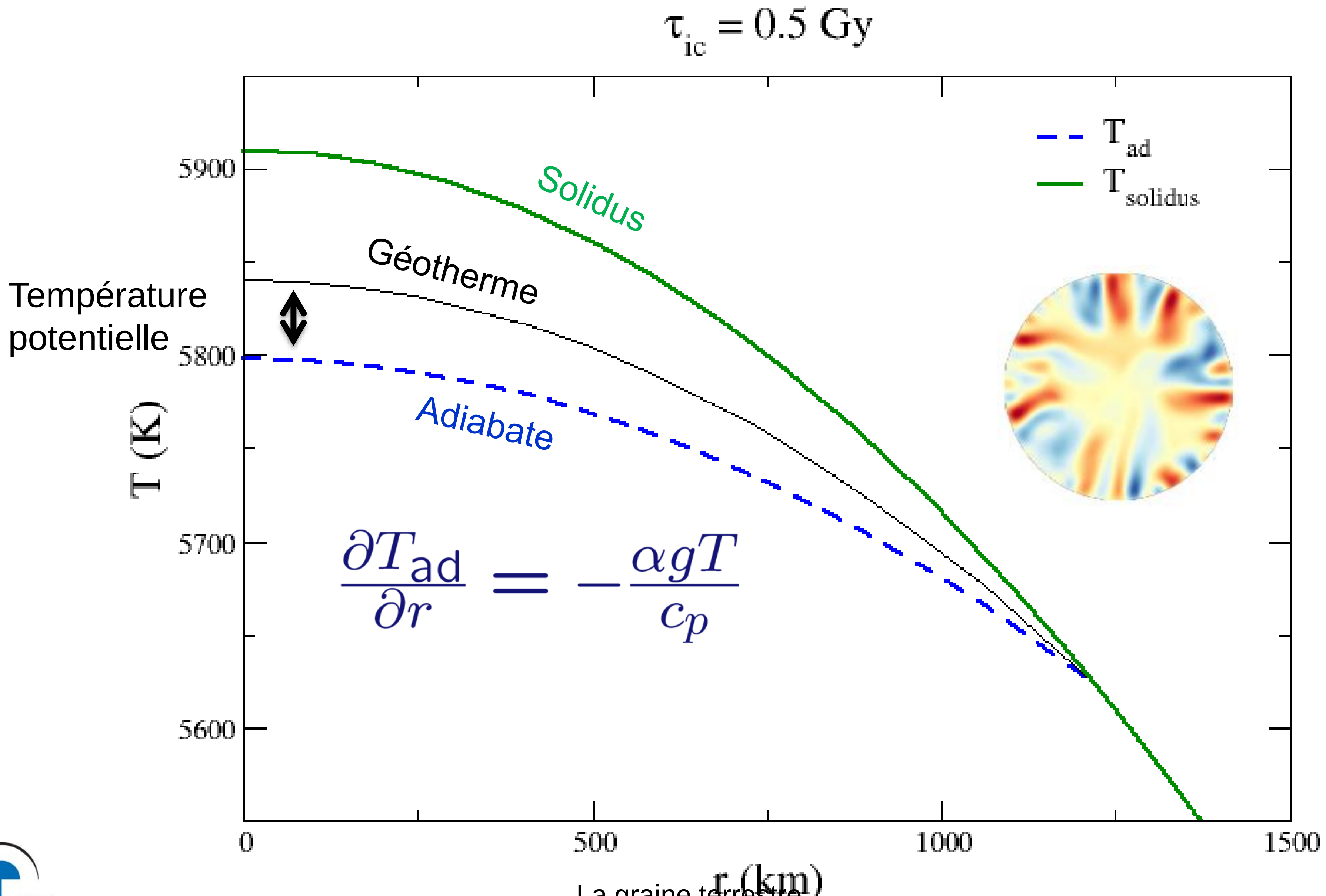


# Et la graine crut…

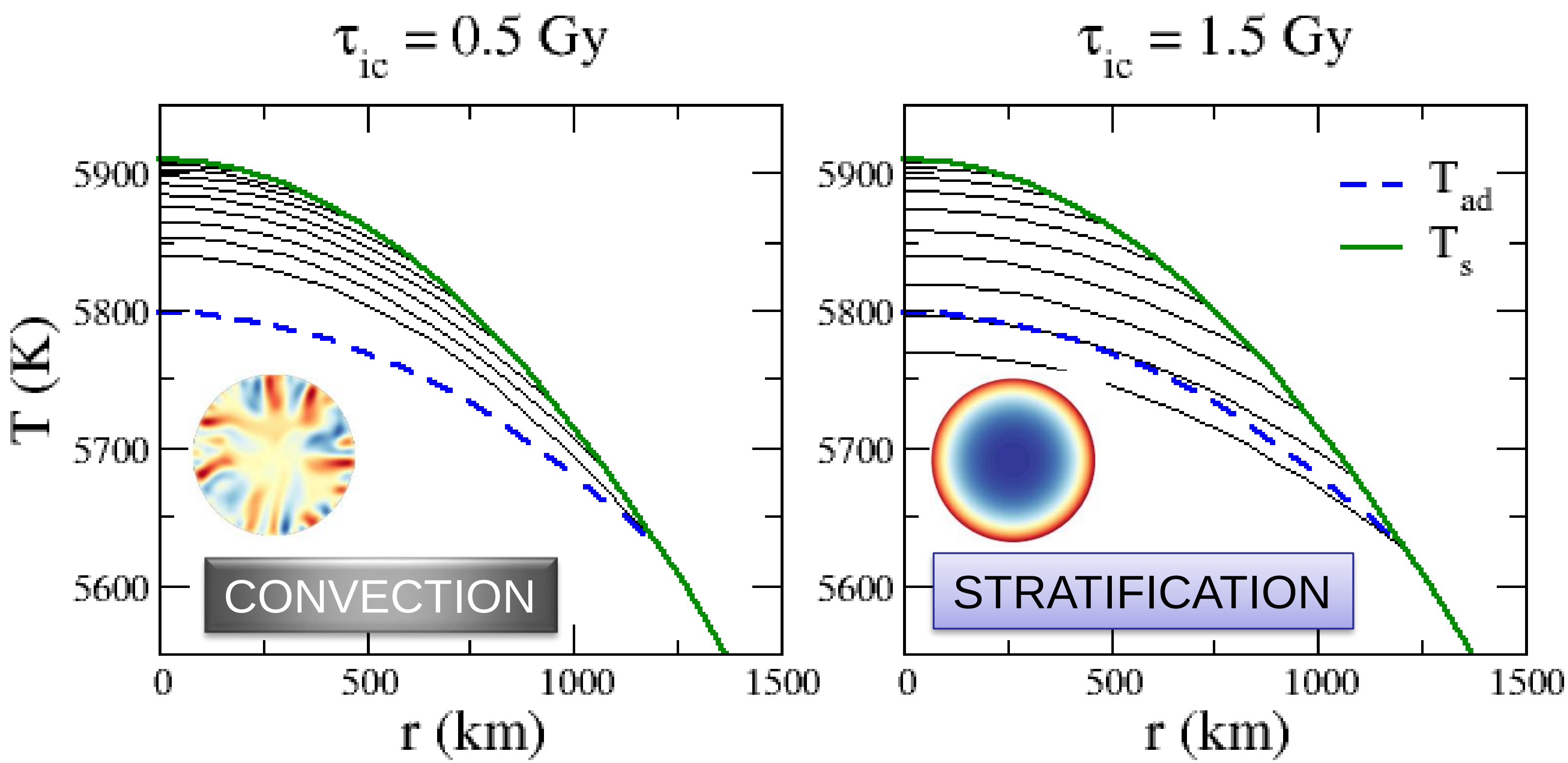



$\tau_{ic}$ = 0.5 Gy
$T_{solidus}$
Solidus
Géotherme
T=500Ma
$R_{IC} \propto \sqrt{t}$
5900
5800
5700
5600
T (K)
GRAINE
NOYAU LIQUID
0
500
1000
1500
r (km)

# Equilibre thermodynamique



# L'âge de la graine




**Le refroidissement de la graine contrôle son état dynamique**

**Flux de chaleur à la CMB**

**Conductivité thermique du Fer**

# Conductivité thermique du Fer

| Fer liquide | | | |
|---|---|---|---|
| Référence | Éléments légers | CMB | ICB |
| Stacey & Anderson (2001) | Si | 46 | 63 |
| Stacey & Loper (2007) | Ø | 28.3 | 29.3 |
| de Koker *et al.* (2012) (Fig. 3) | Ø | ~130 | ~210 |
| | Si ou O | 90-130 | 140-190 |
| Pozzo *et al.* (2013) | Ø | 159 | 246 |
| | $Fe_{82}Si_{10}O_8$ | 107 | 160 |
| | $Fe_{79}Si_8O_{13}$ | 99 | 148 |
| Gomi *et al.* (2013) | $Fe_{77.5}Si_{22.5}$ | 90.1 | 148 |
| | $Fe_{70}C_{30}$ | 84.2 | 136 |
| | $Fe_{76.8}O_{23.2}$ | 125 | 212 |
| | $Fe_{80.6}S_{19.4}$ | 130 | 220 |
| Seagle *et al.* (2013) | Ø | 67-145 | |
| | Si (9% en masse) | 41-60 | |
| Gomi & Hirose (2015) | $Fe_{67.5}Ni_{10}Si_{22.5}$ | 83.3-93.0 | |
| Gomi *et al.* (2016) | $Fe_{65}Ni_{10}Si_{25}$ | 87.1 | |
| Konôpková *et al.* (2016) | Ø | 33±7 | 46±9 |
| | Présents | 25±7 | 35±10 |
| Ohta *et al.* (2016) | $Fe_{67.5}Ni_{10}Si_{22.5}$ | $88^{+29}_{-13}$ | |
| Xu *et al.* (2018) | Présents | 77±10 | |
| Zhang *et al.* (2020) | ~8% en masse et ~5% Ni | 70±10 | |

| Fer solide | | |
|---|---|---|
| Référence | Éléments légers | graine |
| Stacey & Anderson (2001) | Si | 79 |
| Gomi & Hirose (2015) | $Fe_{79}Ni_{10}Si_{11}$ | 166.9-183.4 |
| Konôpková *et al.* (2016) | Ø | 46±9 |
| | Présents | 35±10 |
| Xu *et al.* (2018) | Ø | 147 |

TABLE 3.2 – Estimations de la conductivité du fer en $W.m^{-1}.K^{-1}$ dans les conditions du noyau, les études expérimentales sont grisées, elles donnent une estimation de la conductivité thermique par extrapolation des résultats expérimentaux.

Métayer, 2022)

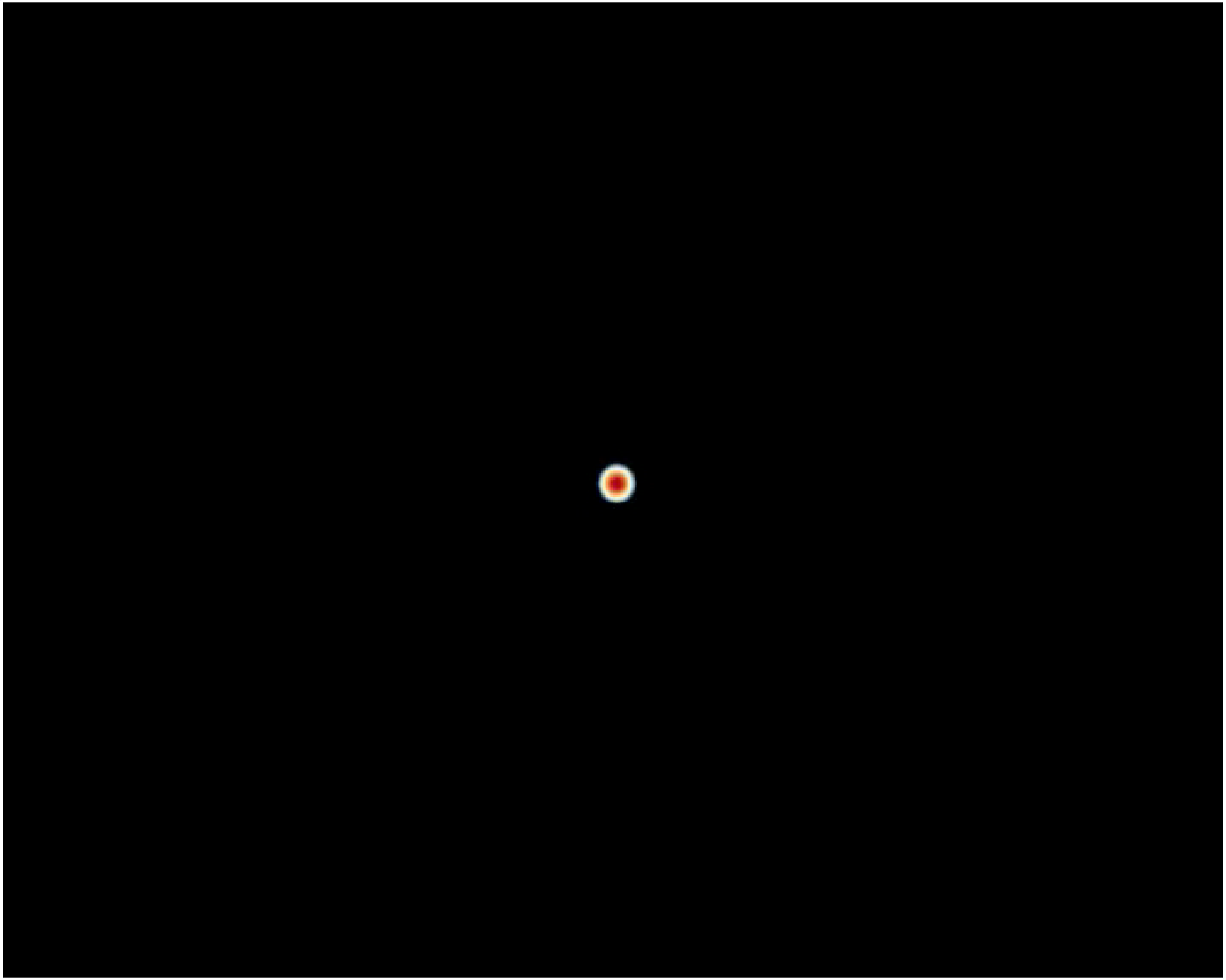
La graine terrestre

ISTerre

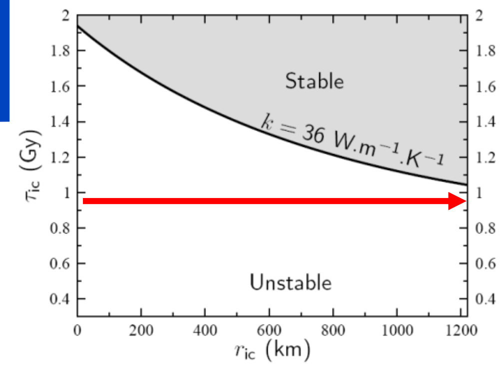
# Plan

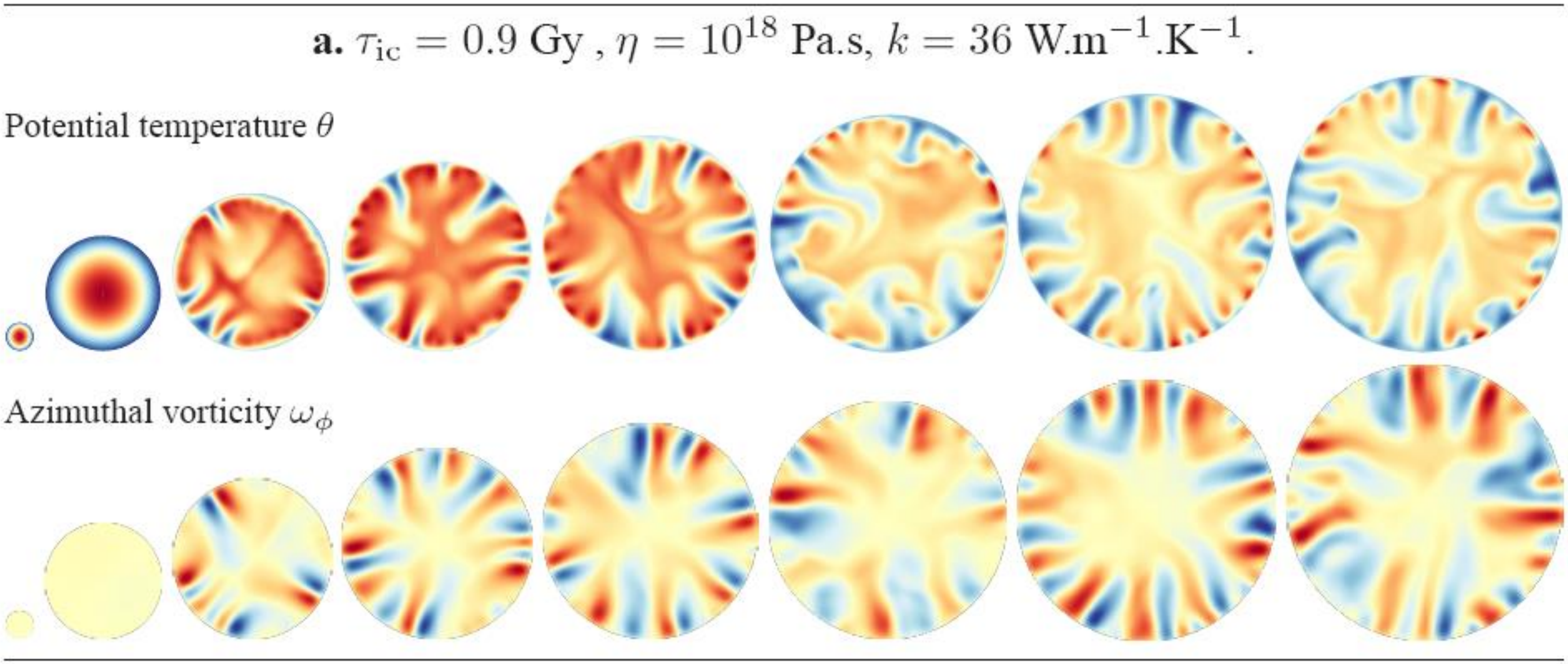
1. Sismologie de la graine
2. Une graine en Fer ?
3. Formation de la graine
4. Dynamique de la graine
5. L'anisotropie de la graine

# Convection thermique dans la graine

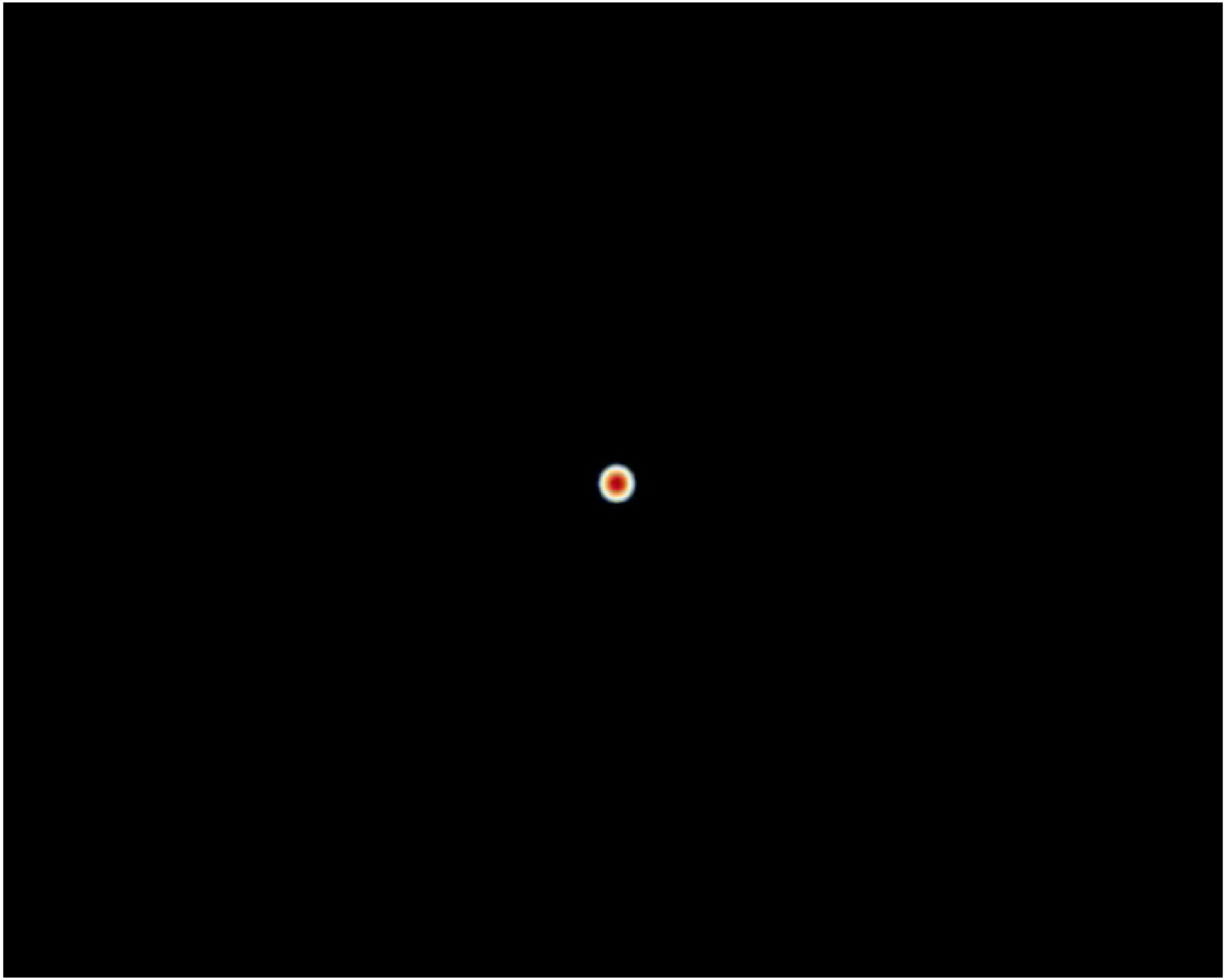


# Convection thermique

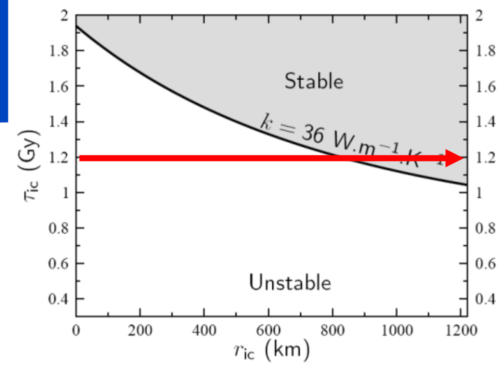


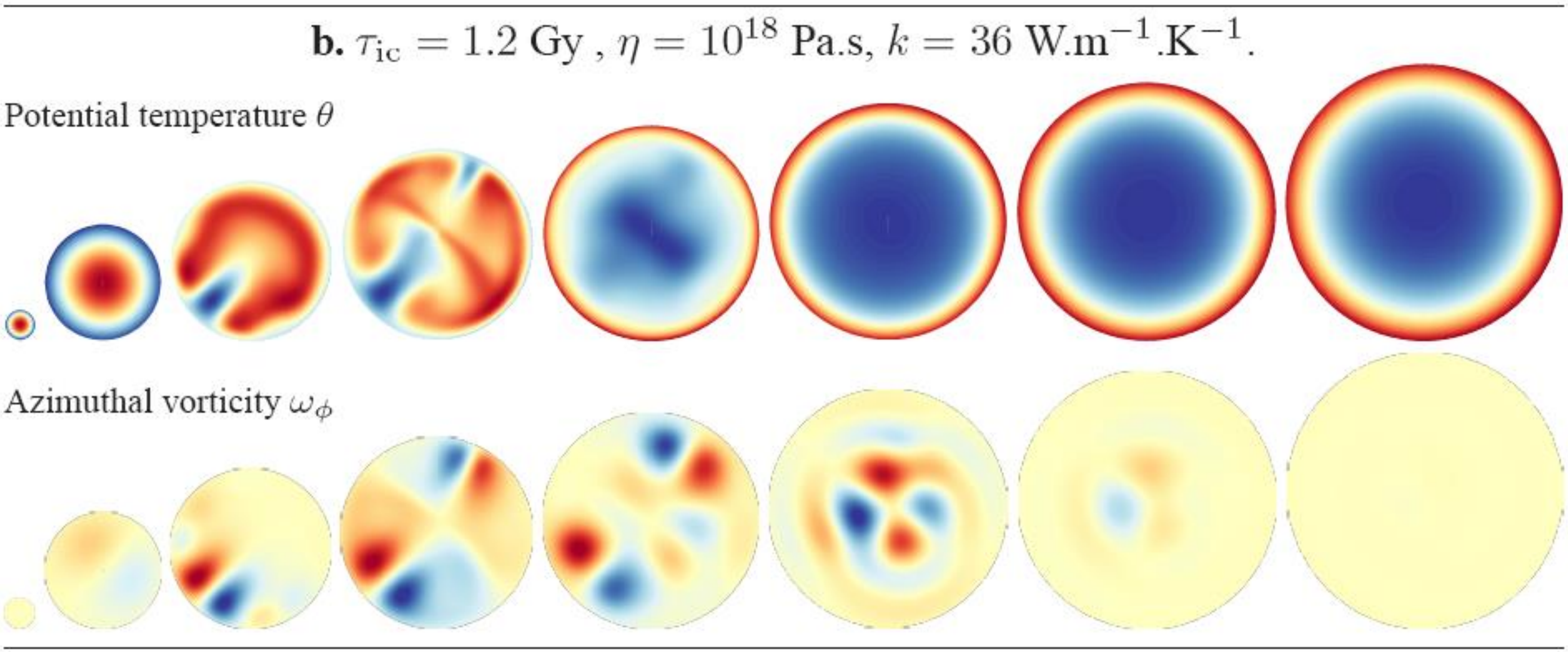



# Convection thermique dans la graine

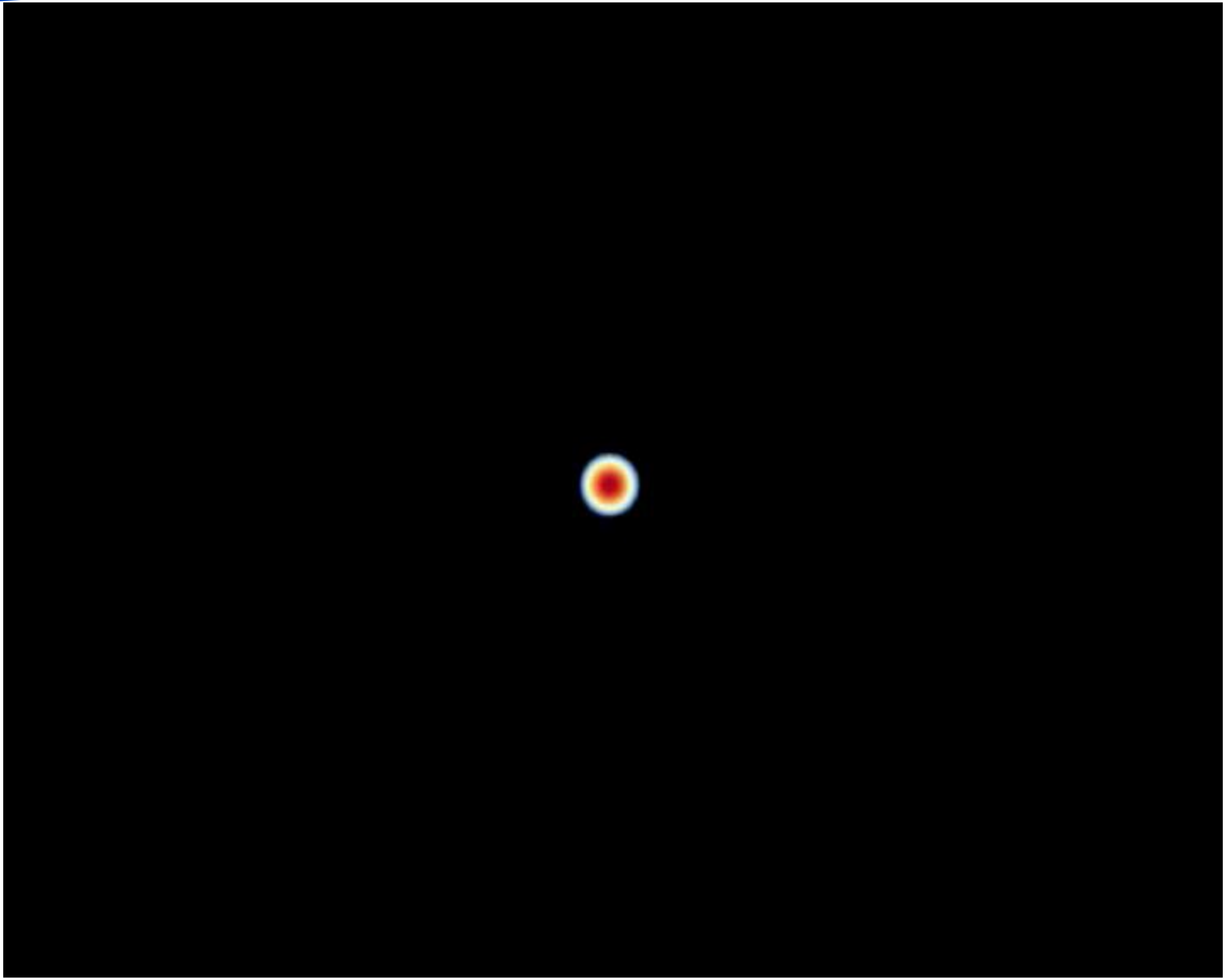


# Une fenêtre convective

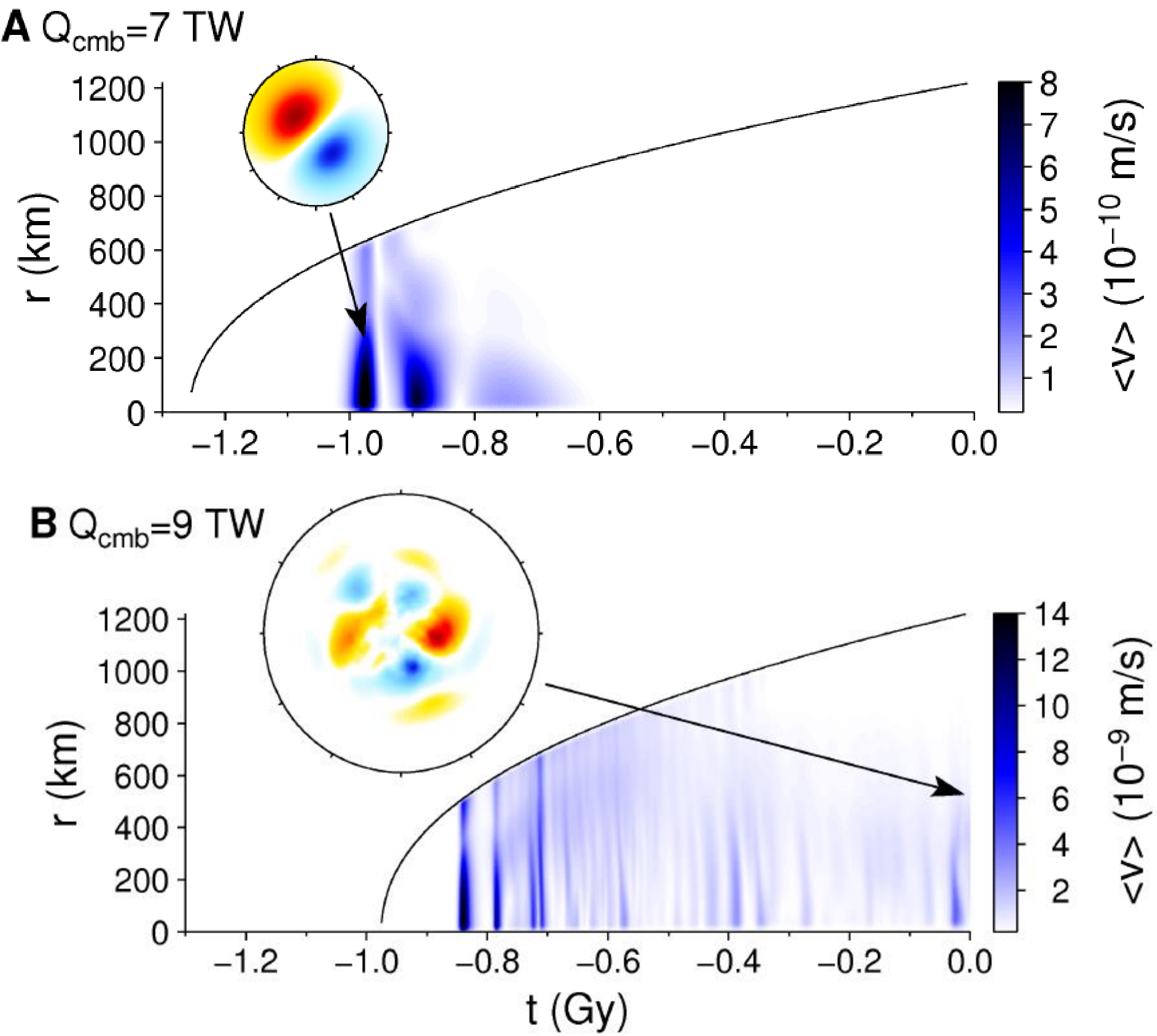


# Épisode convectif dans la graine



# Un pépin dans la graine!

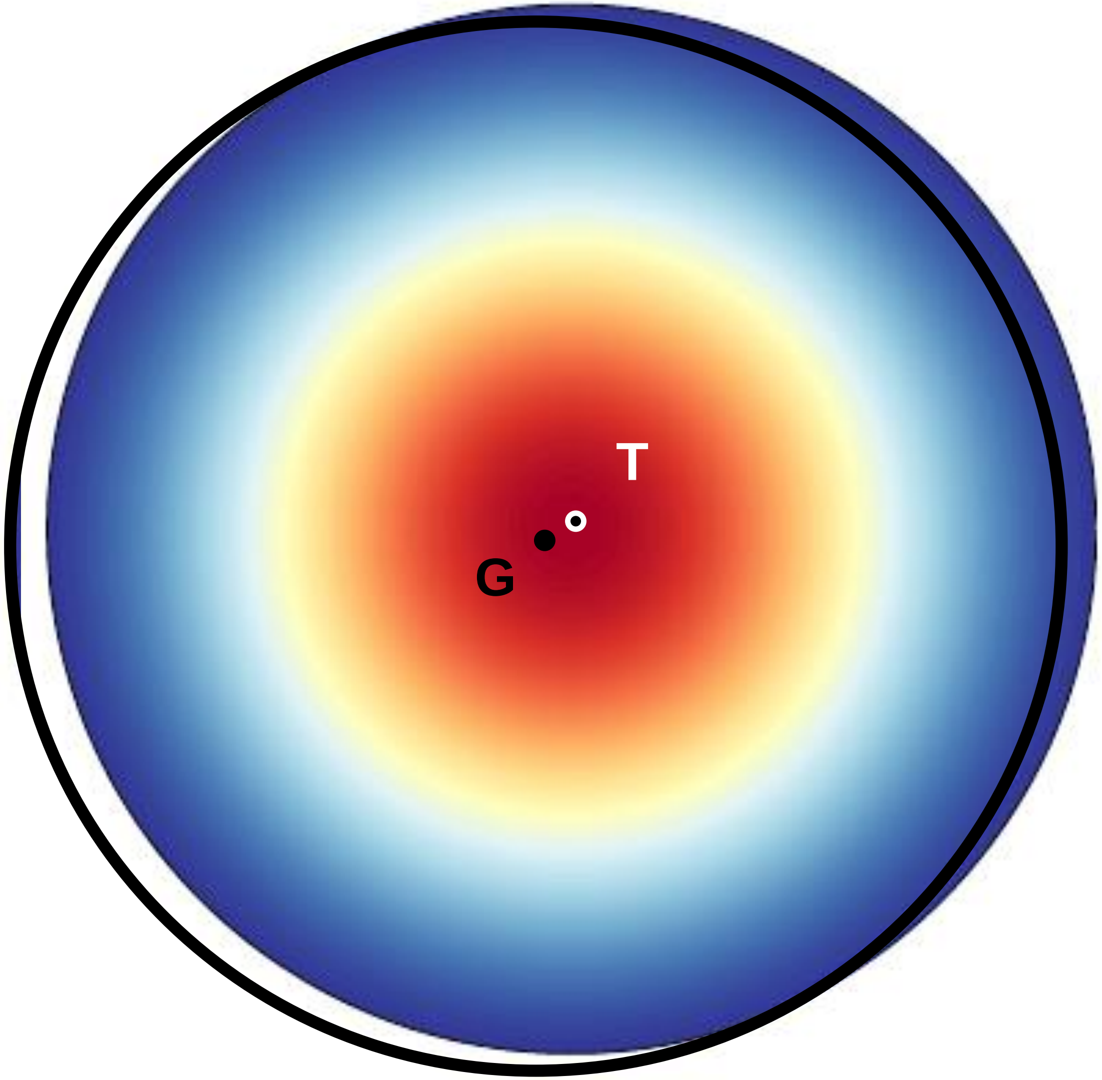


# Un mode convectif particulier

1. Soit une graine
   rigide ou très visqueuse
   thermiquement neutre
   ou sous critique

2. Frontière = solidus (P)

3. Translatez là alors G<>T



# Un mode convectif particulier

1. Soit une graine
   rigide ou très visqueuse
   thermiquement neutre
   ou sous critique

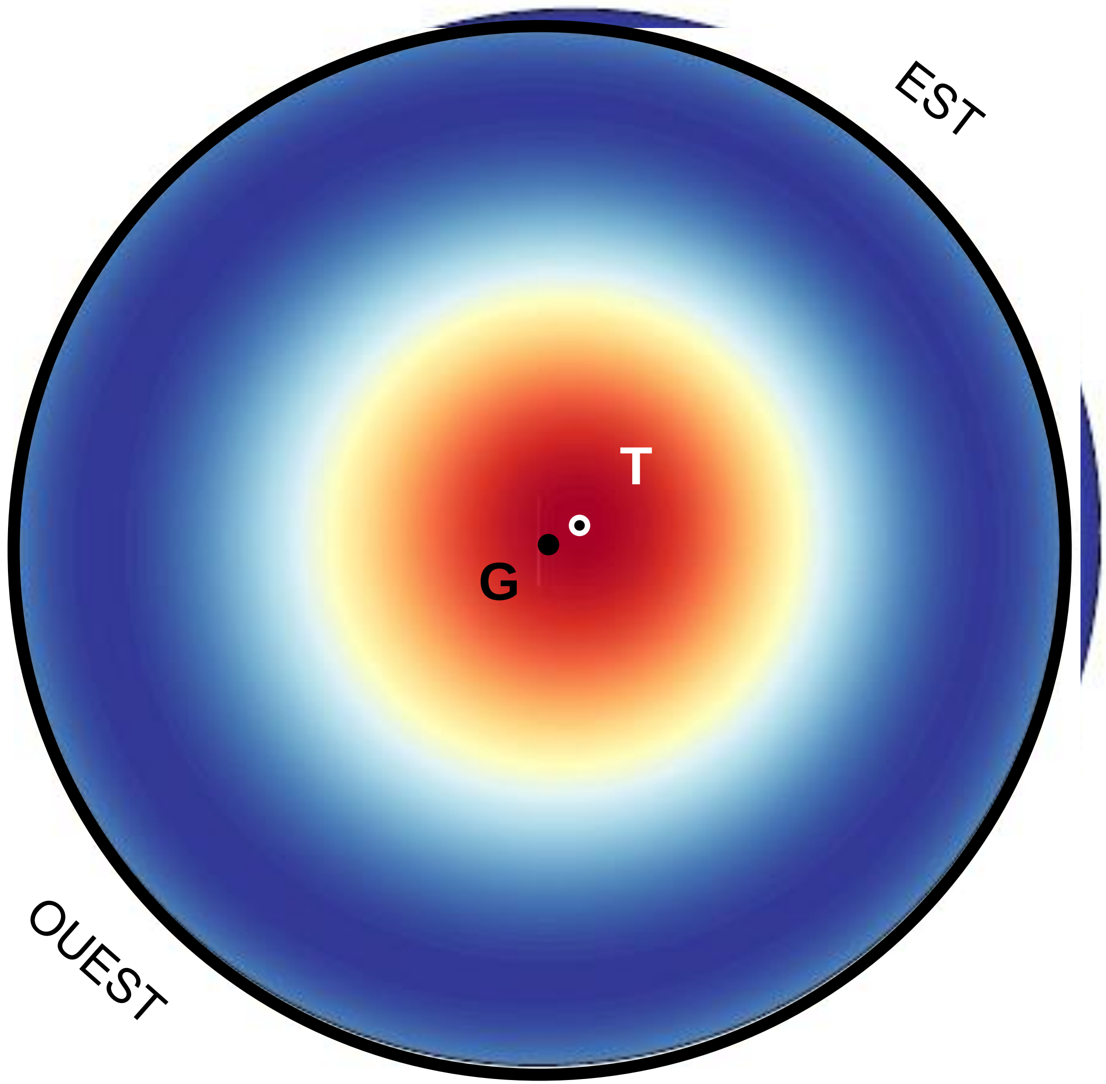
2. Frontière = solidus (P)

3. Translatez là alors G<>T

4. Fondez et cristallisez
   selon le solidus - rapide

5. Force d'Archimède entretient
   la translation

6. Variabilité hémisphérique
   de l'anisotropie



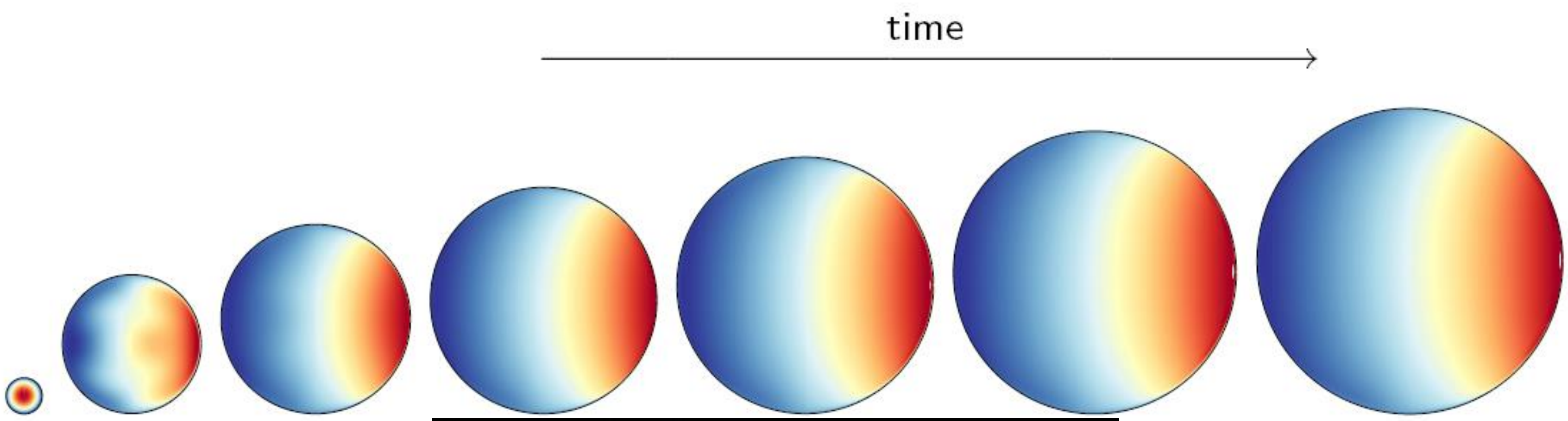

Alboussière et al, Nature, 2010

Monnereau et al, Science, 2010

# translation

$\tau_{ic} = 0.9$ Gy , $k = 36$ W.m$^{-1}$.K$^{-1}$, potential temperature :

- $\eta = 10^{19}$ Pa.s, translation regime :




# Convection et translation

Pour des viscosités modérées

# Plan

1. Sismologie de la graine
2. Une graine en Fer ?
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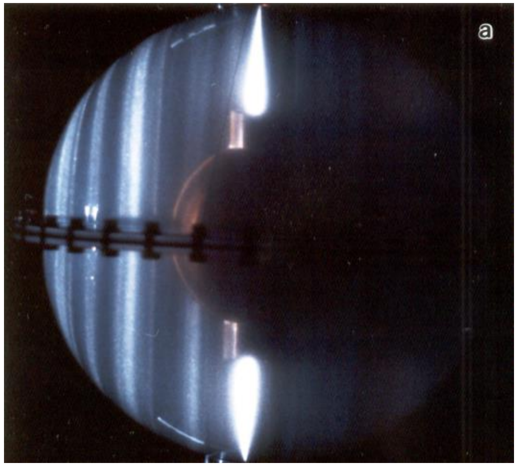
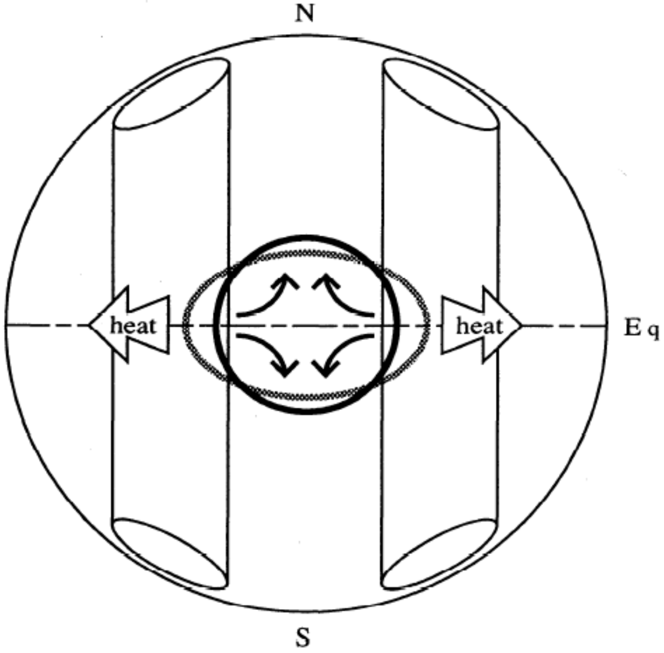
4. Dynamique de la graine
5. L'anisotropie de la graine

# Croissance équatoriale préferentielle



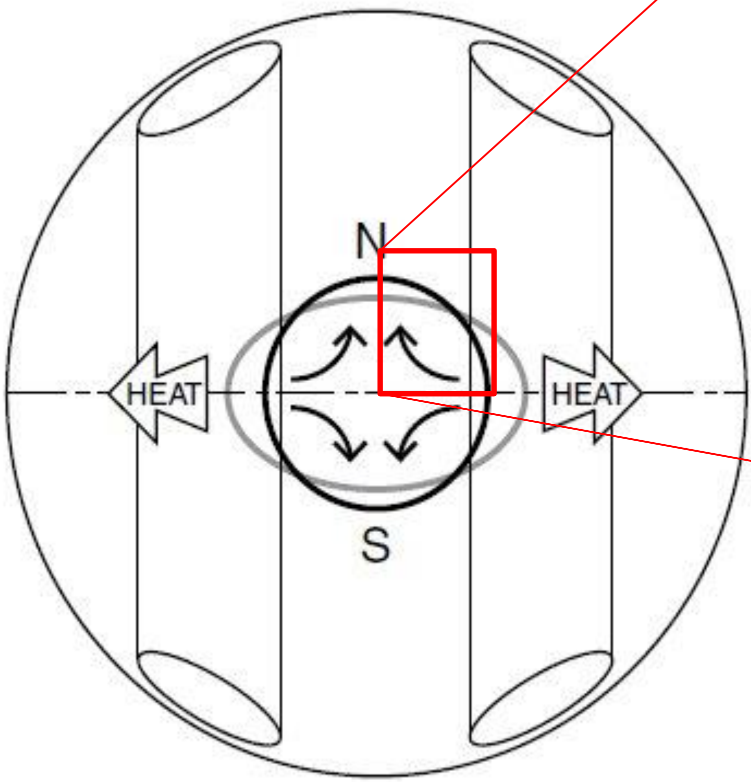


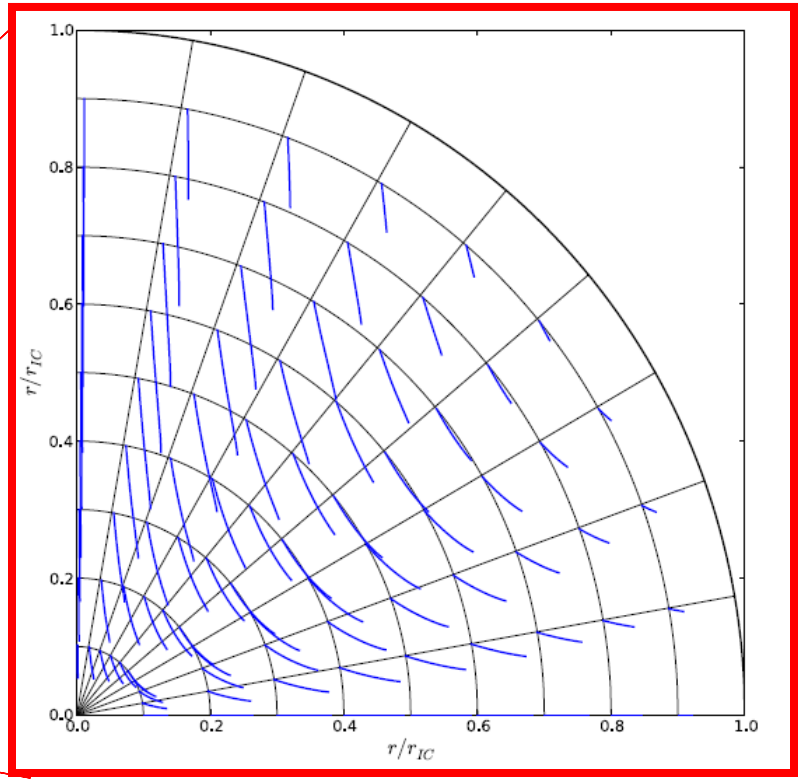

Yoshida et al, 1996

La graine croitrait deux fois plus vite dans sa zone équatoriale que dans sa zone polaire

Relaxation visqueuse quadripolaire

# Equatorial preferential growth




Trajectories of solid particles
(1/4 of a meridionnal plan)

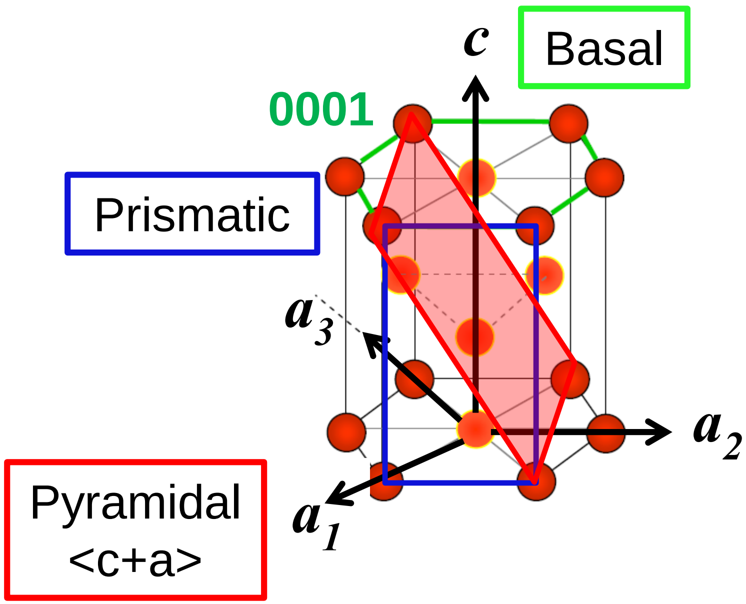
*Yoshida et al. [1996]*

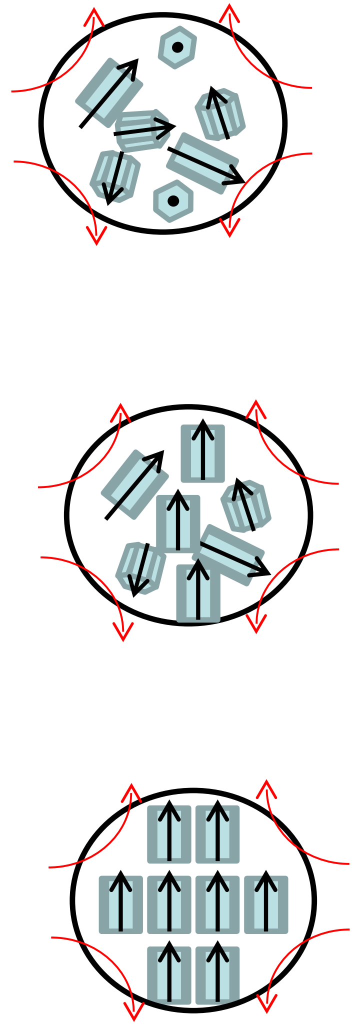
# Anisotropie de texture

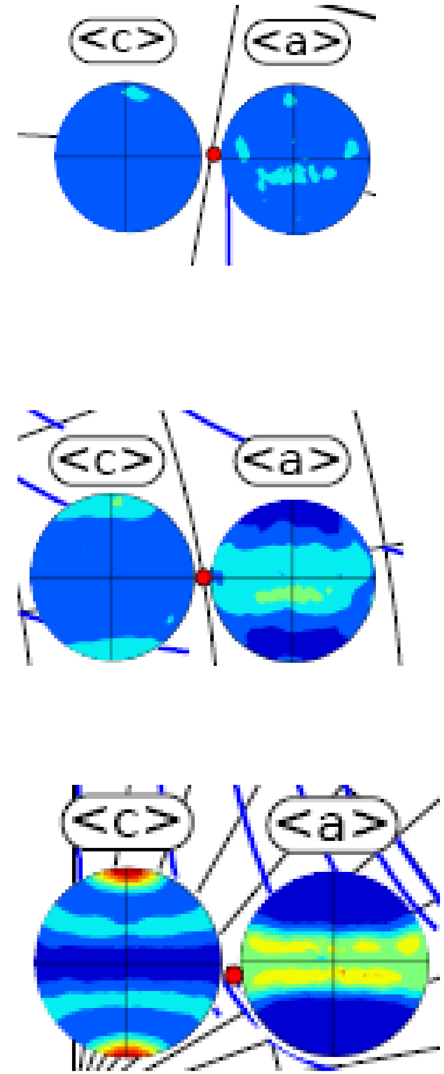
Déformation plastique

ou recristallisation

# Visco Plastic Self Consistent model

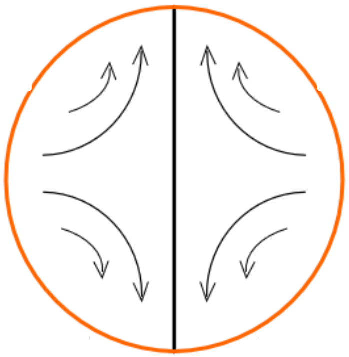




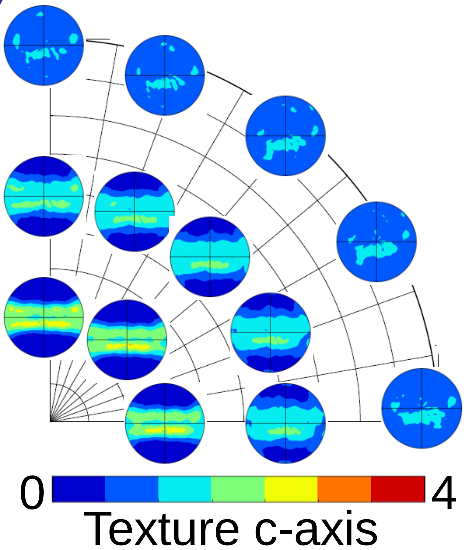
# Direct model of an elastic inner core

Geodynamical model + Crystalline model (basal) → Textured IC VPSC → Elastic IC → Seismic response?

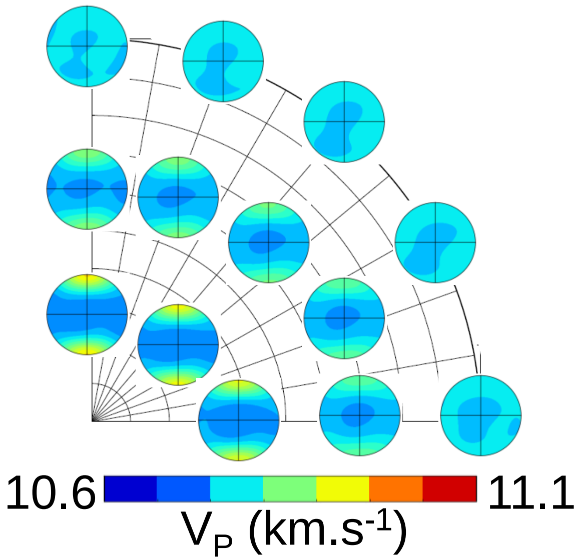


*Yoshida et al [1996]*

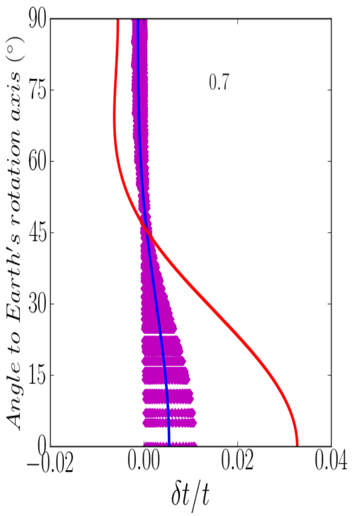
*Merkel et al [2006]*




*Lebenshon et al [1993]*



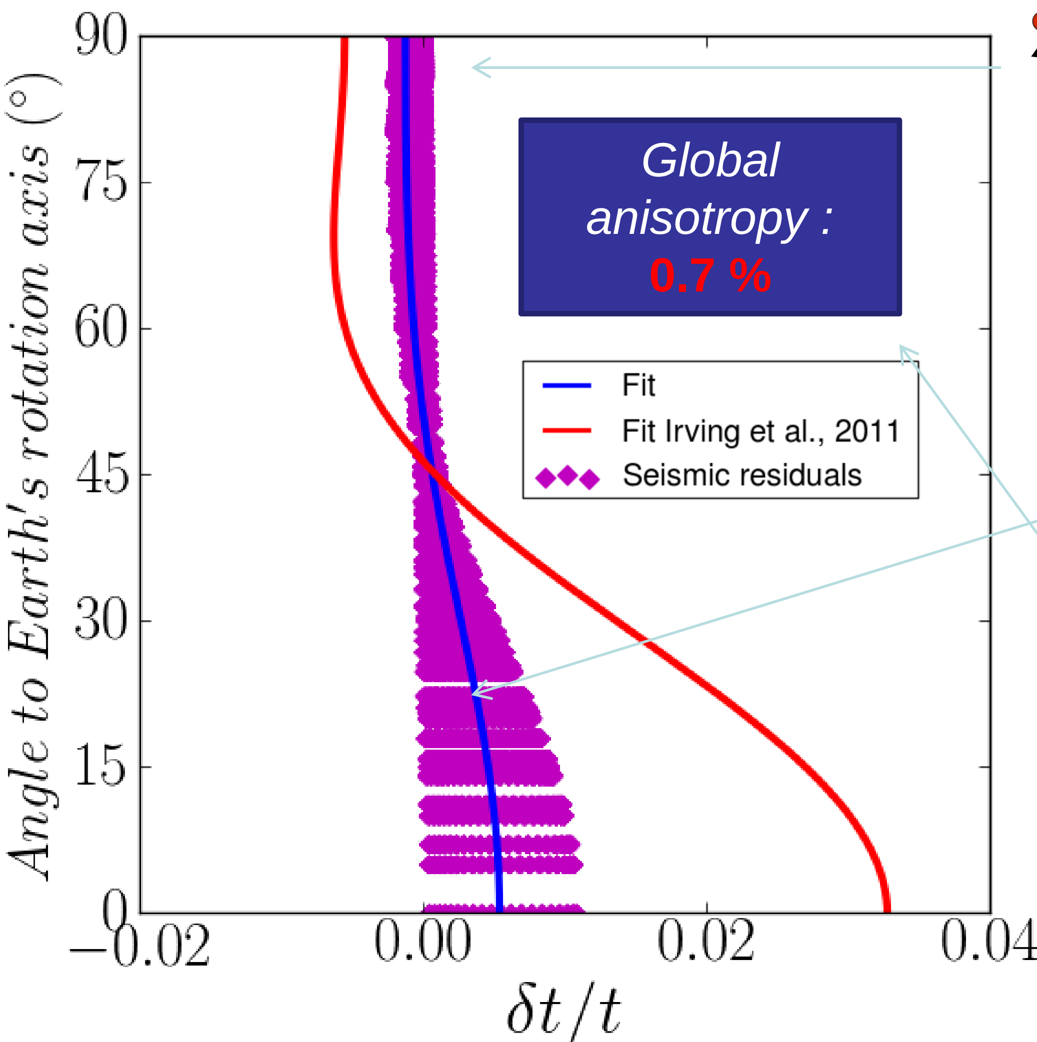

*Vocadlo et al [2009]*

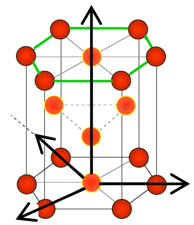



*Lincot et al [2014]*

# Global anisotropy for hcp Fe

*Vocadlo et al. [2009]*



**Seismic residuals**

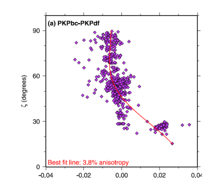
$$\frac{\delta t}{t} = \frac{s_{ray} - s_0}{s_0}$$

Where $s_0$ = average slowness in IC

**Fitting residuals (hyp : homogeneous IC)**

$$\frac{\delta t}{t} = a + b\cos^2\zeta + c\cos^4\zeta$$

**Estimate of N-S anisotropy ($b + c$) → global anisotropy**



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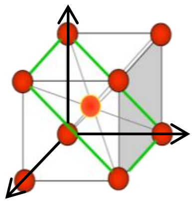
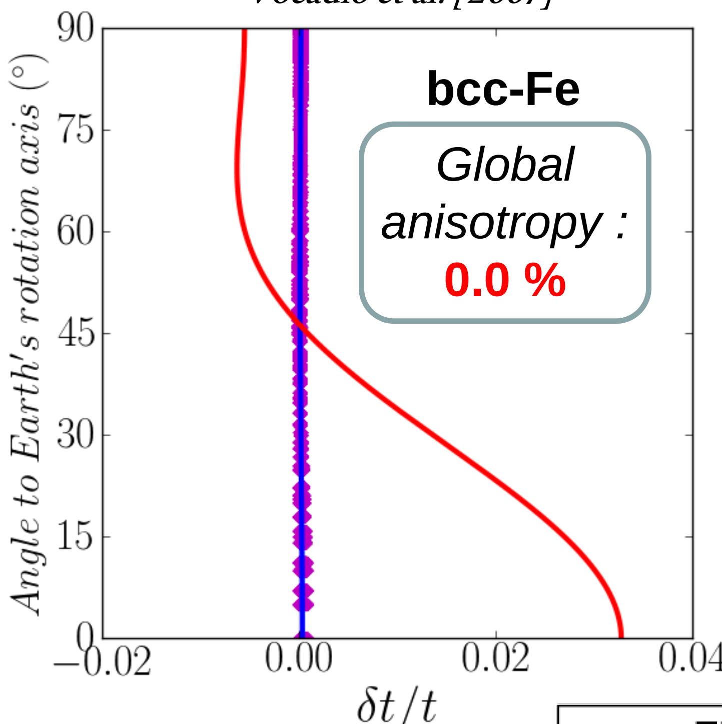
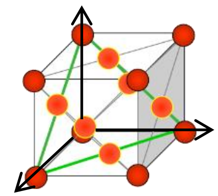
# Seismic response to an IC made of cubic Fe

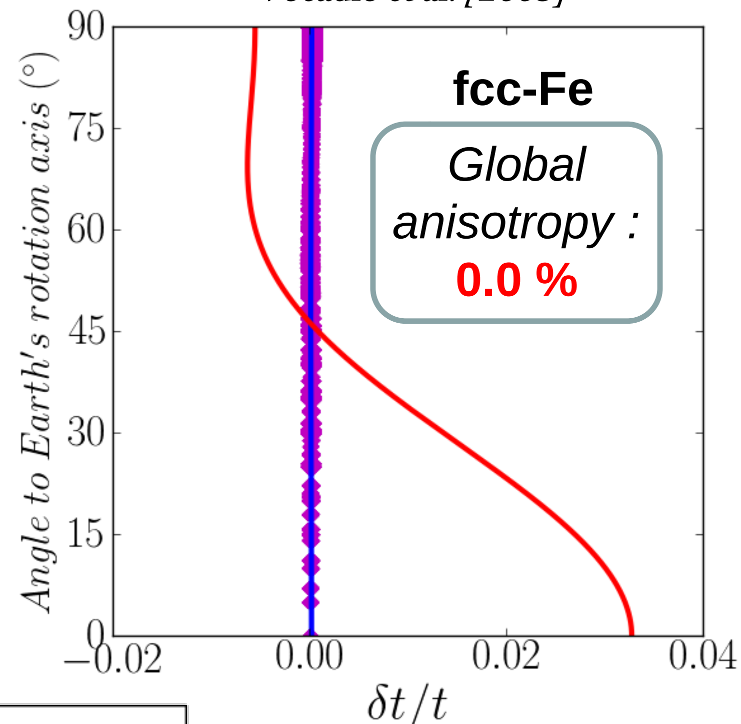


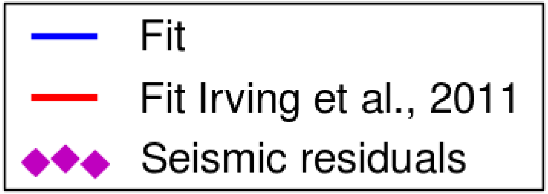
*Vocadlo et al. [2007]*



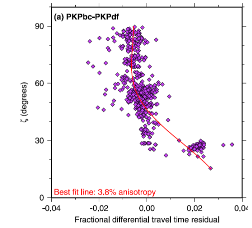



*Vocadlo et al. [2008]*



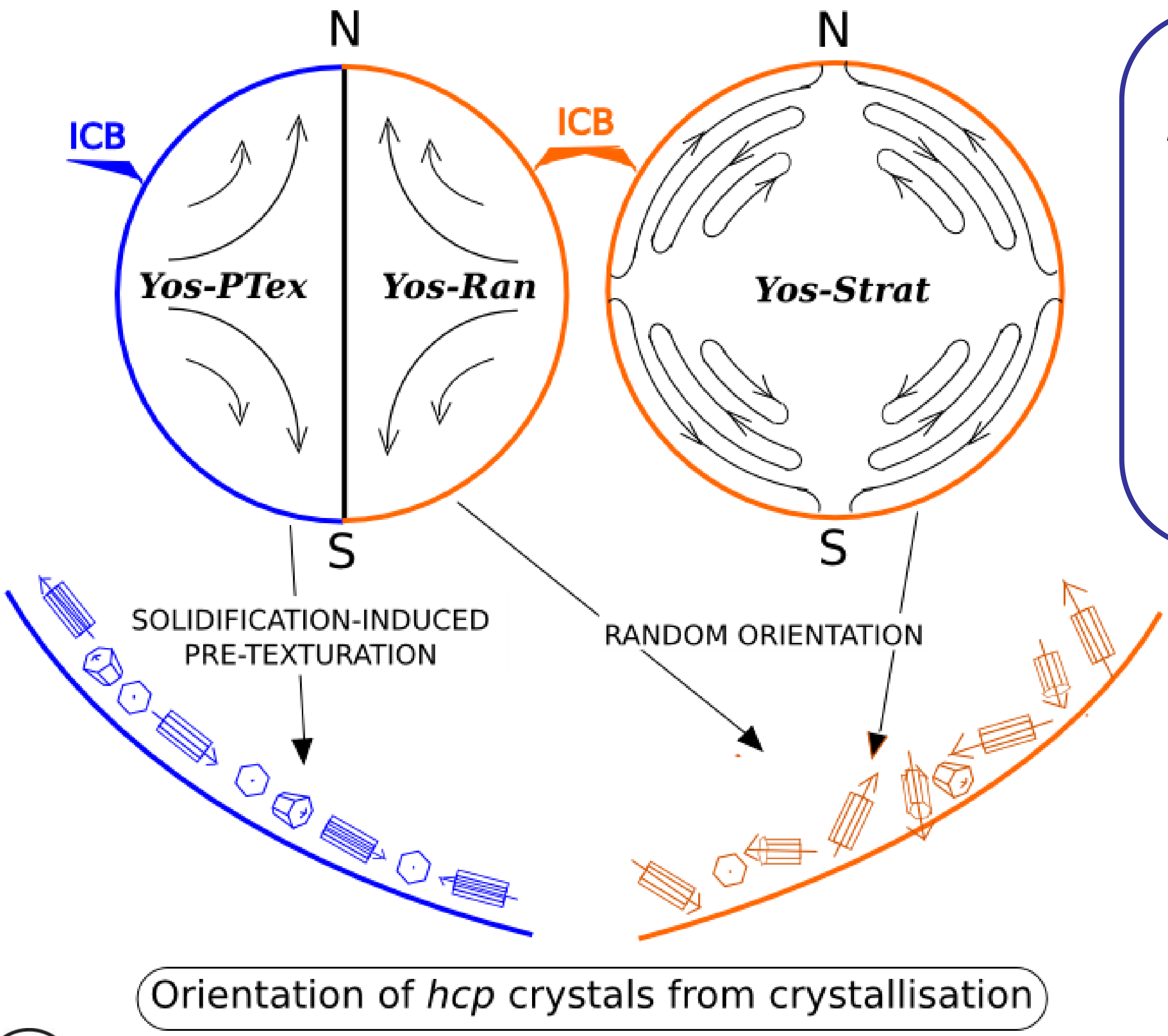




La graine terrestre




ISTerre

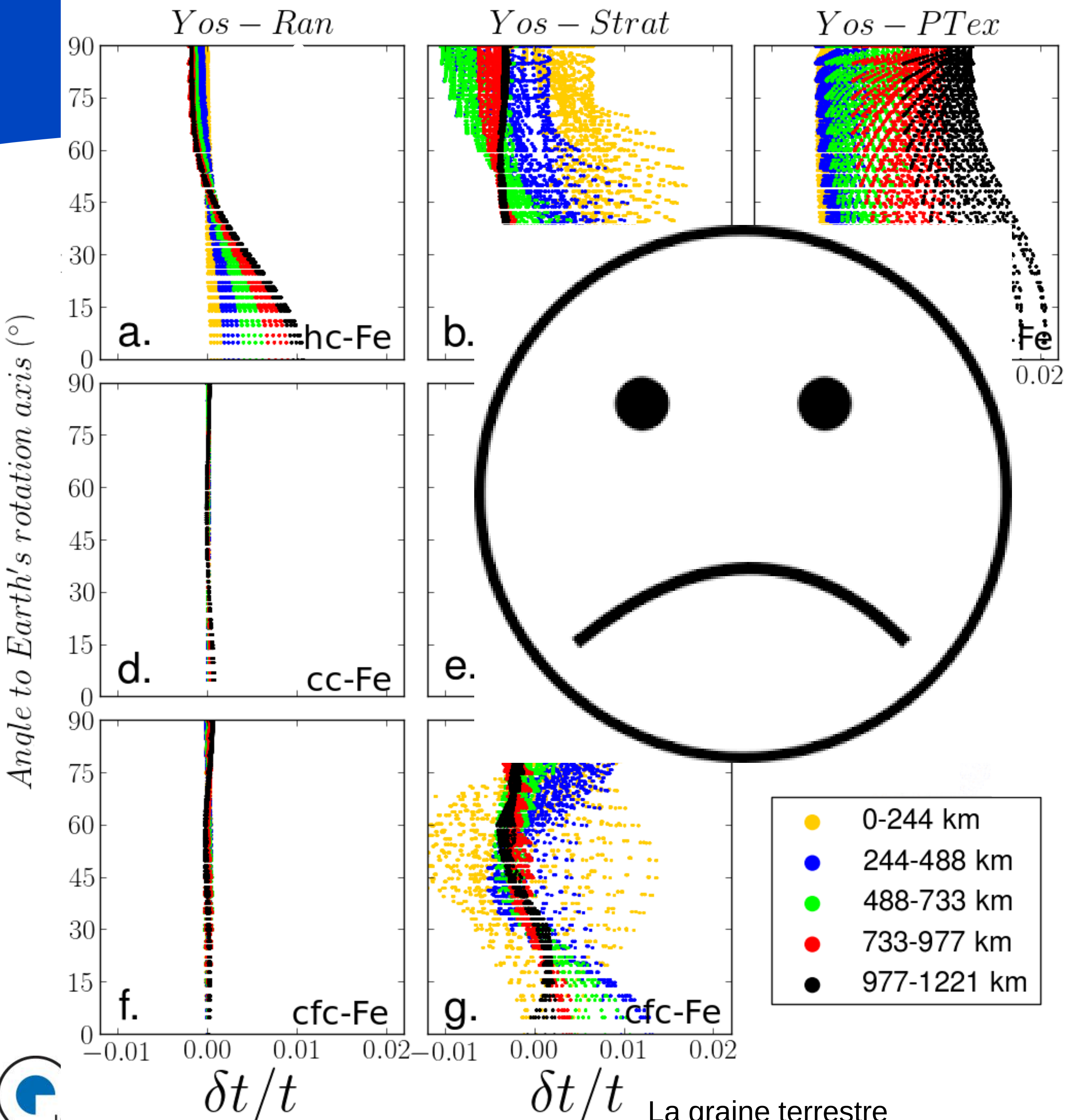
# How to increase the texturing ?



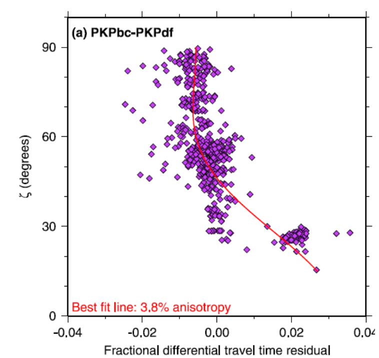

*Other geodynamical processes tested :*

- *Solidification texture CPO for Fe (developping extra texturing at ICB)*
- *Stratification (up to 300% deformation)*

*Deguen et al. [2009]*



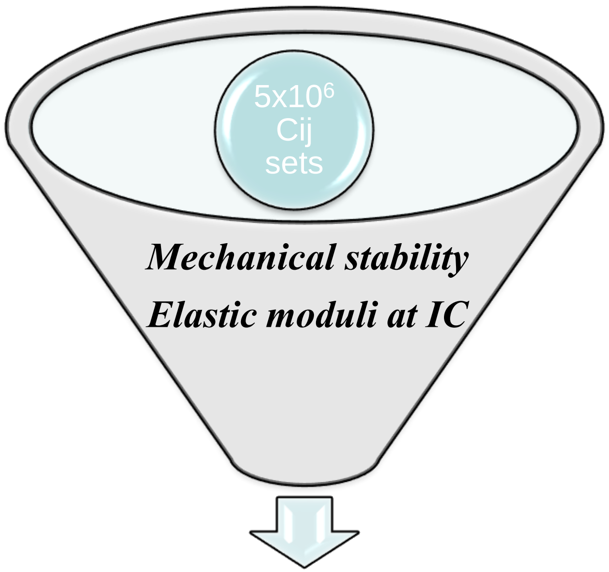
$Yos - Ran$
$Yos - Strat$
$Yos - PTex$
$Angle\ to\ Earth's\ rotation\ axis\ (°)$
a.
hc-Fe
b.
Fe
d.
cc-Fe
e.
f.
cfc-Fe
g.
cfc-Fe
$\delta t / t$
$\delta t / t$
0-244 km
244-488 km
488-733 km
733-977 km
977-1221 km

(a) PKPbc-PKPdf
ζ (degrees)
Best fit line: 3.8% anisotropy
Fractional differential travel time residual

# Random draw of Cij values (Monte Carlo)

– No «a priori» on elasticity




3000 synthetic models

*Note : global anisotropy depends on shape of single crystal anisotropy, not on individual Cij values.*

***Mechanical stability***

**hcp**

$$C_{11} - C_{12} > 0$$
$$C_{11} + C_{12} + C_{33} > 0$$
$$(C_{11} + C_{12})C_{33} - 2C_{13}^2 > 0$$
$$C_{44} > 0$$

**bcc**

$$C_{11} - C_{12} > 0$$
$$C_{11} + 2C_{12}) > 0$$
$$C_{44} > 0$$

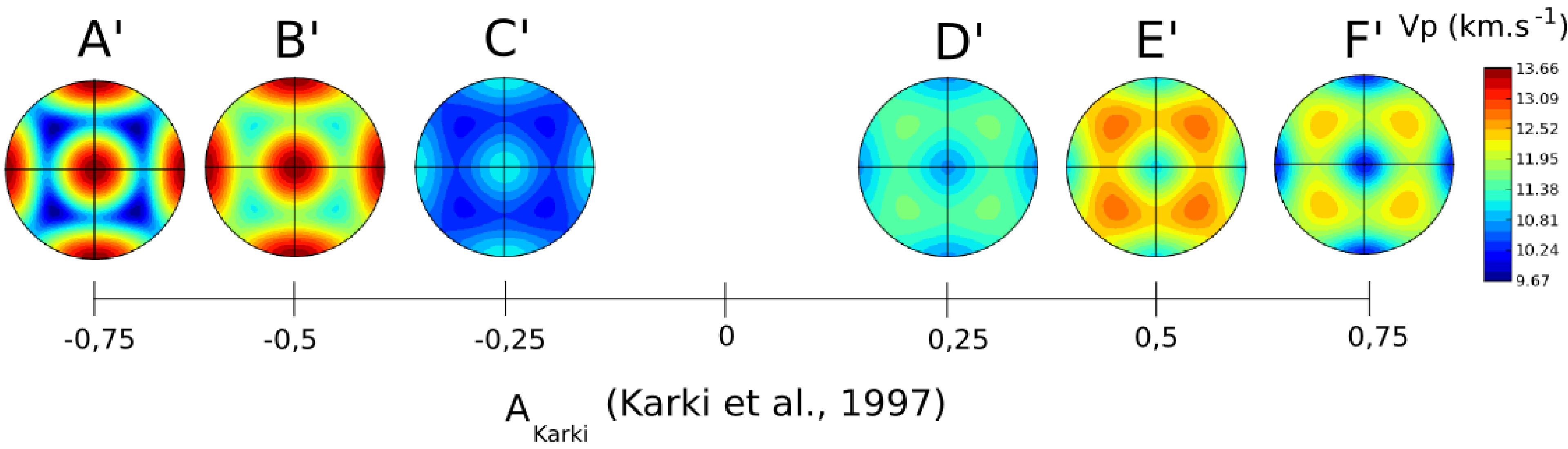
***Elastic moduli at IC conditions***

$$K = 1384.4\ GPa \pm 15\%$$
$$G = 166.4\ GPa \pm 15\%$$

# K dimensionless parameter of critallographic anisotropy

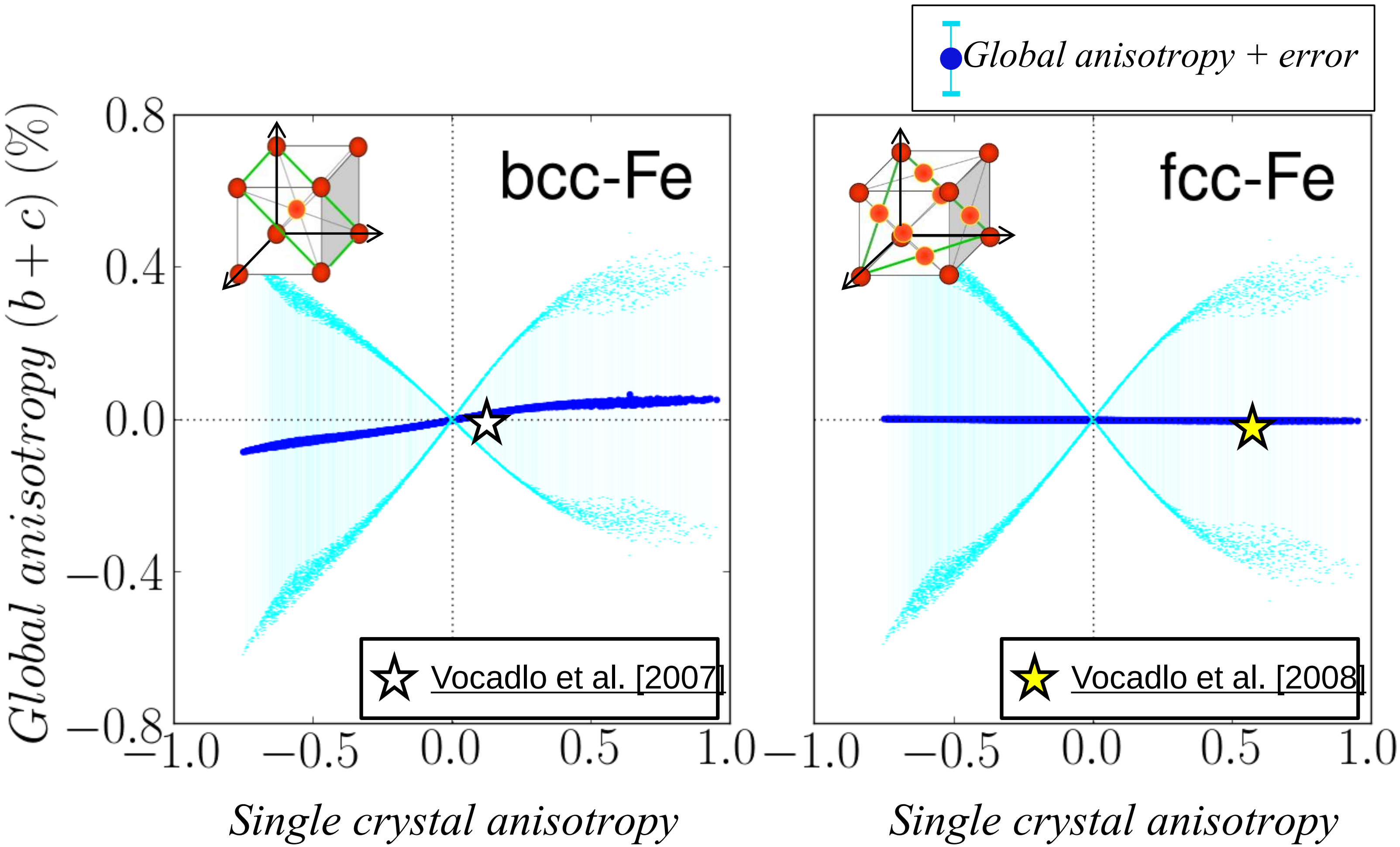
**The Karki parameter**

$$K = \frac{2C_{44} + C_{12}}{C_{11}} - 1$$




(Karki et al., 1997)

# Global anisotropy for a cubic-Fe inner core



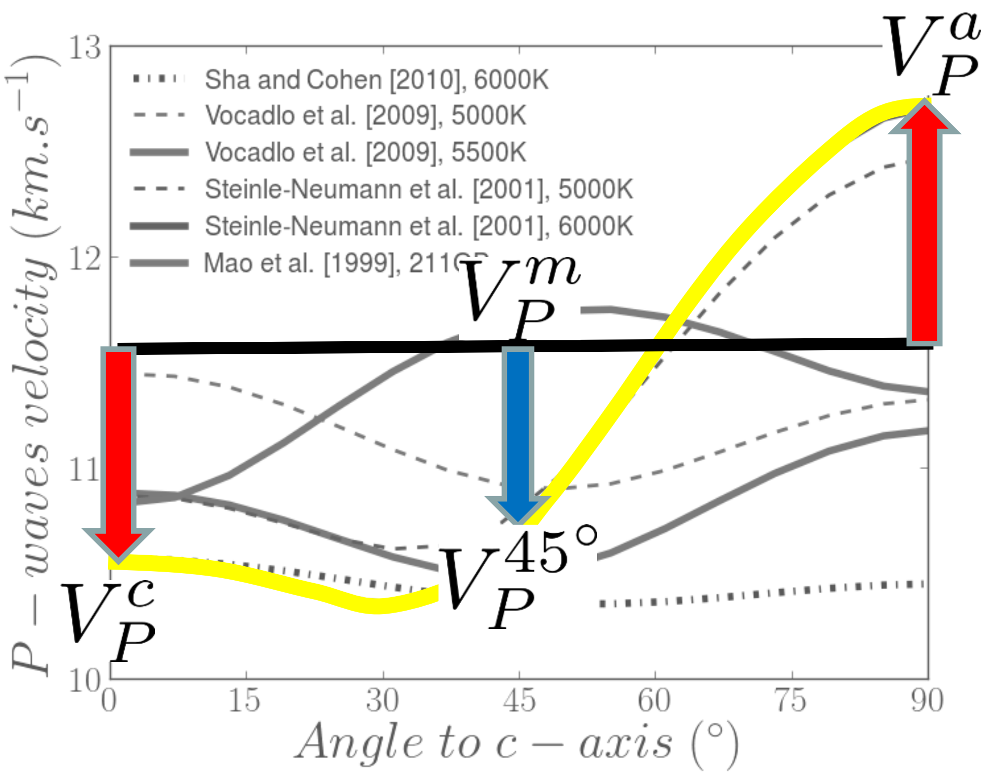

**Global anisotropy is below 0.1%**

ISTerre

# Dimensionless numbers of anisotropy

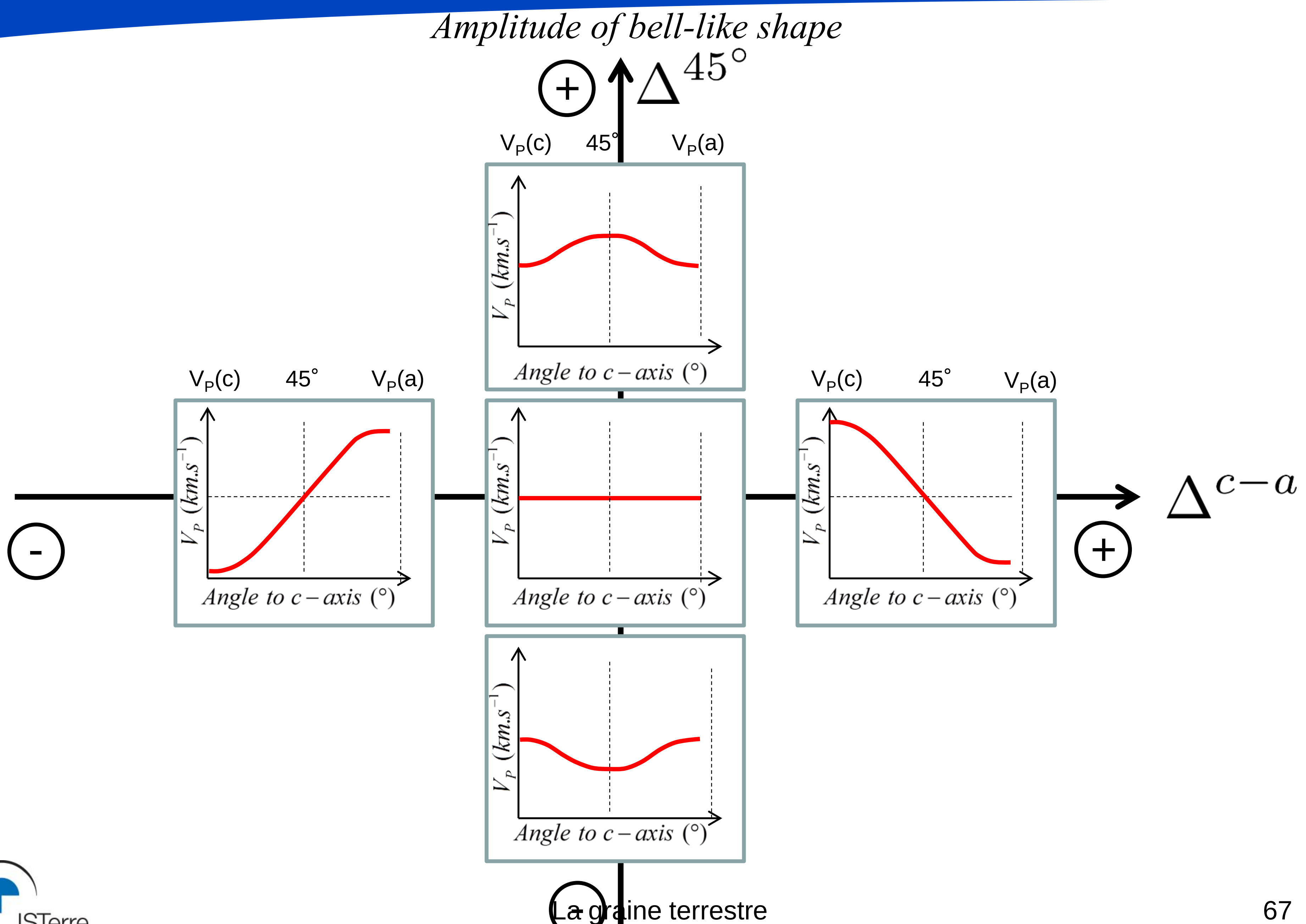
***Contrast Vp c-a***

$$\Delta^{c-a} = \frac{V_P^c - V_P^a}{V_P^m}$$

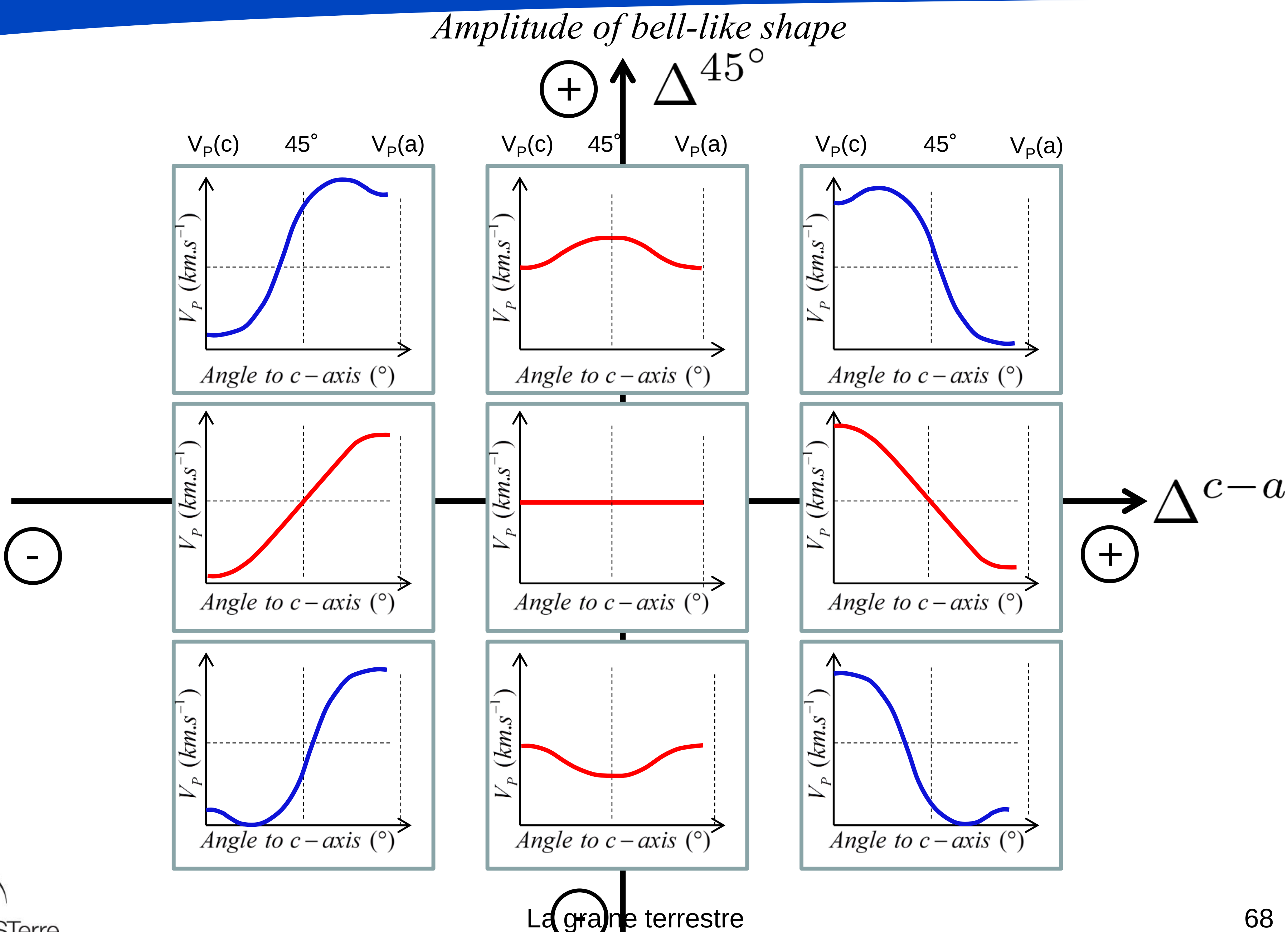



$$\Delta^{45°} = \frac{V_P^{45°} - \left(V_P^c + V_P^a\right)/2}{V_P^m}$$

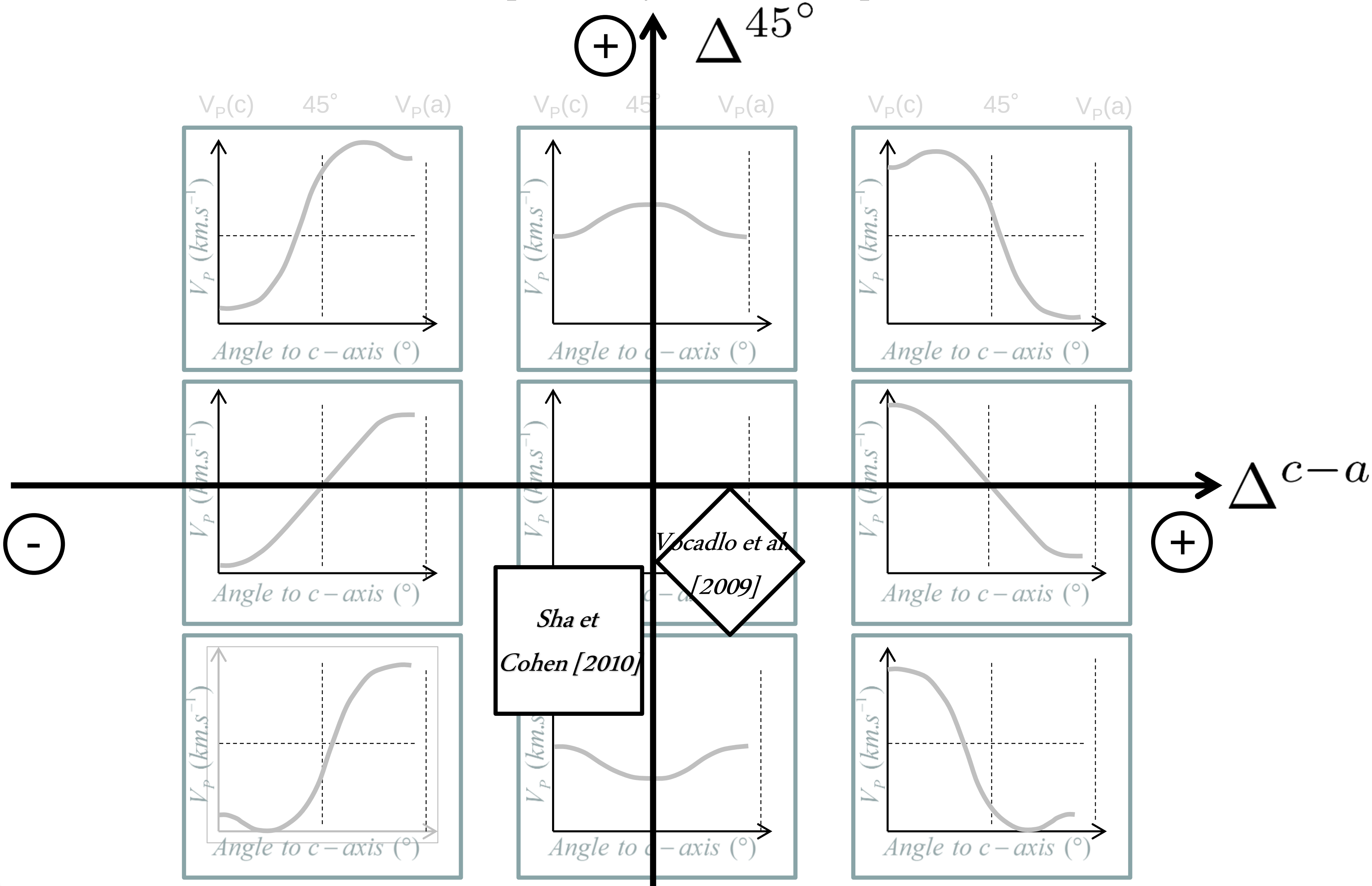
***Amplitude of bell-like shape***

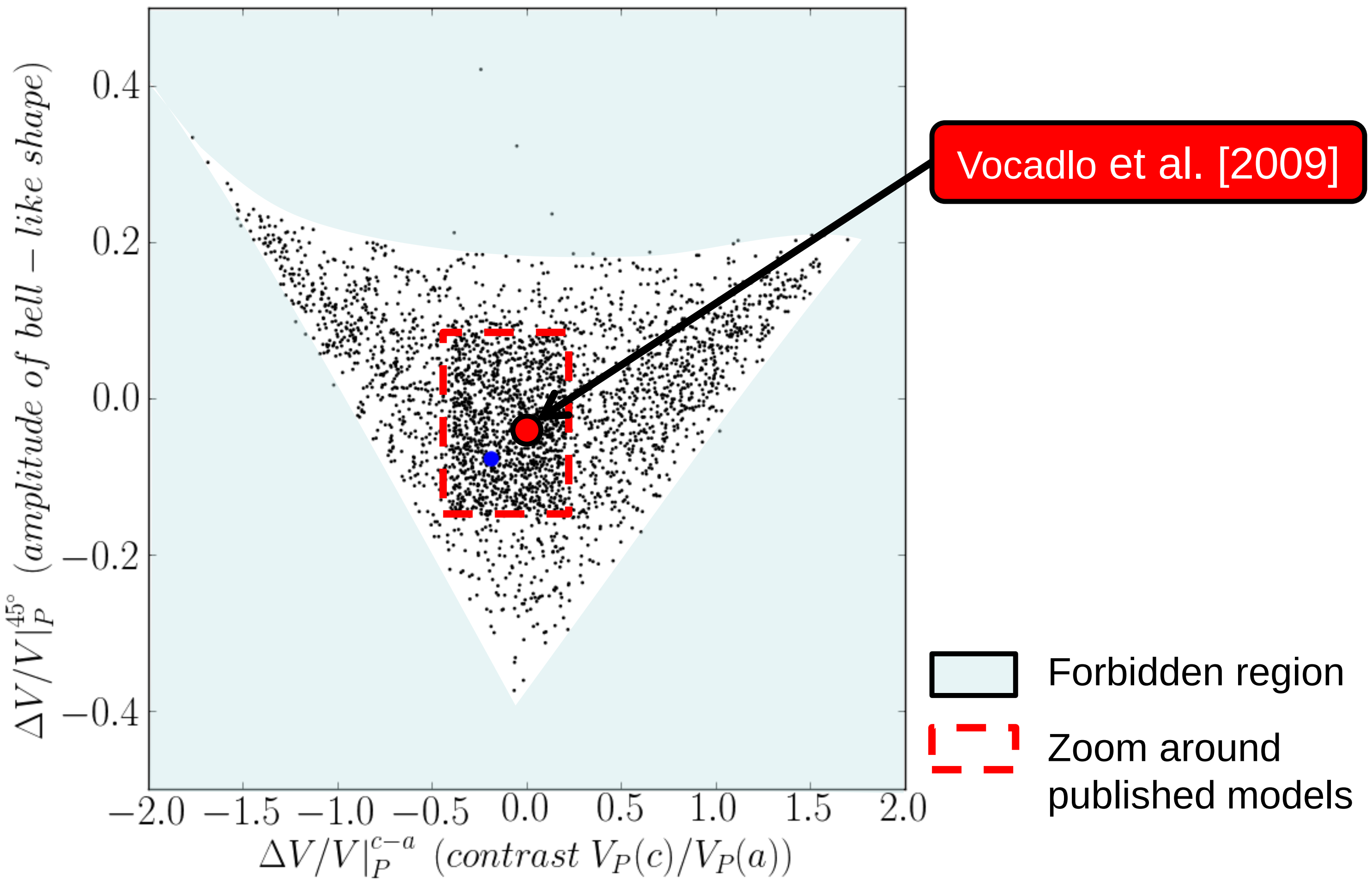


Amplitude of bell-like shape
$\Delta^{45°}$
+
$V_P$(c)
45°
$V_P$(a)
$V_P\ (km.s^{-1})$
$Angle\ to\ c-axis\ (°)$
-
$\Delta^{c-a}$

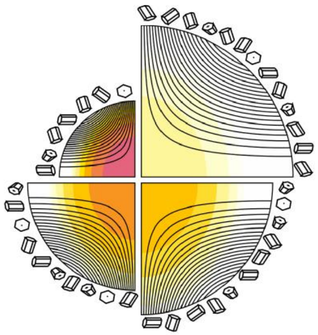

Amplitude of bell-like shape
+
$\Delta^{45°}$
$V_P(c)$
45°
$V_P(a)$
$V_P\ (km.s^{-1})$
$Angle\ to\ c-axis\ (°)$
-
+
$\Delta^{c-a}$
-

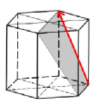
# Amplitude of bell-like shape



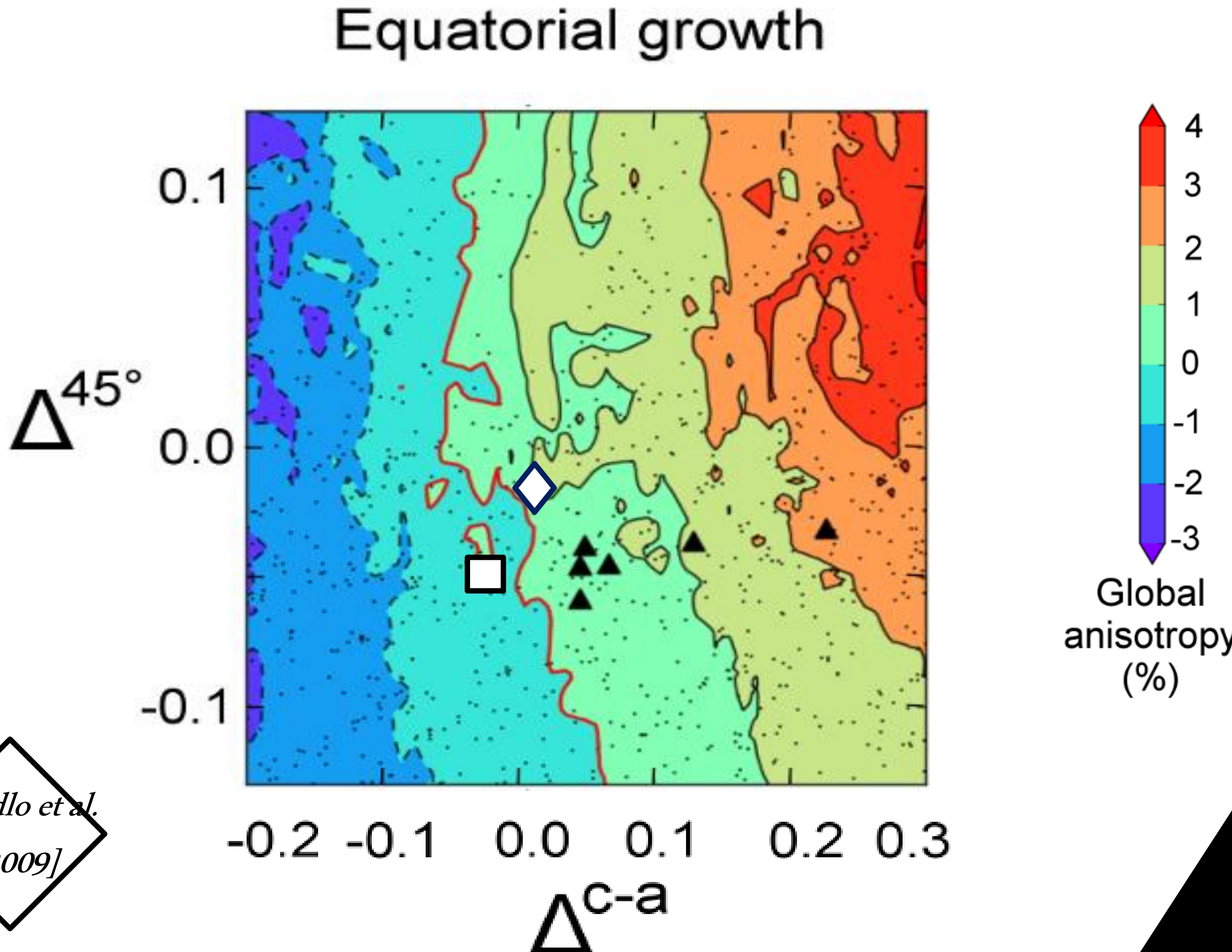

Vocadlo et al. [2009]
Forbidden region
Zoom around published models
$\Delta V/V|_P^{45°}$ (amplitude of bell − like shape)
$\Delta V/V|_P^{c-a}$ (contrast $V_P(c)/V_P(a)$)
0.4
0.2
0.0
−0.2
−0.4
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0

# Monte Carlo Results





Pyramidal
<c+a>
slip

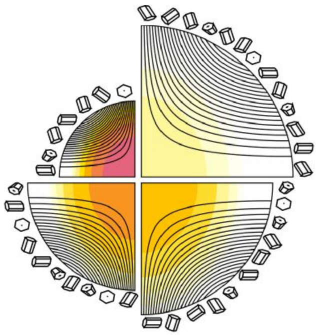


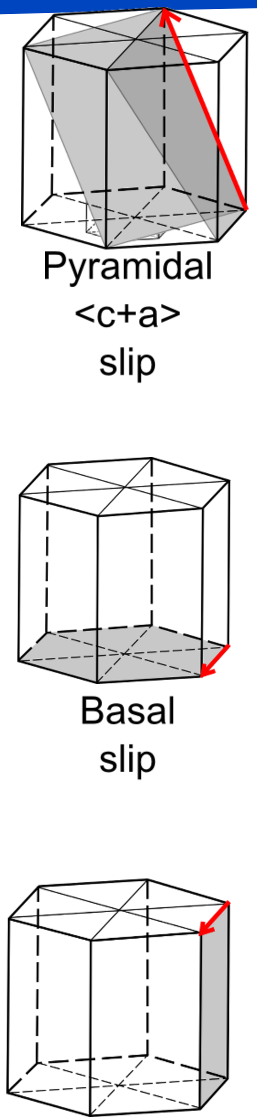

Vocadlo et al. [2009]

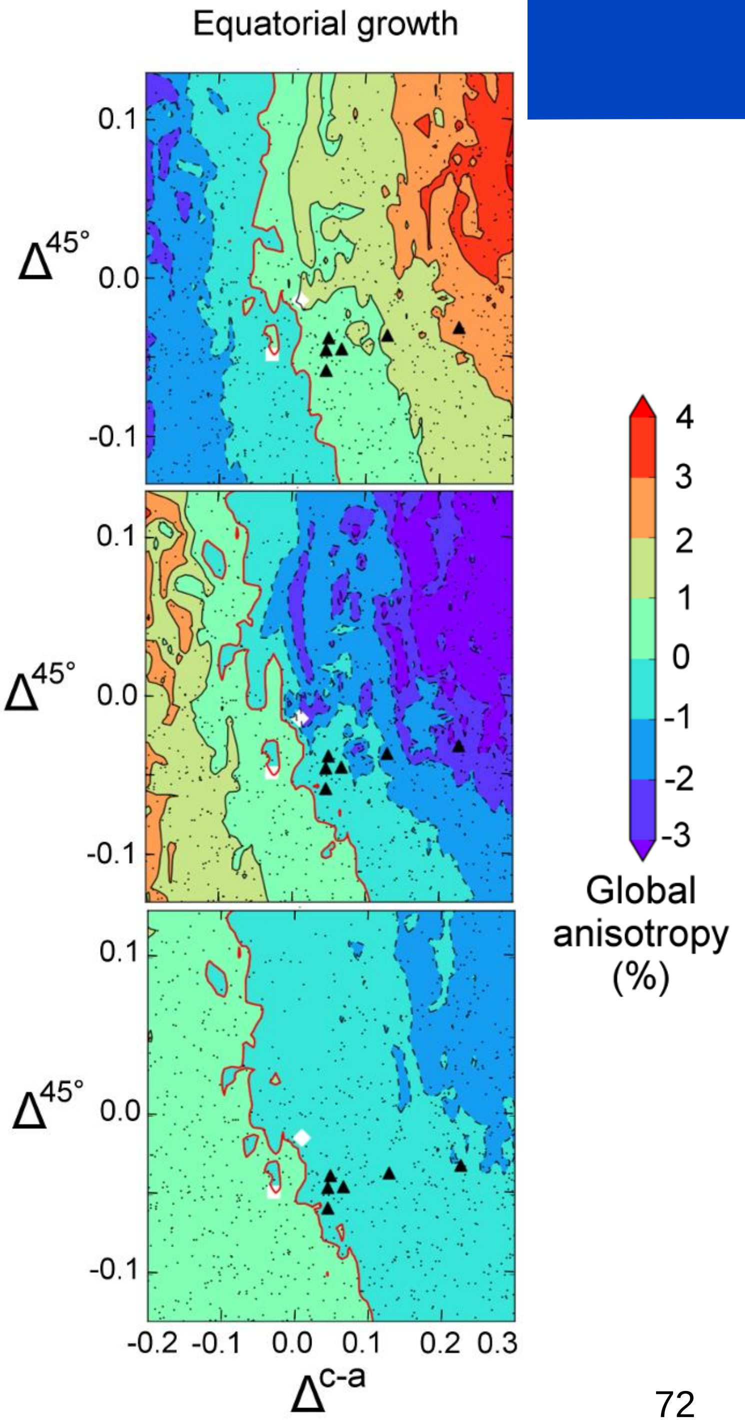
Sha et Cohen [2010]

Martorell et al [2013]

# Influence of the slip system





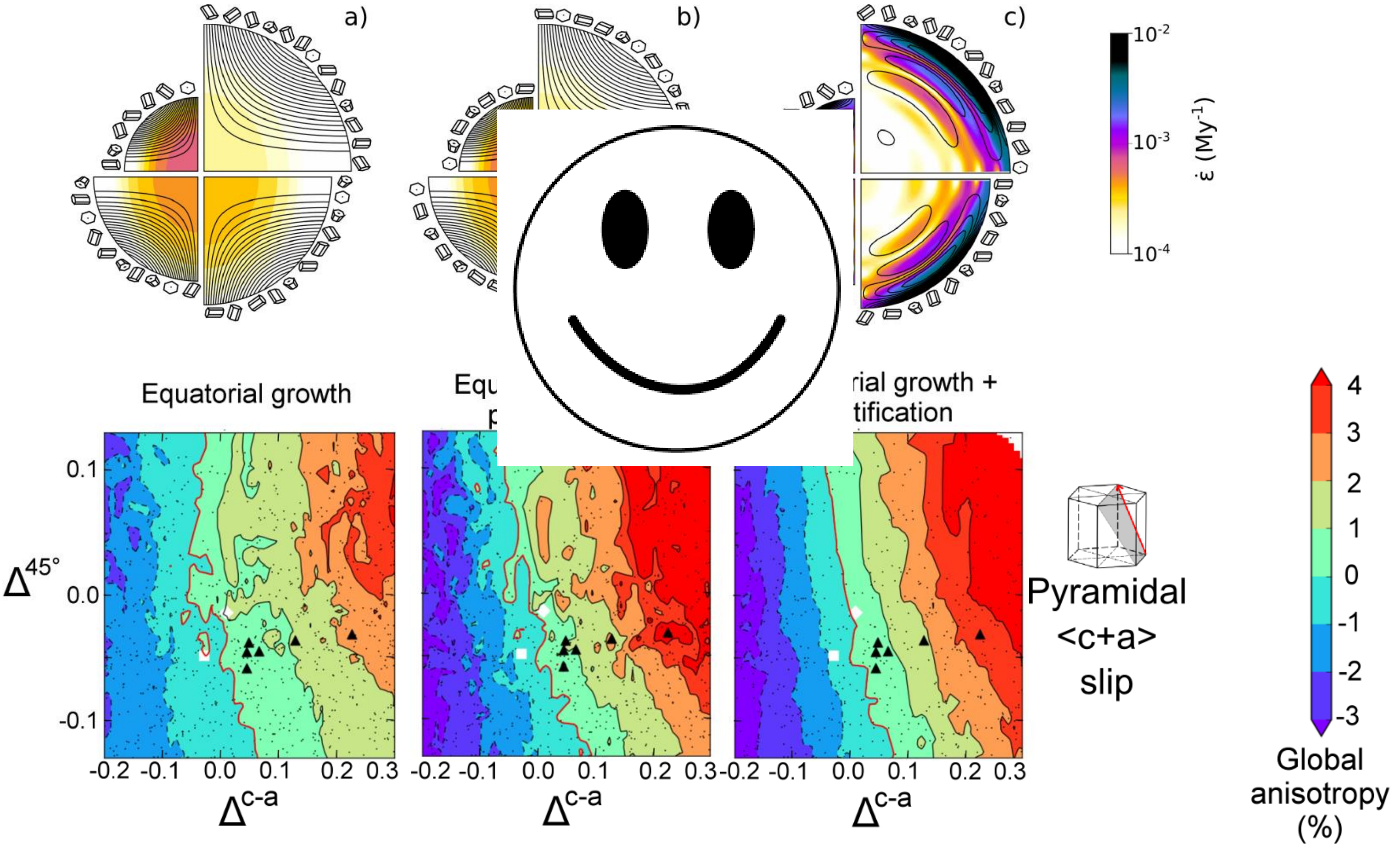




Pyramidal slip system is prone to aligne c axis along the NS axis.

It requires fast velocities along c-axes

Global anisotropy id 5 to 10 times smaller than the single cristal anistropy.

# Enhancement of global anisotropy

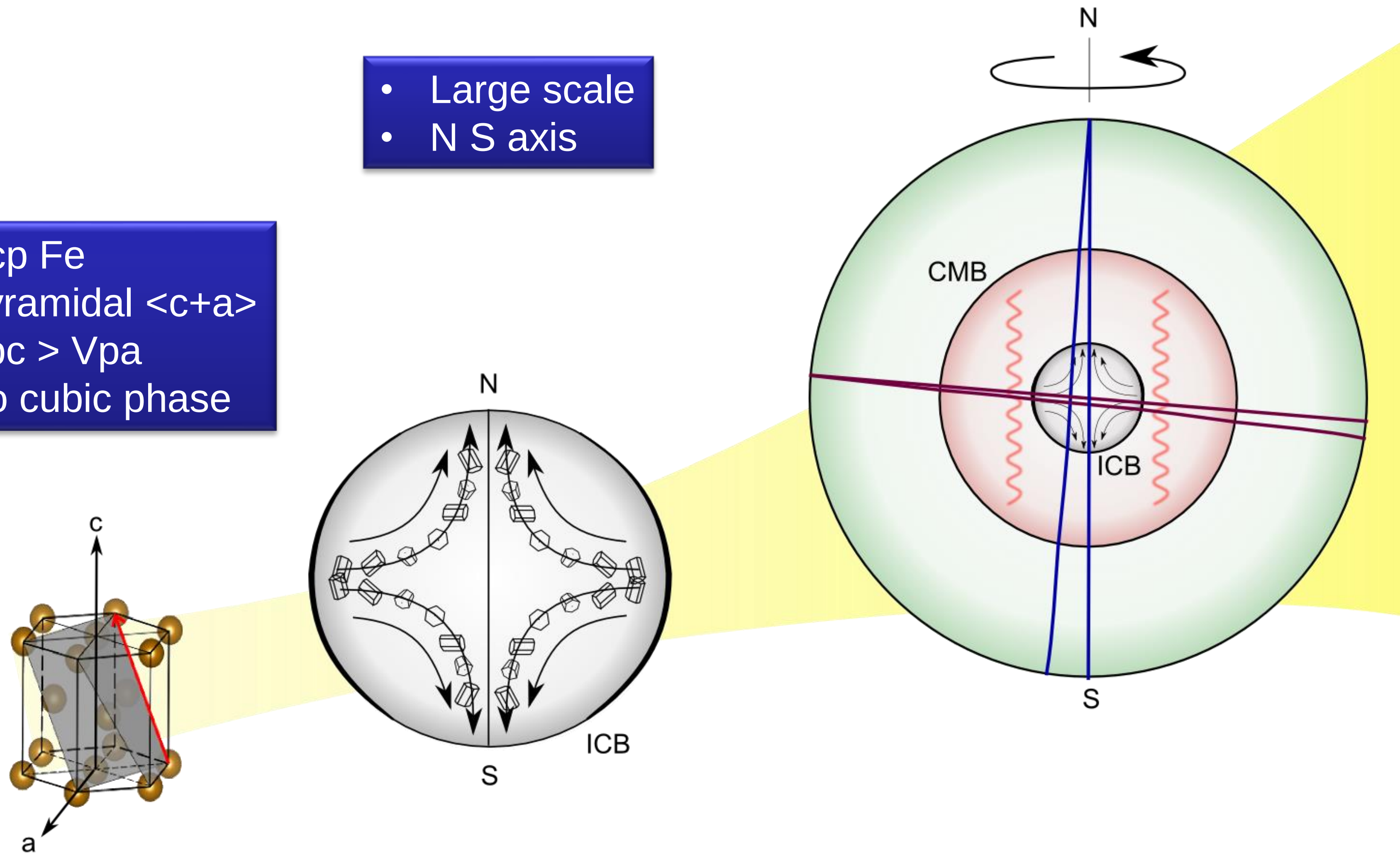


# Multi scale self consistent model

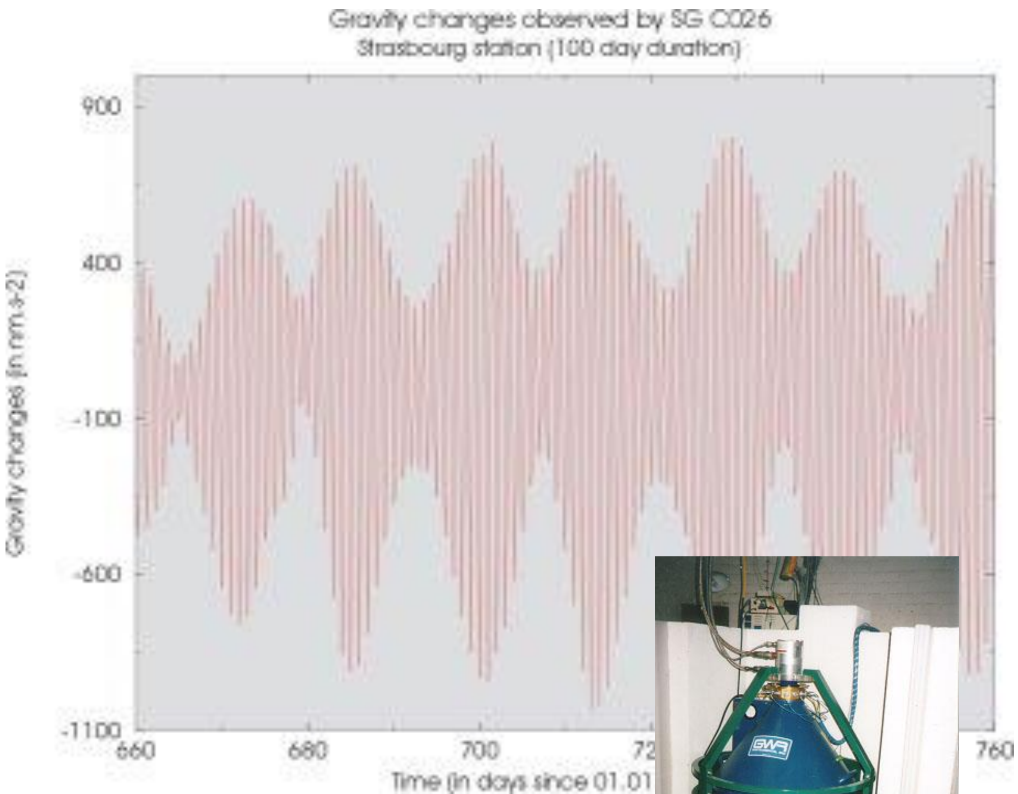
- N-S 3% global anisotropy

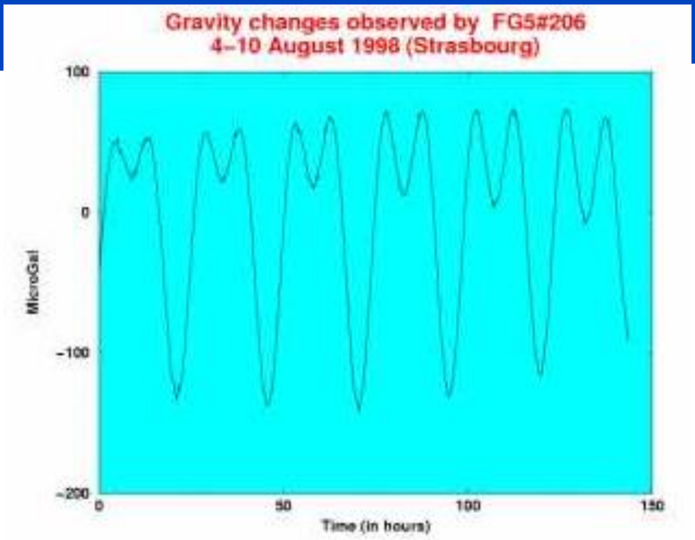
- Large scale
- N S axis

- Hcp Fe
- Pyramidal <c+a>
- Vpc > Vpa
- No cubic phase

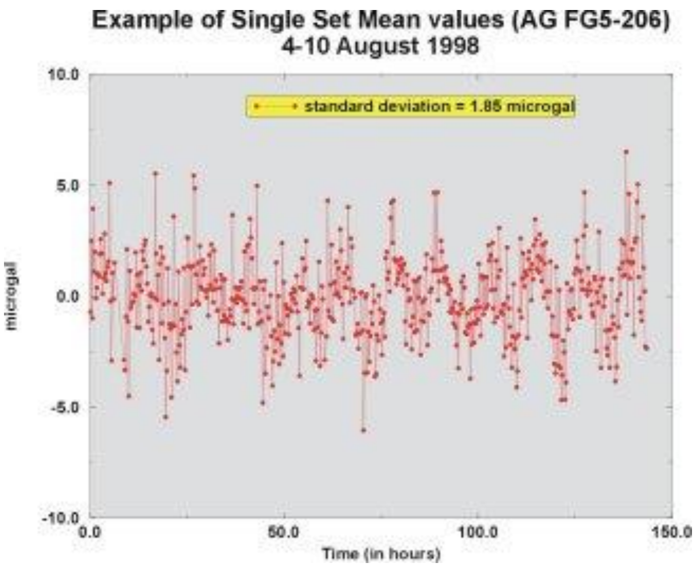


# Données gravimétriques

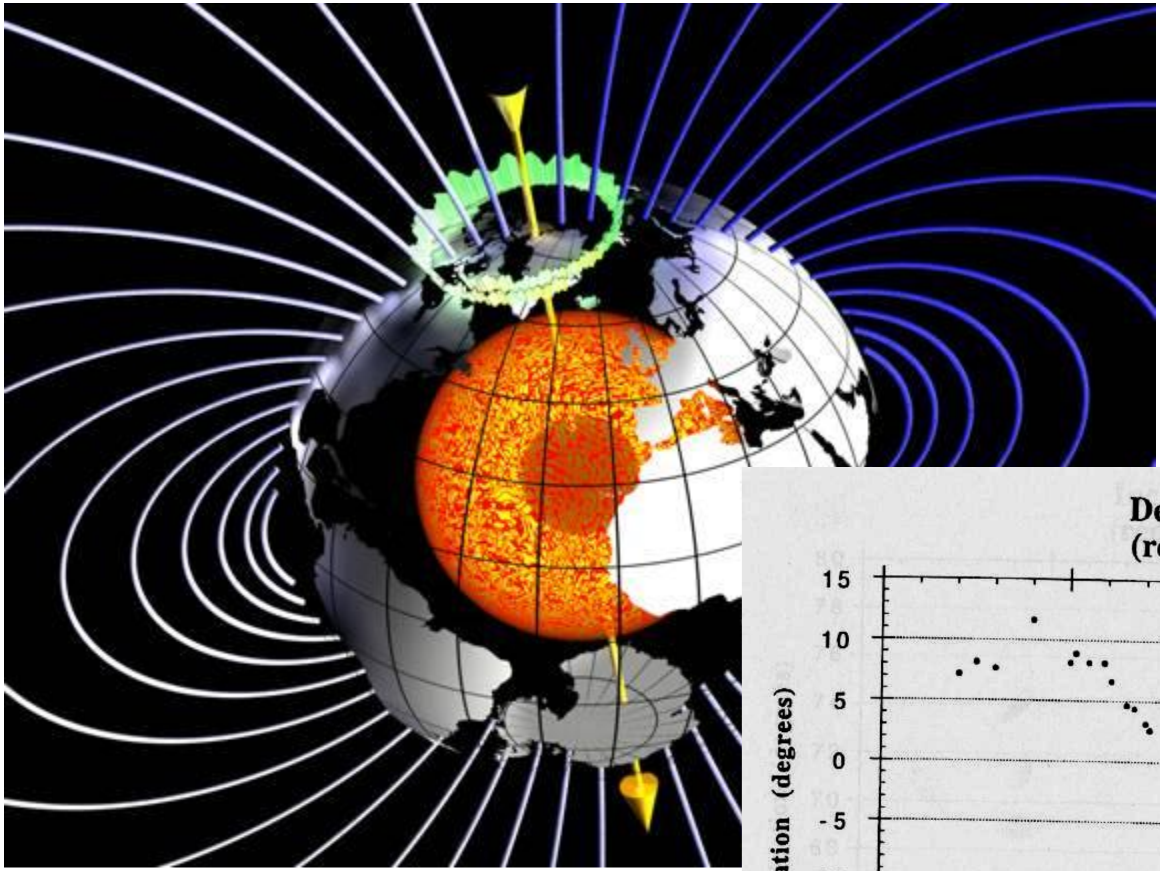


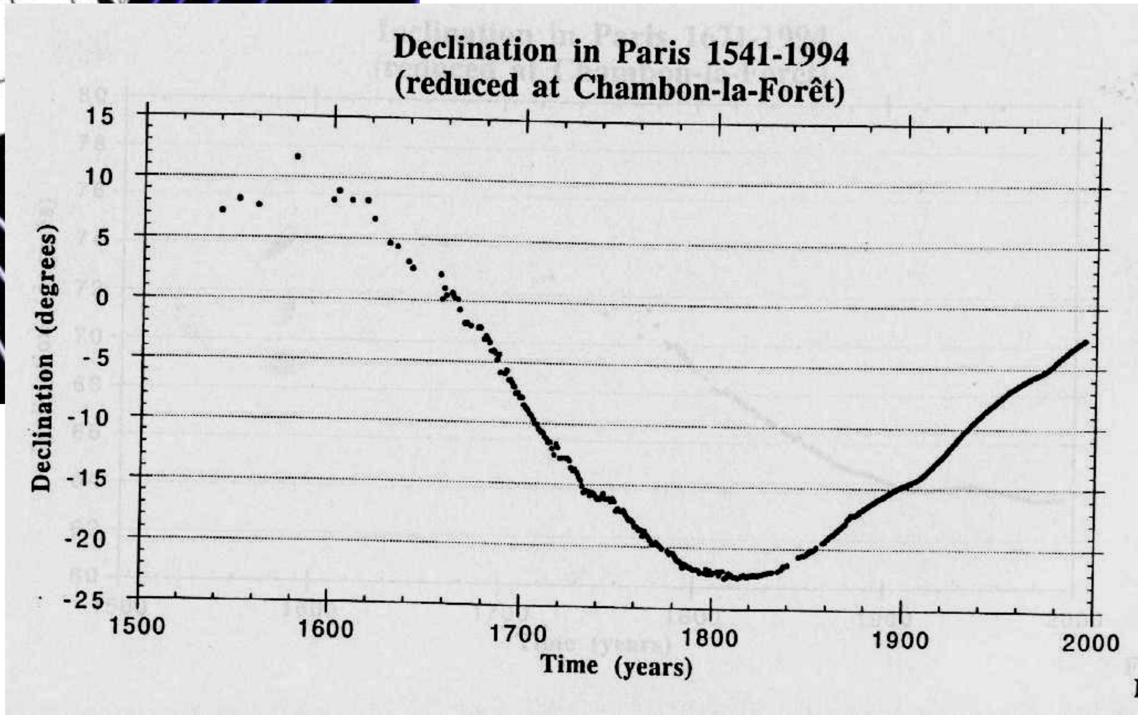




Marées terrestres et océaniques, pression atmosphérique, rotation de la Terre

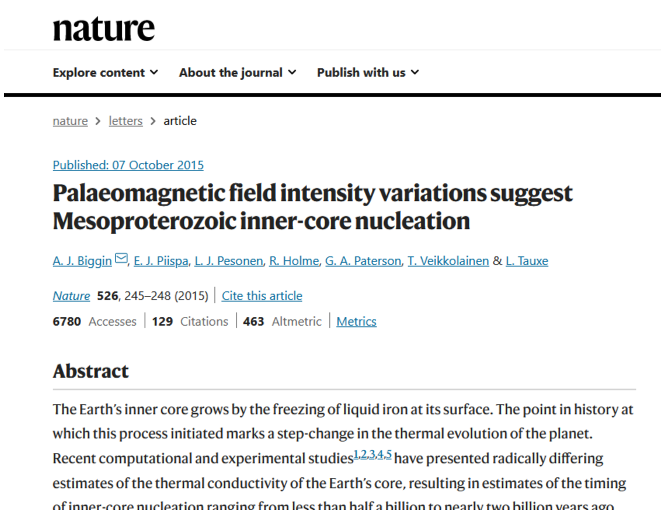


# Données magnétiques





# Paléointensités magnétiques et nucléation de la graine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Published: 07 October 2015

**Palaeomagnetic field intensity variations suggest Mesoproterozoic inner-core nucleation**

A. J. Biggin, E. J. Piispa, L. J. Pesonen, R. Holme, G. A. Paterson, T. Veikkolainen & L. Tauxe

*Nature* **526**, 245–248 (2015) | Cite this article

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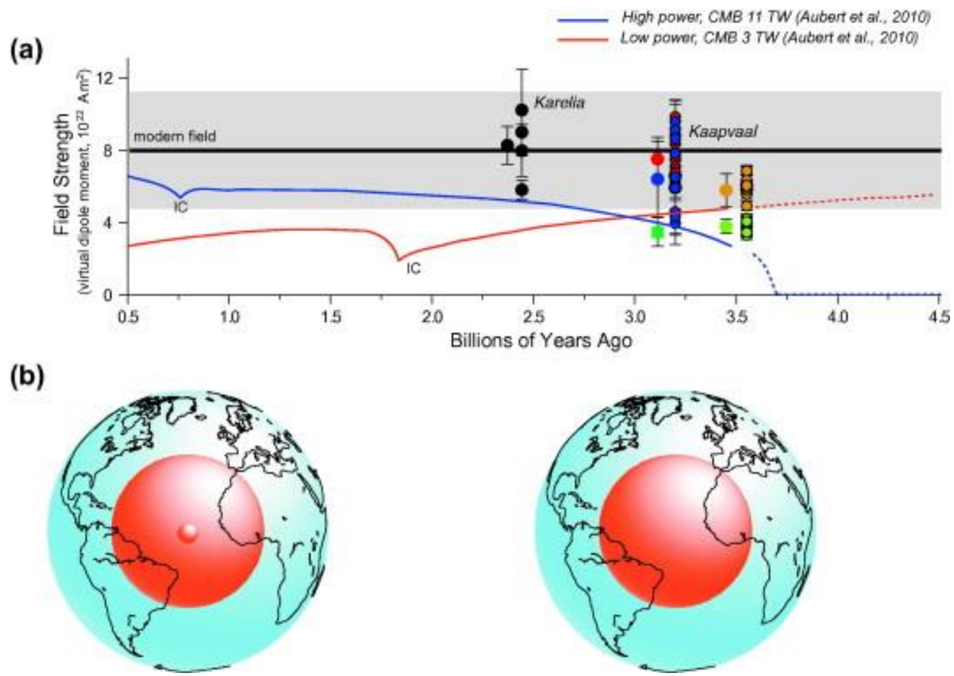
**Abstract**

The Earth's inner core grows by the freezing of liquid iron at its surface. The point in history at which this process initiated marks a step-change in the thermal evolution of the planet. Recent computational and experimental studies[1,2,3,4,5] have presented radically differing estimates of the thermal conductivity of the Earth's core, resulting in estimates of the timing of inner-core nucleation ranging from less than half a billion to nearly two billion years ago




Aubert,Labrosse, Poitou, 09

# Anisotropie?

- La graine est-elle anisotrope?
- Quelle phase minéralogique?
- Dynamique de la Graine?
- Son histoire?
- Son âge?