The inner core

The hemispherical heterogeneity,

Implications for a possible growing mechanism

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Outline

- Some widely accepted features
  - The radial structure of the core
  - The hemispherical heterogeneity inside the inner core

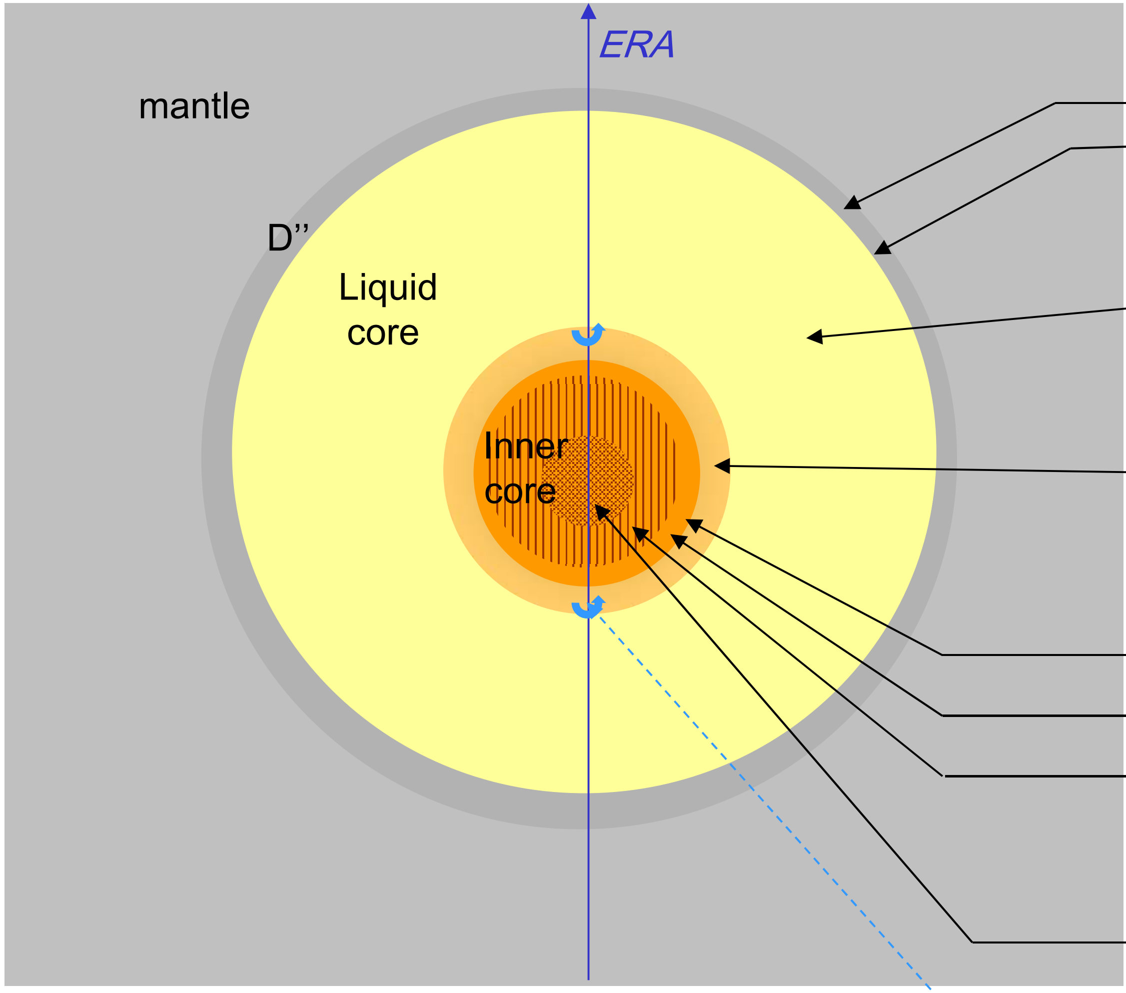
- A dynamical model implying crystallization – translation – fusion of the inner core

- Consequences, difficulties

- Conclusions

- Some widely accepted features

1- the structure of the core



Mantle (silicates of Mg, Fe)

D'' layer: very heterogeneous

CMB: low topography (h< 3 km)

Liquid core: Iron + light elements (S, 0, …)

no S-wave

homogeneous, ~ no attenuation

Low velocity gradient
at the base of the liquid core

Inner core (almost pure iron)

ICB (sharp discontinuity)

Isotropic layer (h=100 km)

Anisotropy (properties are debated):
high velocities and strong attenuation
// to Earth rotation axis
Preferred orientation of crystals

A different anisotropy at the centre
(innermost inner core)

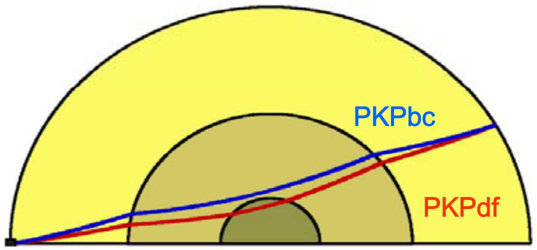
Differential rotation with respect to the mantle?
(<0.2 dg/yr) (debated)

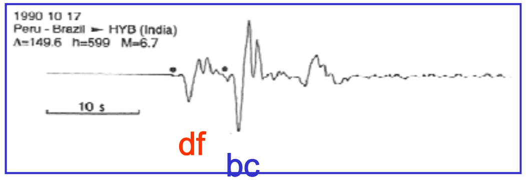
The inner core is young (1.0 to 1.5 Gyr), its radius increases at rate ~ 0.5 to 1 mm/yr (grows as $t^{1/2}$)

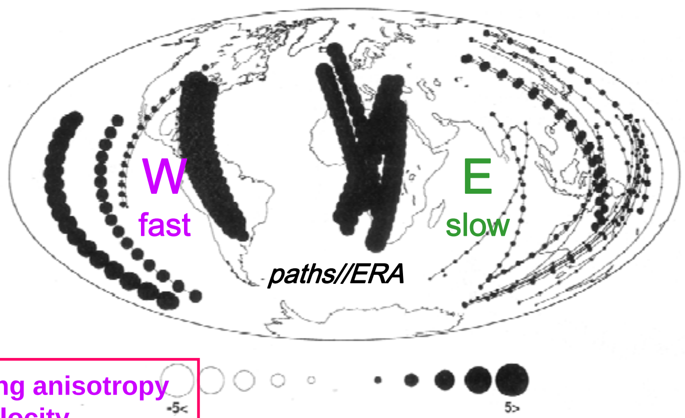
(Labrosse et al., 2001; Deguen, 2009)

- **Some widely accepted features:** the hemispherical heterogeneity

2- the asymmetry of anisotropy:
between depths 100 and 500 km below ICB



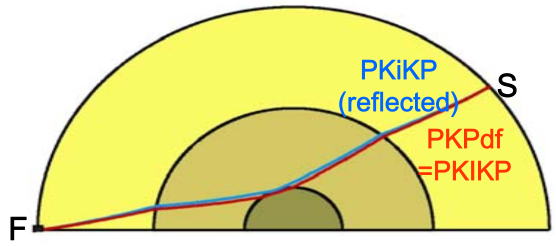


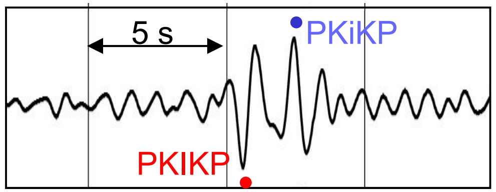


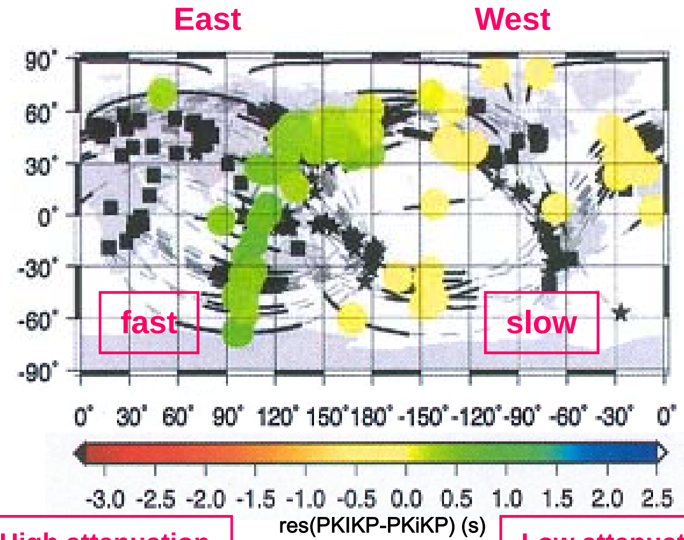
Strong anisotropy
in velocity
and attenuation

Tanaka and Hamaguchi, 1997

3- the asymmetry of the isotropic layer
between depths 30 and 100 km below ICB







High attenuation

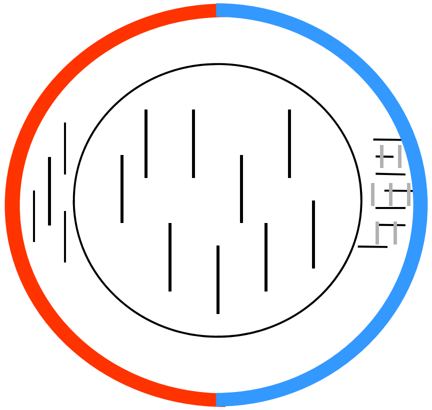
Low attenuation

Cao and Romanowicz, 2004

W

Uppermost isotropic inner core
(30-100 km below ICB):
Slow, low attenuation

100 to 400 km below ICB :
anisotropic



E

Uppermost isotropic inner core
(30-100 km below ICB):
Fast, strong attenuation

100 to 400 km below ICB
No detectable anisotropy

How to explain this asymmetry? Two models:

1- A texture forced by the **thermal heterogeneities at the base of the mantle**

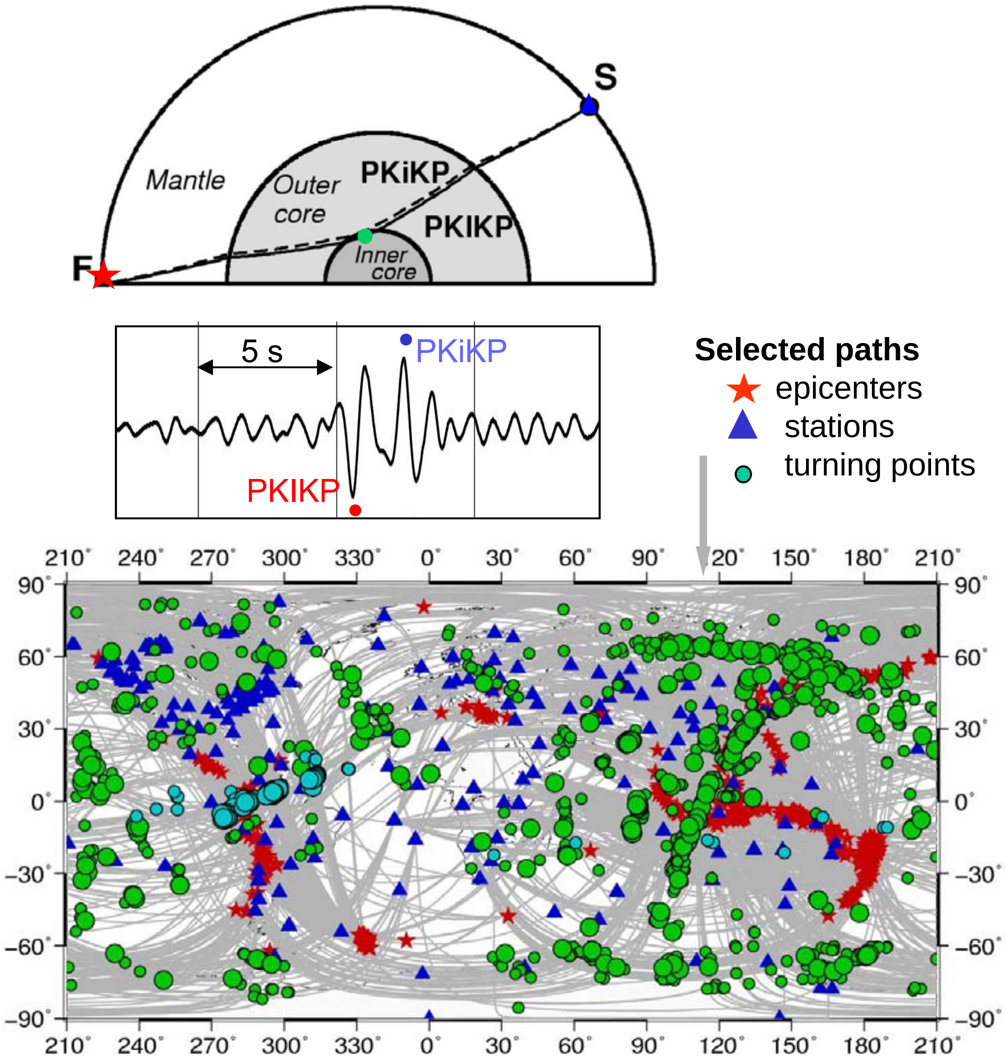
(model proposed by Aubert et al. 2008, + Bergmann 1997 + Cormier 2007)

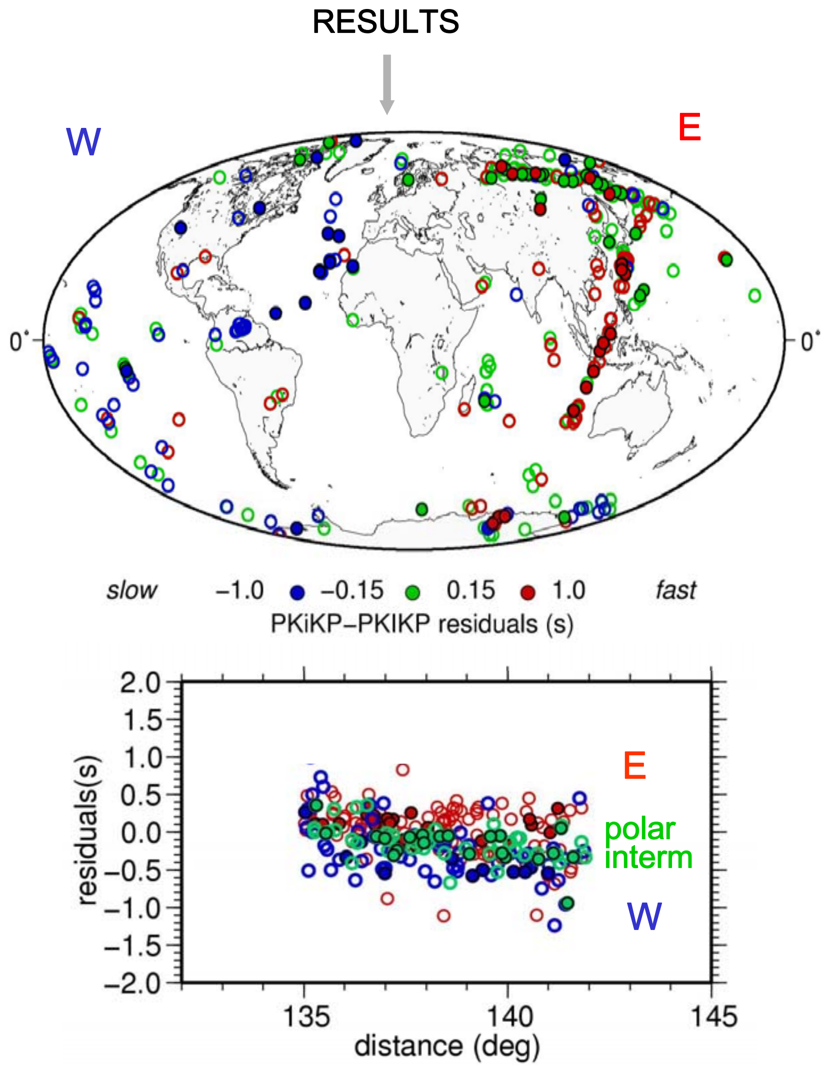
2- A model implying a permanent lateral translation of the inner core from W to E

(model proposed by Monnereau et al. 2010 + Alboussière et al. 2010)

Seismological data sampling the uppermost inner core

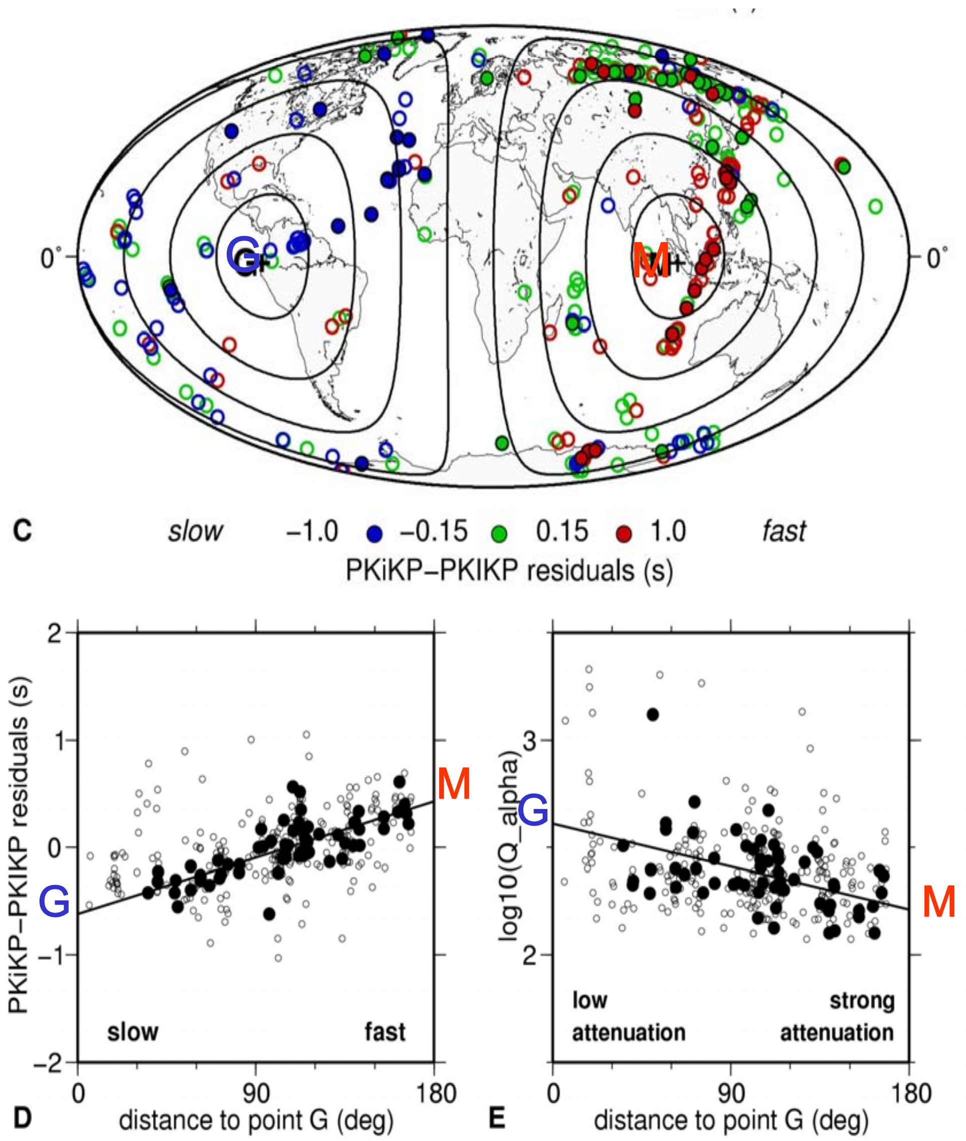
attempt to better sample polar regions





Monnereau et al., 2010

Constraints given by the data



A degree 1 pattern explains rather well the data

in G:	Vp = 10.93 -10.99 km/s Qp= 310 - 540
in M:	Vp=11.10 - 11.16 km/s Qp=120 - 210

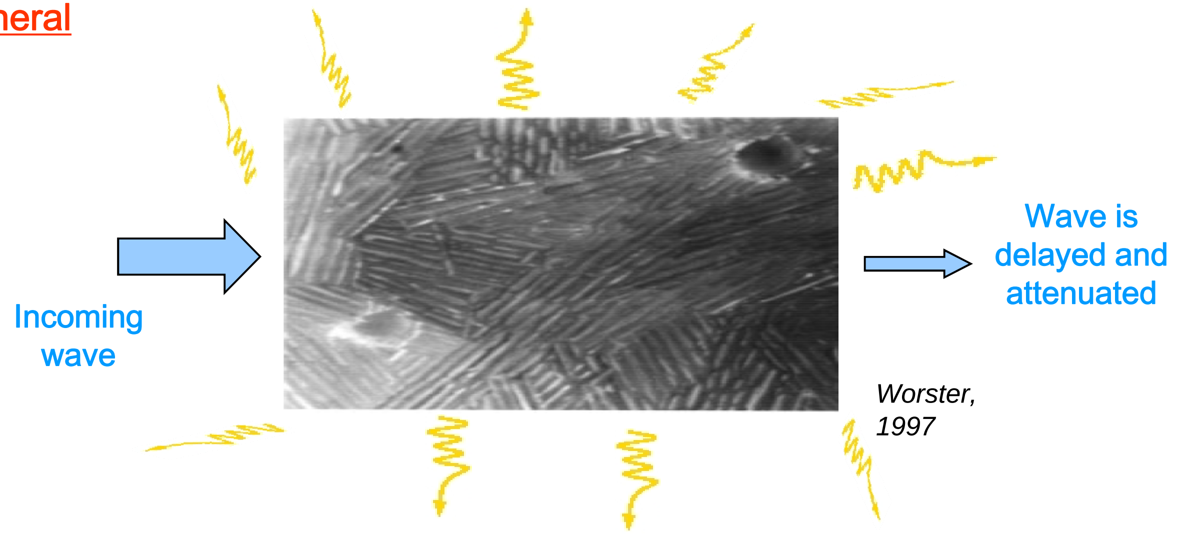
↓

Possibility to determine the size of the grains of iron

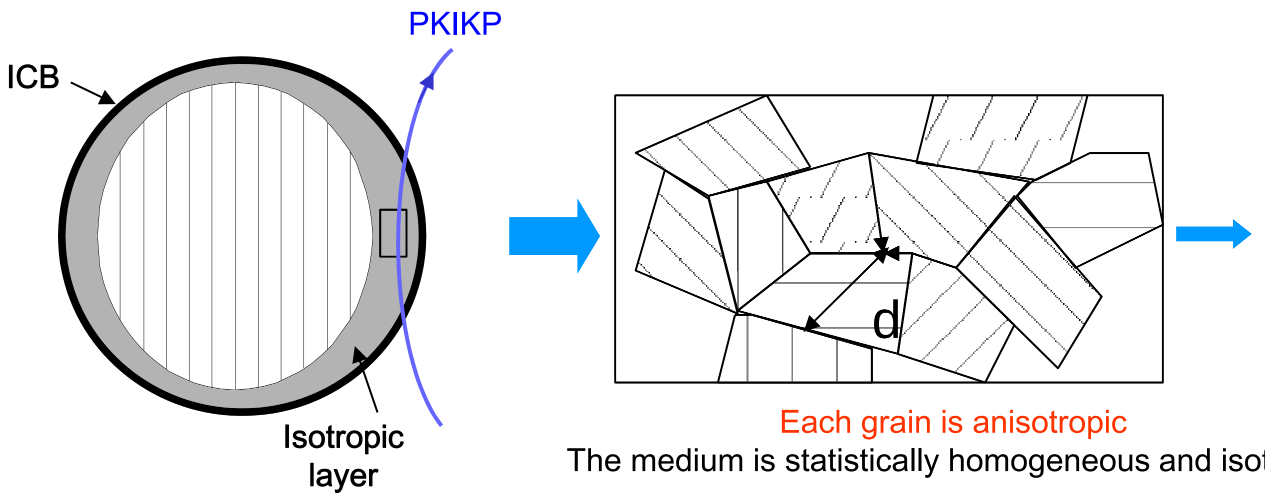
Monnereau et al., 2010

Multiple scattering of seismic waves

General



Inner core



Each grain is anisotropic
The medium is statistically homogeneous and isotropic

Parameters characteristic of the grains:

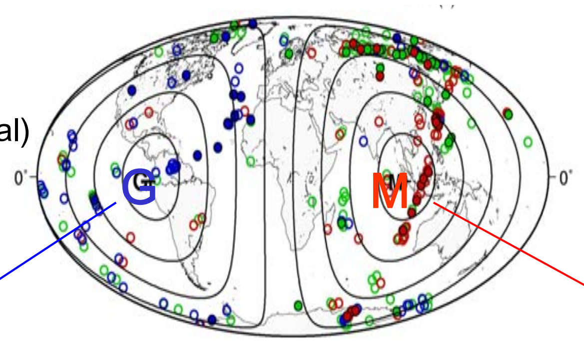
-Lattice of iron:
  cubic (bcc)
  or
  hexagonal (hcp)
- Elastic constants
- Size of grains

Calvet et Margerin 2008, Cormier 2007

Determination of the grain size from seismic velocities and attenuation (multiple scattering modeling)

hcp (hexagonal) iron (Vočadlo, 2007)

Similar results for bcc (cubic) iron
(Belonoshko et al., 2007)
(No sensitivity to the symmetry of the crystal)

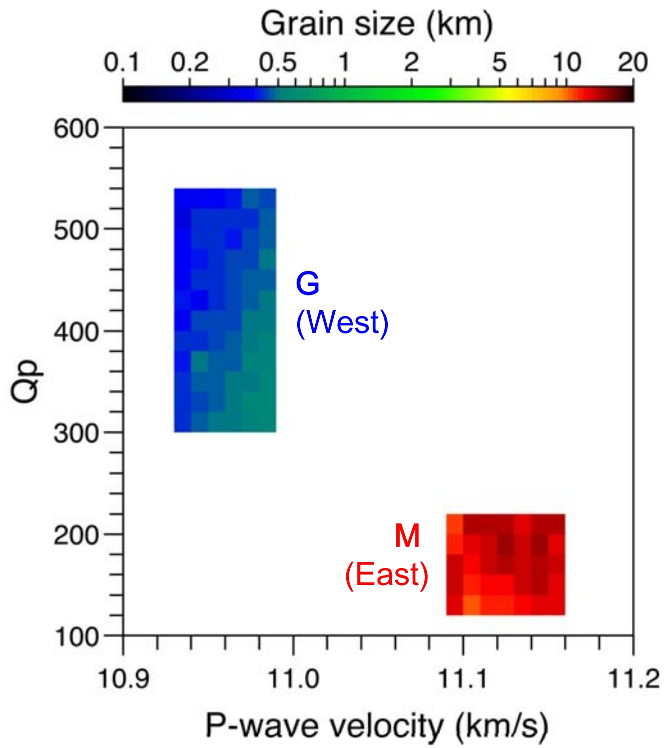


G

Vp=10.93 – 10.99 km/s
Qp = 310 - 540

↓

Grain size ~ 500 m



M

Vp=11.10 - 11.16 km/s
Qp = 120 - 210

↓

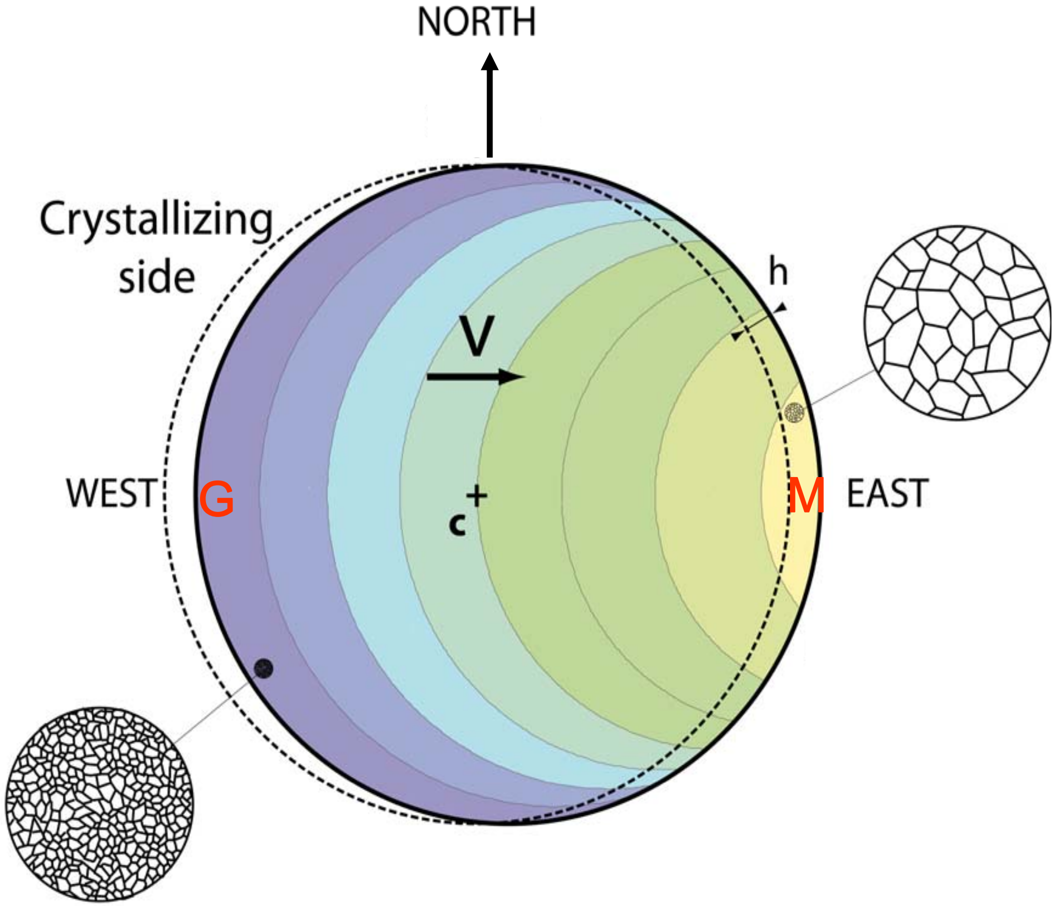
Grain size ~ 10 km

Grain size ratio: 7 to 50

Calvet et Margerin 2008, Monnereau et al. 2010

The evolution of grain size in the inner core

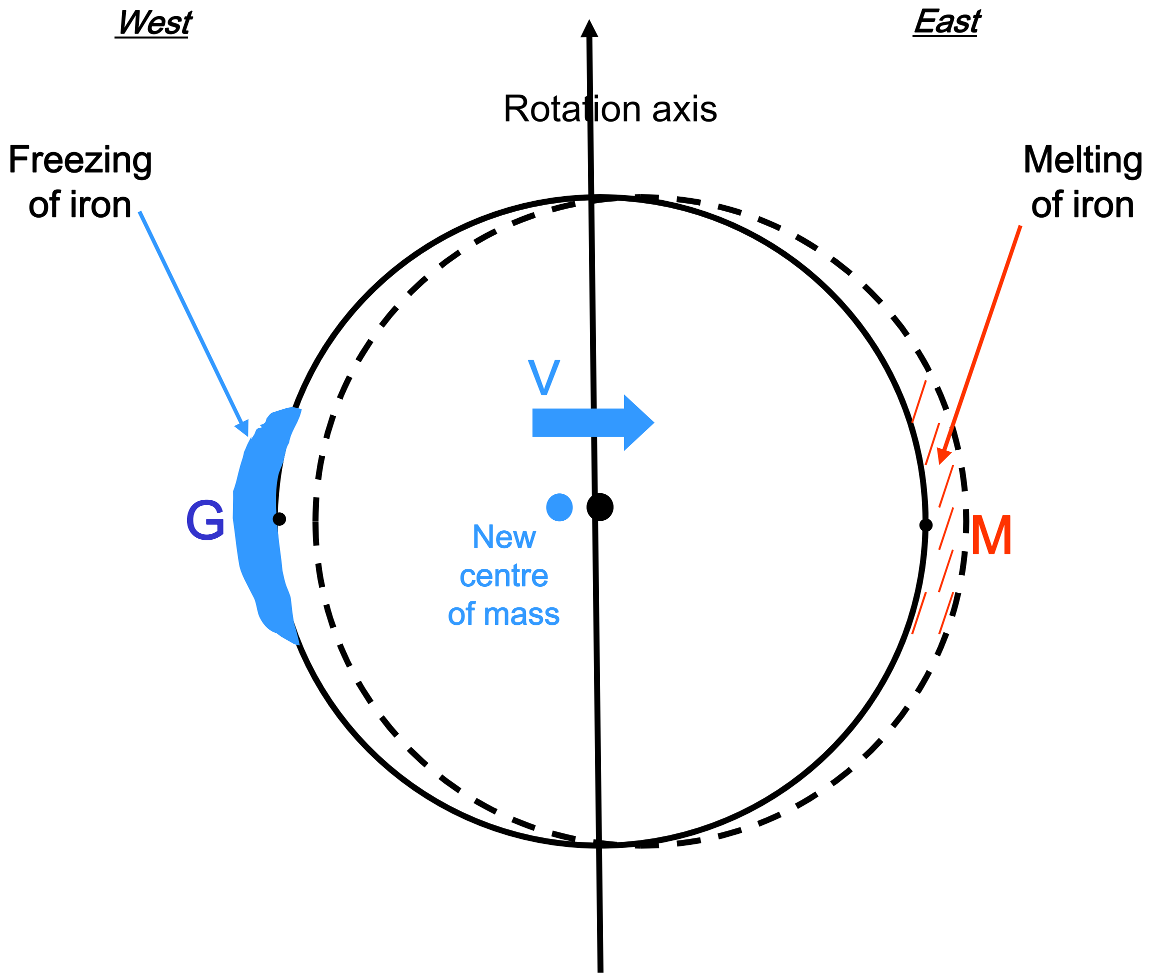
- Growth of the grains occurs by migration of the boundaries *(Venet et al., 2009)*
- **Small grains to the West => cristallization occurs at side G *(G=growing)***
- **Increase of grain size from West to East => East side older than West side**



Monnereau et al., 2010, Venet et al., 2009

A translational mode of thermal convection:

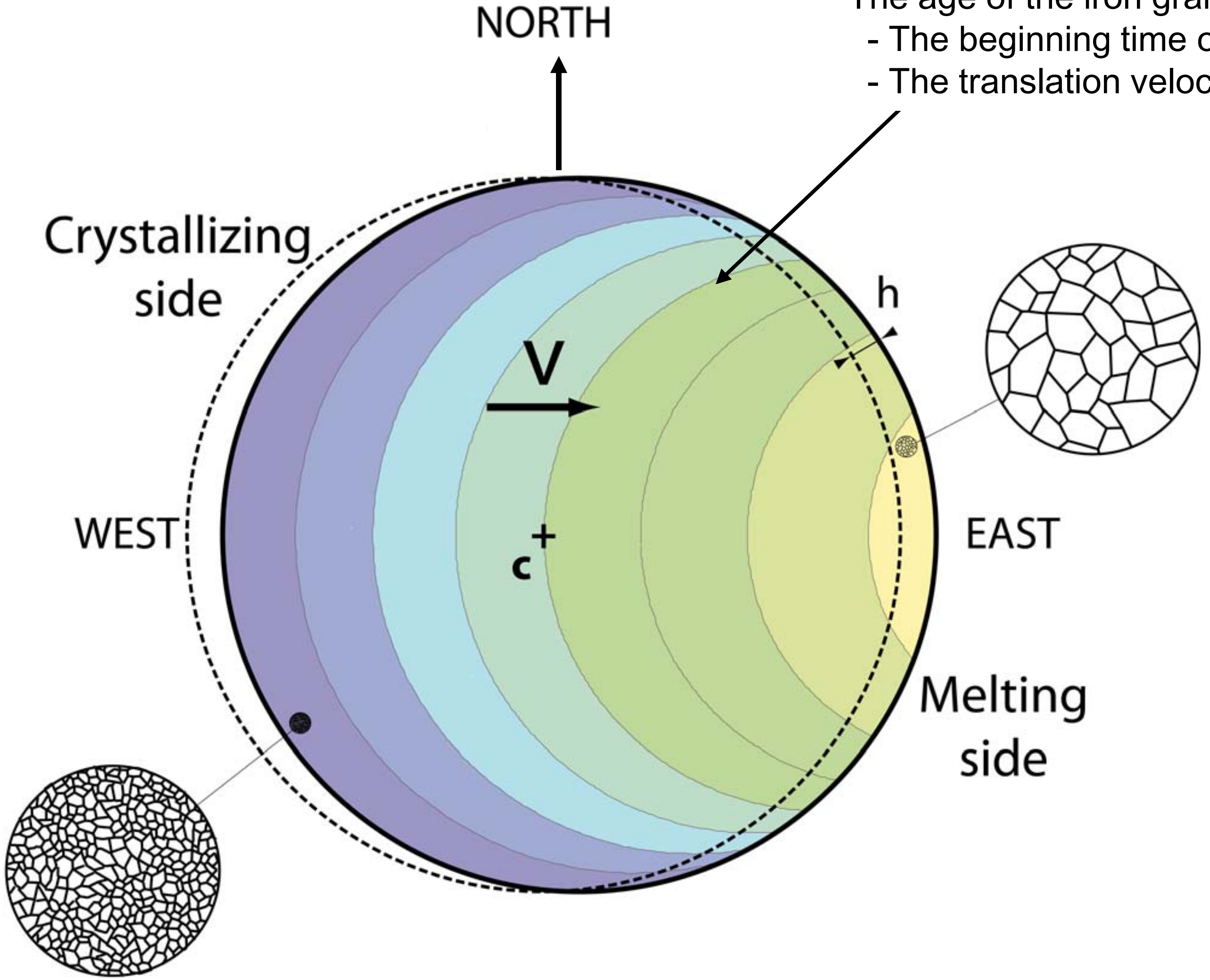
Model of inner core convection with open boundaries (phase change at the surface is allowed)



Monnereau et al., 2010; Alboussière et al., 2010

age variation inside the inner core

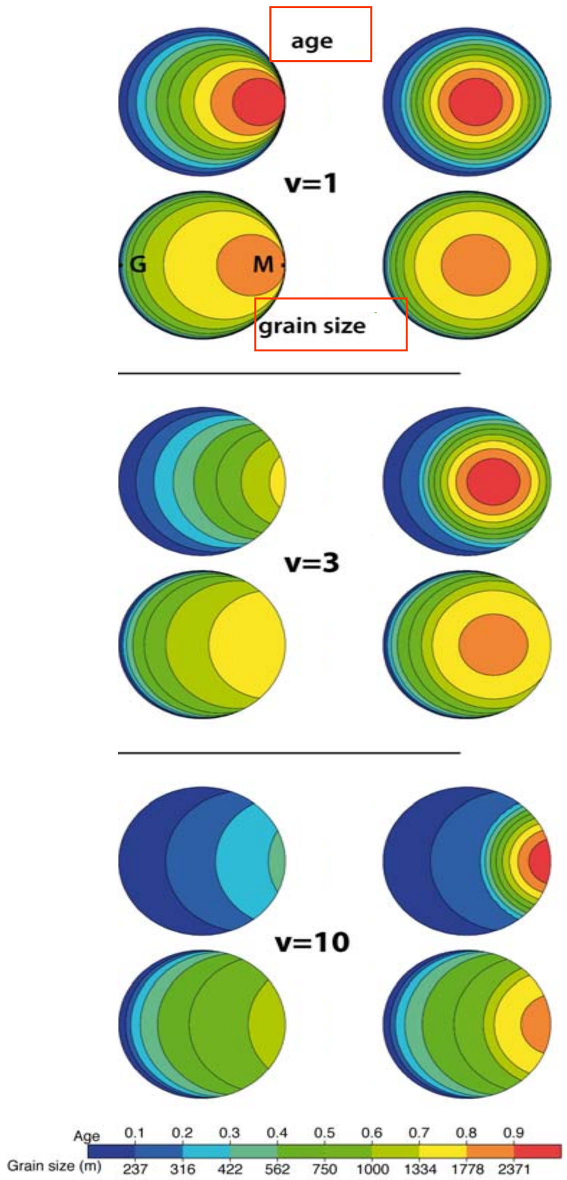
The age of the iron grains depends on:
- The beginning time of the process
- The translation velocity



Monnereau et al., 2010; Alboussière et al., 2010

Age and grain size in the inner core

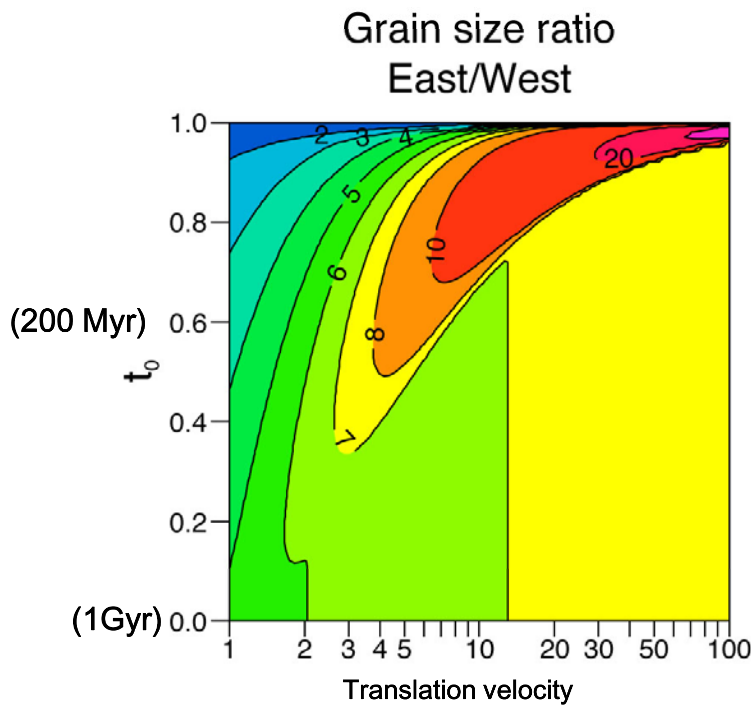
Translation since 1 Gyr   since 200 Myr



Translation velocity = Crystallization velocity

Translation velocity = 3 x Crystallization velocity

Translation velocity = 10 x Crystallization velocity



Grain size ratio = 7 to 50

Translation velocity > 3 x crystallization velocity

Monnereau et al., 2010

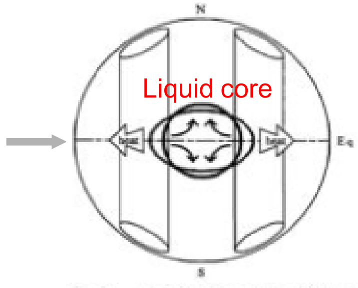
Consequences and difficulties

1- This process is still active today

=> Convection, thus super-adiabatic conditions,
thus the inner core is young

2- Why is the translation in the equatorial plane?

- Heat is preferentially extracted at equator
  - liquid core convection cells along the tangent cylinder *(Yoshida et al., 1996)*
  - Influence of the forcing by thermal heterogeneities at CMB *(Aubert et al., 2008)*
- Influence of the inner core flattening *(Alboussière et al., 2010)*



3- This process is hardly compatible with inner core differential rotation

4- How to maintain the innermost inner core at the center of the Earth?

Possible if it corresponds to a phase transition of iron related to (P, T) conditions

5- A possible explanation of the dense layer at the base of the liquid core

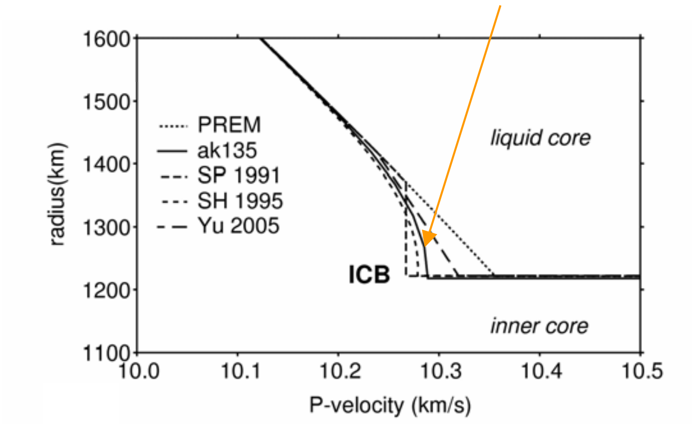
6- How to explain the anisotropy (strong to the W, low to the E)

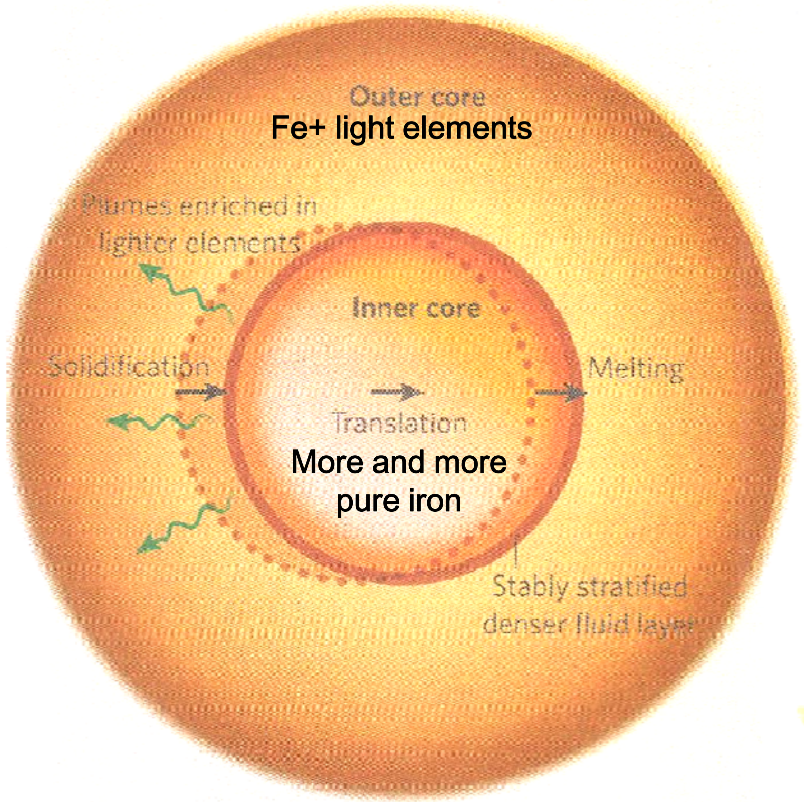
Invoke higher degrees of convection

5- A possible explanation of the dense layer at the base of the liquid core

Freezing / melting results in a fractionation of impurities of the liquid and in an enrichment of the solid in iron

High density layer
at the base of the liquid core



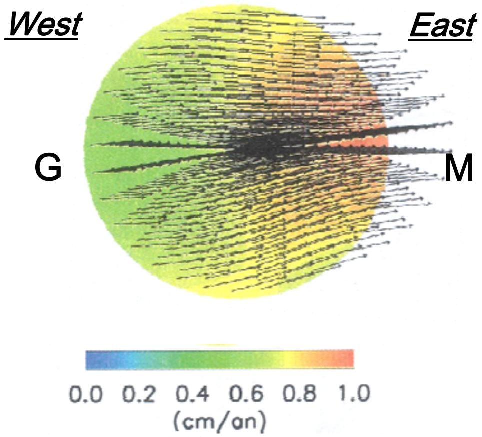


(Alboussière et al., 2010)

6- Explain the anisotropy: Influence of the viscosity on the style of convection

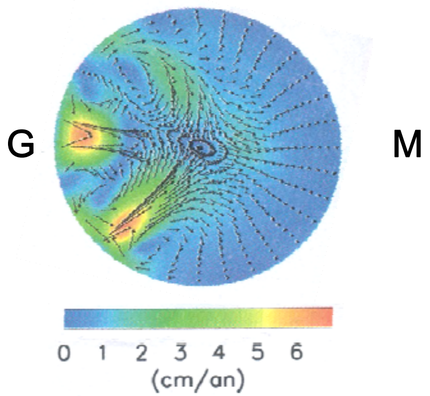
Velocity field for 3 different viscosities of the inner core

$\eta=10^{20}$ Pa.s



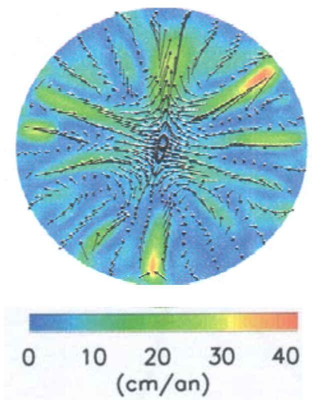
High viscosity
→ Uniform velocity field (translation)
Lobsided growth, age increase from F to M

$\eta=10^{18}$ Pa.s



Intermediate viscosity
→ Convective structures at the freezing side
Uniform velocity at the melting side
Lobsided growth, age more or less uniform on side F, increasing from center to M on side M

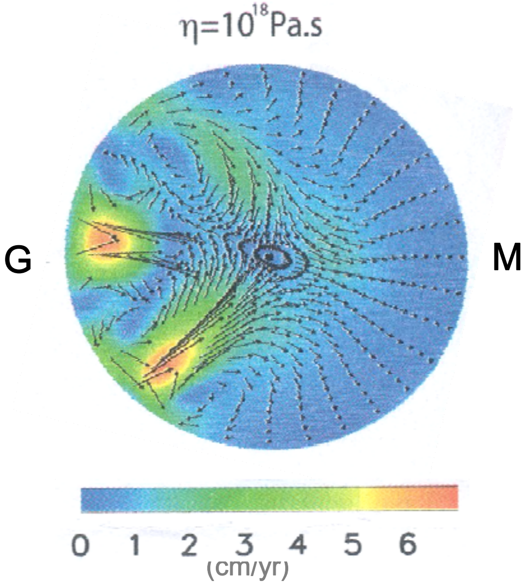
$\eta=10^{16}$ Pa.s

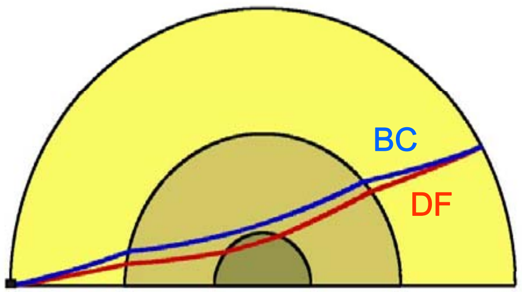


Low viscosity
→ Convective structures everywhere
Radial growth

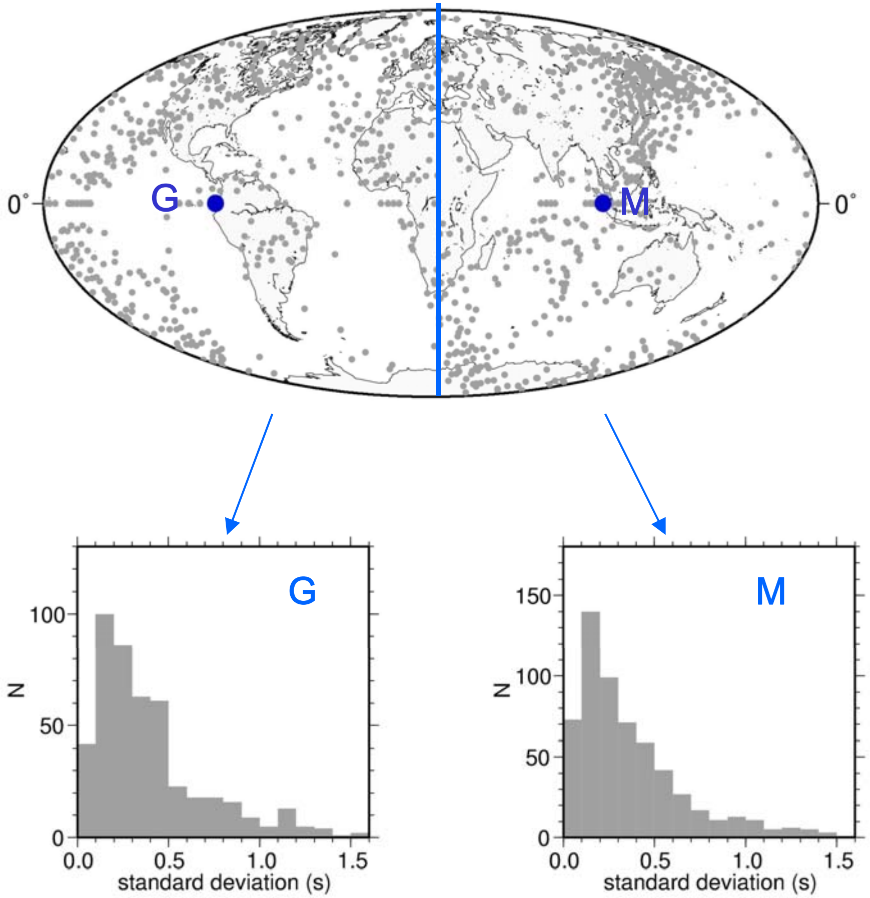
Mizzon and Monnereau, AGU Fall meeting, 2011

A test from seismological data using the differential travel times PKP(BC)-PKP(DF)





Turning points in the inner core:
BC-DF mean residuals on equal area sectors (5°x5°)



The standard deviations of the travel time anomalies are only slightly larger on side G than on side M

CONCLUSIONS

Seismic observations

- ***The isotropic layer between 30 et 90 km beneath ICB has a cylindrical symmetry with horizontal axis GM***

- ***Evolution of seismic velocities and attenuation from G to M :***
  G to the West, slow with low attenuation
  M to the East, fast with a higher attenuation

Iron grain size

- These W-E differences may be explained by an *increase in iron grain size from West to East* (~500 m at G, a few km at M)

Dynamical model (with open boundaries)

- *The inner core is subject to a permanent translation from W to E, with crystallization on side G and melting on side M.*

Consequences of the crystallization-fusion-translation model

- *The inner core growth only from side West, but there is a net radius increase in all the directions.*

- *The age of the inner core increases from West to East. The iron crystals in the inner core are younger than the inner core itself (i.e. younger than the beginning of formation of the inner core)*

- *The crystal size ratio at W and E sides imposes a translation velocity > 3 crystallization rate*

- *This model explains the formation of a dense layer at the base of the liquid core*

- *This model explains the hemispherical variations in Vp et Qp of the isotropic layer.*

- *A model with higher degrees of convection also explains the hemispherical variations of anisotropy, if viscosity is of the order of 10^{18} Pa.s.*

In the future:

- *Combine thermal forcing by the mantle + permeable boundaries of the inner core*
- *Test the different models with seismic observations*

Verne. Caricature par Gill, parue dans *L'Éclipse* du 13 déc. 1874. *Phot. © Roger-Viollet*

La science est faite d'erreurs, mais d'erreurs qu'il est bon de commettre, car elles mènent peu à peu à la vérité.

J.V.