40 years of core studies

from broadband data

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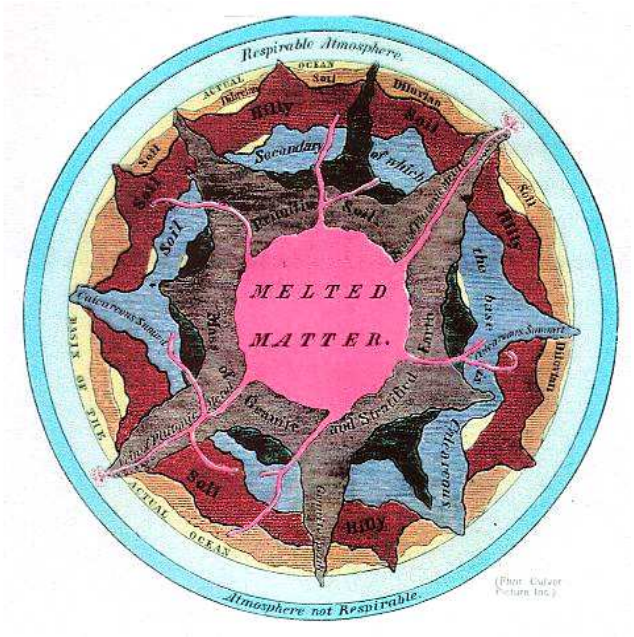
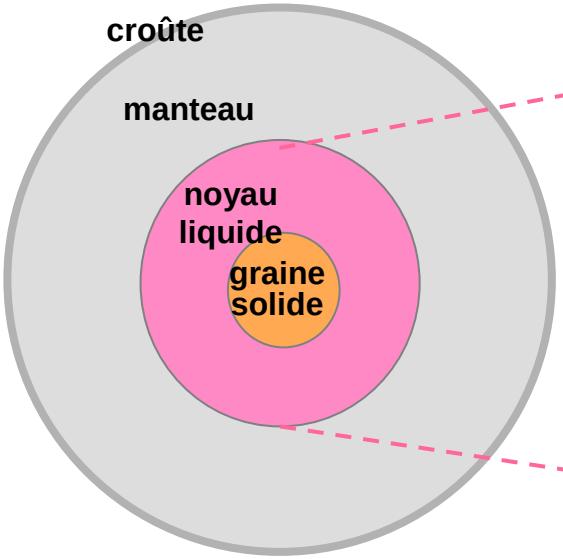
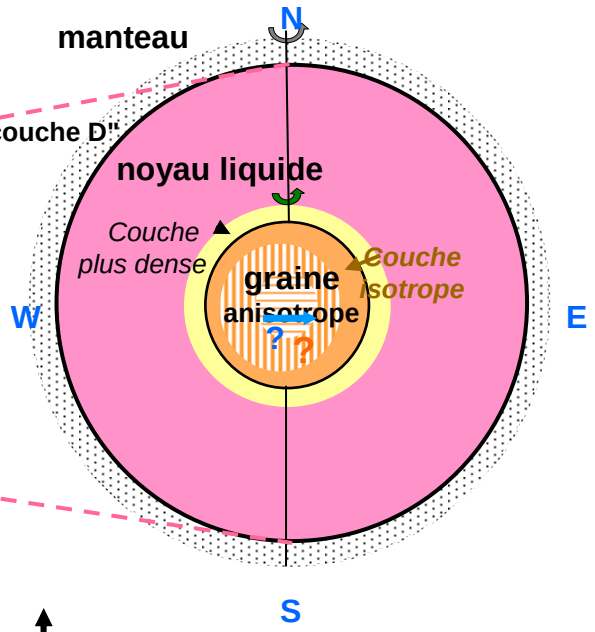
Introduction : evolution of data and ideas



19th century



~ 1980



~ 2020

Roche (1881), Wiechert (1896), **Oldham (1906)**, Gutenberg (1913), Wiechert, 1924, Jeffreys (1926), **Lehmann (1936)**, Bullen (1946), Birch (1952), Jacobs (1953)

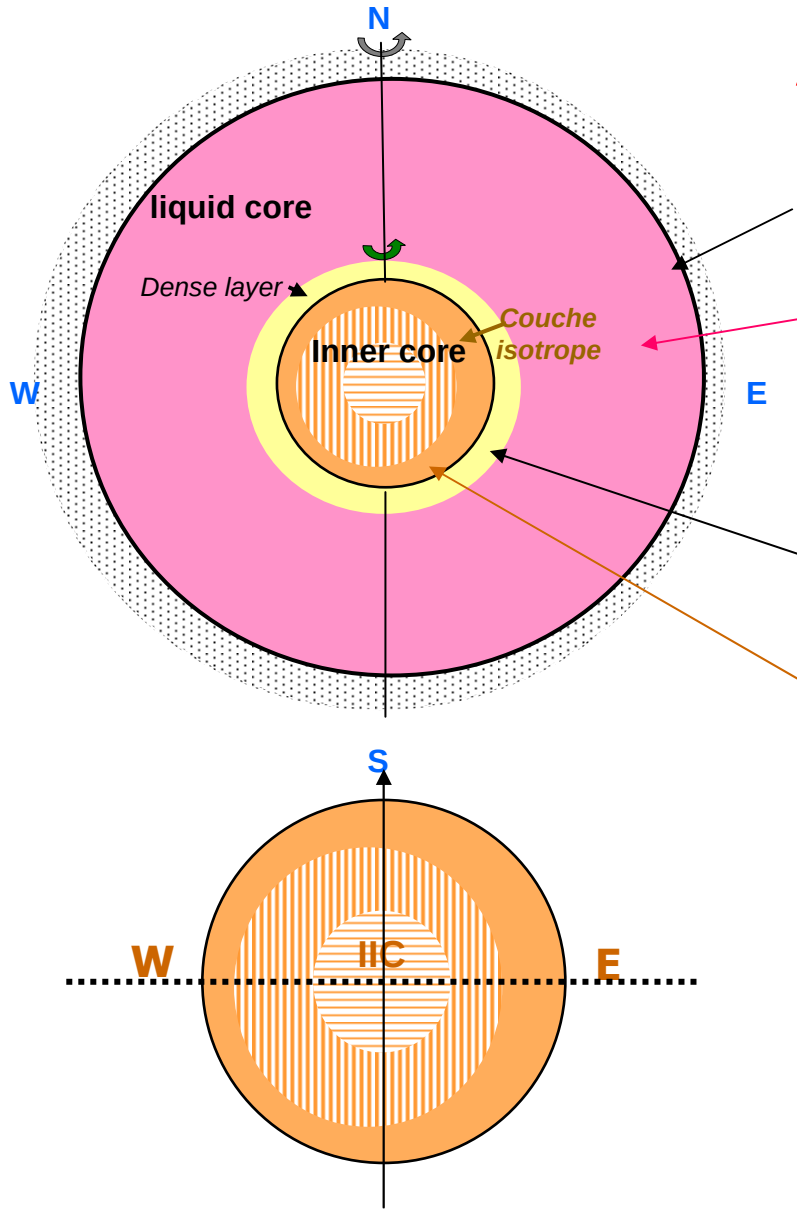
SP (ISC) **and LP data** (WWSSN)

Broadband data
Worldwide deployment of **networks**

GEOSCOPE, IRIS, …

Groueff, 1974 ; Poirier, 1996

A few information about the core



CMB: Core mantle boundary

Liquid core

- Molten iron alloy with light elements
- Low viscosity
- Homogeneous, except a dense basal layer

ICB: Inner core boundary

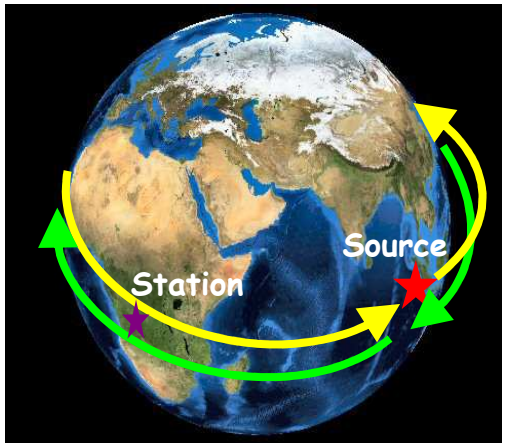
Solid inner core

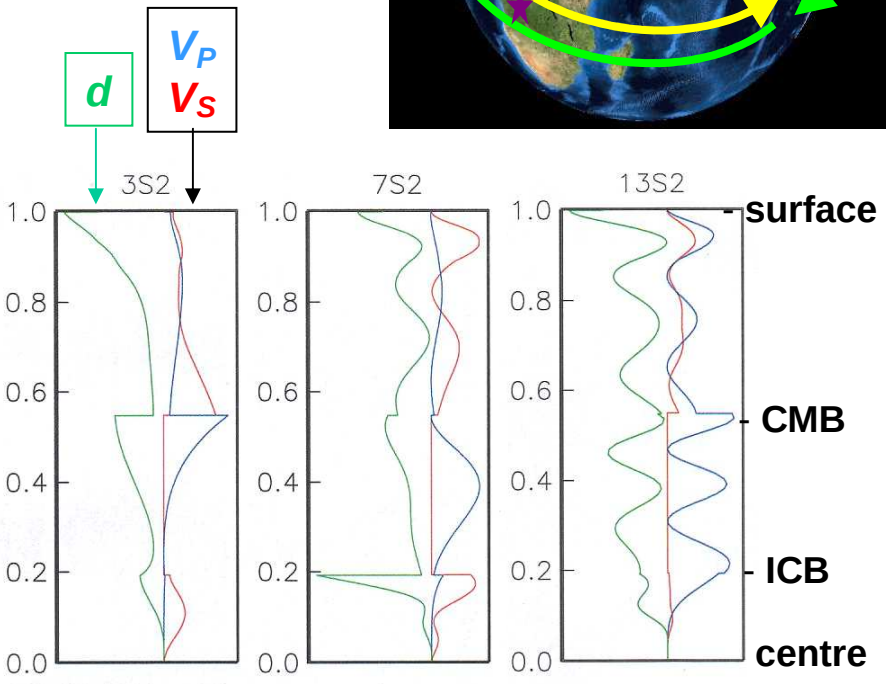
- Results from crystallization of the outer core
- almost pure iron
- Globally anisotropic for both V_P and Q
  (fast axis and high attenuation // rotation axis)
- A different anisotropy at the center
  (innermost inner core)
- An external isotropic layer
- An East-West dichotomy
- Correlation attenuation-velocity ≠ mantle

See references in the chapter *"The Earth's core"* by Souriau A. and Calvet M., in the *Treatise on Geophysics*, G. Schubert, Ed. in chief, 2nd Edition, Vol. 1, 2015, p. 725-757

The tools in seismology

Normal modes



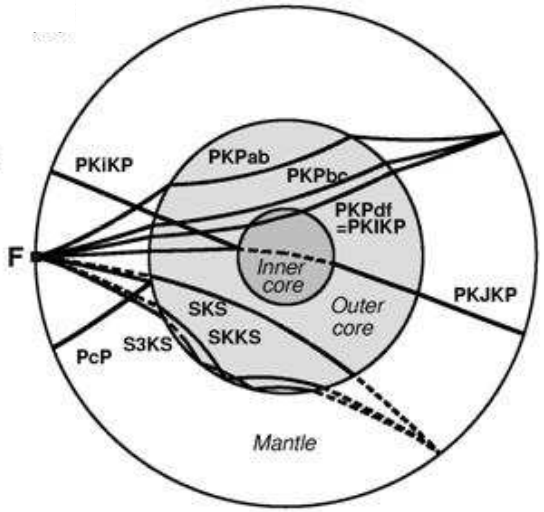


- A global approach for V_P, V_S and density
- No sensitivity at the Earth center

Laske 2006

Body waves

- Ray approximation (infinite frequency)
- Travel times, amplitudes and waveforms
- P and S waves (no S in the liquid)



PKPbc
(base of liquid core)
PKPdf = PKIKP
(inner core)

- A poor distribution of paths
  Deficit of N-S paths

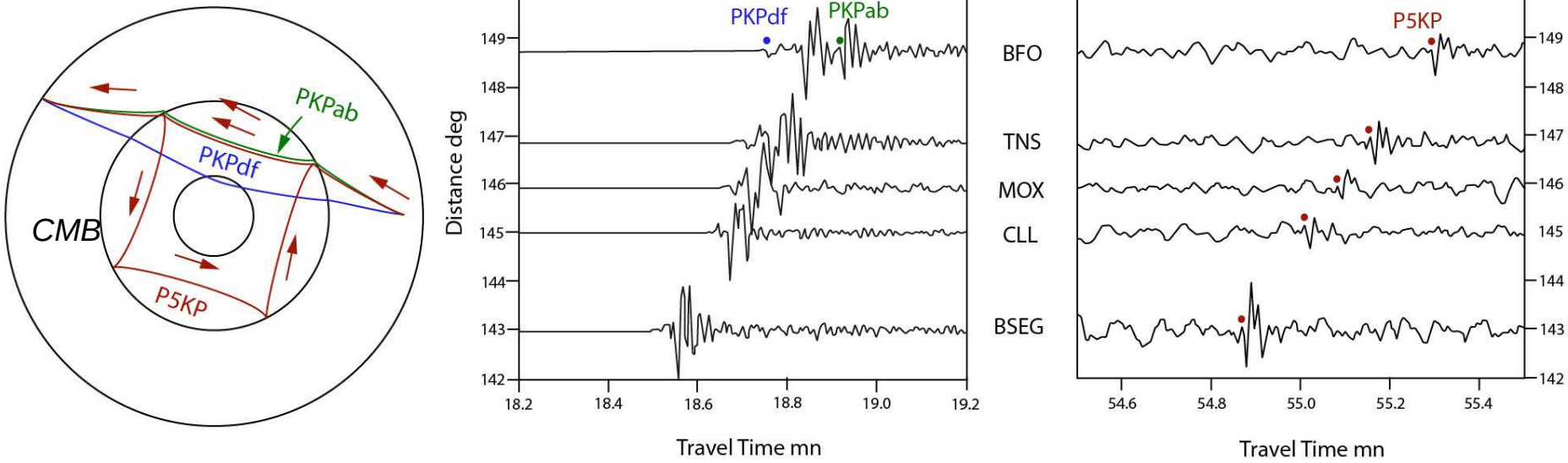
Scattered waves

- departure from balistic propagation, diffusion information on the texture

The CMB and the liquid core

Comparison of PKP and P5KP

(BRB data)

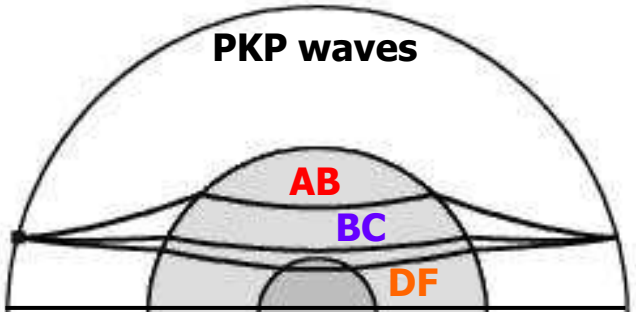


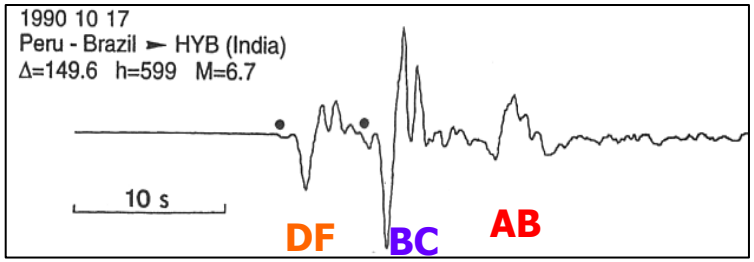
- Almost no attenuation in the liquid core (Qp = 5000-10000, *Qamar and Eisenberg, 1974*)
- No lateral heterogeneity in the liquid core

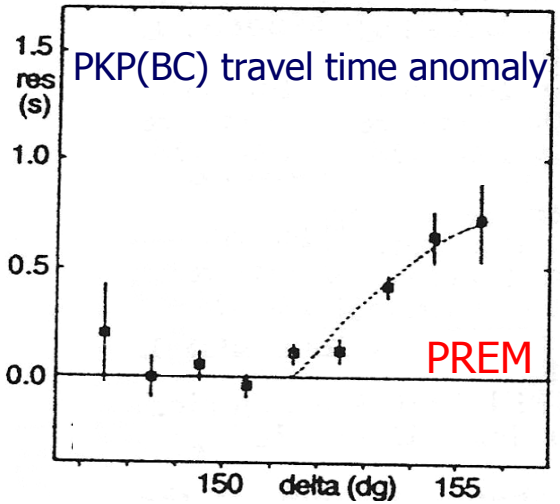
- Core-mantle boundary (CMB) is a sharp discontinuity
- The reflexion coefficient at CMB is high for this incidence angle
- No strong topography at CMB (< 2 km, *Bolt, 1982*)

Fig. modified from Bormann, Klinge and Wendt, Potsdam GFZ, 2002

Stratification at the base of the liquid core

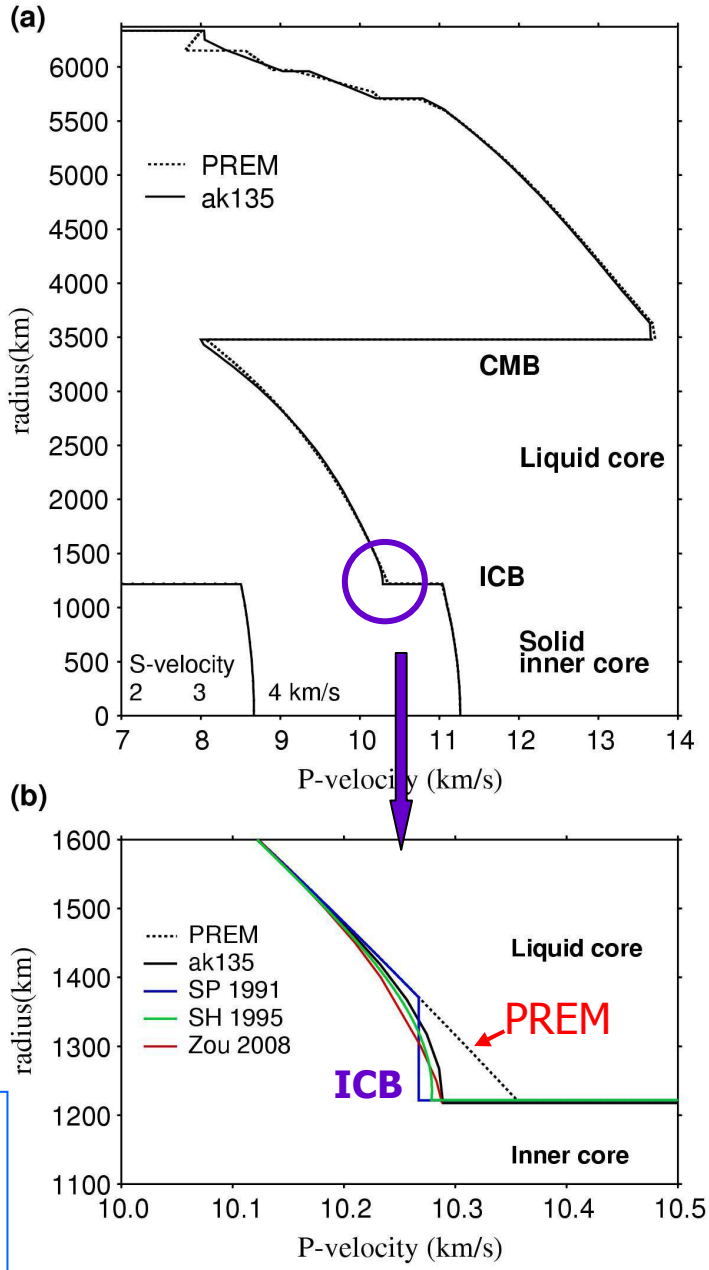






=> dense layer above the inner core boundary (F-layer)

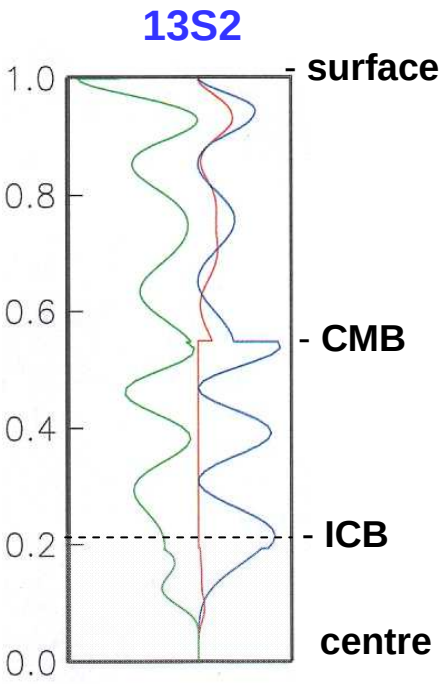
- possibly related to partial re-melting of the inner core
- or of primordial origin



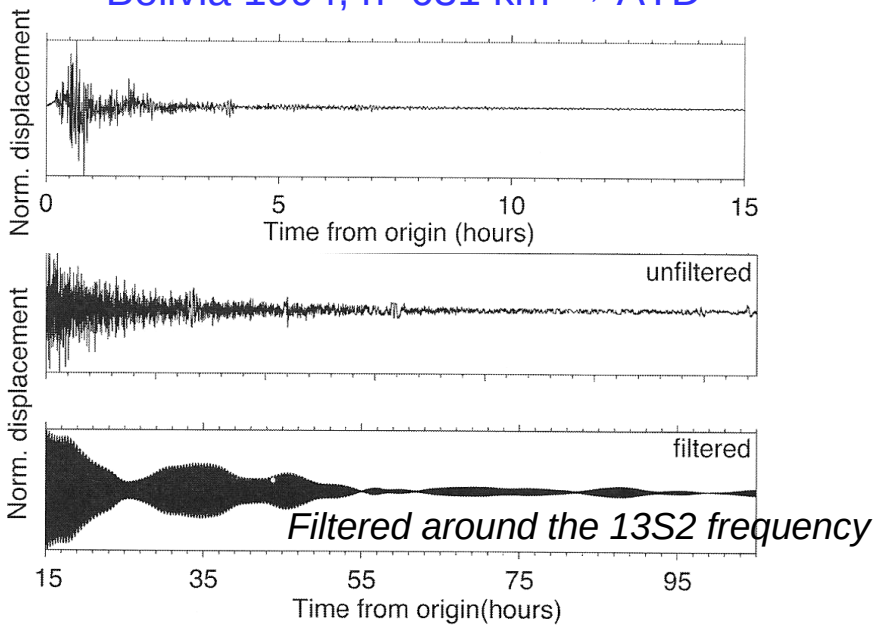
Souriau and Poupinet, 1991

The solid inner core

Normal modes, evidence for cylindrical anisotropy inside the inner core



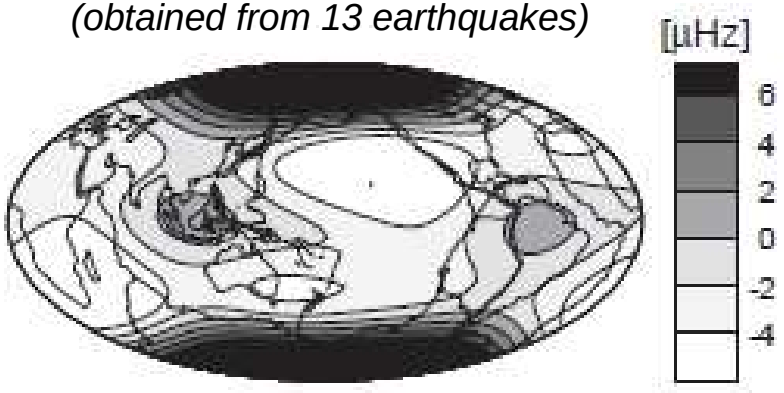
Bolivia 1994, h=631 km → ATD

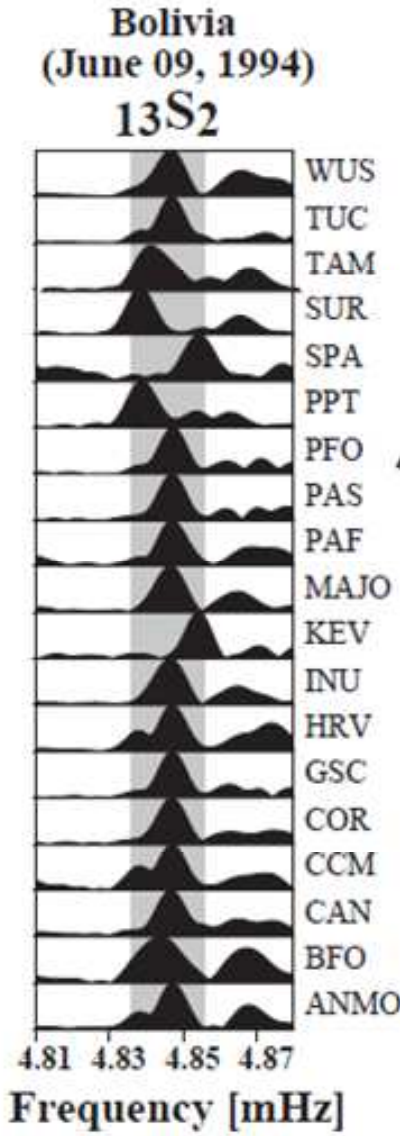


Filtered around the 13S2 frequency

Splitting function for 13S2 (elastic)

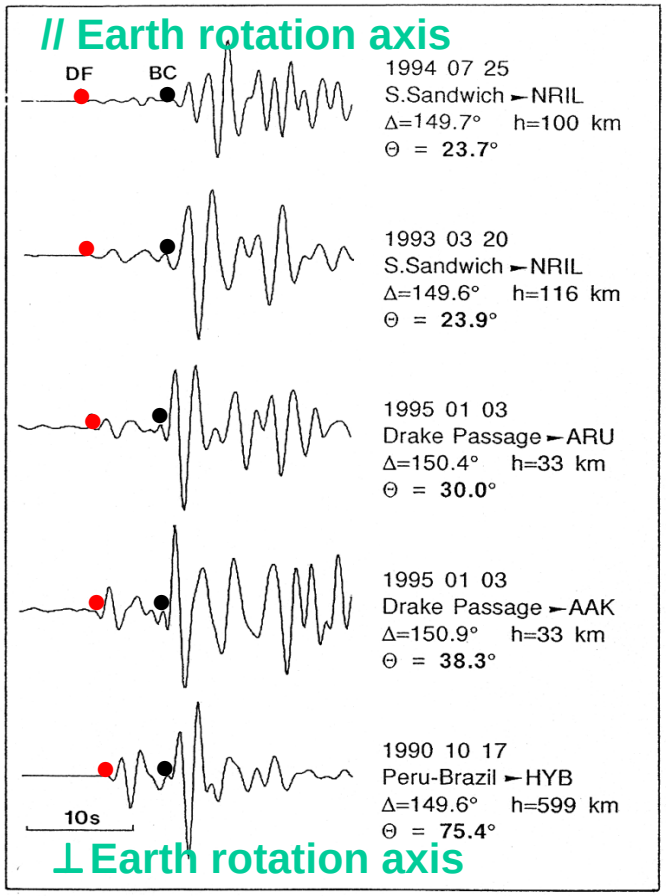
(obtained from 13 earthquakes)

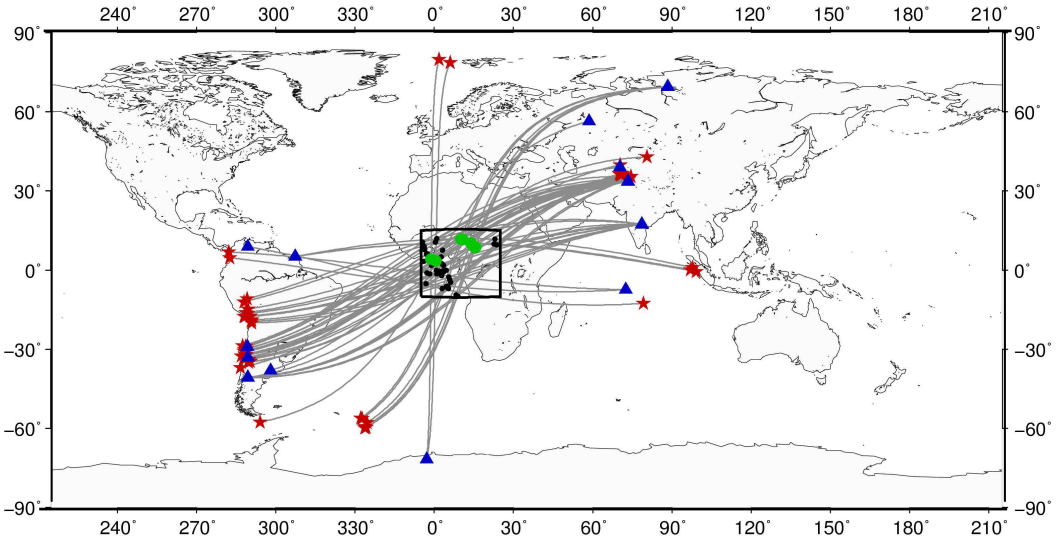




Laske and Widmer, 2006; Courtesy of Laske, 2006; Tkalčić, 2017

Anisotropy in P-wave velocity and attenuation: evidence from P-waves

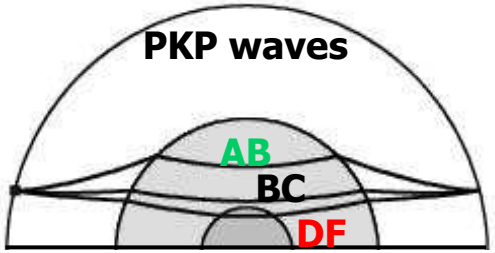




P-waves // to Earth rotation axis are faster and more attenuated than those parallel to equatorial plane.

High velocity ⇔ high attenuation
Correlation opposite to that observed in the mantle

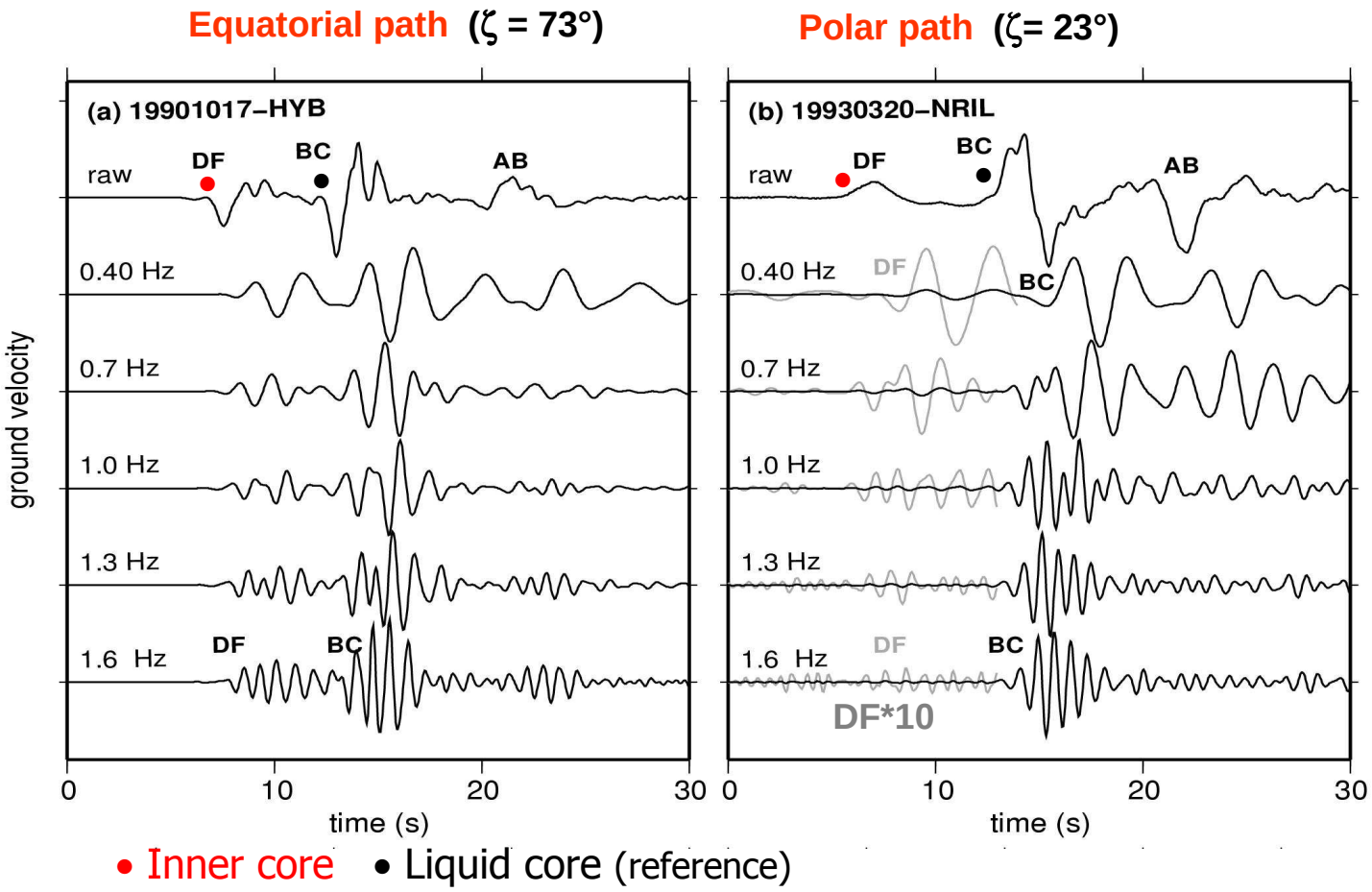
• Inner core • Liquid core (reference)



Preferred orientation of iron crystals or grains
(+ preferred orientation of ellipsoidal fluid pockets)

Souriau et Romanowicz, 1996

The frequency dependence of the attenuation is also anisotropic



Polar paths:
Very strong dependence of the attenuation to frequency
(not observed for equatorial paths)

Souriau, 2009

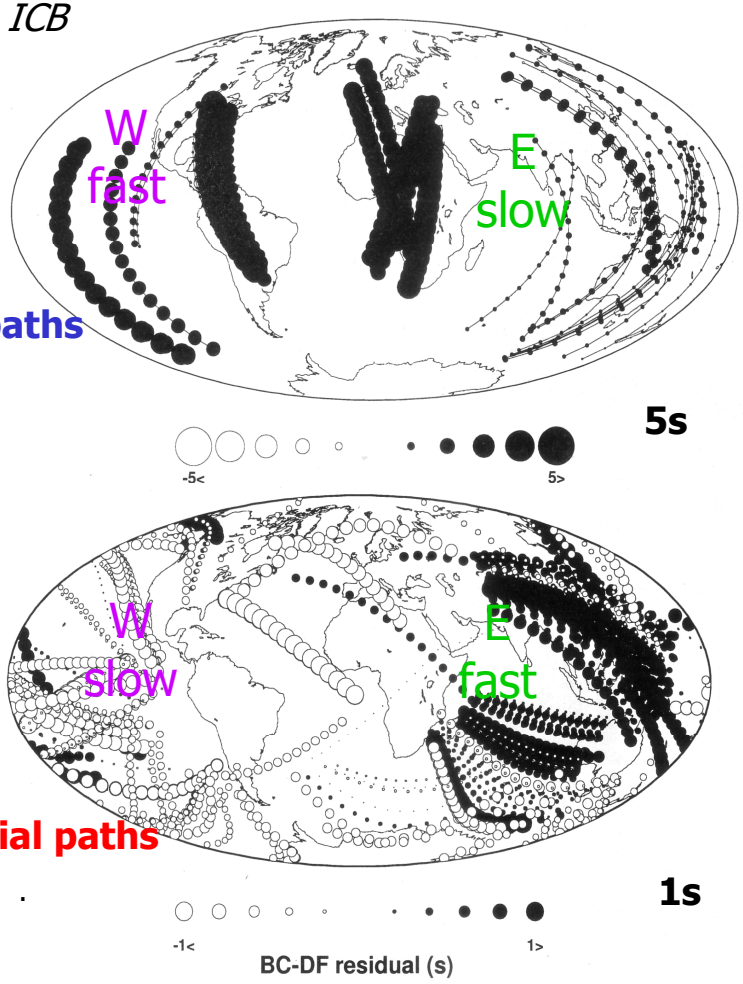
• Inner core • Liquid core (reference)

Velocity, attenuation, but also their frequency dependence vary with ray orientation
High velocities ↔ high attenuation
This may give strong constraints on the texture of the inner core

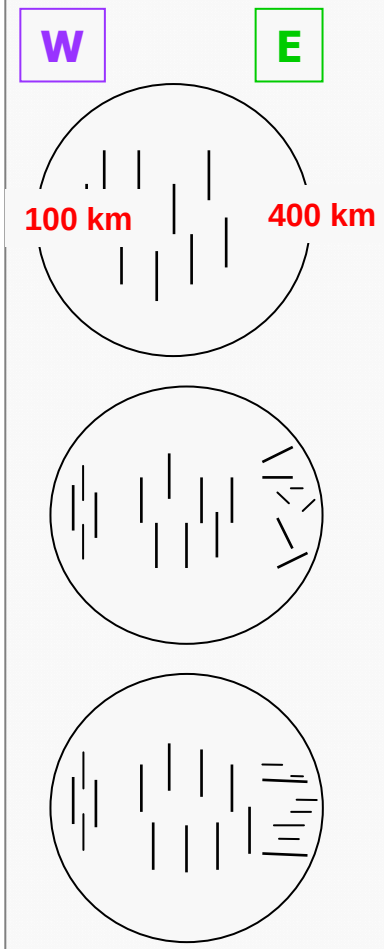
The puzzling hemisphericity of the inner core

The hemispherical variation in anisotropy

Travel times
100-500 km
beneath ICB



Tanaka and Hamaguchi, 1997



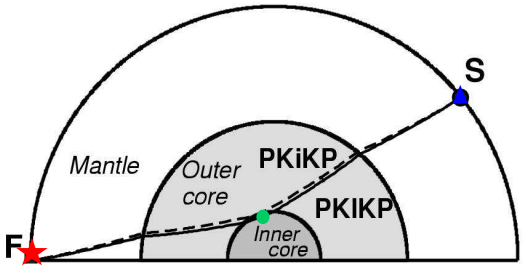
3 possible explanations:

1- a thickness of the isotropic layer different at each sides *(Creager, 1999, Garcia et Souriau, 2000)*

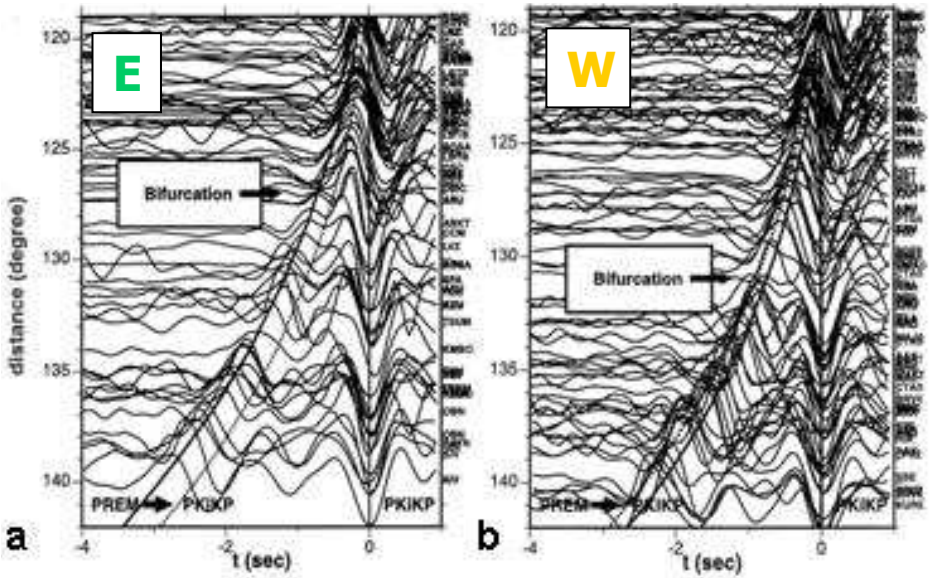
2- a progressive desorientation of the crystals from W to E *(Garcia, 2002)*

3- a different texture on each side (*Cormier, 2007)*

The hemisphericity in the isotropic layer heterogeneity

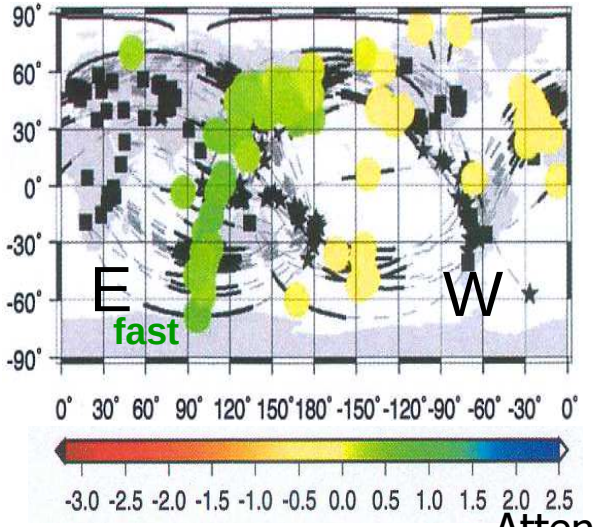


30-85 km beneath ICB

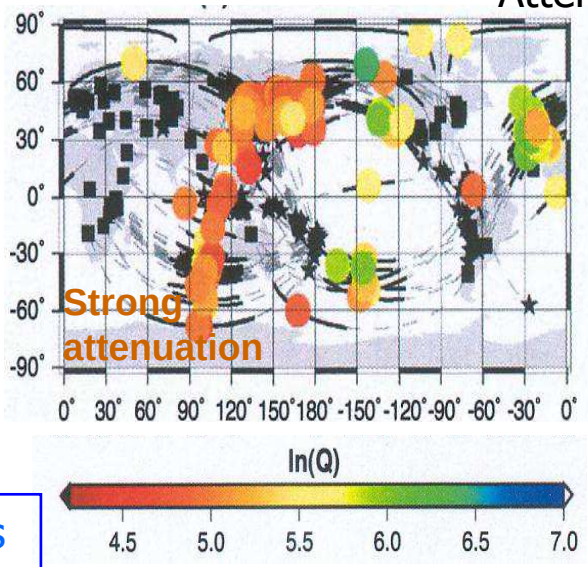


Hemisphericity for both velocity and attenuation
with again a correlation opposite to that in the mantle

P-velocity



Attenuation



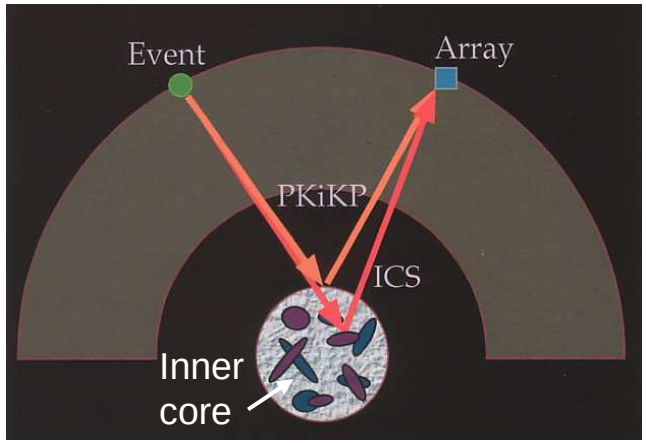
- Forcing of crystallization by mantle thermal heterogeneities *(Aubert, 2013)*
- Thermally or chemically driven translation of the inner core *(Monnereau et al. 2010, Alboussière et al. 2010, Degen et al. 2018)*

Wen and Niu, 2002;
Cao et Romanowicz, 2004

The scatterers

Scatterers inside the inner core : Observations

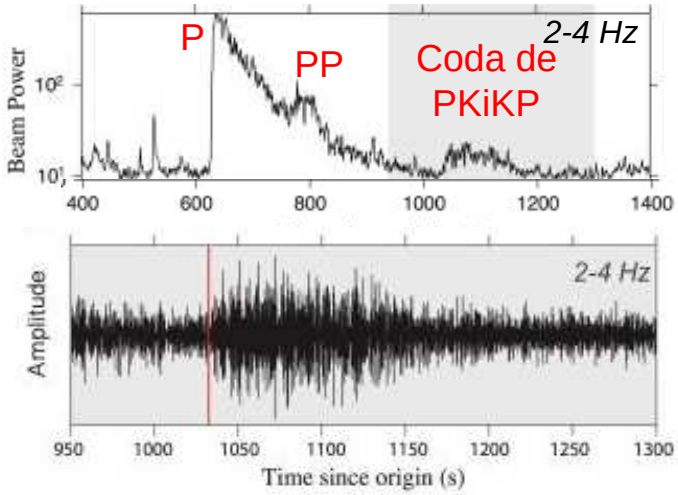
Evidence given by the coda of PKiKP waves reflected at ICB



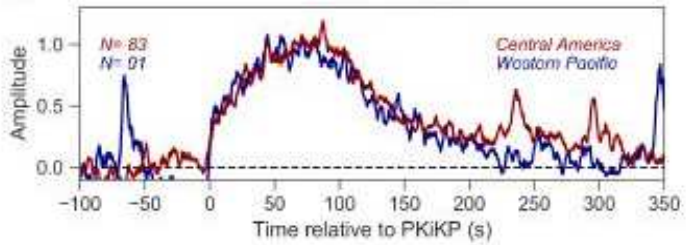
Vidale and Earle, 2000

stacking on small aperture arrays, on many events

C.Am. 2004 11 20 → ILAR Alaska

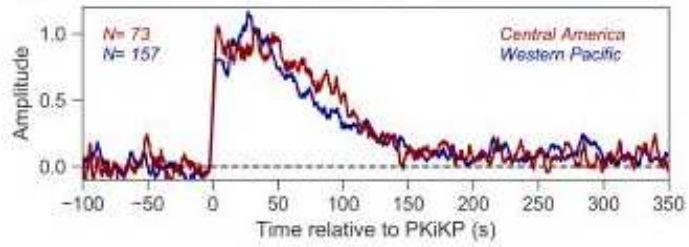


Stacks **ILAR Alaska** *2-4 Hz*



deep scatterers

Stacks **YKA Canada** *2-4 Hz*



more superficial scatterers

See also: *Cormier and Li, 2002; Koper 2007, Poupinet and Kennett, 2004; Calvet and Margerin, 2008*

Wu, Pang and Koper, JGR 2022, submitted

Concluding remarks

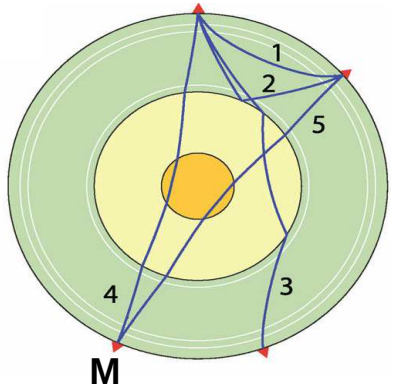
A great contribution of broadband data (e.g. Geoscope) to core studies

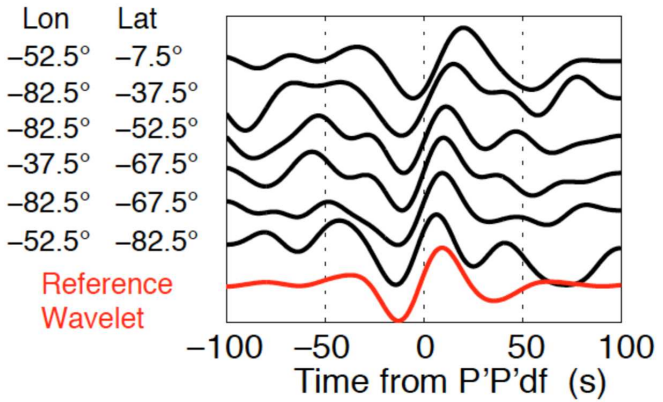
A promising future

- Many unsolved exciting problems, implying observations, modelling, interactions with other fields of physics and chemistry

- New observational approches (arrays, ambient seismic noise correlations, coda correlations, big data approaches, deep learning, time dependent seismology…)

correlations of ambient seismic noise:
PKPPKP (wave 5)





Boué et al., 2013

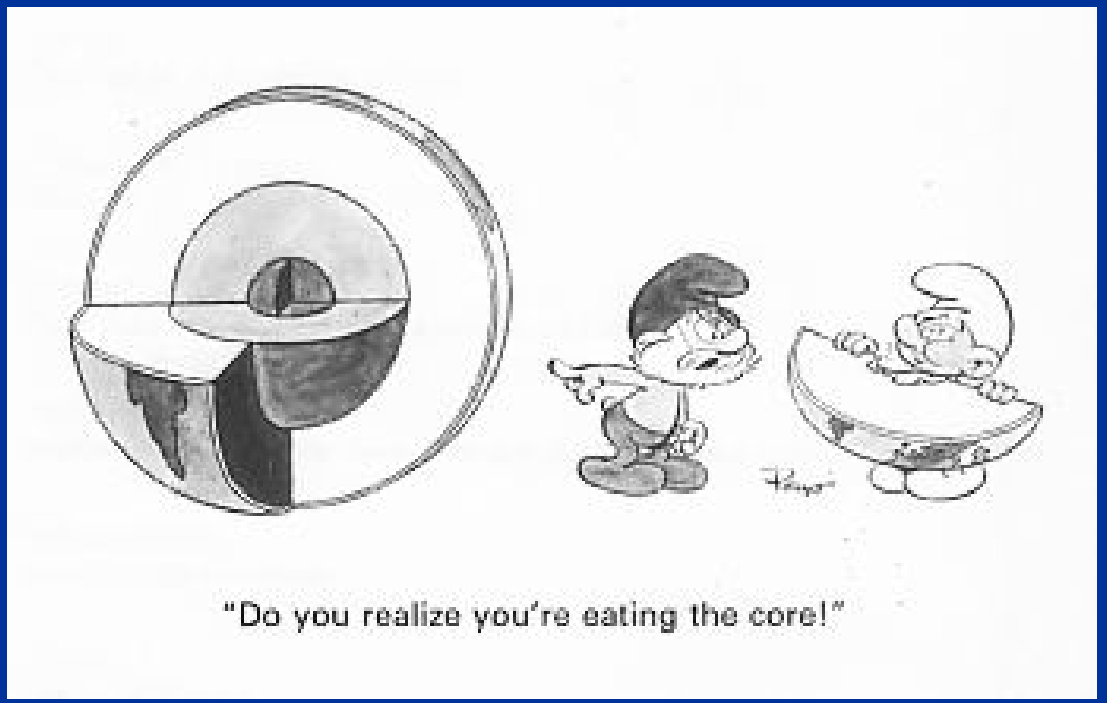
It is imperative to patiently collect data on stable networks

And in addition, for core studies:

- More polar paths (more stations at high latitudes)
- Small aperture arrays

PKPPKP: *see also Tkalčić, 2015, for direct observations*

Thank you!



Peyo, for Paul Melchior, The Earth's core, 1986