The Abdus Salam International Centre for Theoretical Physics

2048-6

From Core to Crust: Towards an Integrated Vision of Earth's Interior

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Earth's Core: Seismological Perspective

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The Earth's Core: a seismological perspective

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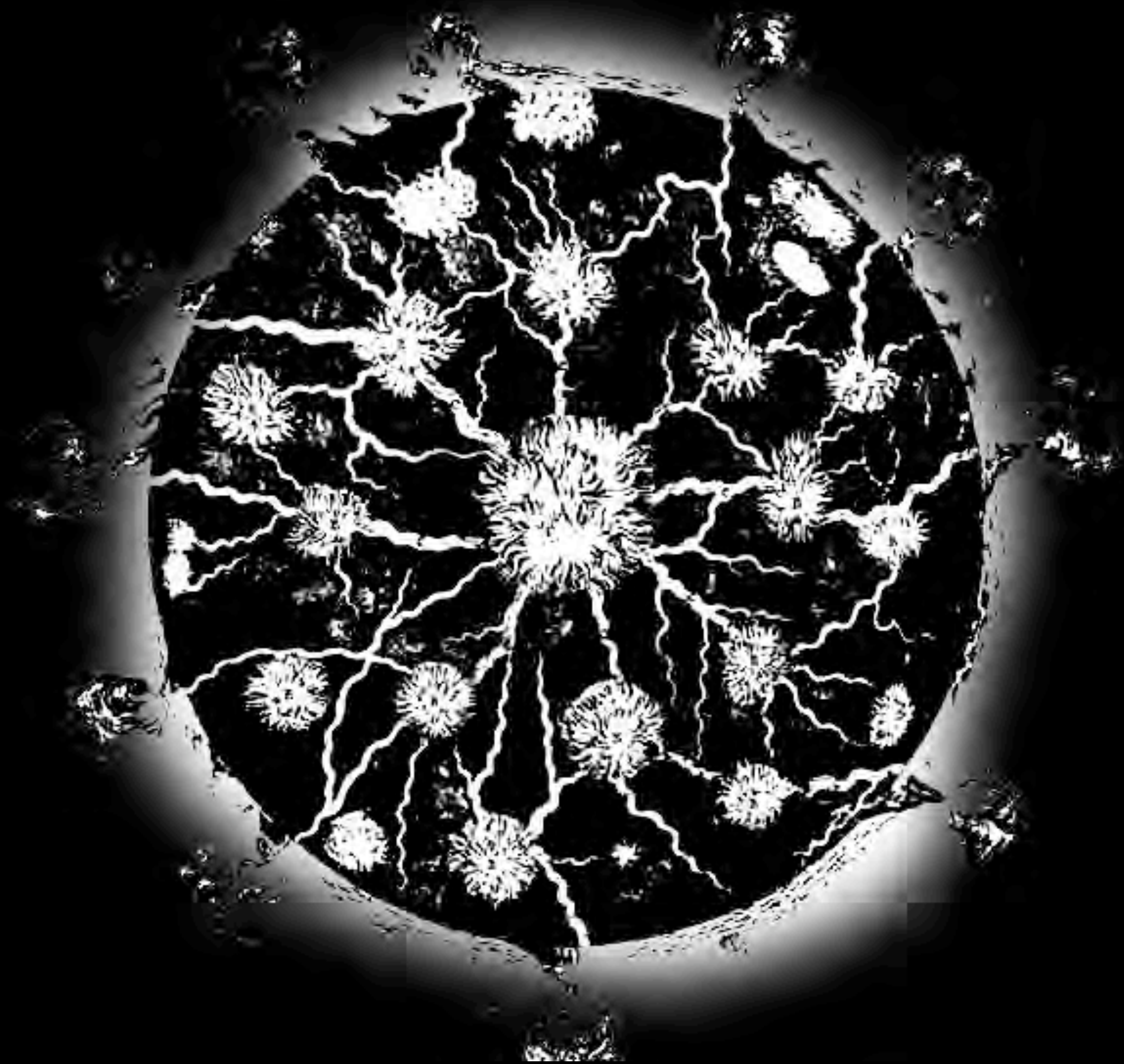
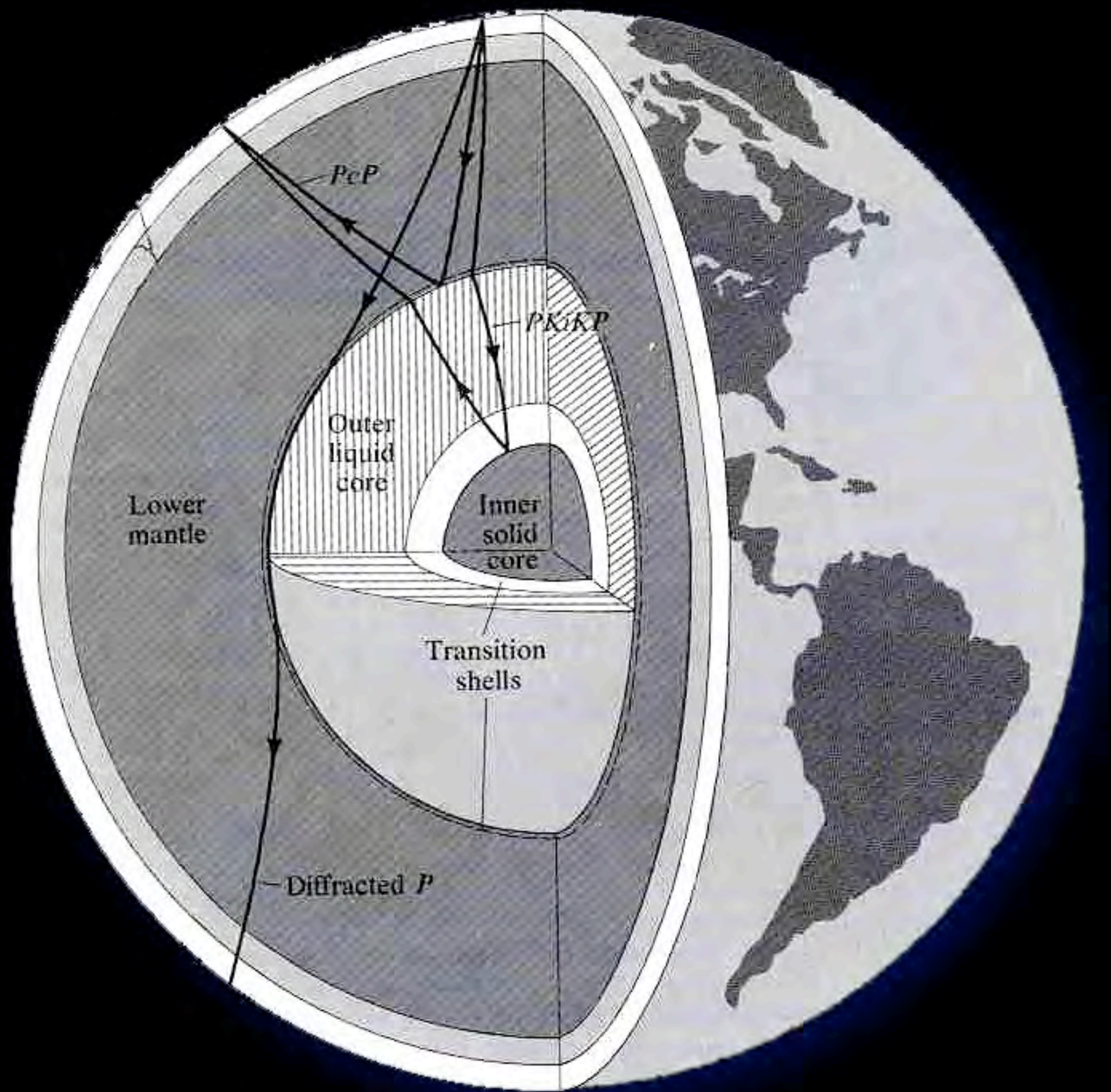
"But in the cause of science men are expected to suffer."
(p. 28, A Journey to the Center of the Earth, Jules Verne, 1864)

1600's view of Earth's interior



Athanasius Kircher, Mundus Subterraneus (1664/65)

1973 view of Earth



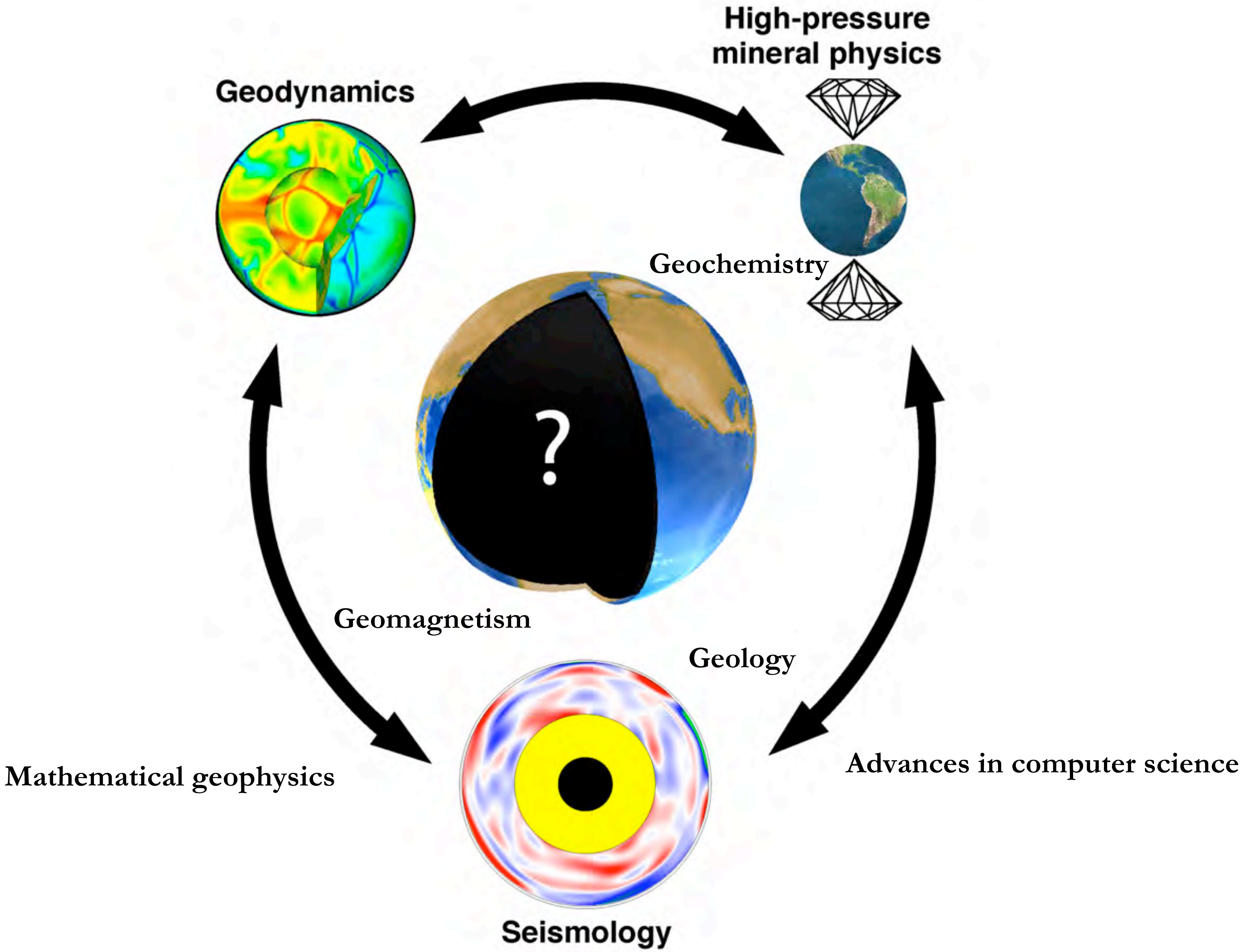
BOLT (Inside the Earth, 1973)

Outline

- Introduction: Seismology and structure of the Earth's core

Focus on observational seismology

- Recent seismological observations and interpretations
- Anisotropy in the inner core and anomalous PKP travel times
  - alternative views: outer core and core-mantle boundary
  - alternative ways to study anisotropy and recent observations of PKPPKP waves and their precursors => upper mantle structure
- The density jump at the inner core boundary and recent observations of seismic waves reflected from the core (PcP and PKiKP waves) at very short epicentral distances => upper mantle structure
- Conclusions and future research



Note: A mineral physicist and a geodynamicist always welcome for discussions and collaboration on deep Earth structure topics (some will be presented here)

What do (we think) we know about the inner core

- Small on planetary scale (0.7% of Earth's volume)
- Pressure from ICB to center: 329 to 363 GPa
- Iron and Nickel alloy with impurities (O, Si, Al, S, C, K?)
- ICB temperature estimates: 5000-6000K (density contrast speculative)
- Phase diagram of iron not well known at IC conditions (T of the melting point of iron not well constrained) thereby T of the ICB uncertain =>
- Temperature gradient ΔT across core-mantle thermal boundary layer uncertain due to ICB temperature and mantle conductivity uncertainties => current estimates yielding heat flow of 6-12 TW (relatively high) =>
- Extraction of light elements and release of latent heat due to the solidification => buoyant fluid which drives vigorous convection in the outer core

  => the magnetic field generation (1 TW sufficient to power the geodynamo)

Some difficulties

- Uncertainties in the density translate directly to the uncertainties in the composition
- Seismic data cannot generally distinguish between two chemical elements of the same density
- Extrapolation from meteorites useful but should be taken with caution because meteorites were not formed from the planets whose cores were exposed to the quite same pressures as the Earth's core
- Phase diagram of iron is not well known - this imposes problems for understanding anisotropy and the precise temperature and thermal history of the inner core (when it was formed)

Chemical composition of the core

- IC is 3% less dense than pure Fe and OC is 6-10% less dense than pure Fe -> this argues for the existence of lighter elements and also that less dense material from iron-depleted alloy partitions in the OC during the solidification

- Oxygen is a serious candidate, although FeO is not present in meteorites and is not soluble in Fe at atmospheric conditions.
  O'Neill et al. (1998) showed that up to 2% could have been dissolved into the core.

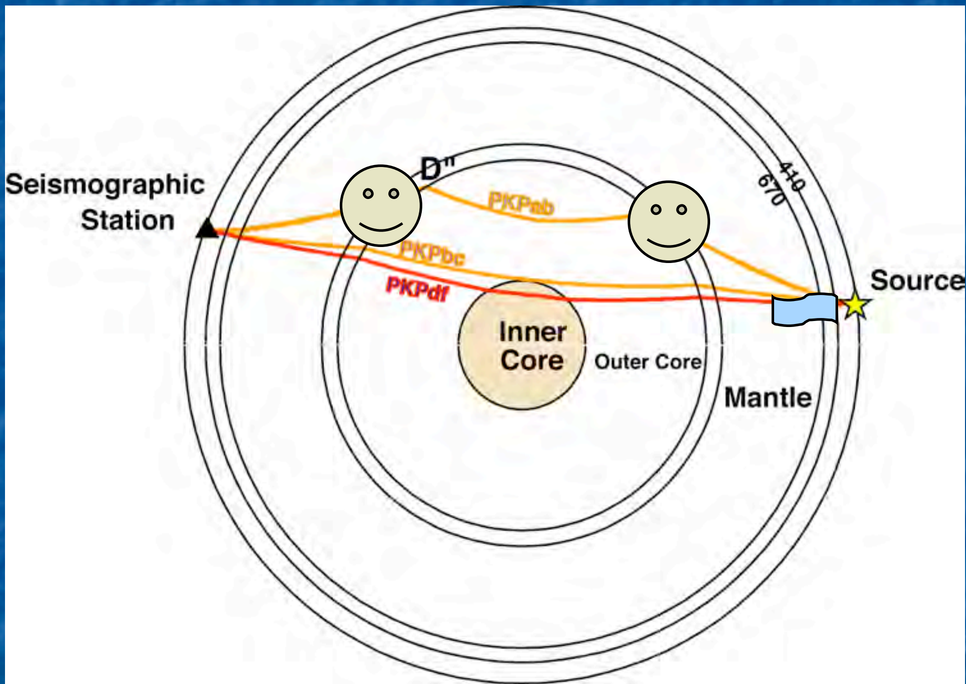
- S, C and P content is too small to account for the density deficit, however Si is though to be a likely element present in the core (*Ringwood 1959).*

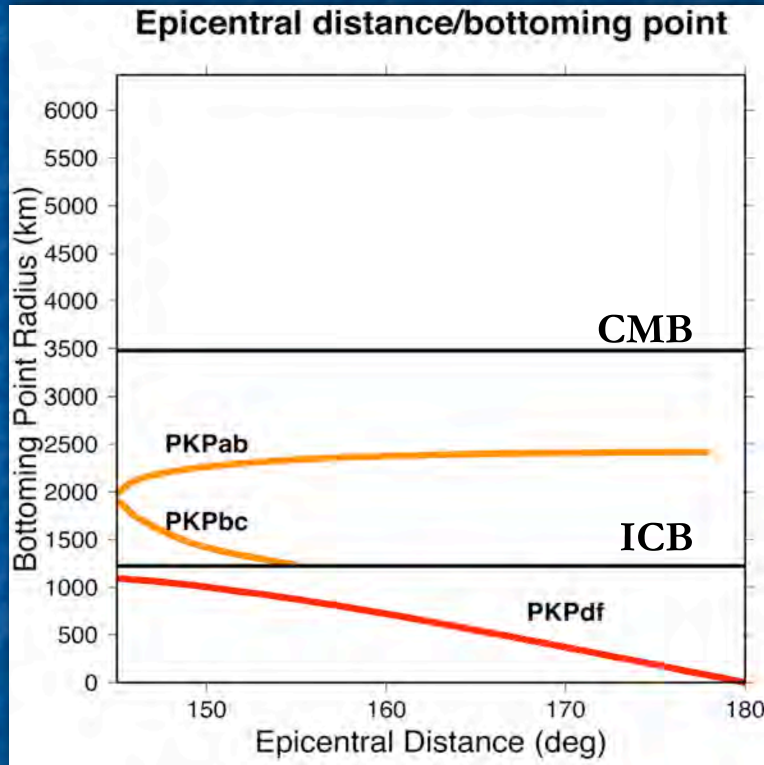
- FeO and FeSi extraction on the top of the OC would form sediments (*Buffett et al. 2000*) - ULVZ and heterogeneity support that but should be more frequently observed.

- *Lee et al. (2003)* found that Fe-K alloy is unlikely to be present in the core because the core differentiation started before the conditions were favorable for K to alloy with Fe.

- Seismology is unlikely to detect radioactive and other trace elements if their presence is not somehow reflected on physical properties of material or the dynamics of the core on short time scales.

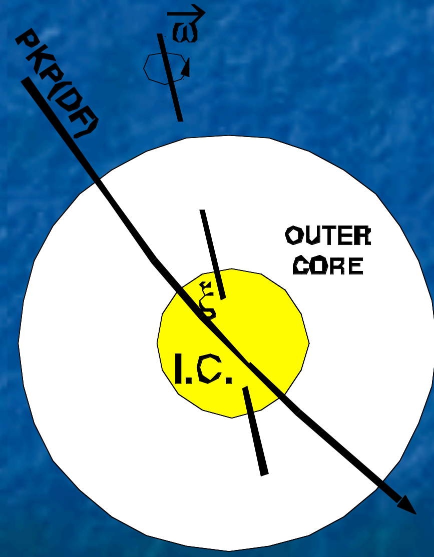
PKP Waves - Core Sensitive



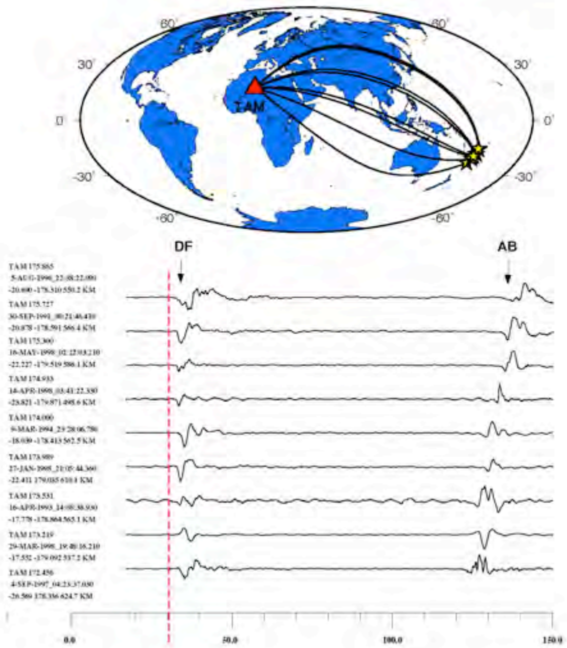


Inner Core Anisotropy - Short History

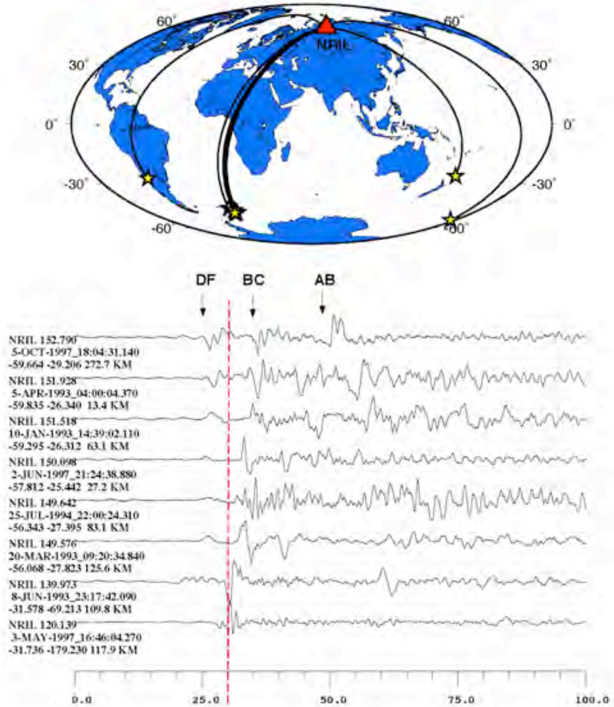
- Core-sensitive free oscillations of Earth are split anomalously (*Masters and Gilbert, 1981*)
- P waves traversing the inner core nearly parallel to the spin axis travel faster than waves with the trajectories in the equatorial plane (*Poupinet et al., 1983*)
- IC anisotropy proposed (*Morelli et al. & Woodhouse et al. 1986*)



Anomalous PKP Travel Times



ak135



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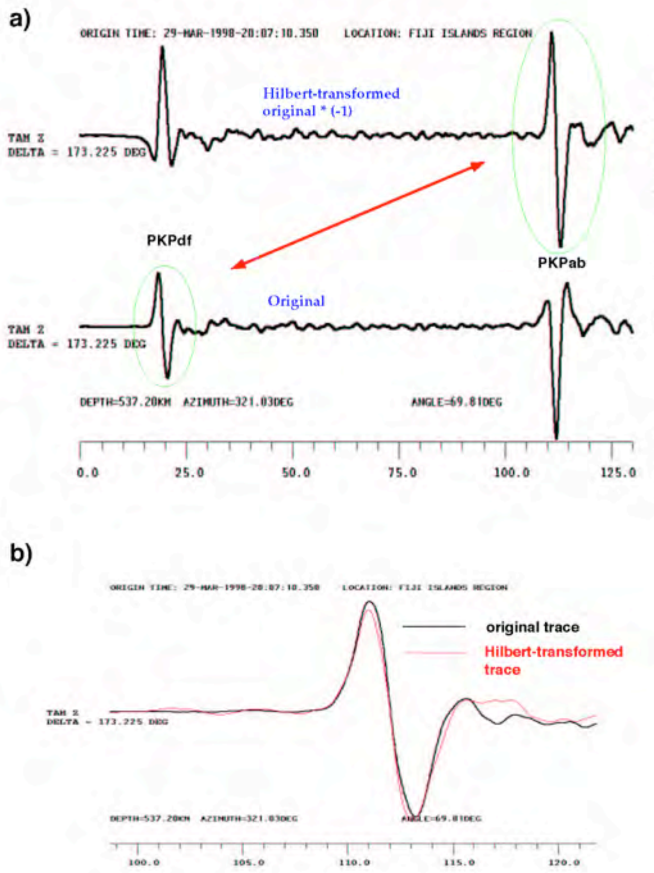
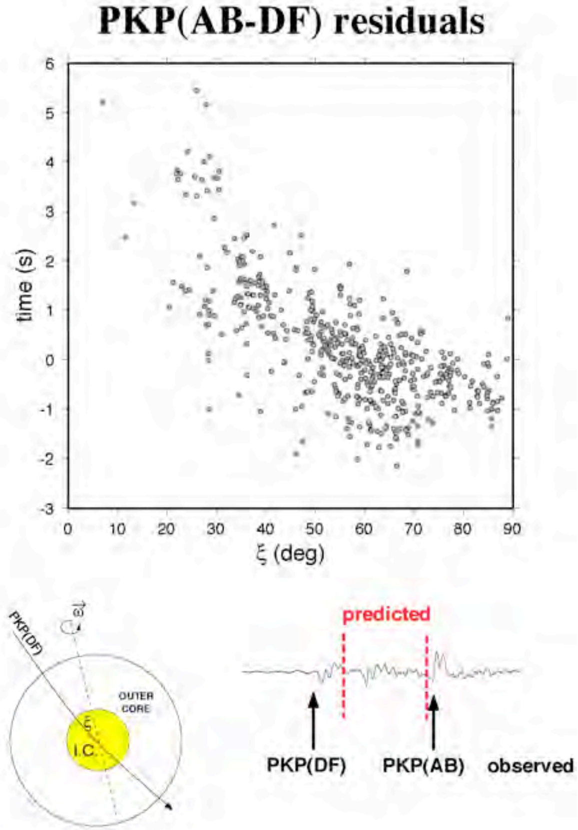
example from PhD thesis; Tkalčić, 2001

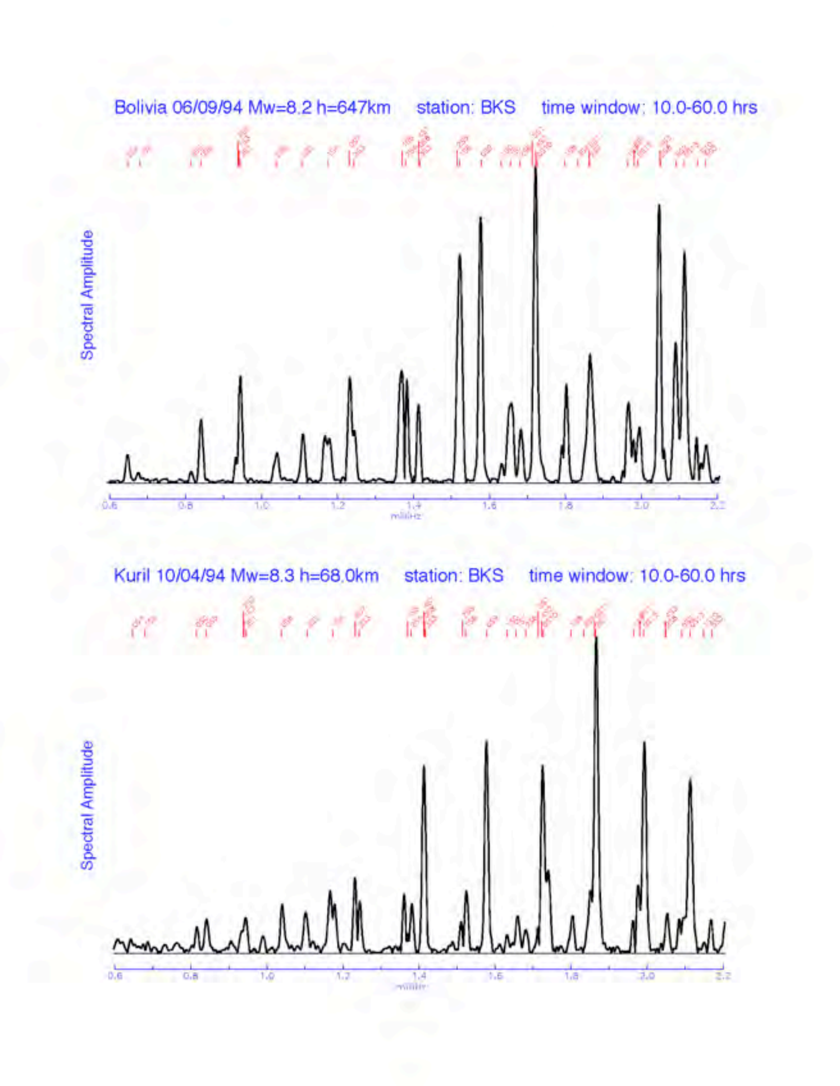
PKP Travel Time Residuals and IC Anisotropy

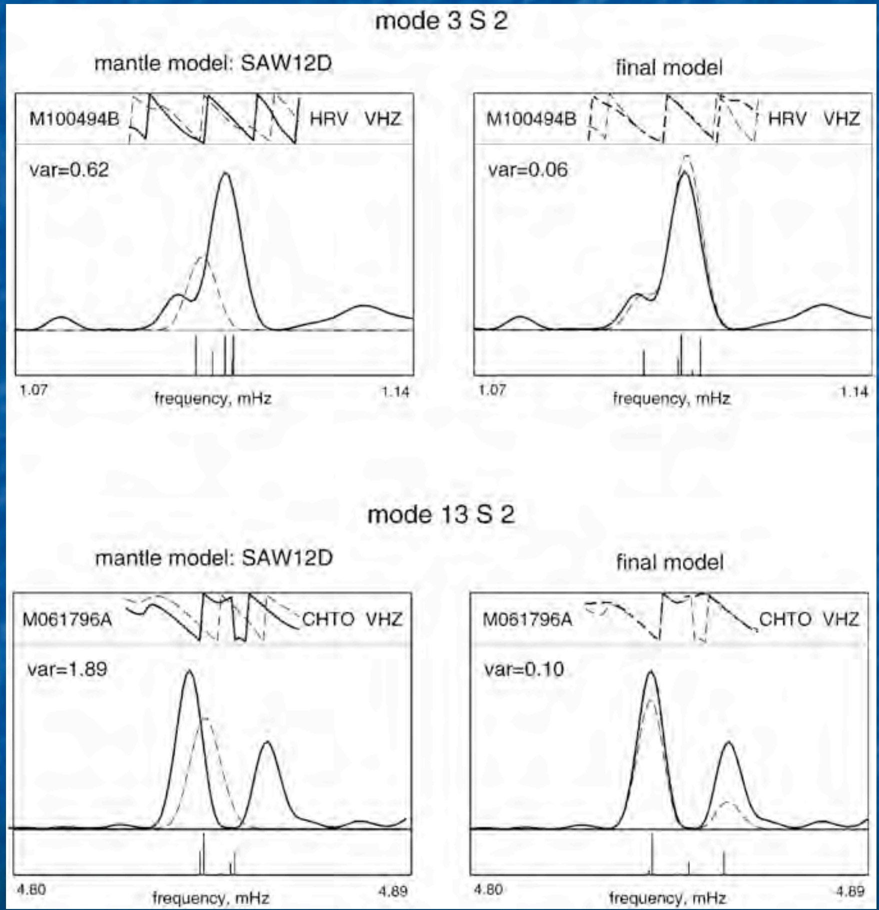




example from PhD thesis; Tkalčić, 2001

Anomalous Splitting of Free Oscillations





Durek and Romanowicz, 1999

Physical causes of inner core anisotropy

Hypotheses involve solidification and post-solidification deformation

Solidification

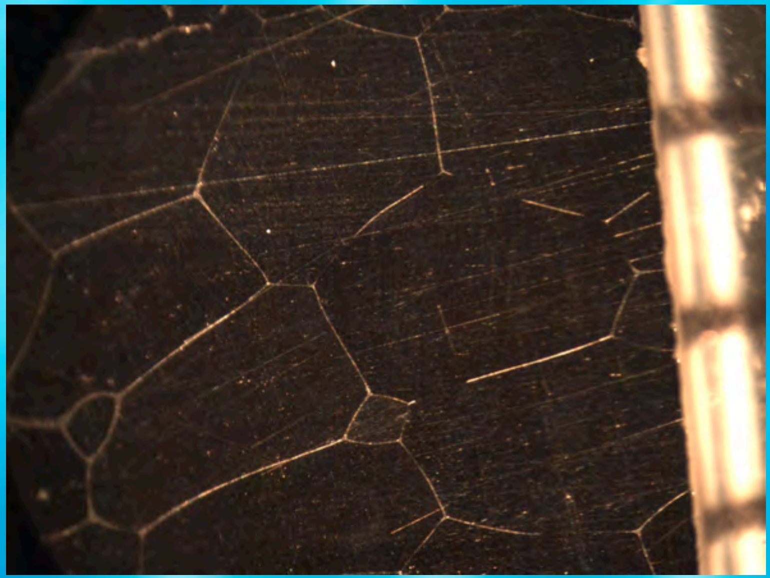
- Texturing due to anisotropic paramagnetic susceptibility (Karato, 1993)
- The inner core as a single crystal (Stixrude and Cohen, 1995)
- Texturing due to directional solidification (Bergman, 1997)

Post-solidification deformation

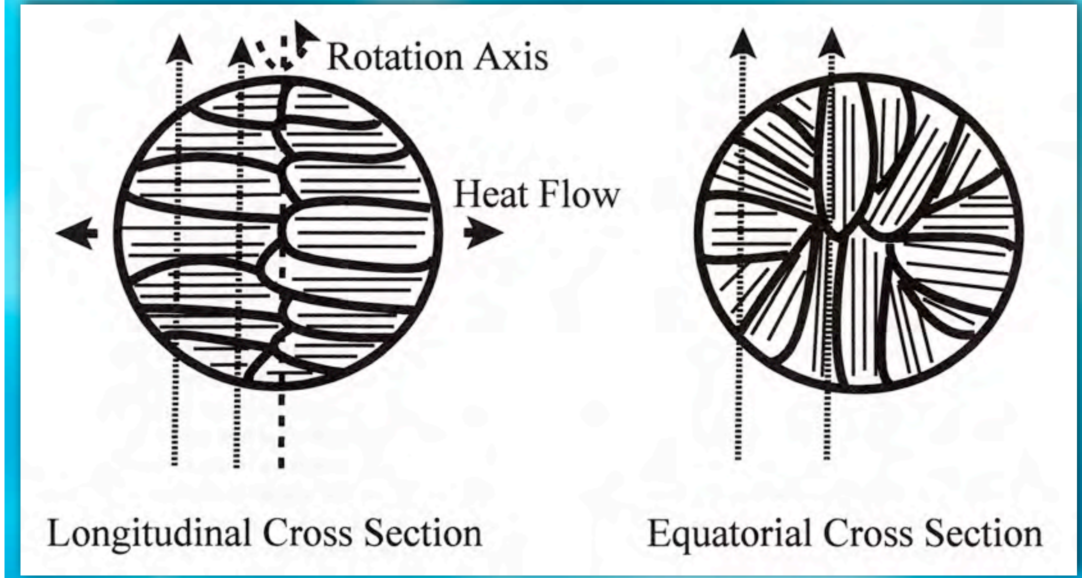
- Inner core thermal convection (Jeanloz and Wenk, 1988)
- Solid state flow due to misalignment between the gravitational equipotential and the thermodynamical equilibrium of the inner core (Yoshida et al., 1996)
- Radial flow due to Lorentz stresses (Karato, 1999)
- Longitudinal flow due to Lorentz stresses (Buffett and Wenk, 2001)

Inner Core Dendritic Growth

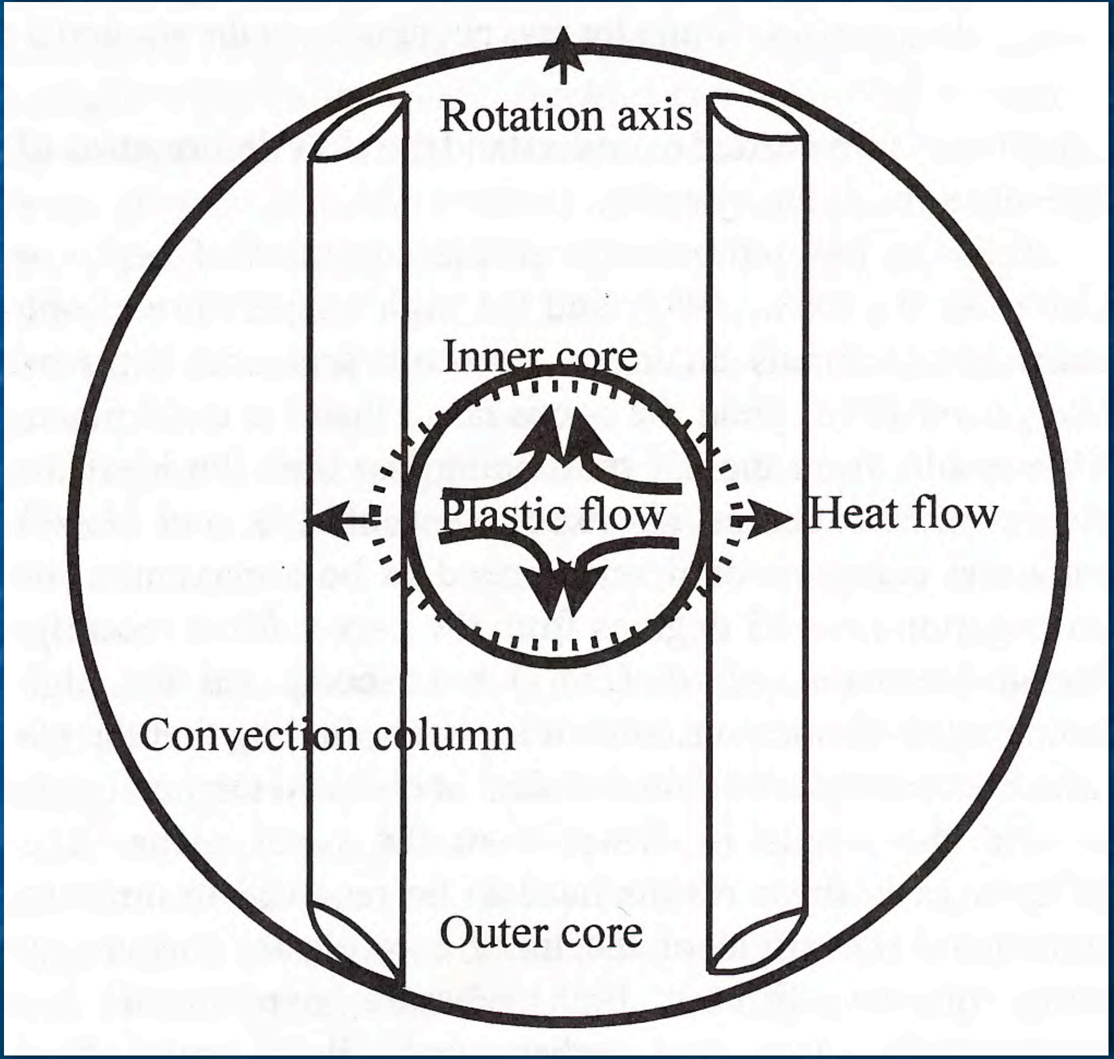
M. Bergman



Cause of anisotropy: solidification

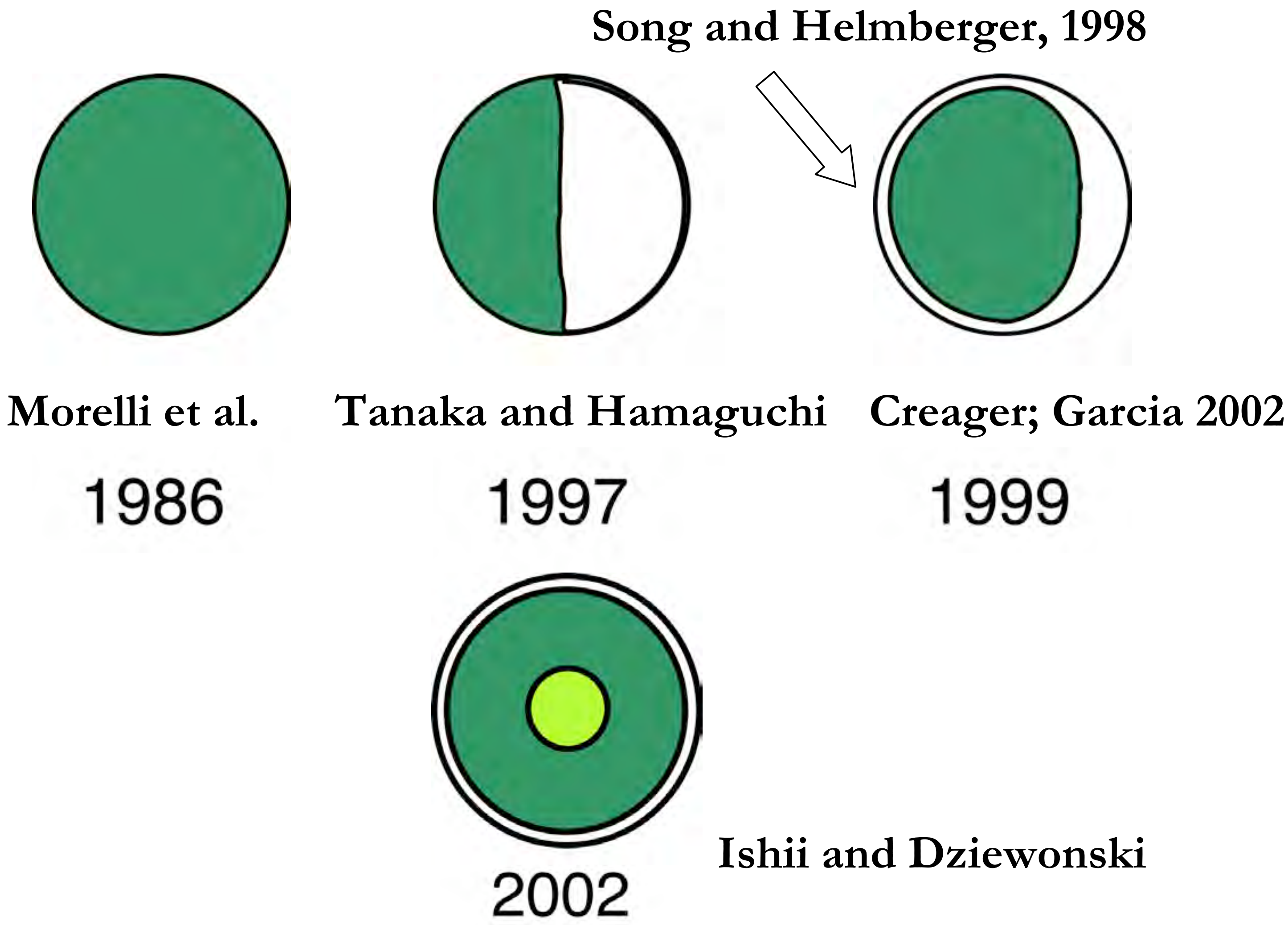


Cause of anisotropy: post-solidification



Yoshida, 1996

IC Anisotropy Conceptual Models



Anomalous PKP travel times: alternative explanations

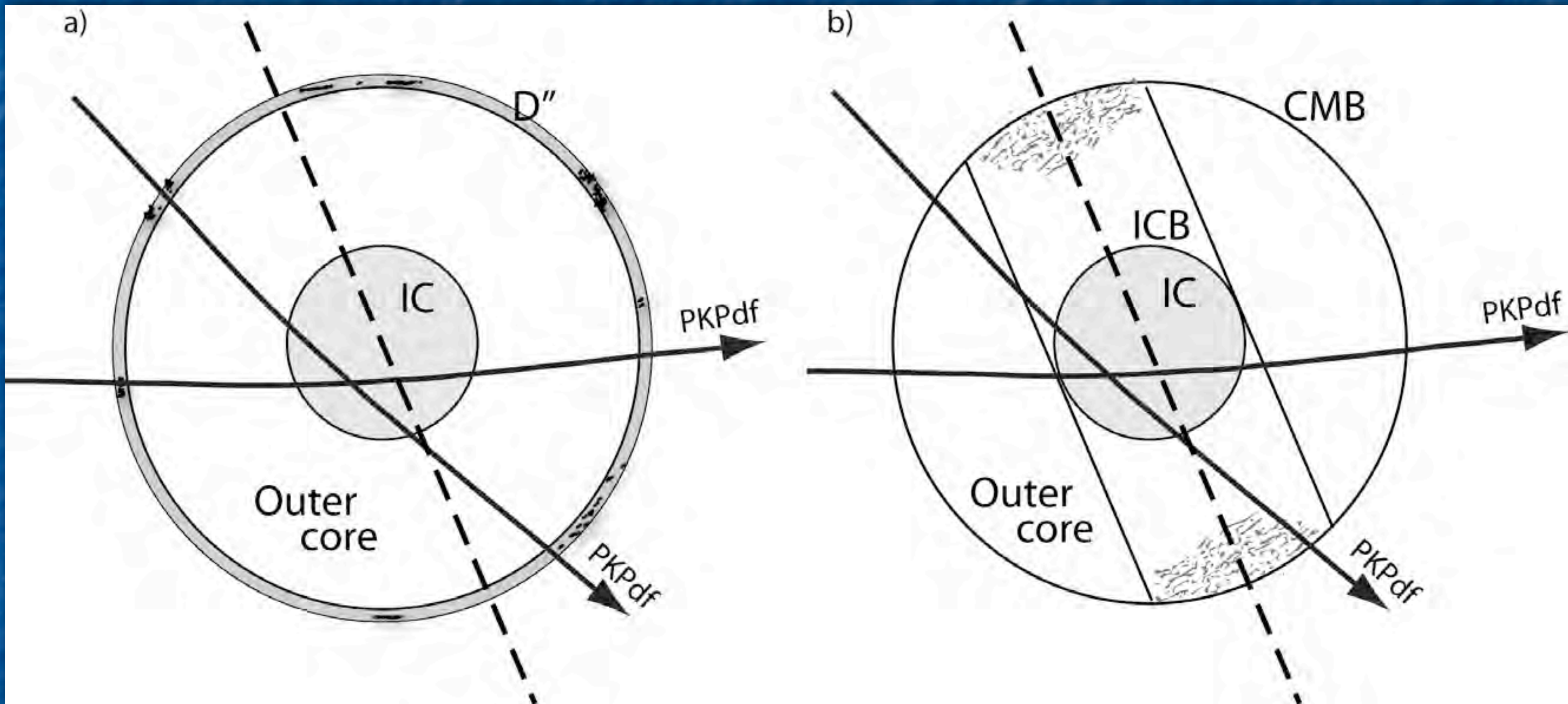
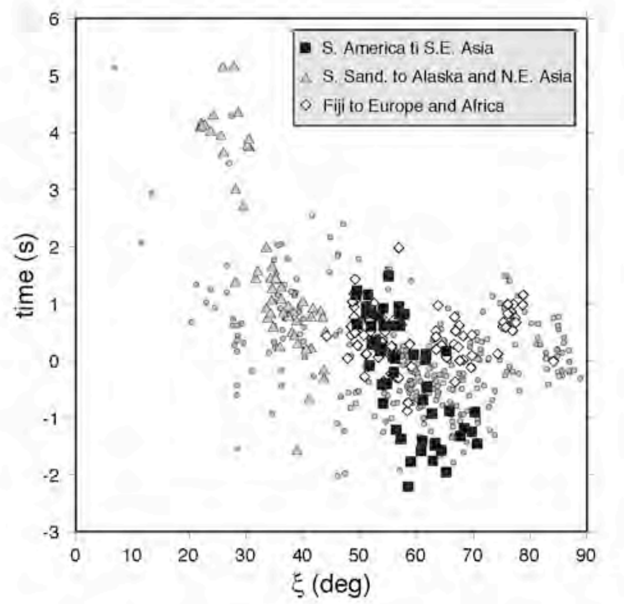
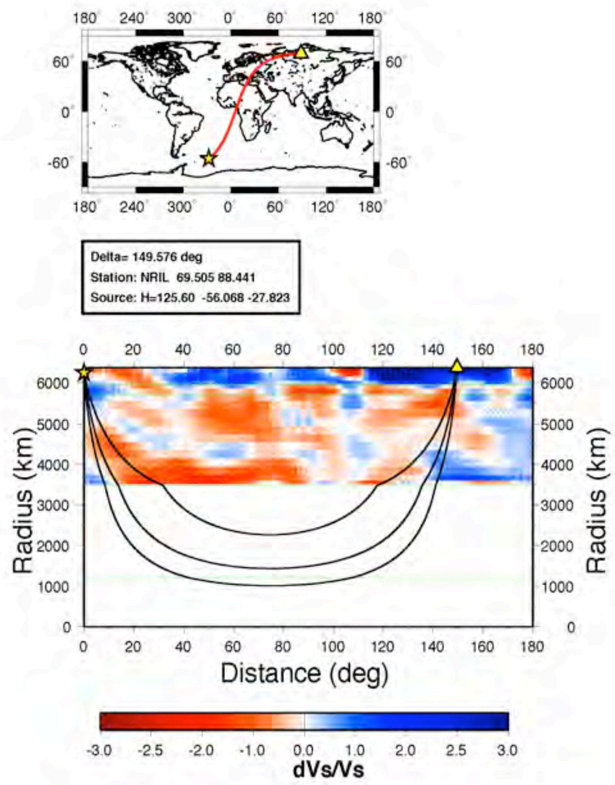


illustration from Tkalčić and Kennett, 2008

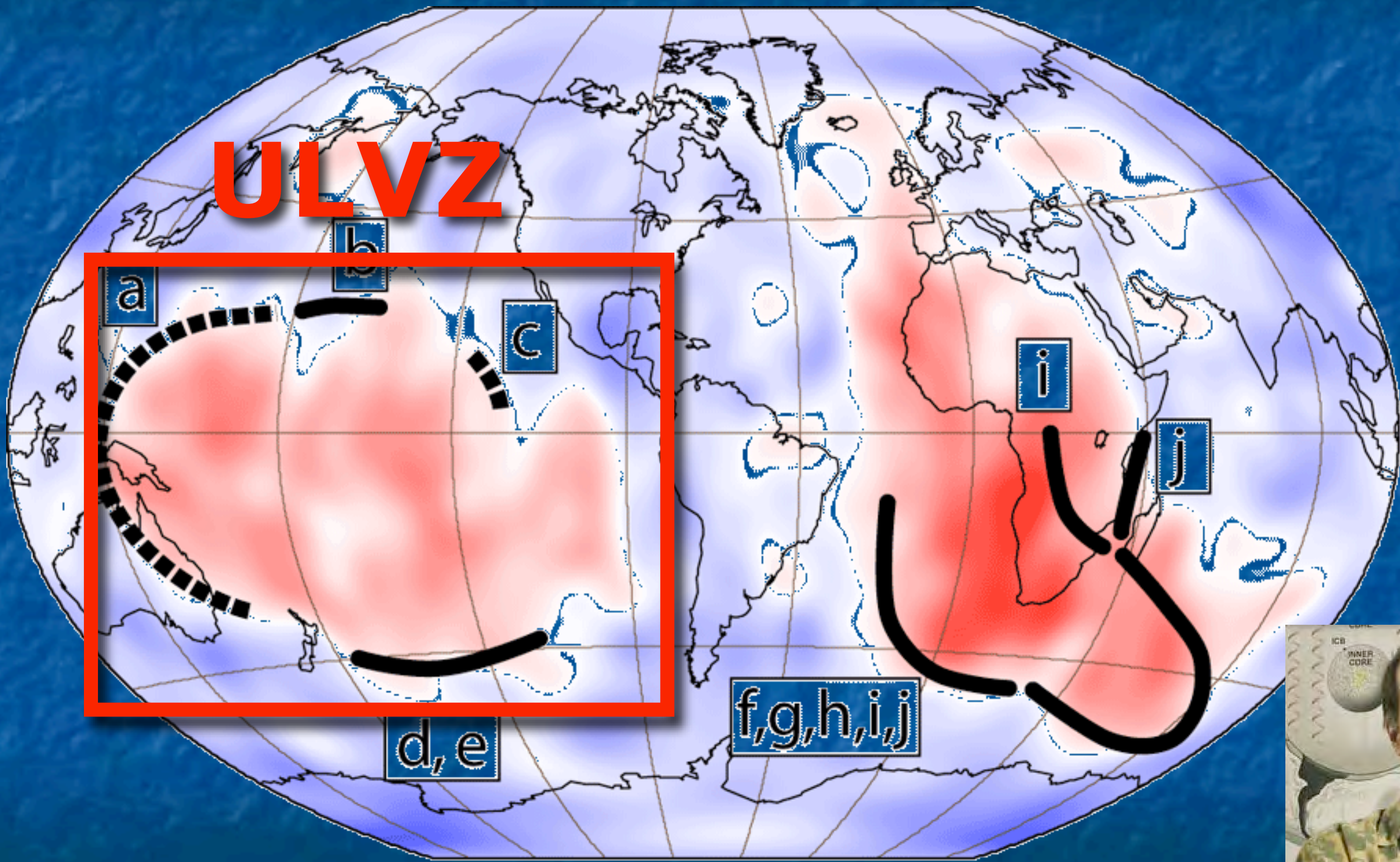
Geographical dependence of PKP(AB-DF) residuals





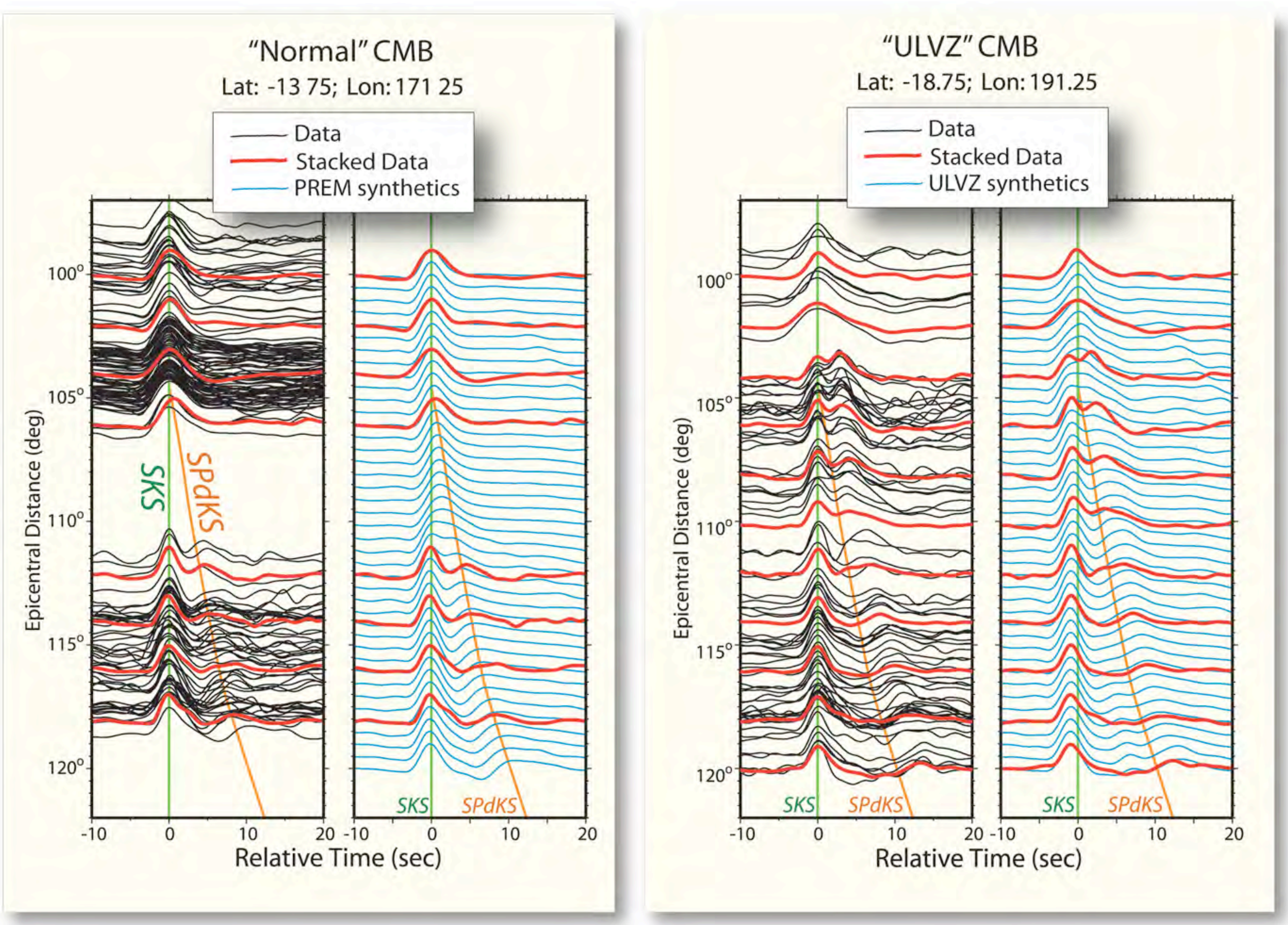
example from PhD thesis; Tkalčić, 2001

Seismic "edge detection" of deep mantle low velocities



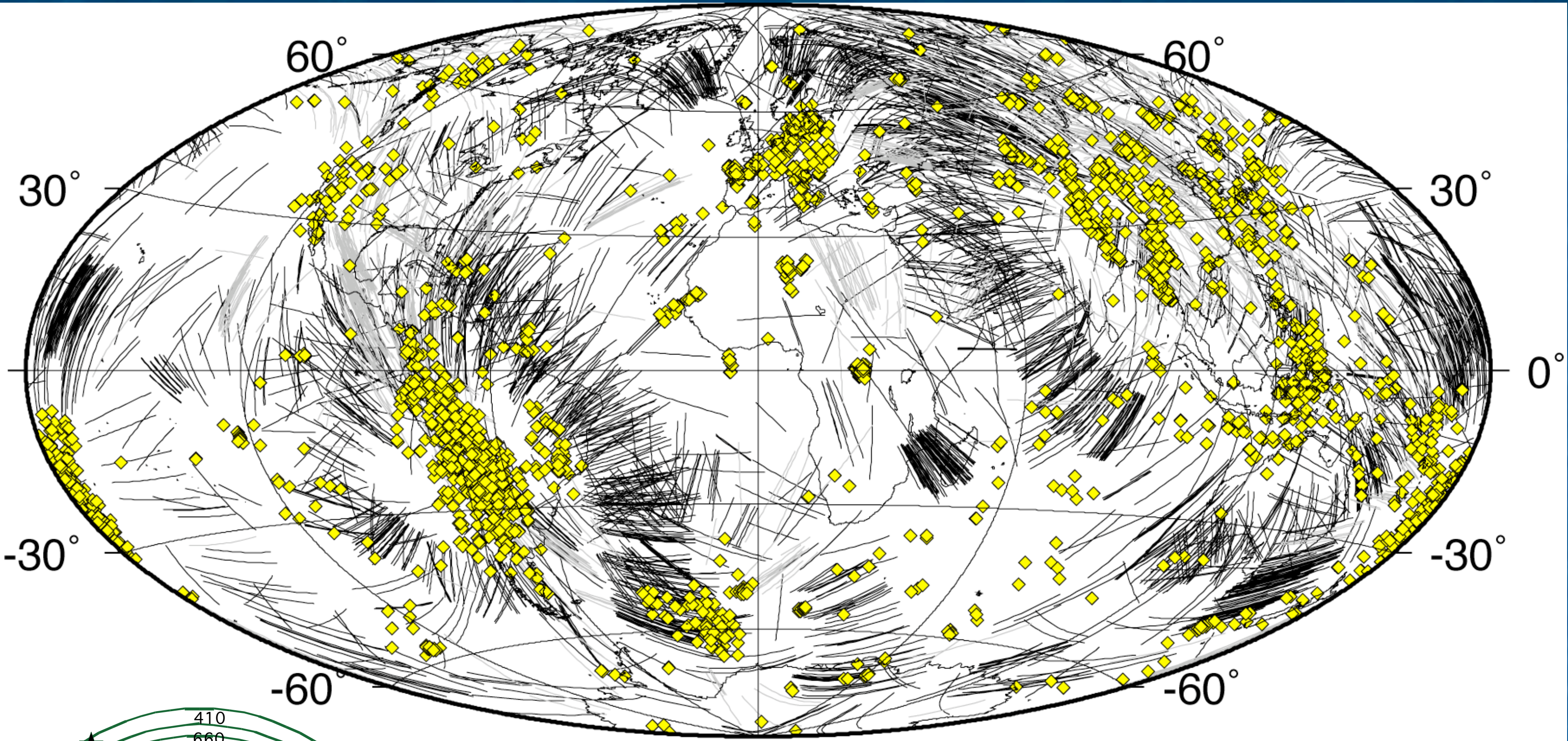
Ed Garnero

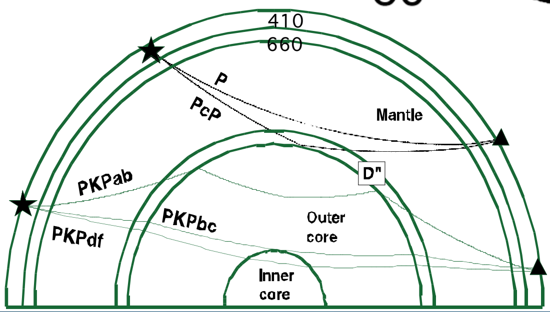
Garnero, Lay, and McNamara. [2007, P4 Monograph, GSA]



Thorne & Garnero. [in prep, 2009]

Lowermost Mantle Coverage

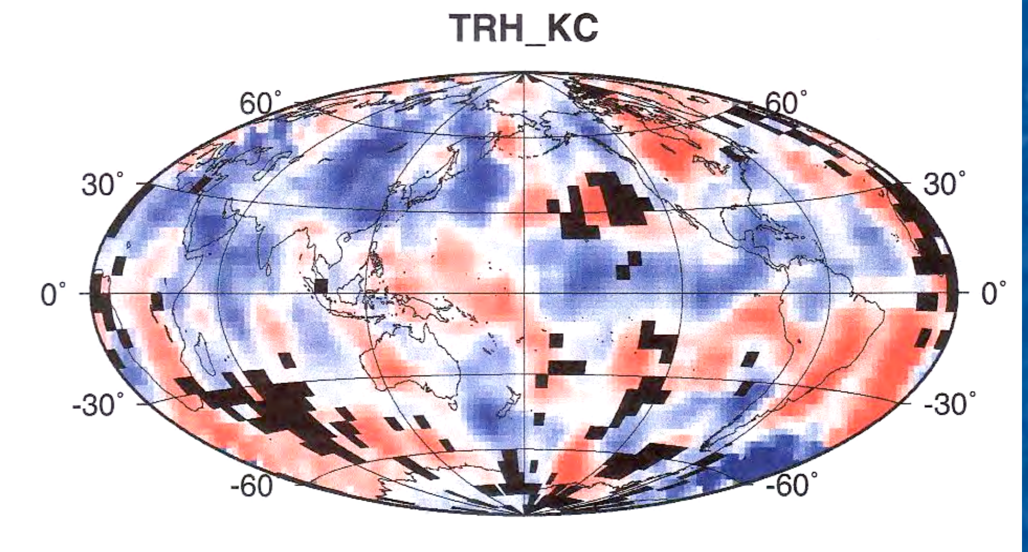




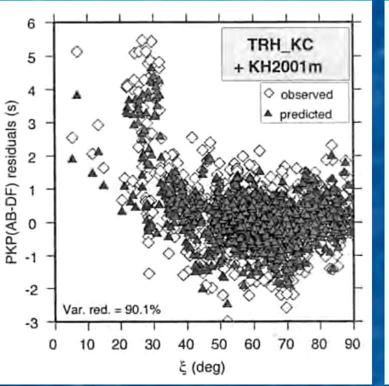
— PKP(AB) legs
◇ PKP(DF) legs
— PcP legs

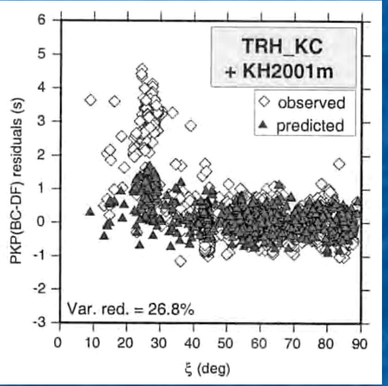
Tkalčić, Romanowicz and Huoy, GJI 2002

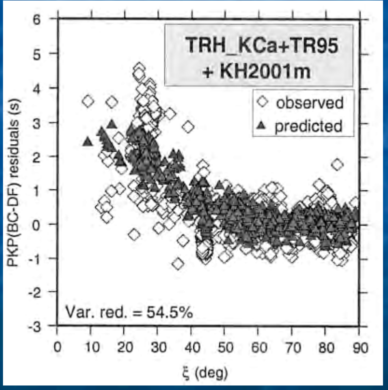
Travel times of PKP waves affected by lowermost mantle structure



From PKP(AB-DF) and PcP-P diff. travel times

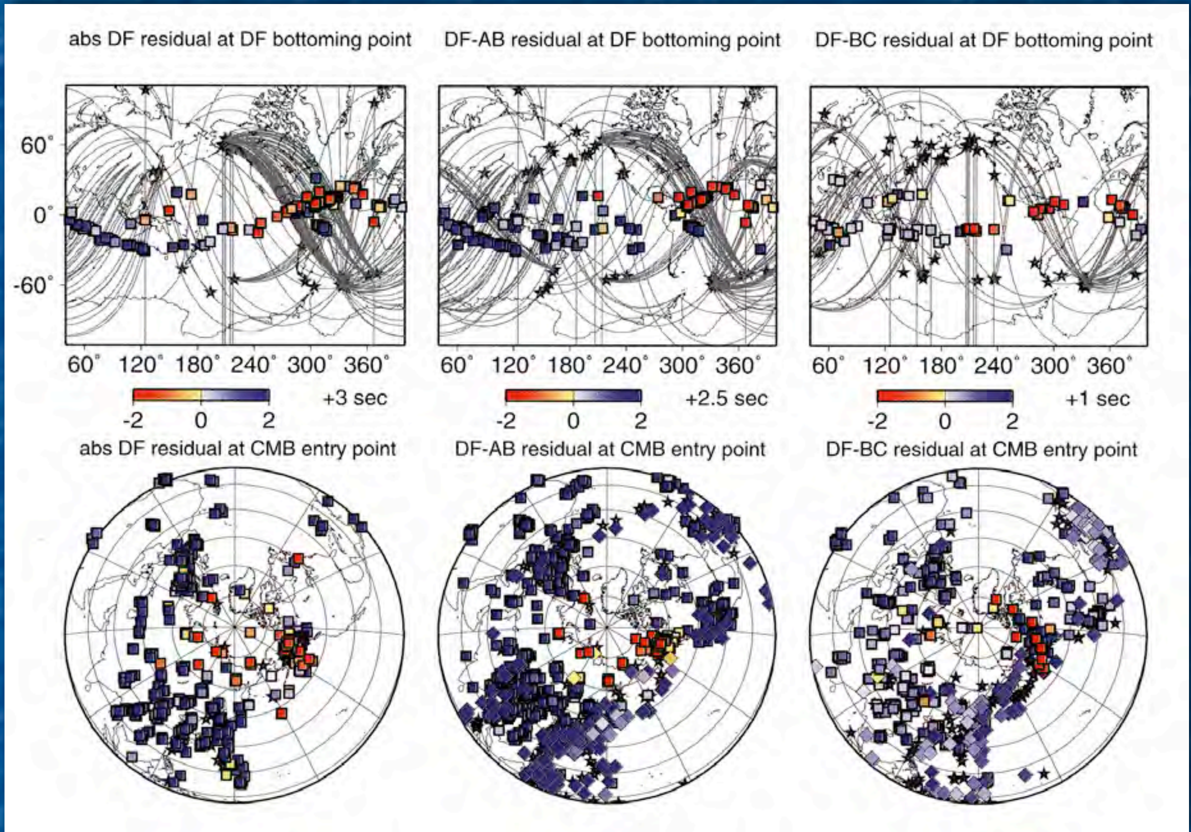


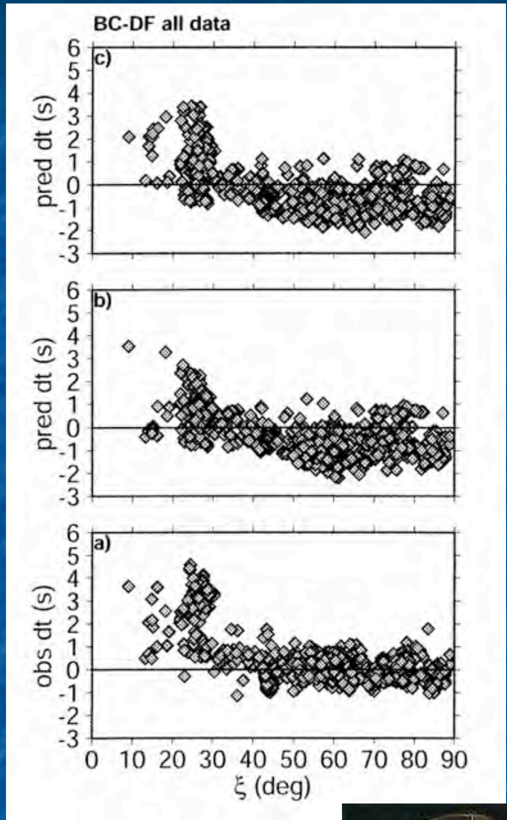




Tkalčić, Romanowicz and Huoy, GJI 2002

Alternative hypothesis: outer core structure

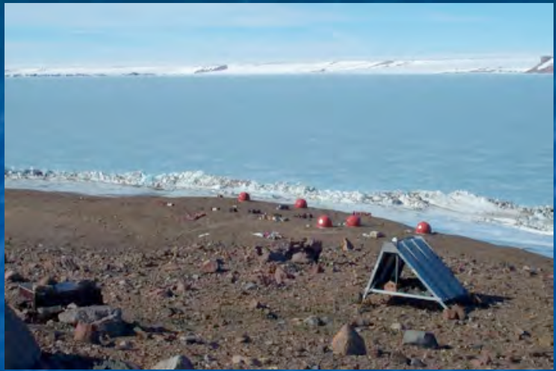




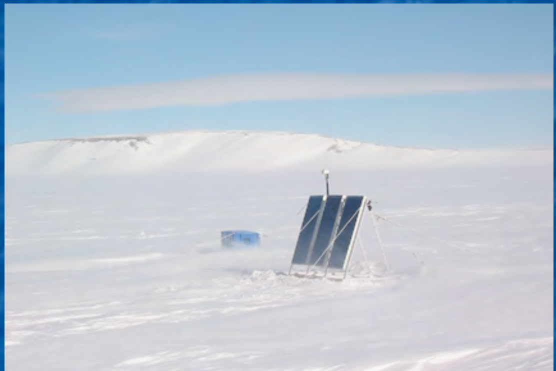
Romanowicz, Tkalčić and Breger, AGU Monograph 2003

Barbara Romanowicz

Antarctic SSCUA stations

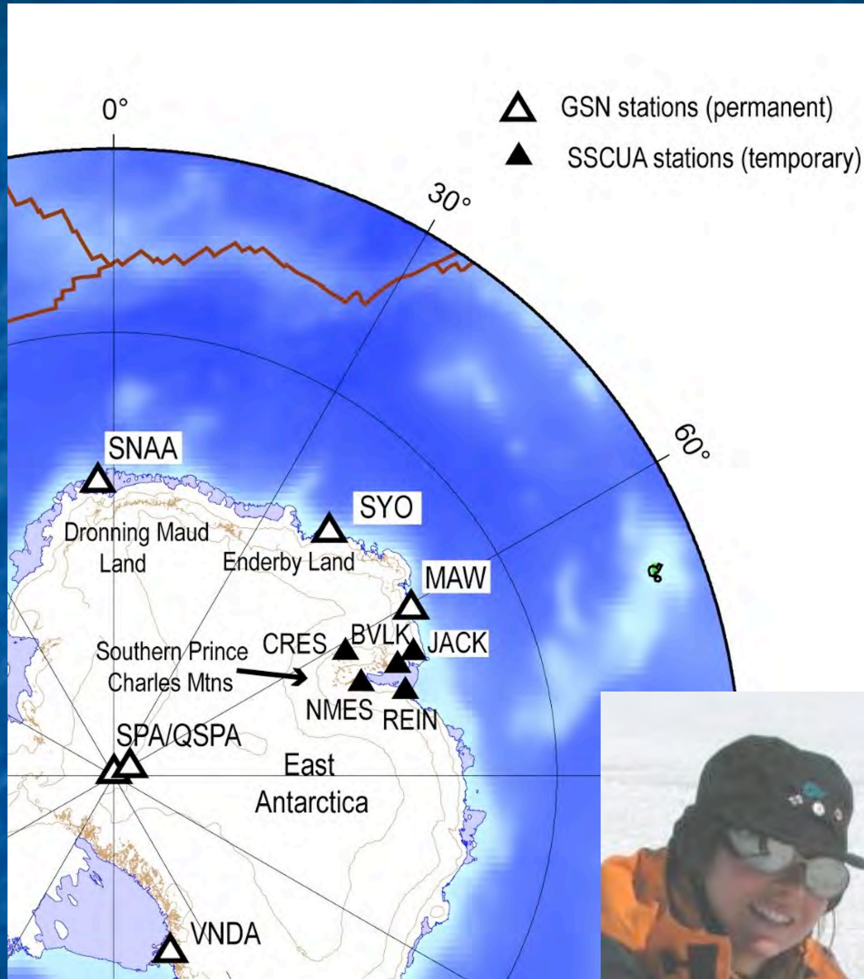


BVLK



CRES

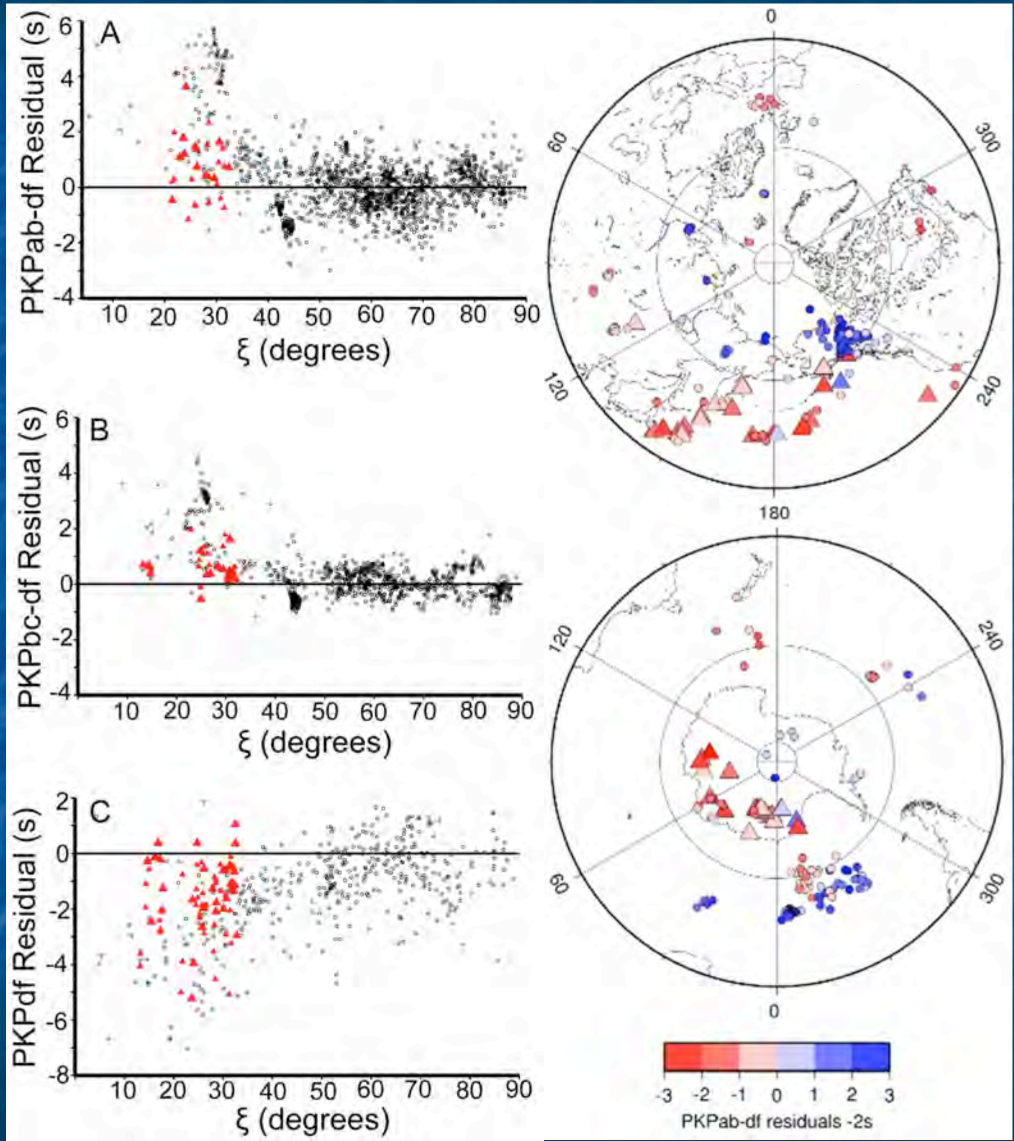
NMES



Anya Reading

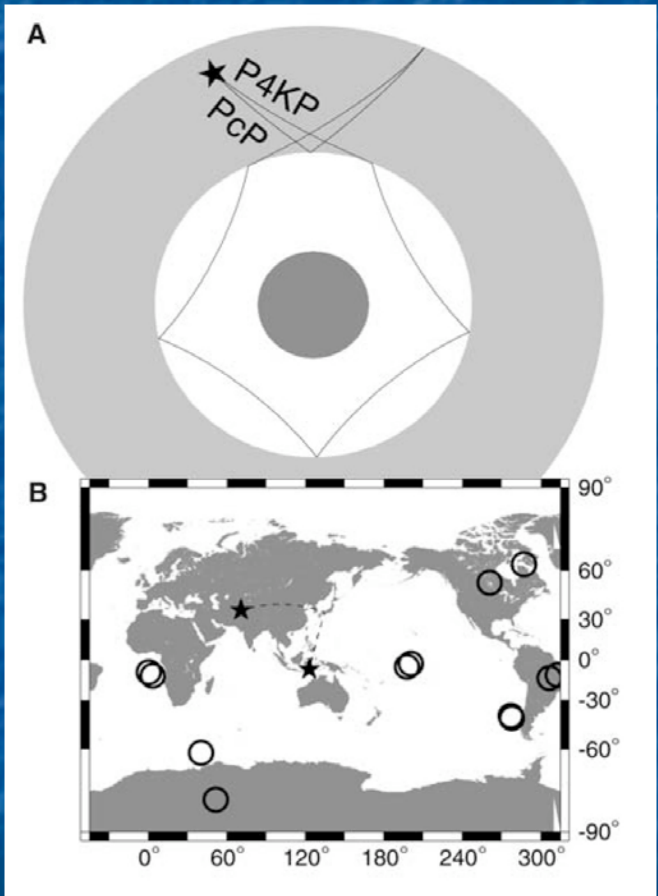
TC Coverage by polar PKP paths

- New differential travel time residuals consistently < 2s
- Axially symmetric inner core anisotropy consistent with our observations must be weak, at most
- Coverage of quasi-eastern hemisphere improved, but that of quasi-western hemisphere of IC along polar paths still poor
- Most anomalous arrivals cross CMB beneath Alaska
- No significant anomalies beneath southern polar cap

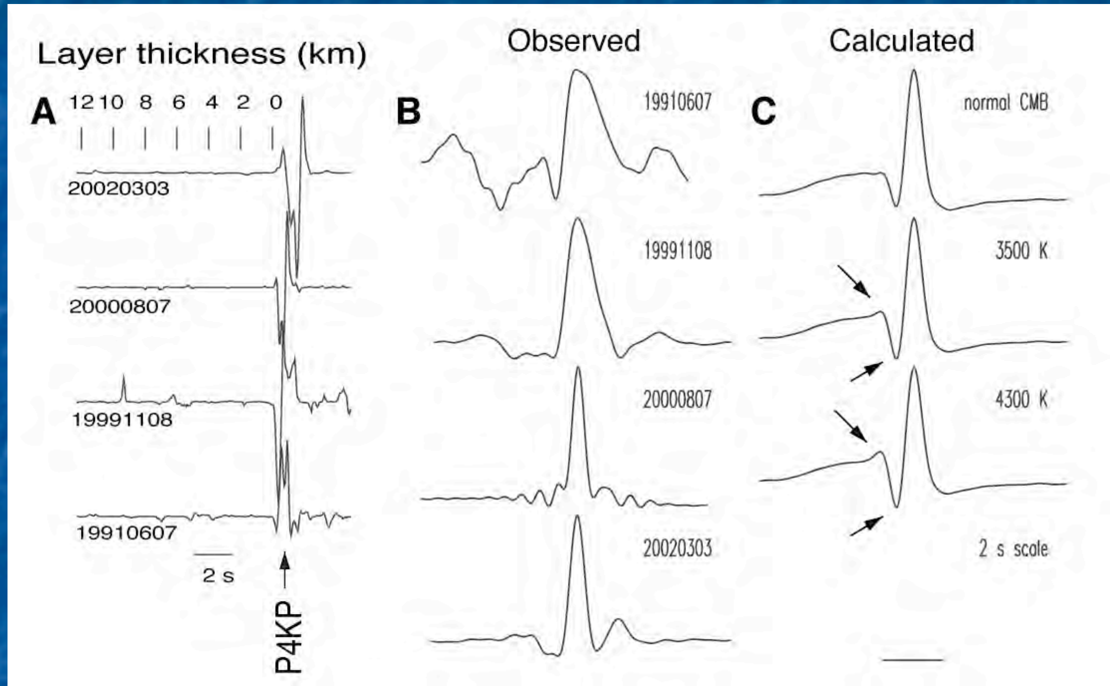


Leykam, Tkalčić and Reading, submitted to GJI

Multiple reflections from the lower side of the CMB: possible stratification in the outer core?



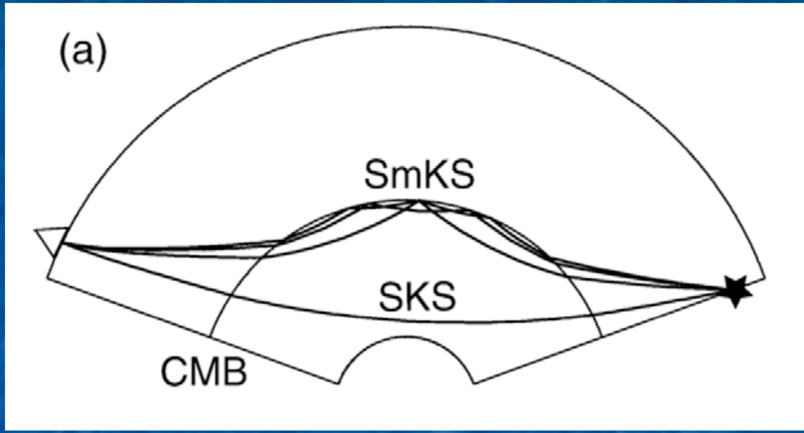
Helfrich and Kaneshima, Science 2004

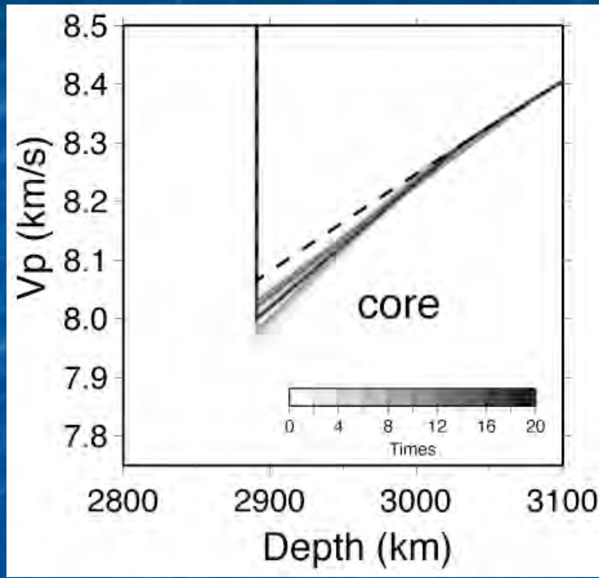


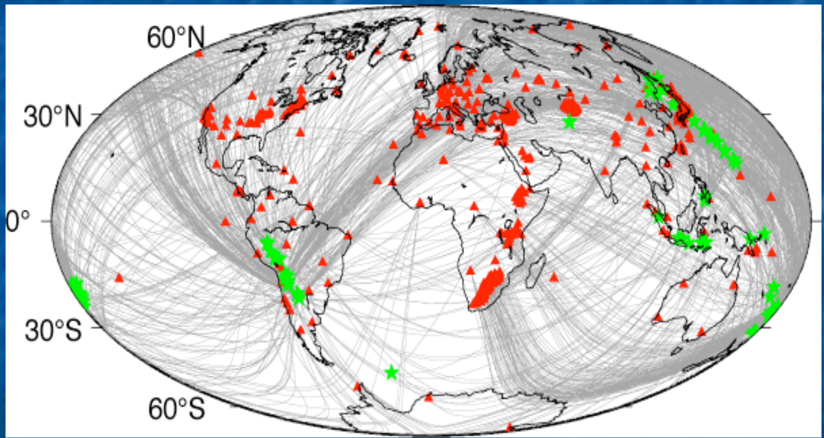
- They have not detected a stratified layer
- Eaton and Kendall (2006) supported its existence based on the anomaly in S4KS and S3KS amplitudes
- More high pressure experiments needed to investigate the relationship between P velocity and density

George Helffrich

SmKS waves modeling confirms a low P velocity layer in the outermost core on a global scale





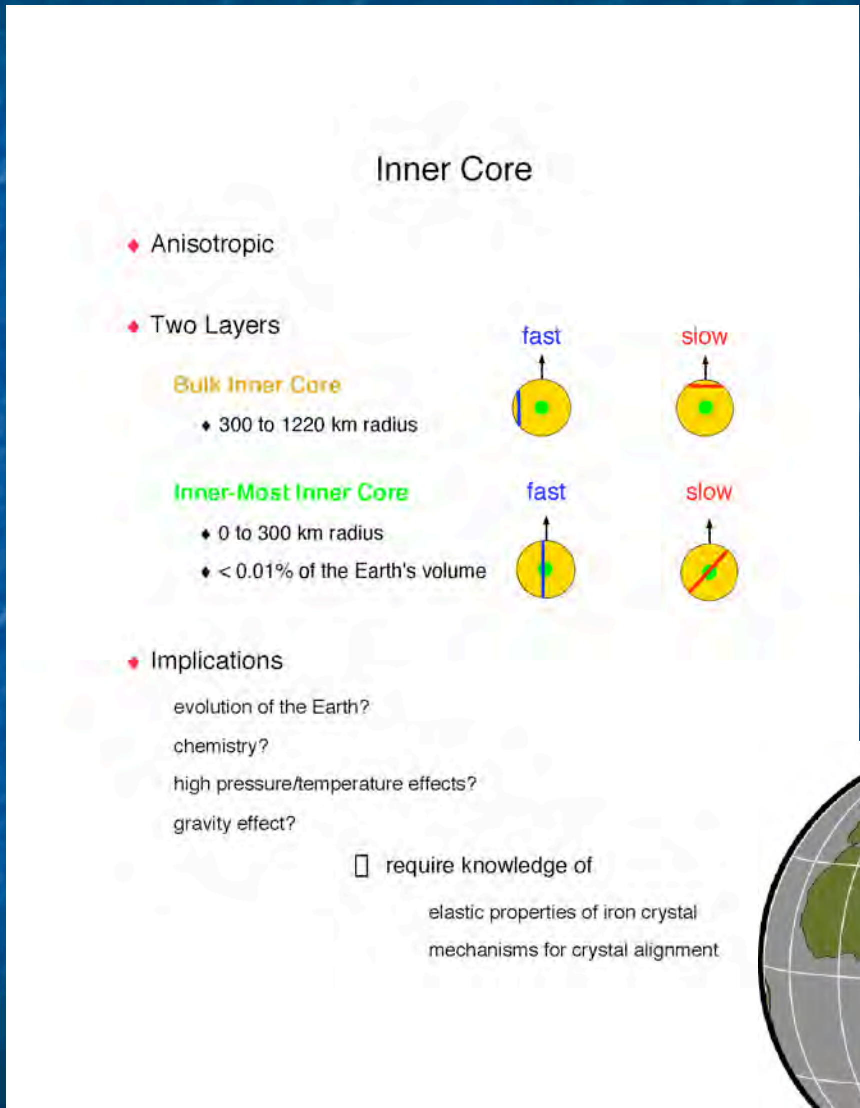


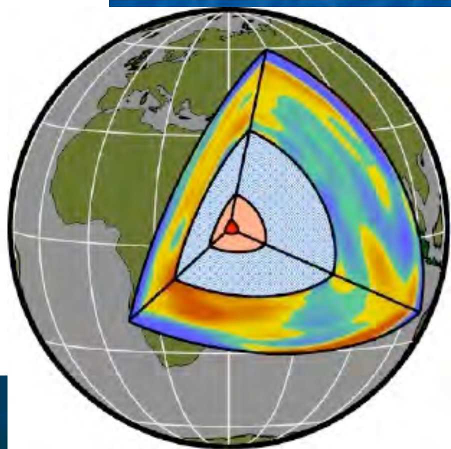
- Possibility of the low P-wave velocity in the outermost core (h = 90km)
- A stratified layer? Low density? Physical properties? Thermal state?

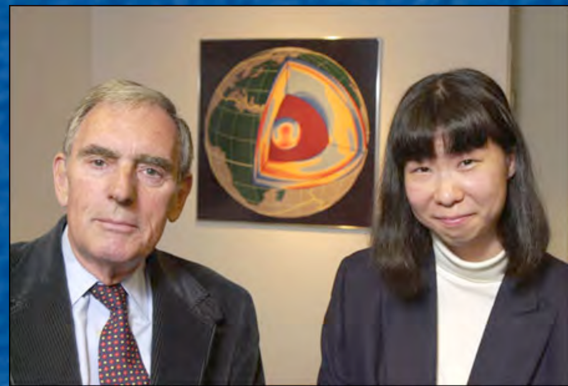
Satoru Tanaka

Tanaka, EPSL, 2007

The innermost inner core



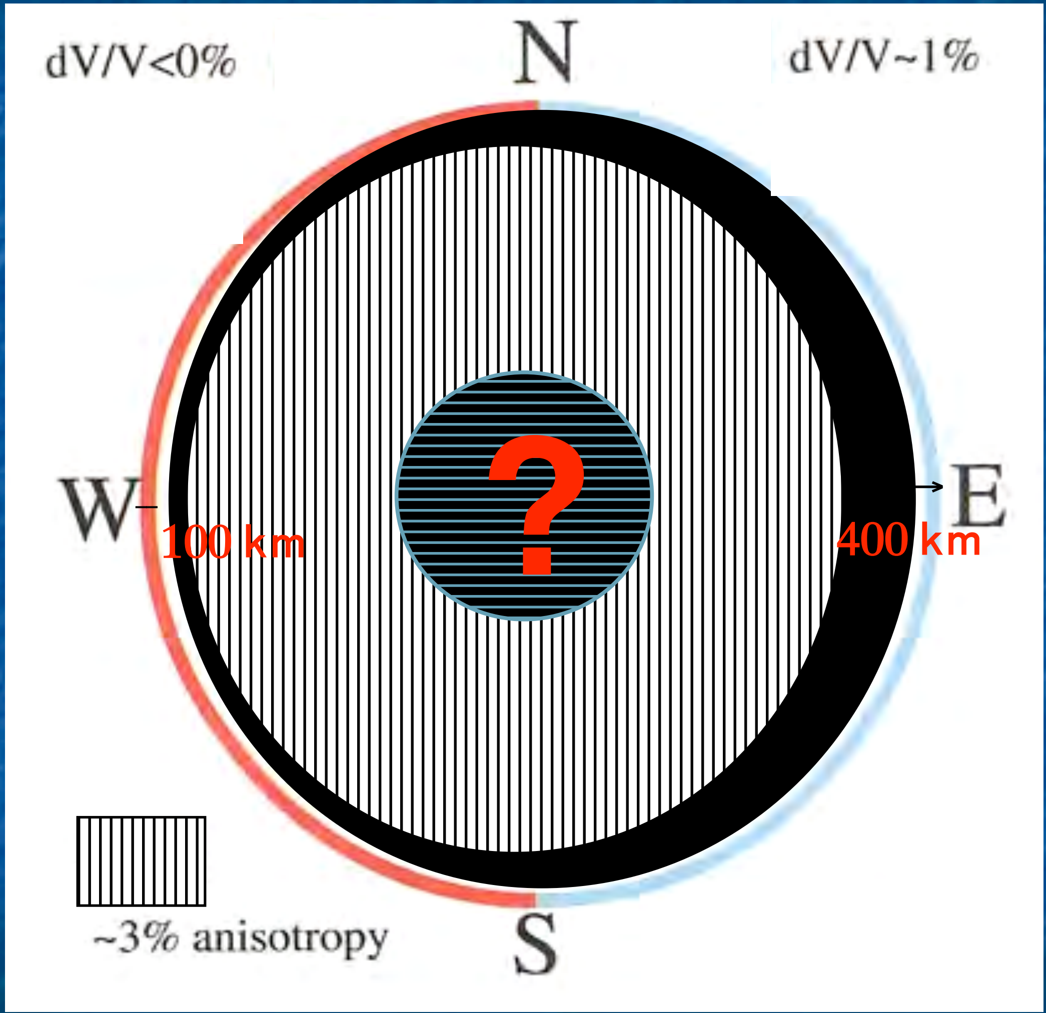


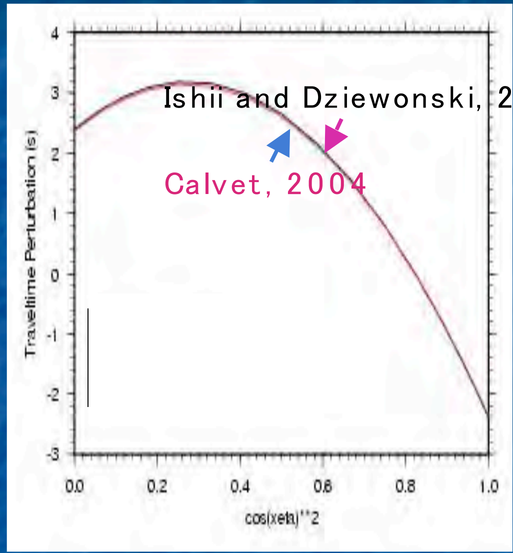


Adam Dziewonski & Miaki Ishii

Courtesy of
Miaki Ishii

New Interpretations of the IC structure





Annie Souriau

Courtesy of *Annie Souriau and Marie Calvet*

Grain size

From mineral physics and geodynamics

1200 km - to explain seismic observations (Stixrude & Cohen, 1995)

5 mm - from geodynamical constraints (Buffett, 1997)

5 m - assuming dynamic recrystallisation (Yoshida, 1996)

200 m - from observed attenuation and velocity anisotropy (Bergman 1998)

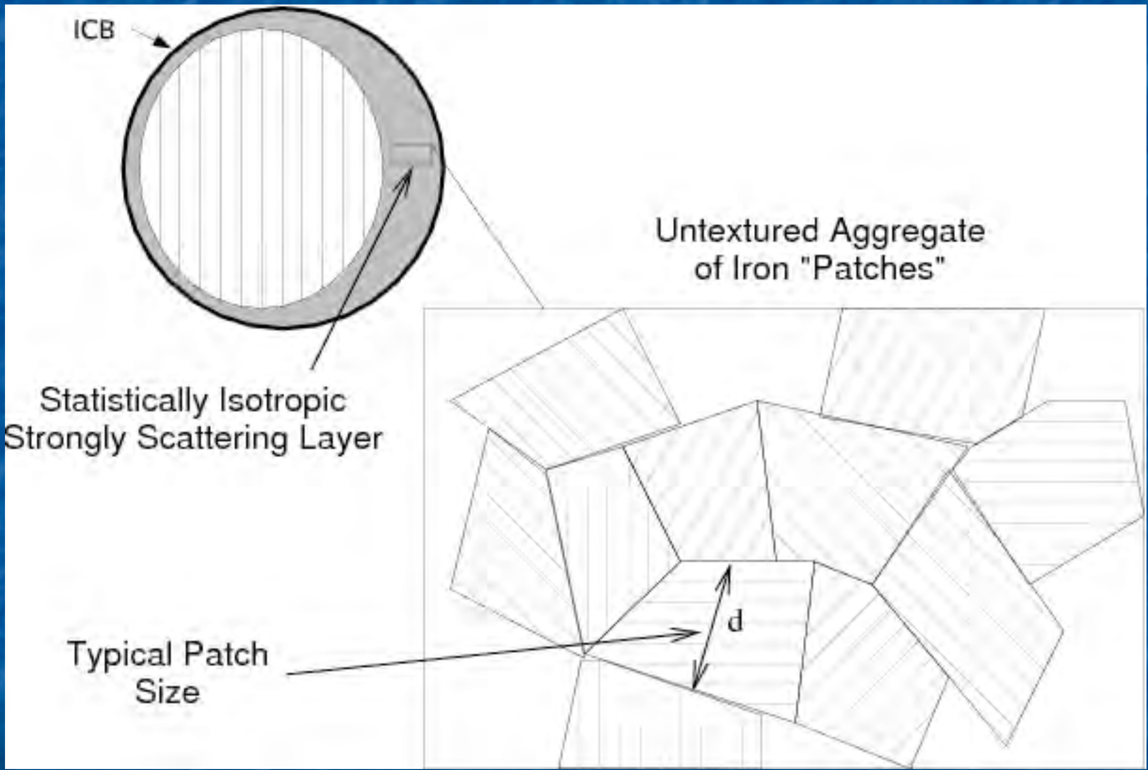
From seismology

10 km - from seismic attenuation observations (Cormier and Li, 2002)

2 km - from energy envelopes of PKiKP coda (Vidale and Earle, 2000)

400 m - from multiple scattering calculations (Calvet and Margerin, 2008)

Multiple scattering modeling in the uppermost inner core: constraints on the grain size and stable iron phases

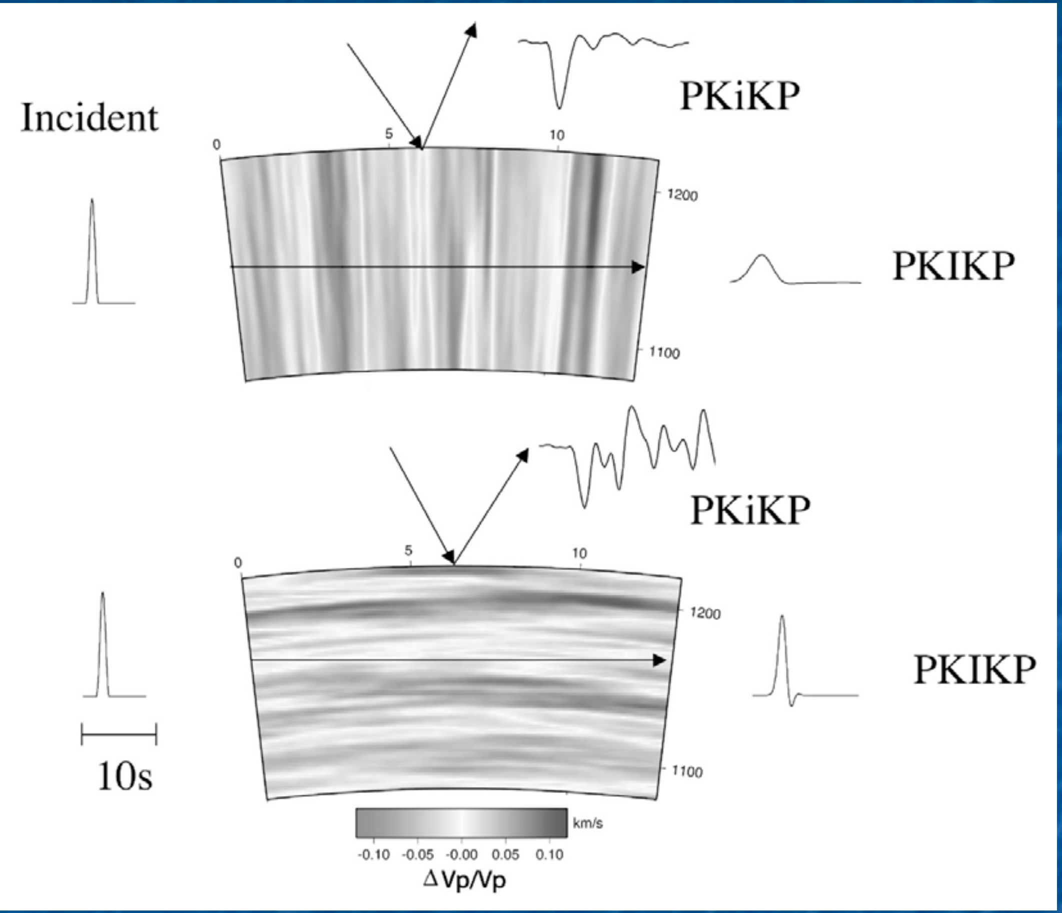


- Grain size ~ 400 m
- bcc phase of iron stable
at the uppermost IC conditions

Marie Calvet

Calvet & Margerin, 2008

Texture of the inner core

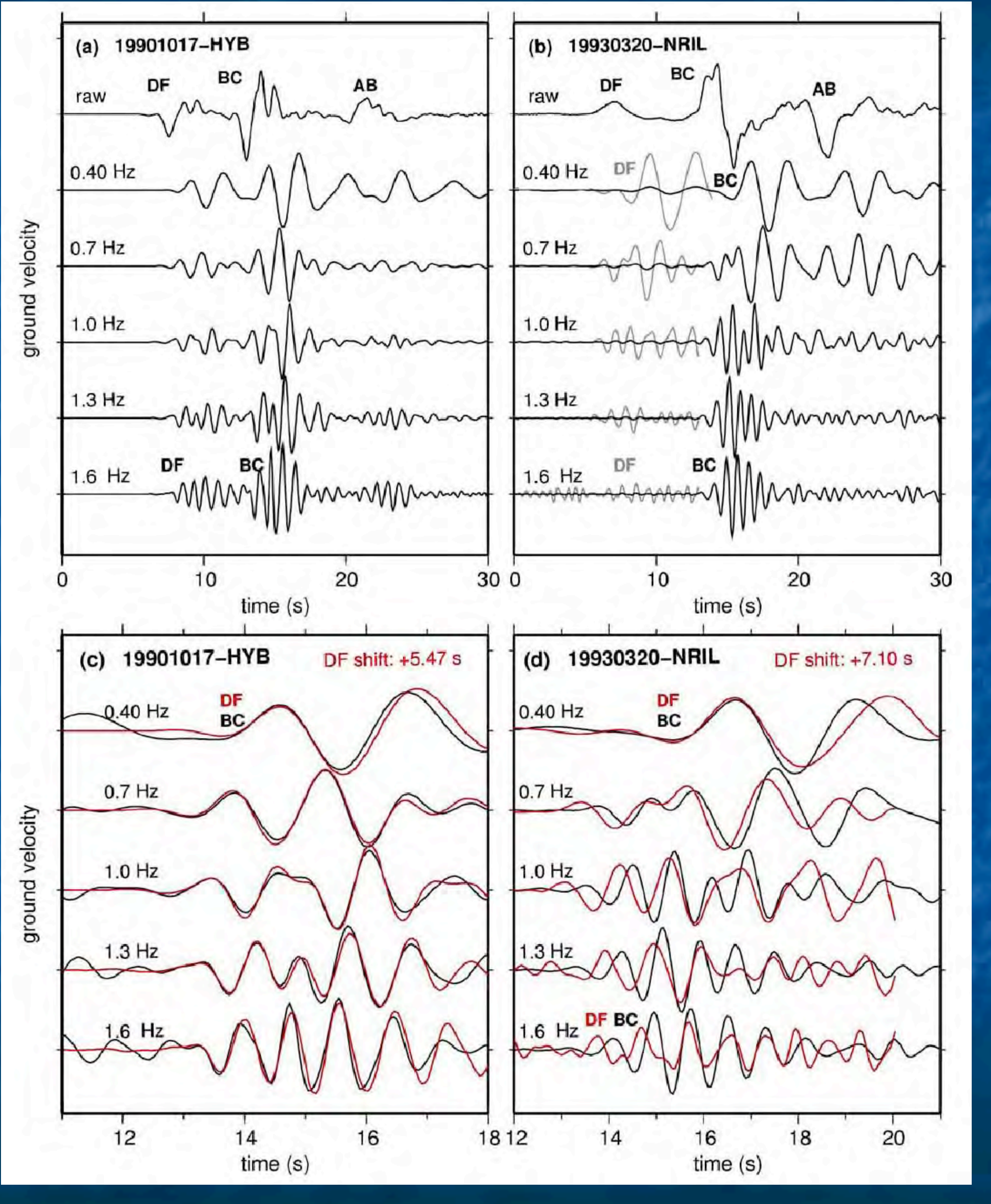


Vernon Cormier

- Scattering by a fabric in the uppermost inner core
- Ratio between viscoelastic and scattering attenuation still unknown
- Scattering related to the directions of flow

Cormier, EPSL, 2007

Attenuation along quasi-polar paths

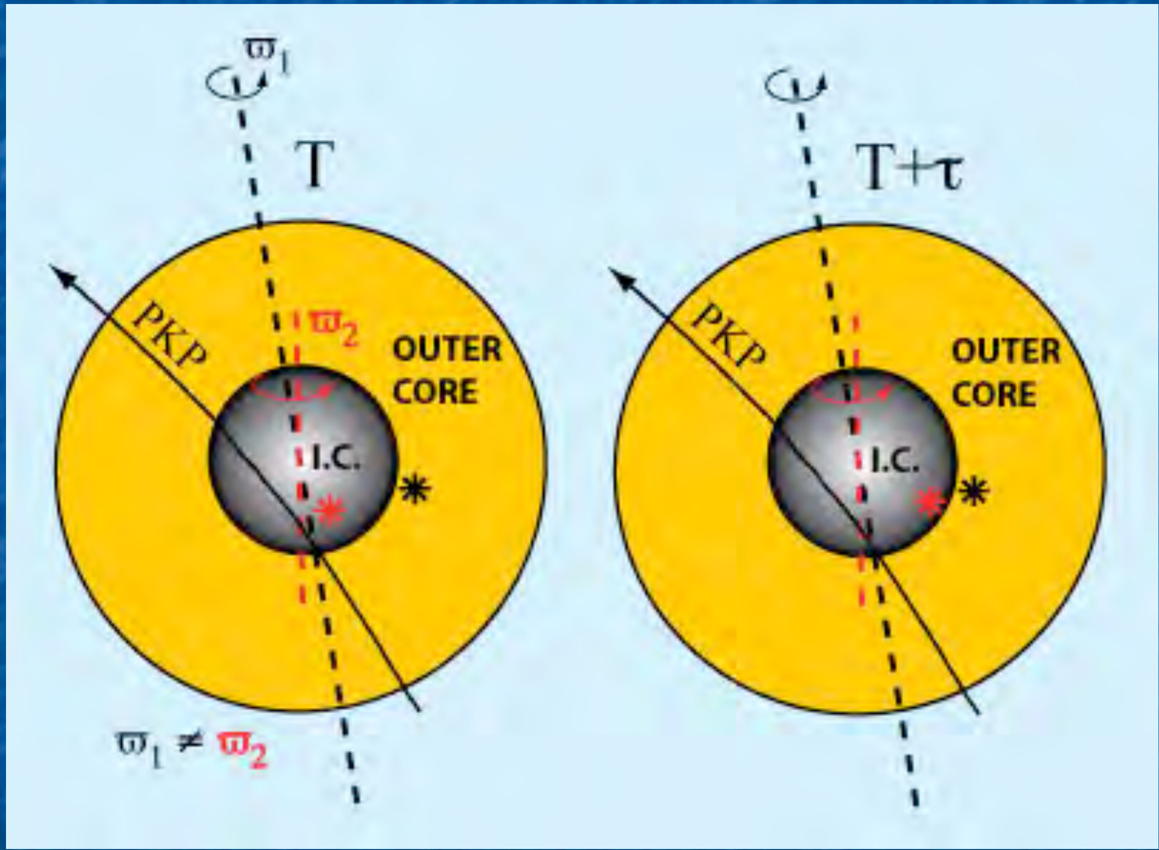


A. Souriau

Souriau, C.R. Geoscience, 2009

The differential rotation of the inner core

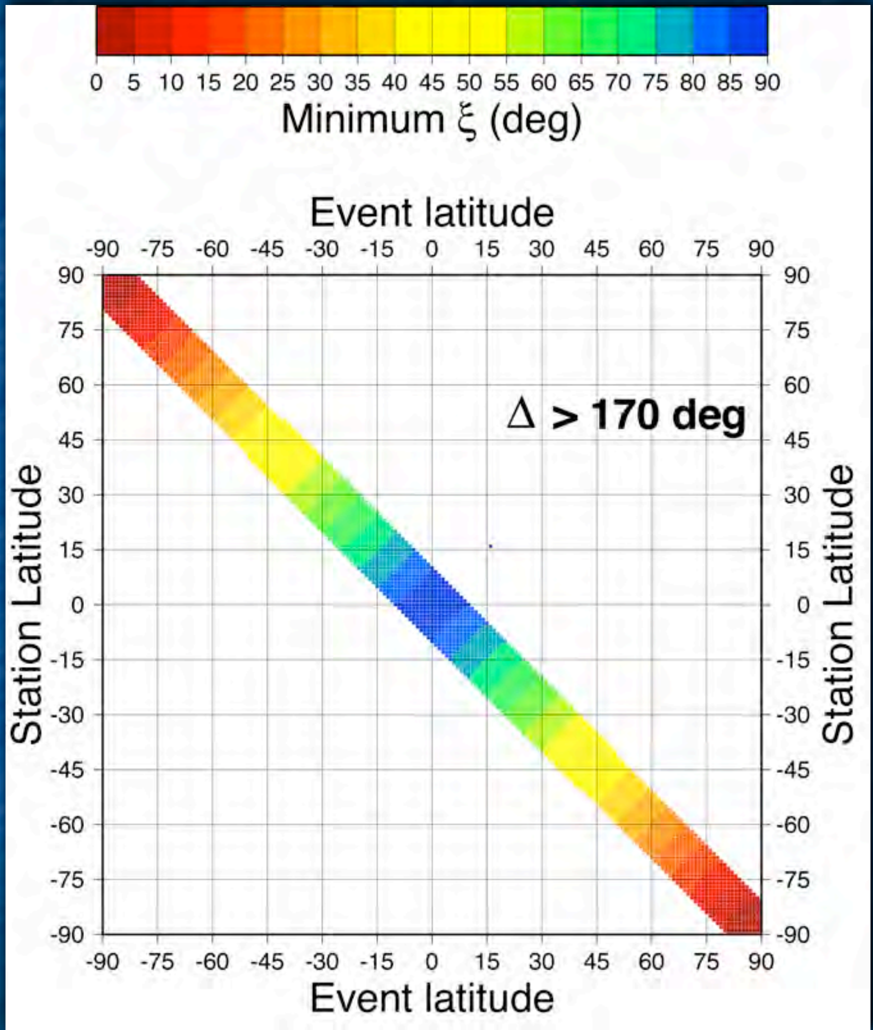
Xiaodong Song

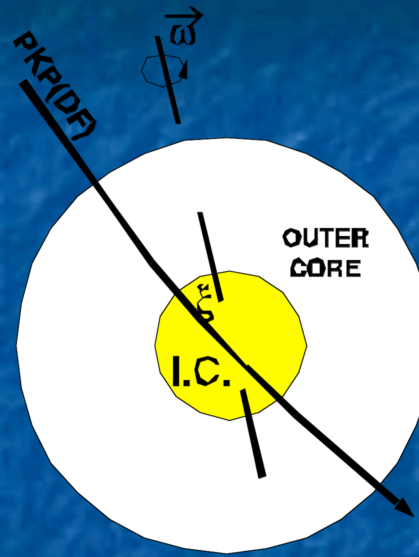


Paul Richards

Song & Richards, 1998

Map of Possible "Minimum Ksi"





Lack of geometrical sampling of the innermost inner core by PKP *polar-antipodal* paths

Broader Objective

To increase constraints on the structure of the core, particularly on the extent and radial dependence of inner core anisotropy.

a) To identify rarely observed core-sensitive seismic phases such as PKPPKP or PnKP waves with new spatial sampling of the inner core.

b) To design and apply new methods for analyzing existing core-sensitive data (e.g. a method of measuring differential travel times and attenuation of PKP waves by non linear inversion).

c) To deploy seismic instruments at extreme geographical latitudes and remote places in order to increase the coverage of the core and the lowermost mantle (e.g. Antarctica and oceanic islands).

PKJKP

The rigidity of the inner core has been very difficult to prove (from body waves).

There have been several observations interpreted as the shear waves in the inner core (P waves converted to S waves in the inner core).

Some observations:

Julian et al., 1972

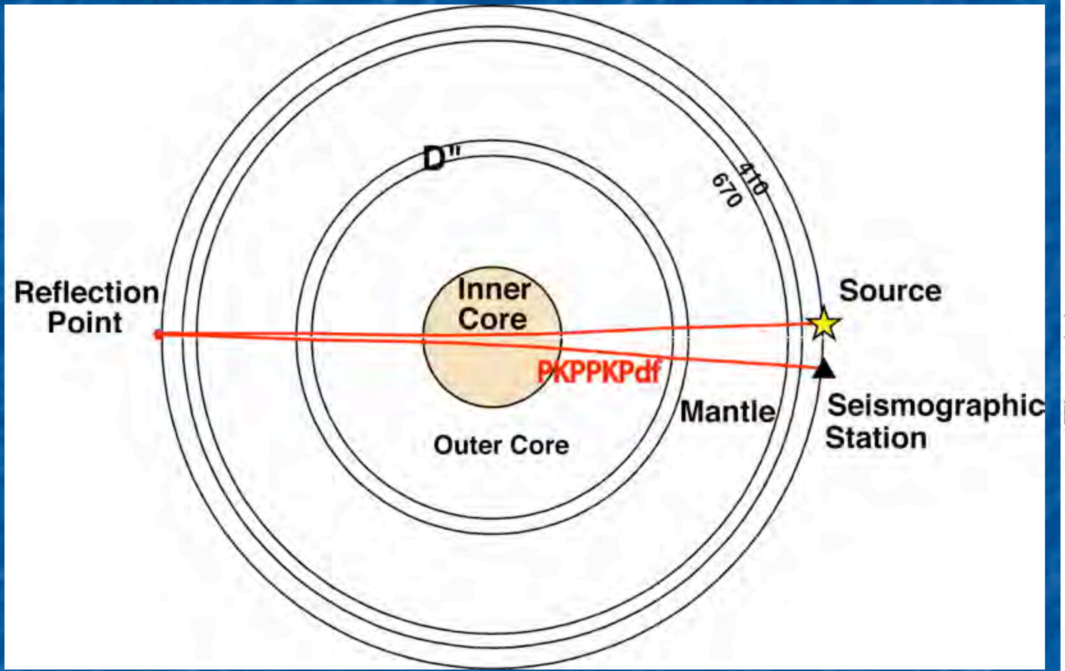
Okal and Scansi, 1998

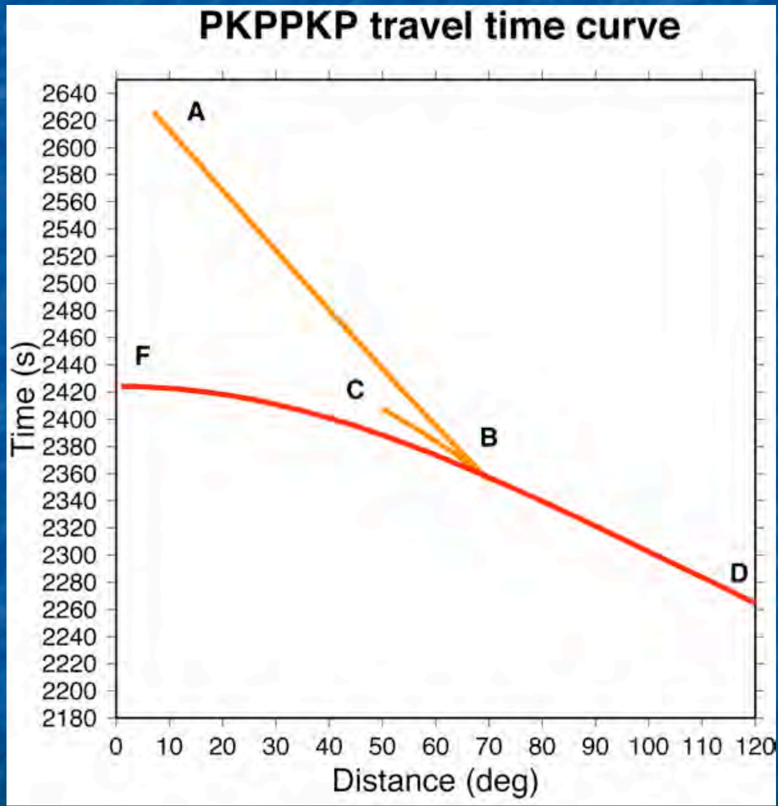
Deuss et al. 2000

Cao et al. 2005

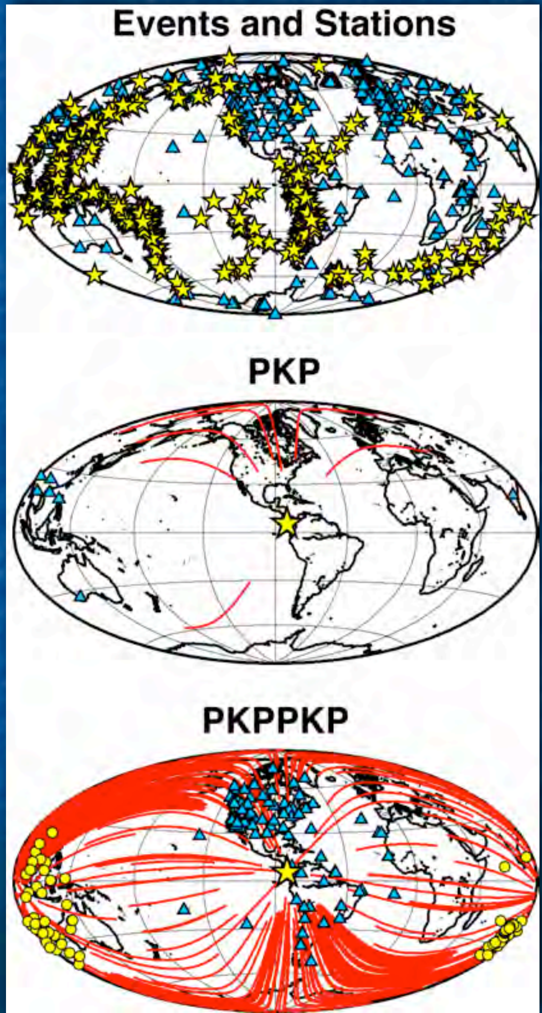
Due to a poor signal to noise ratio and inability to be observed more readily, these observations are still subject to skepticism.

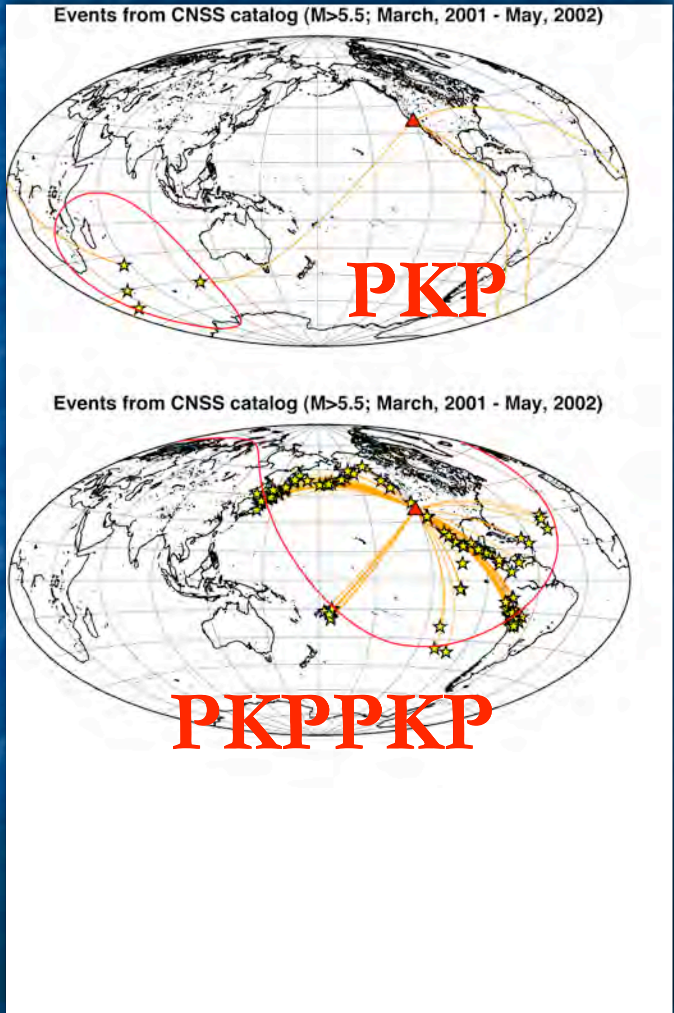
PKPPKP Waves and the Inner Core



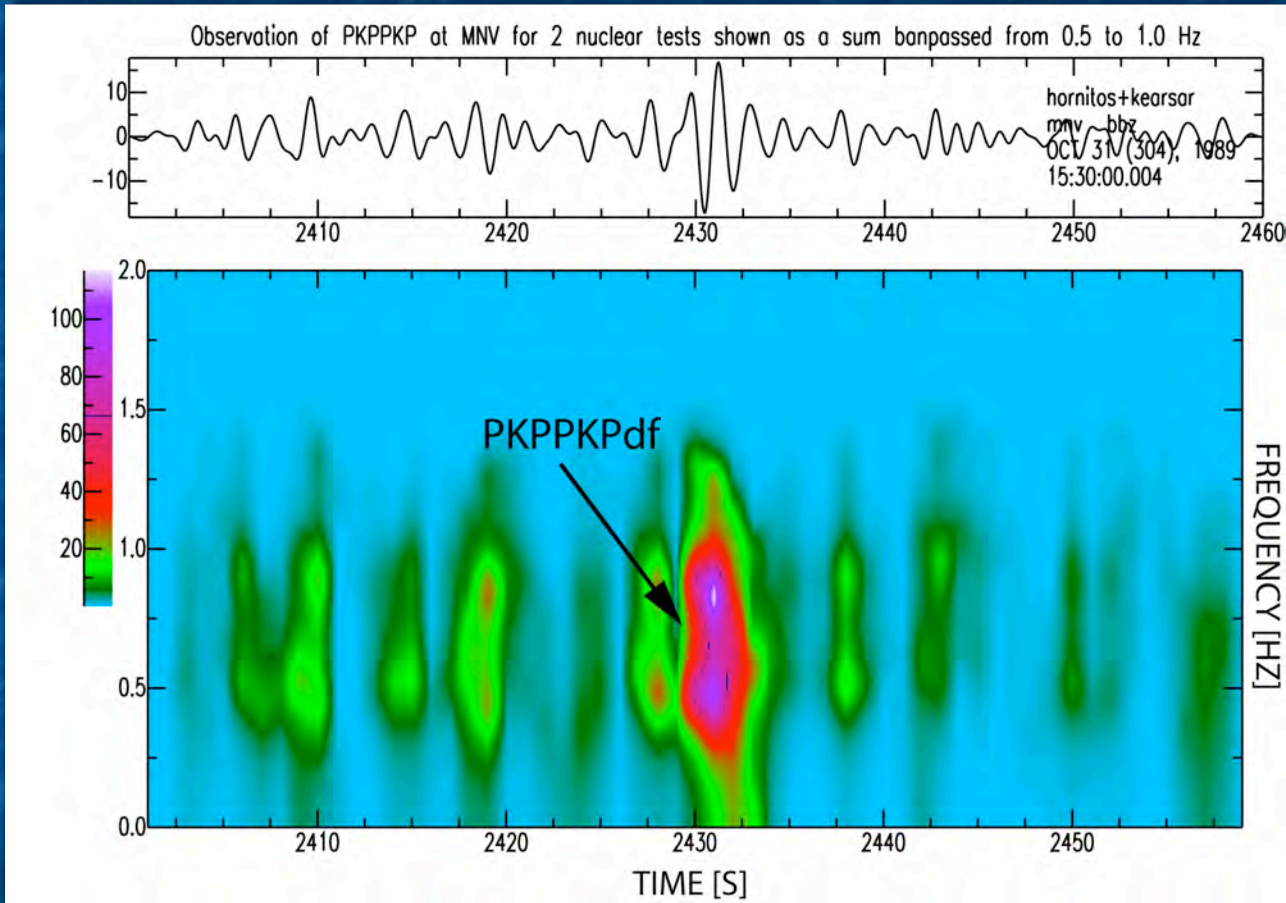


PKP Versus PKPPKP Sampling: Comparison





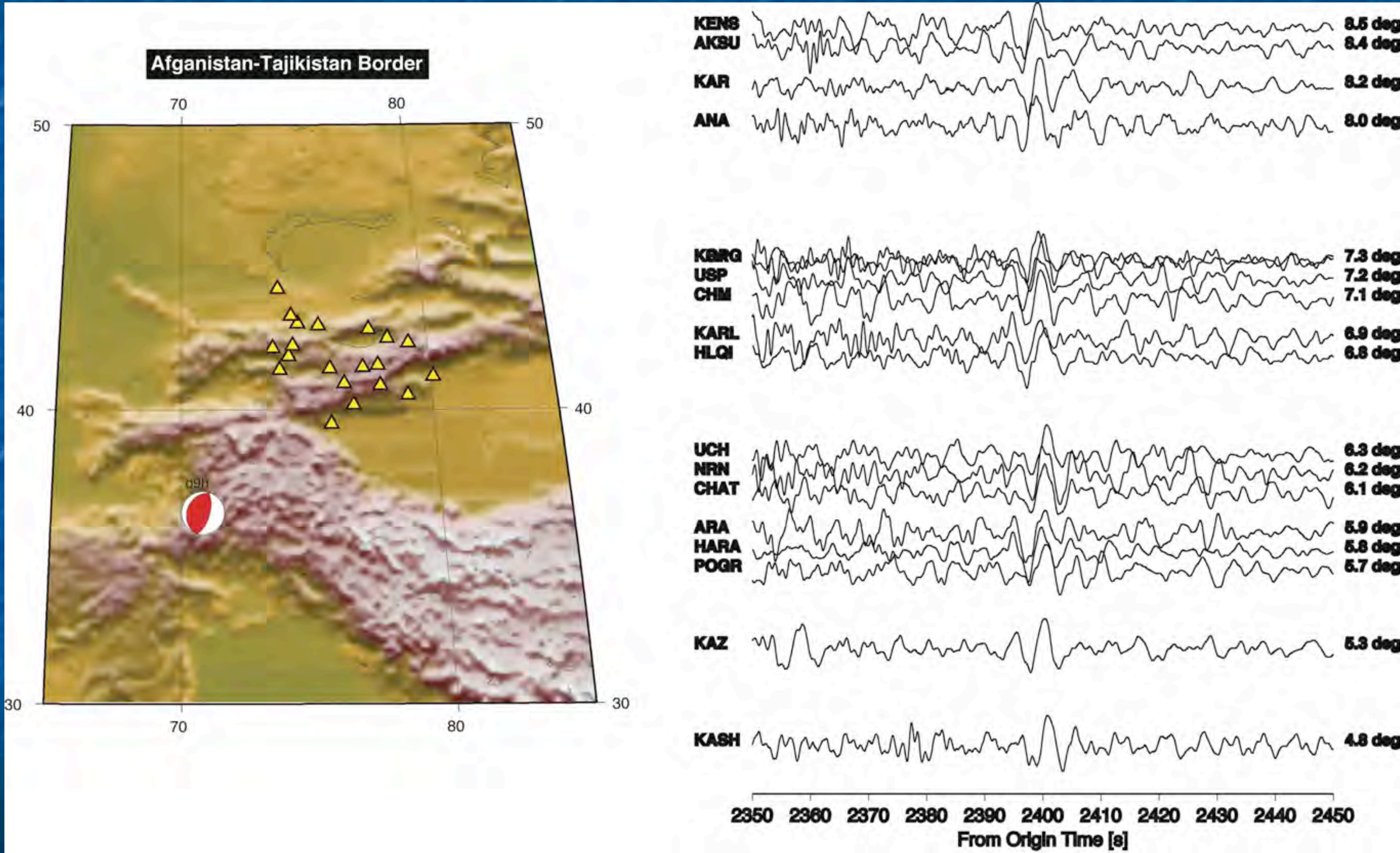
Podal PKPPKPdf observed from NTS (epic. Distance < 2 deg)!!!



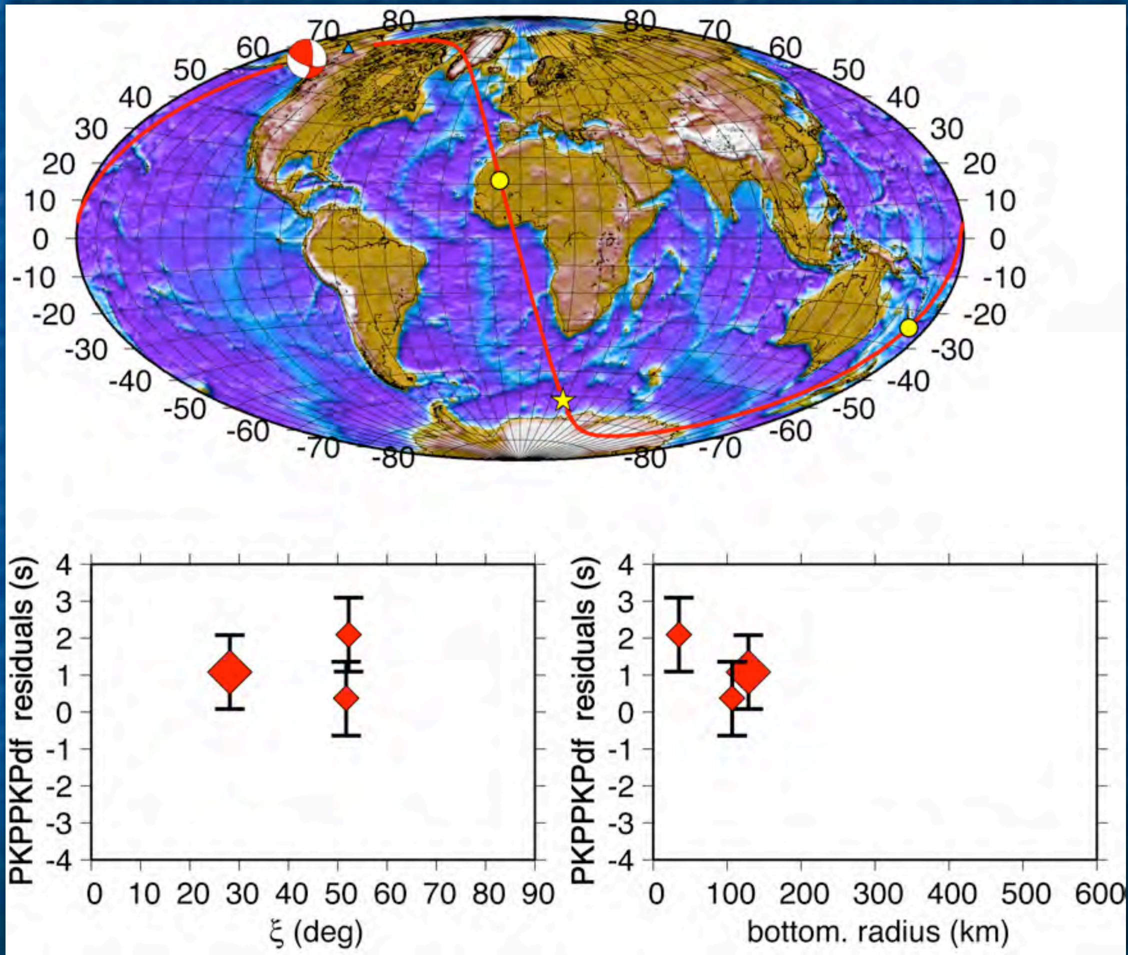
Megan Flanagan

Tkalčić and Flanagan, 2004

Podal PKPPKPdf Observation

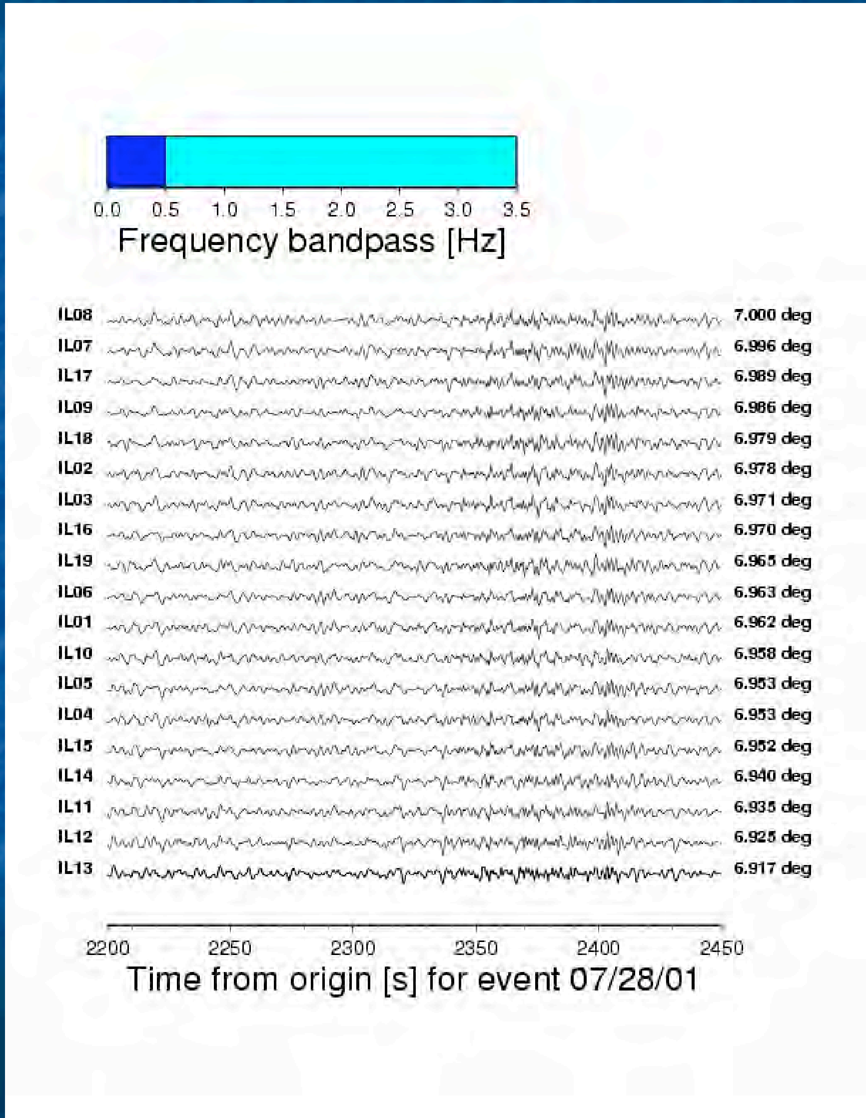


Polar-Podal PKPPKPdf Travel-Time Measurement (Epic. Distance ~7 deg)

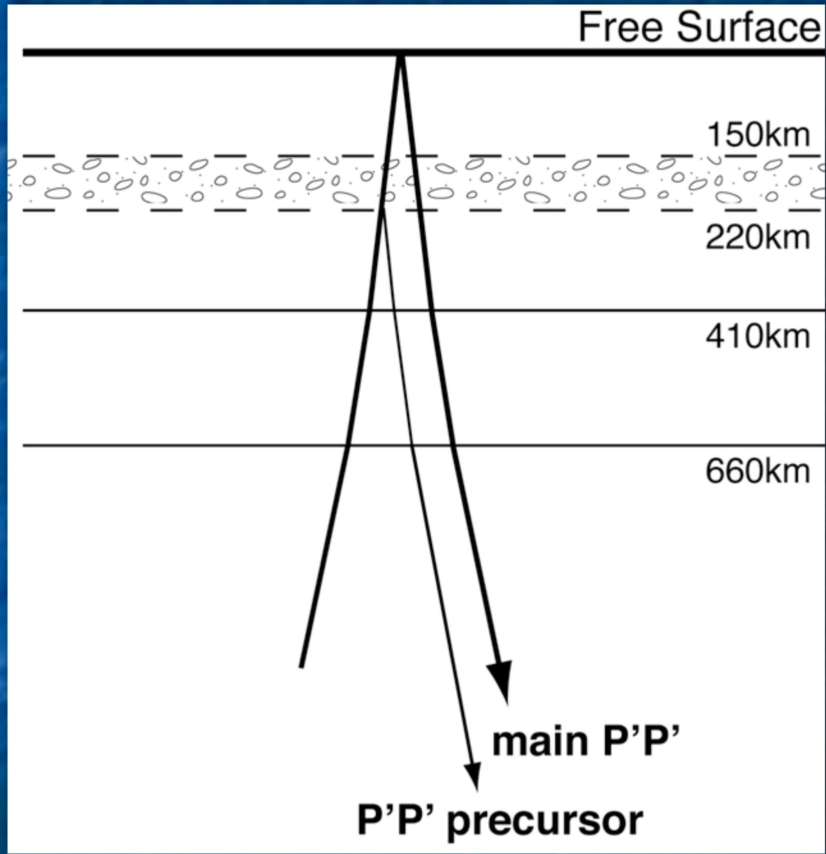


Travel Times are Not Advanced!

Podal PKPPKPdf Precursors



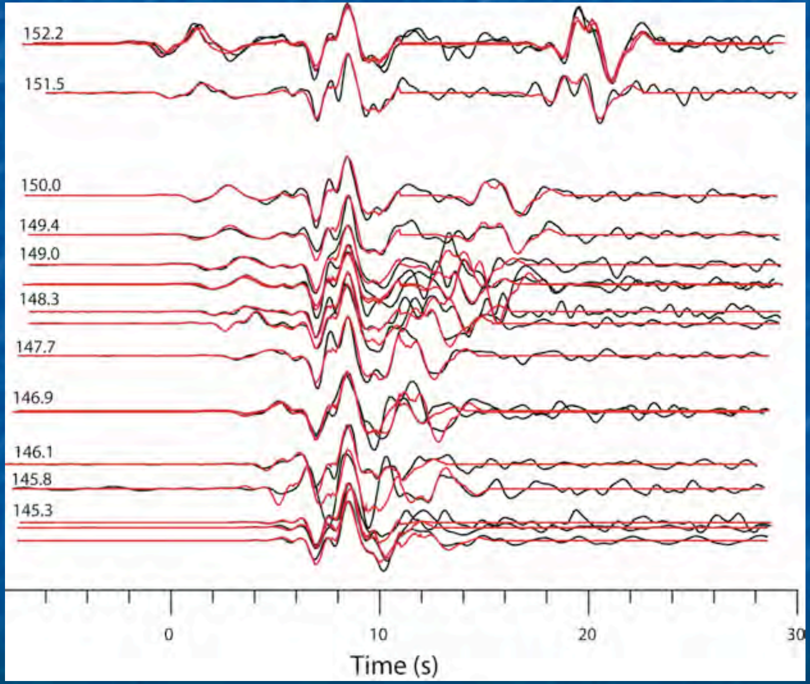
PKPPKP Back-scattering From Reflectors in the Upper Mantle



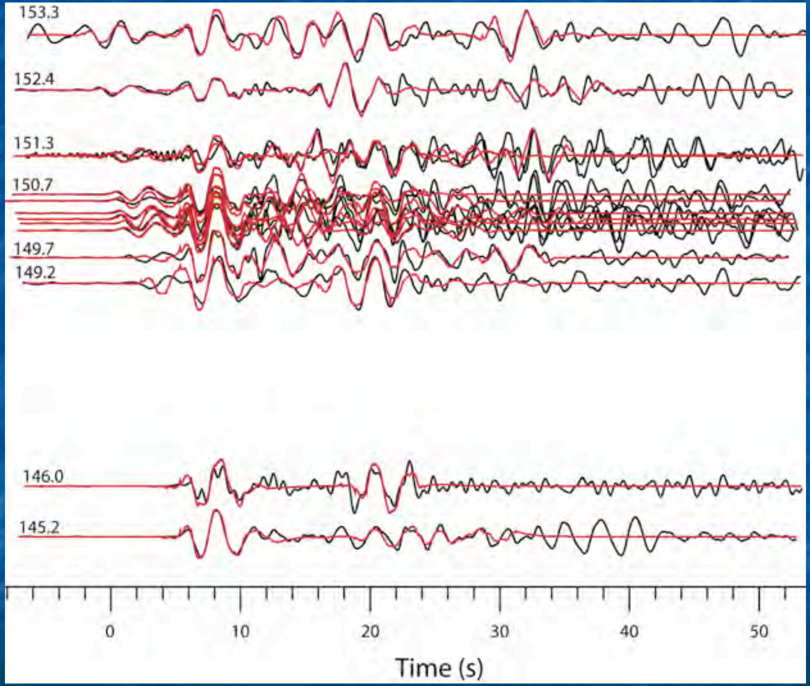
Tkalčić, Cormier and Flanagan, GRL 2006

SAWIB (Simulated Annealing Waveform Inversion of Body Waves)

$$S_i(t) = R_i^{DF} * A_i^{DF} * A(t_i^*) * W(t+\tau_i^{DF}) + W(t+\tau_i^{BC}) + R_i^{AB} * A_i^{AB} * H * W(t+\tau_i^{AB})$$



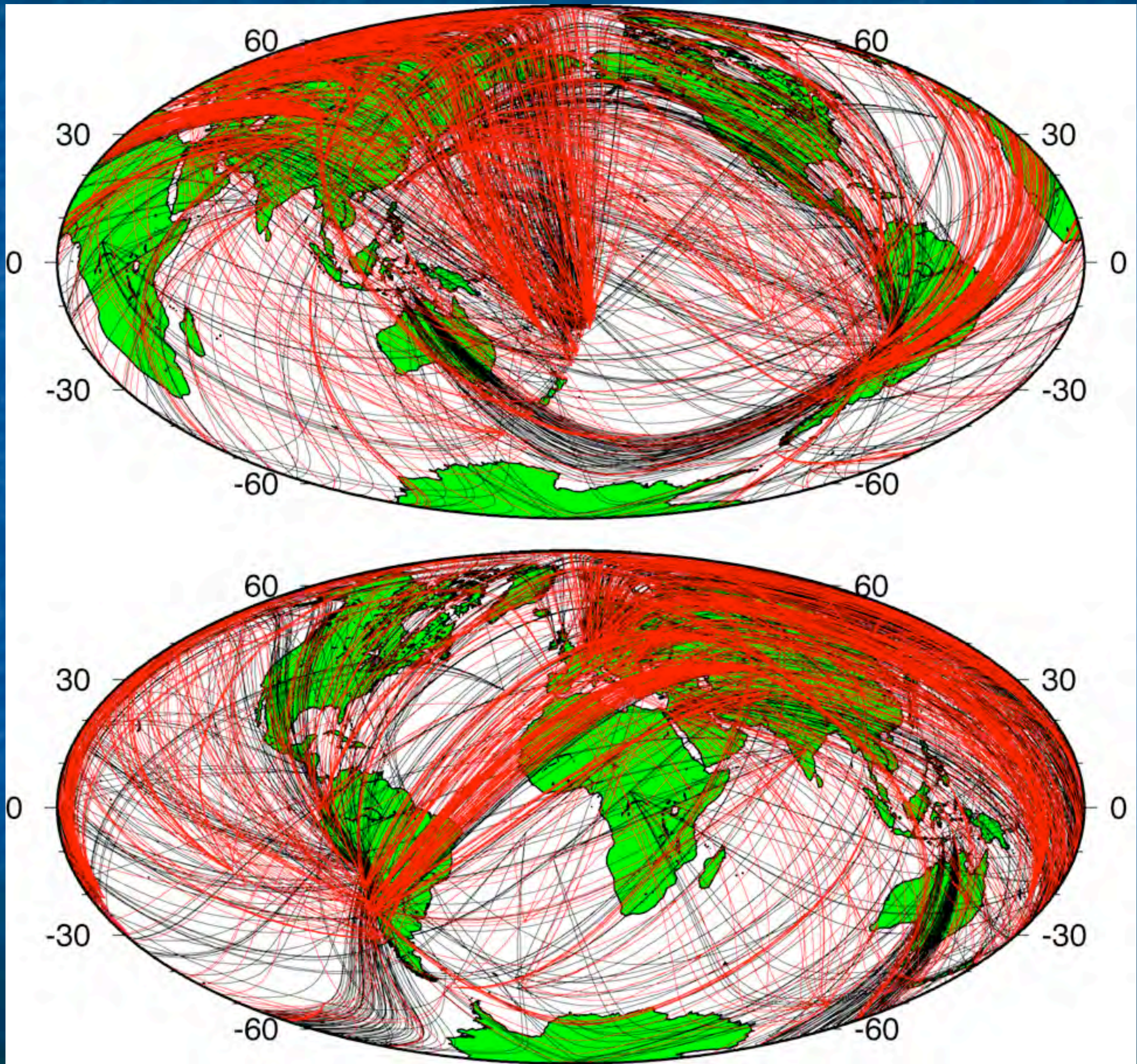
Deep earthquake (Fiji)



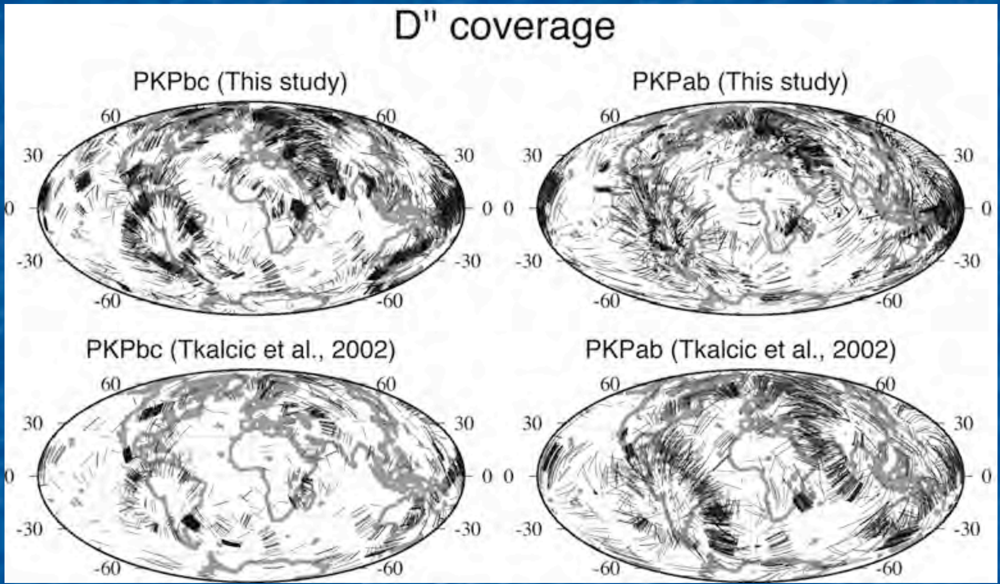
Shallow Earthquake (Chile)

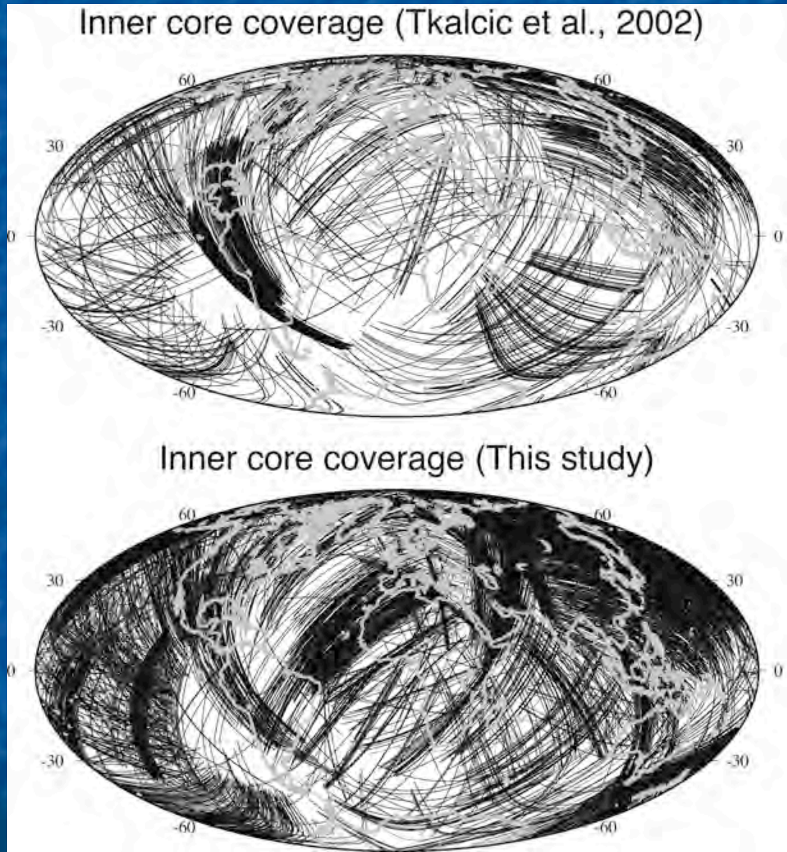
Garcia, Tkalčić, & Chevrot, PEPI, 2006

Improved Ray-Coverage by Adding Shallow Earthquakes



Improved Sampling of the Inner Core and D'' Region



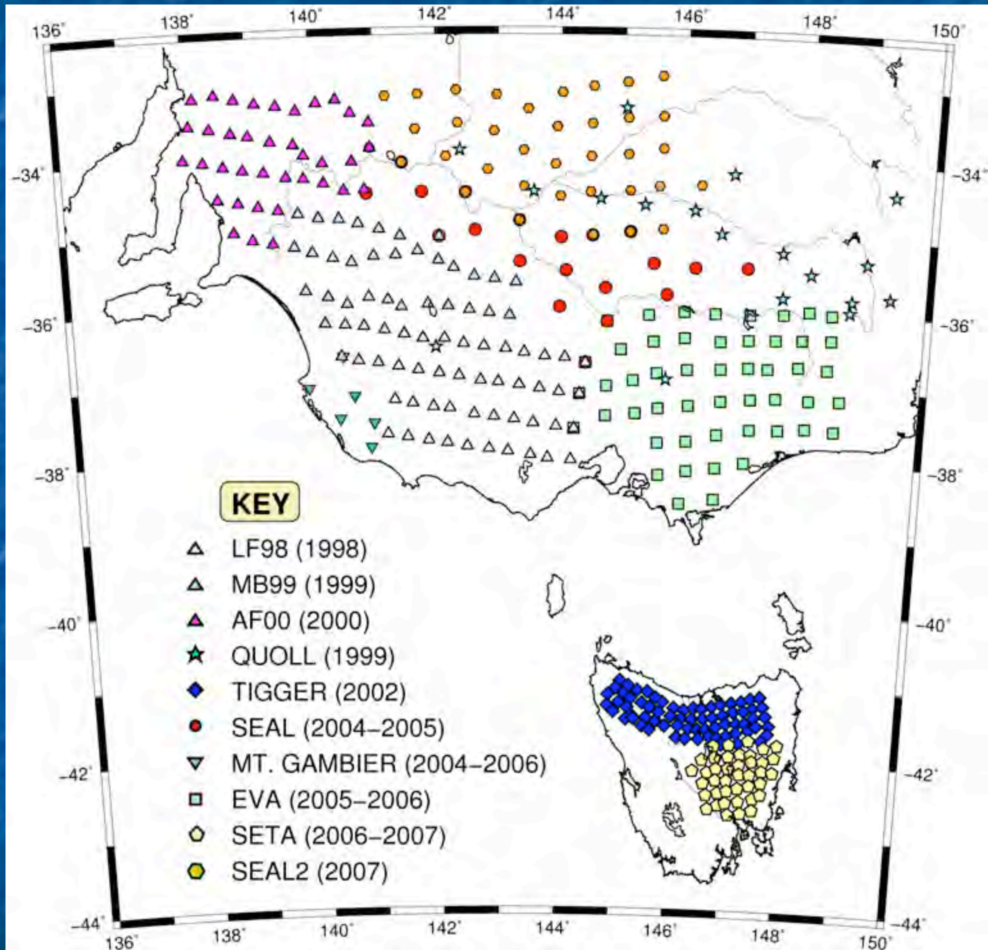


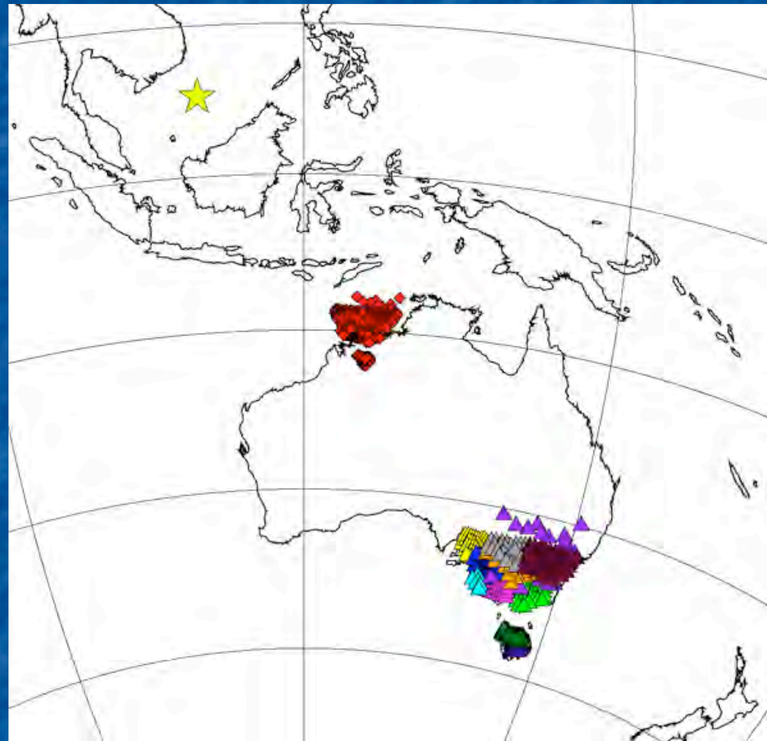
Raphael Garcia

Sebastien Chevrot

Garcia, Tkalčić and Chevrot, PEPI, 2006

Mapping the core mantle boundary using short period data from RSES deployments



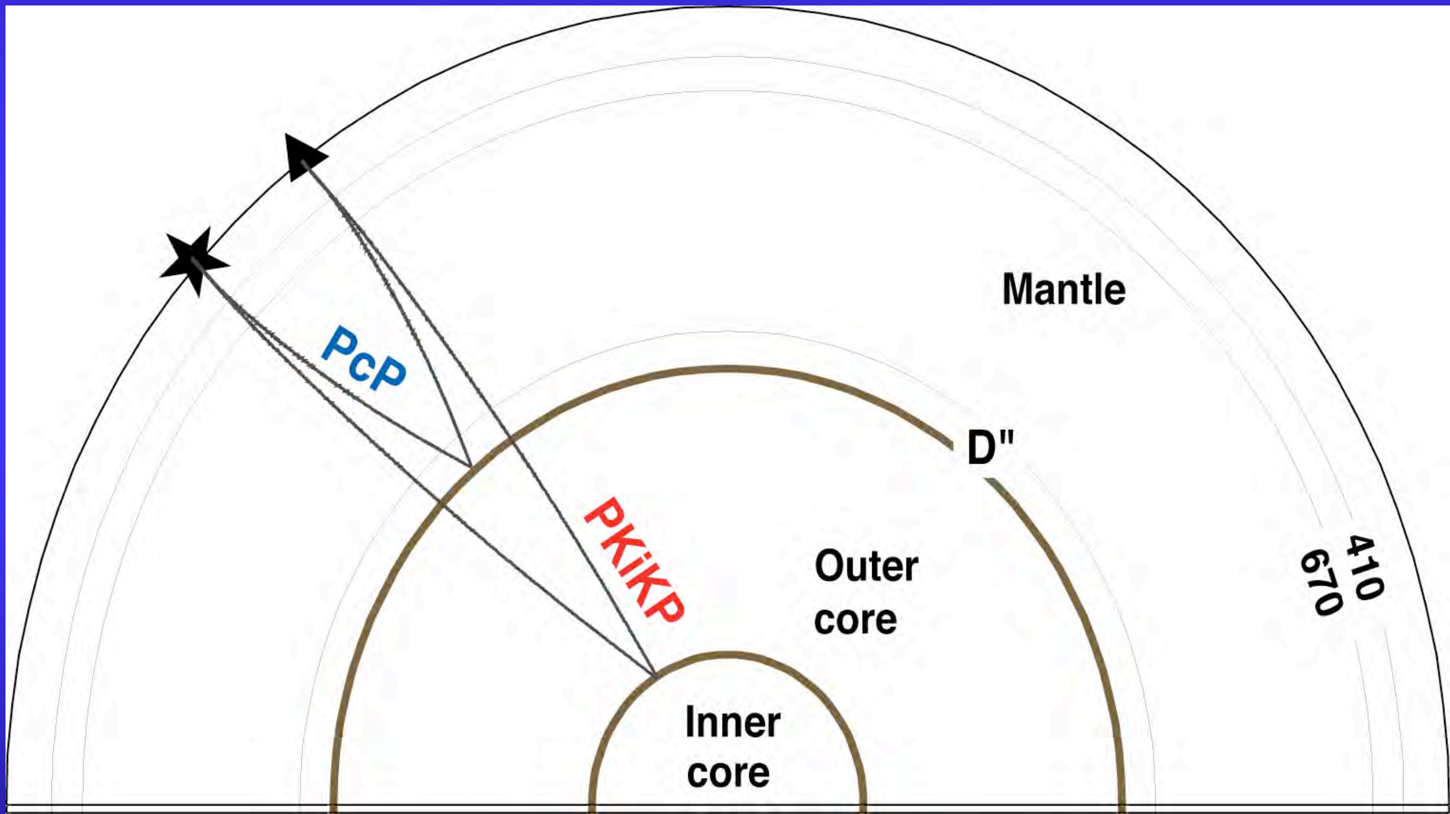


with Sara Pozgay and Nick Rawlinson, work in progress

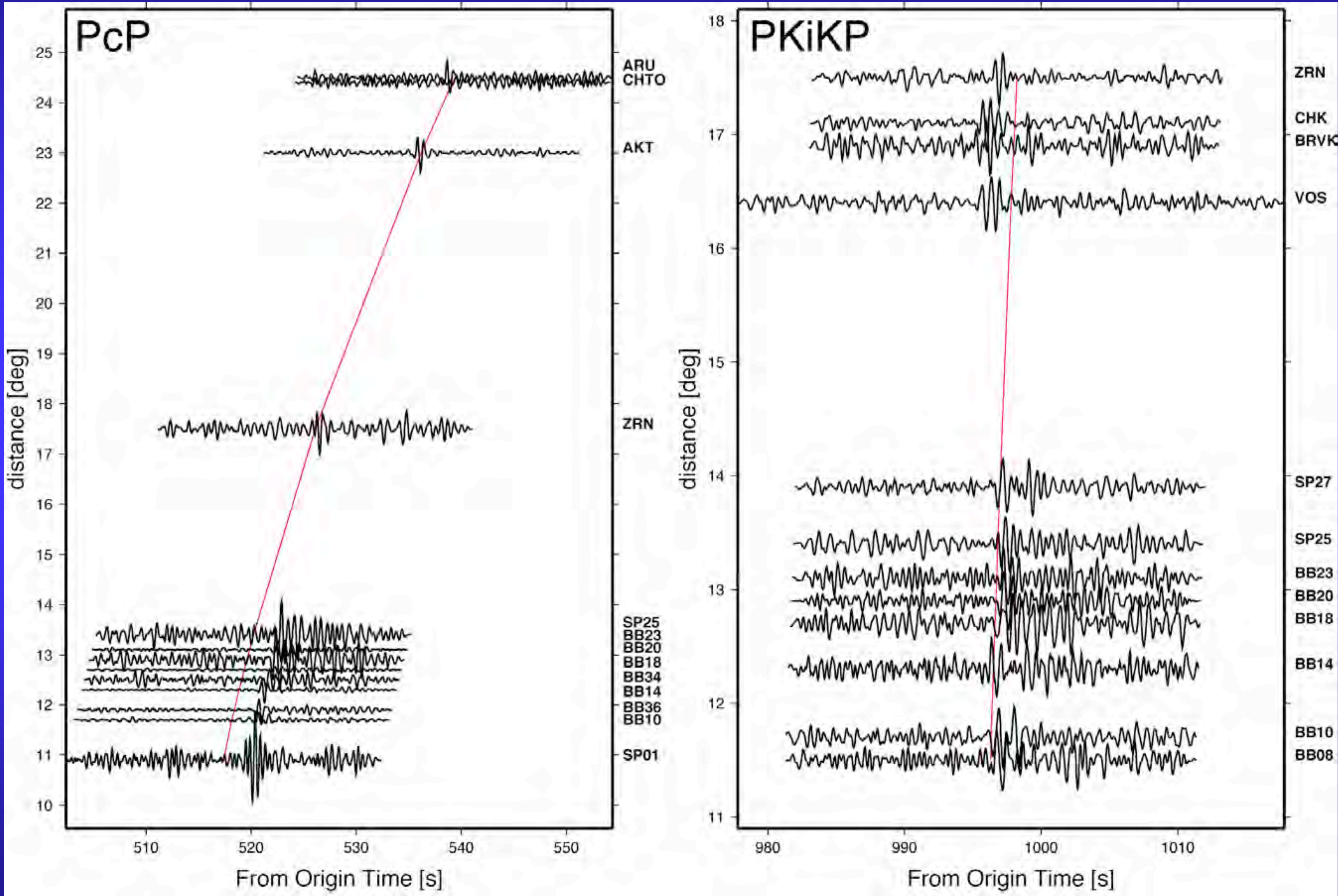
Previous estimates of the ICB density contrast

- Important for calculations of thermal evolution of the inner core and geodynamo (e.g., Stevenson et al., 1983; Buffett et al., 1996; Nimmo et al., 2004)
- Bolt and Qamar (1971) 1800 kg/m^3
- Engdahl et al. (1971); Buchbinder et al. (1974) PKiKP observations
- Dziewonski and Anderson (1981) 550 kg/m^3
- Souriau and Souriau (1989) 1350-1660 kg/m^3
- Shearer and Masters (1990) 550 kg/m^3
- Kennett et al. (1995) 600 kg/m^3
- Masters and Gubbins (2003) 820 kg/m^3
- Koper and Pyle (2004) 450 kg/m^3
- Cao and Romanowicz (2004) 600-900 kg/m^3
- Gubbins et al. (2008) 600 kg/m^3

PcP and PKiKP waves

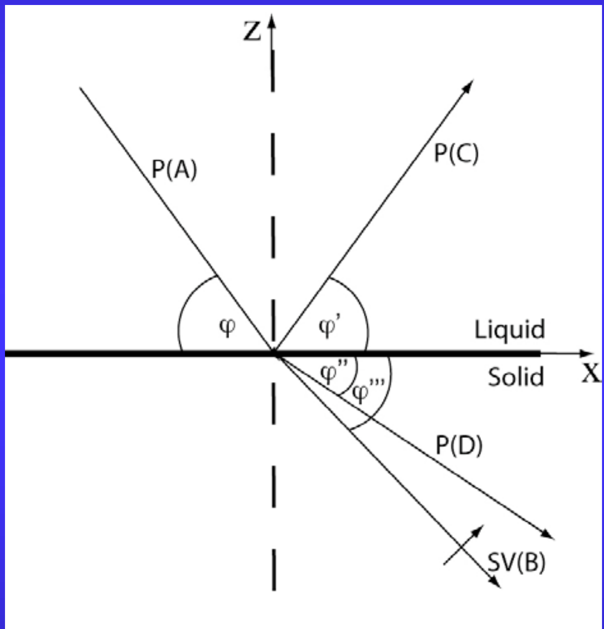


Lop Nor test site nuclear explosion (1994)



Tkalčić, Kennett & Cormier, GJI 2009, in press

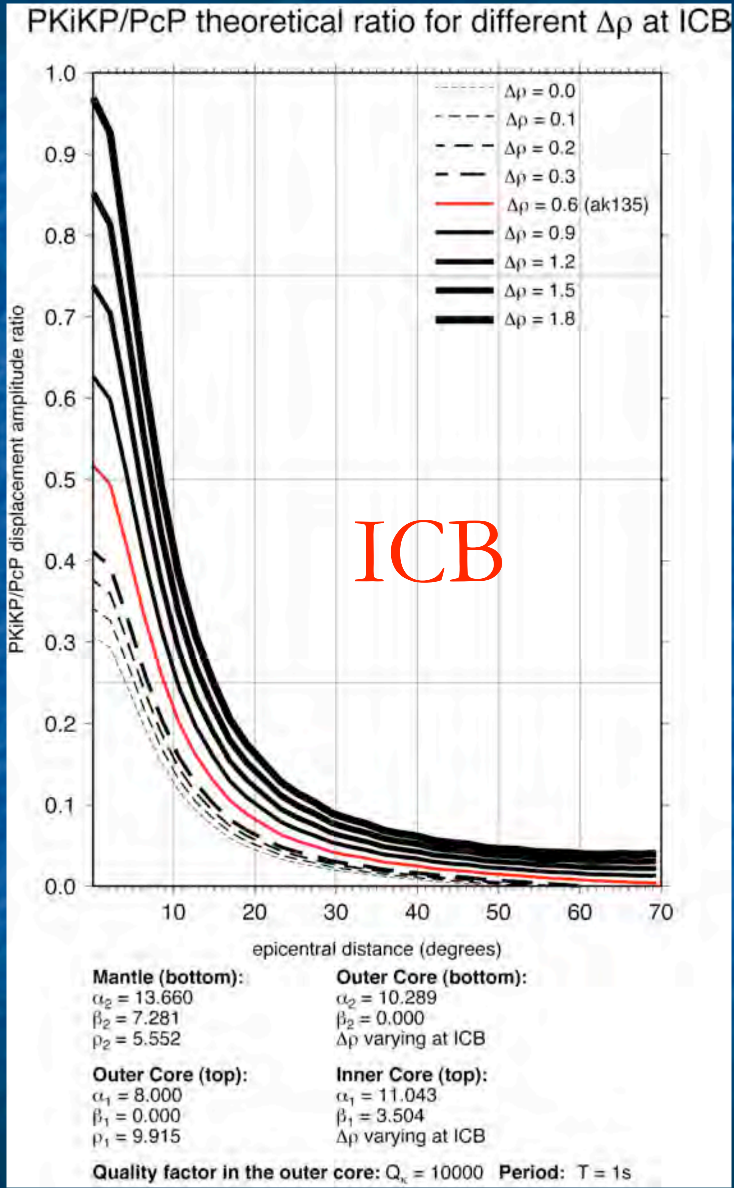
The amplitude ratio between PKiKP and PcP waves is controlled largely by the reflection/refraction coefficients

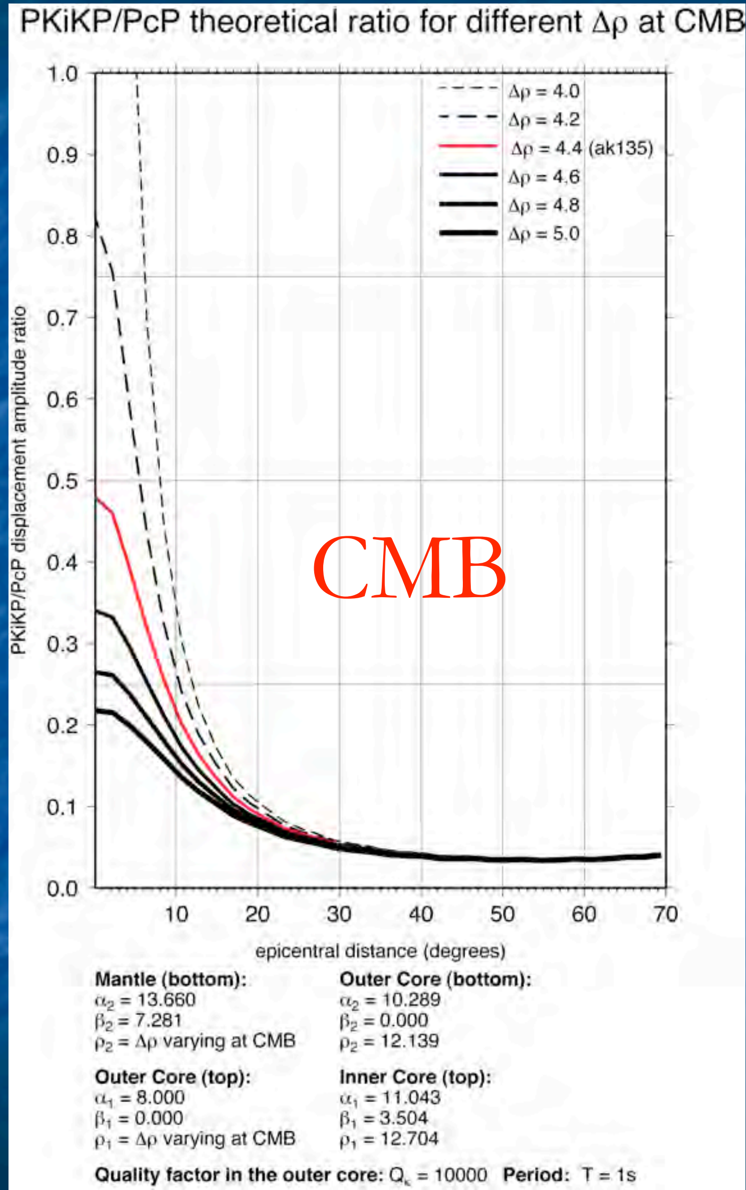


$$\begin{bmatrix} \beta_2\left(\tan^2\varphi'''-1\right) & 0 & 2\alpha_2\tan\varphi'' \\ \beta_2 & -\alpha_1\tan\varphi & -\alpha_2\tan\varphi'' \\ 2\dfrac{\beta_2^{\,3}}{\alpha_1^{\,2}}\tan\varphi''' & \dfrac{\rho_1}{\rho_2}\alpha_1\sec^2\varphi & -\alpha_2\dfrac{\beta_2^{\,2}}{\alpha_1^{\,2}}\left(\tan^2\varphi'''-1\right) \end{bmatrix} \begin{bmatrix} B/A \\ C/A \\ D/A \end{bmatrix} = \begin{bmatrix} 0 \\ -\alpha_1\tan\varphi \\ -\dfrac{\rho_1}{\rho_2}\alpha_1\sec^2\varphi \end{bmatrix}$$

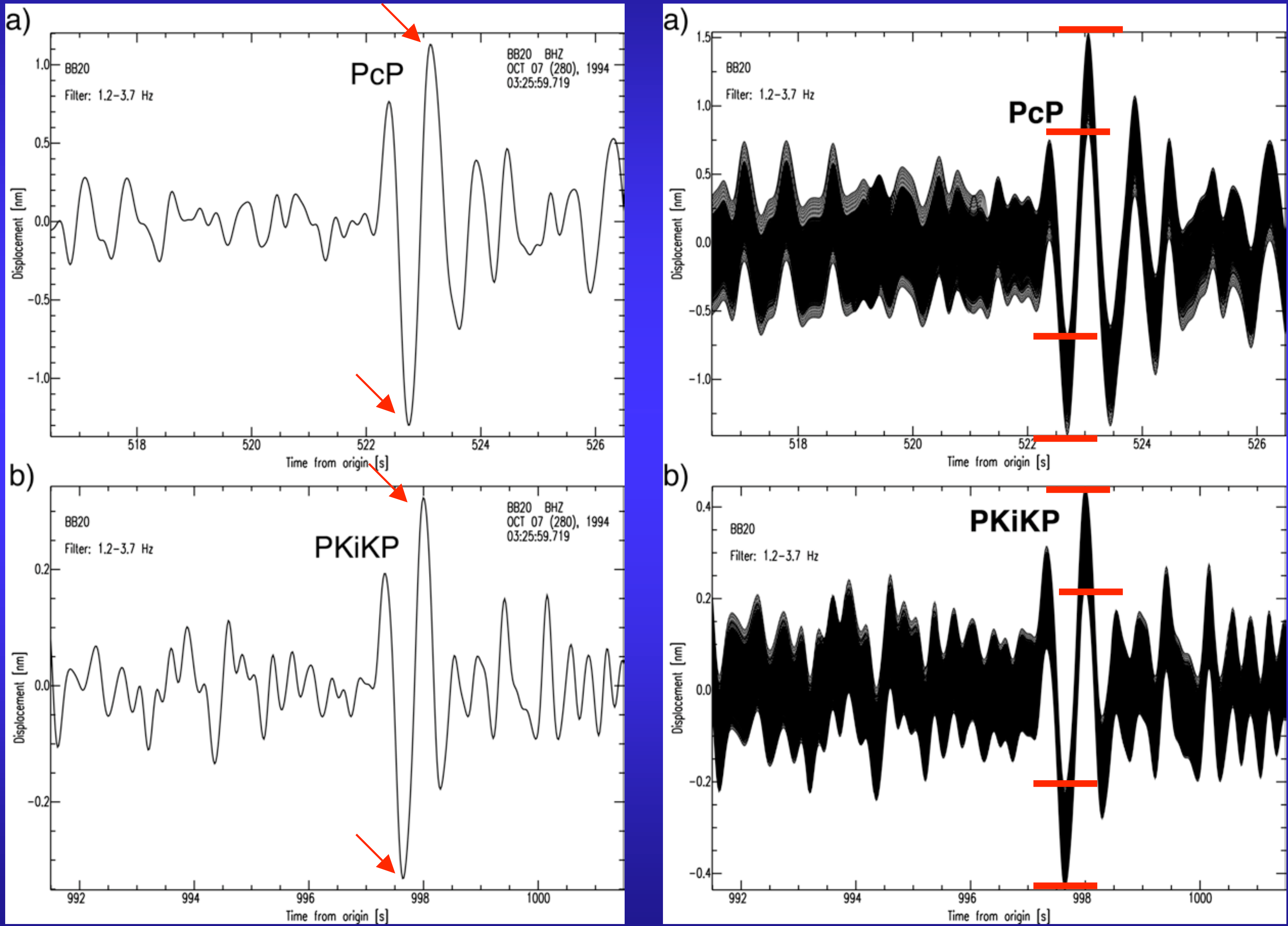
$$\frac{\mathcal{A}(PKiKP)}{\mathcal{A}(PcP)}(\Delta) = \frac{\mathcal{T}_{CMB\text{-}D}(\Delta)\,\mathcal{R}_{ICB}(\Delta)\,\mathcal{T}_{CMB\text{-}U}(\Delta)}{\mathcal{R}_{CMB}(\Delta)}\;\frac{\eta_Q(\Delta)}{\eta_S(\Delta)}$$

Amplitude ratio as a function of density contrast

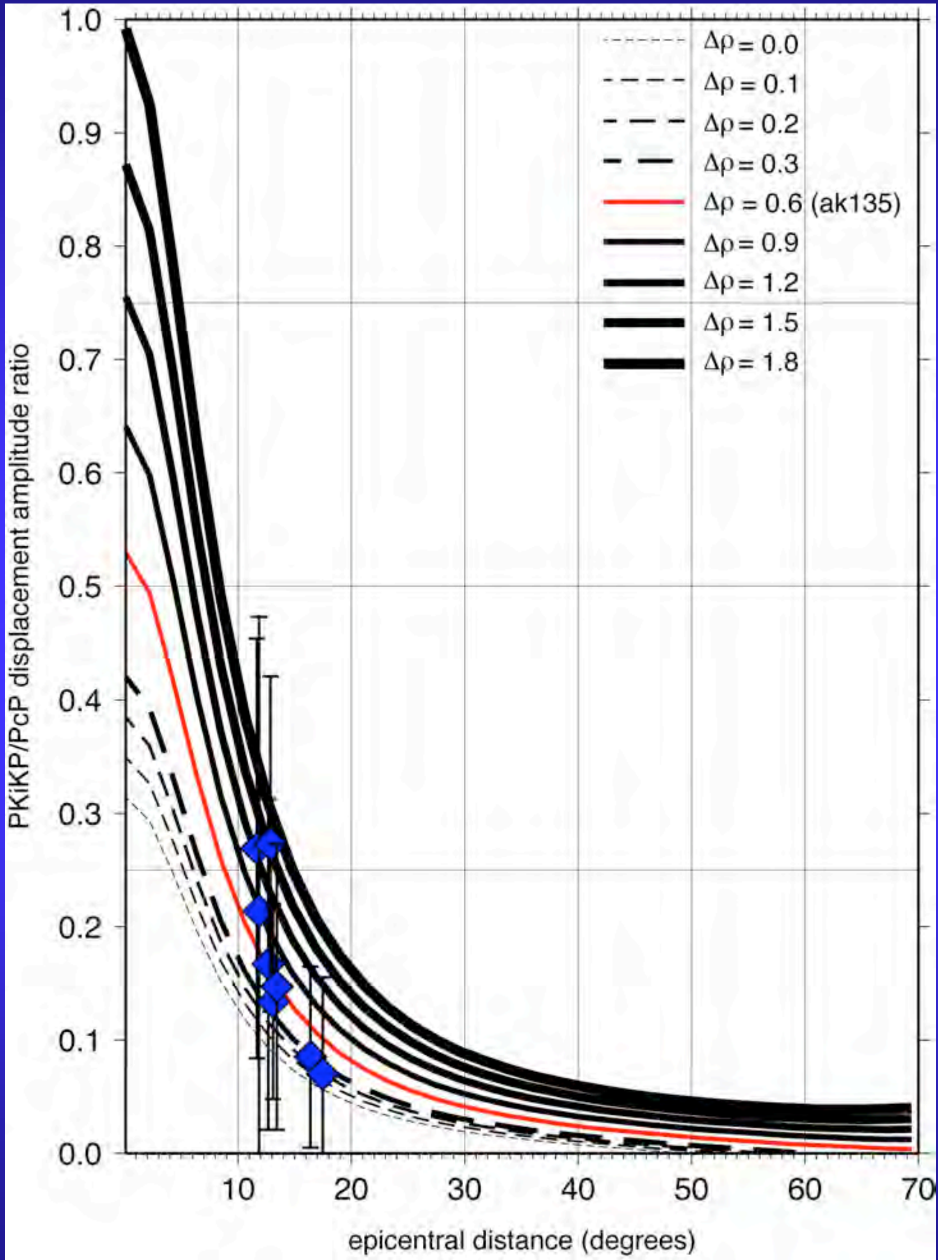




Amplitude measurements including seismic noise



Tkalčić, Kennett & Cormier, GJI 2009, in press



PKiKP/PcP medians very close to the theoretical values from 1D models

PKiKP/PcP uncertainties conservatively high

PKiKP/PcP ratios inconsistent with a single density ratio estimate

Tkalčić, Kennett & Cormier, GJI 2009, in press

ANTI-CORRELATION of PcP and PKiKP

THE AUSTRALIAN NATIONAL UNIVERSITY

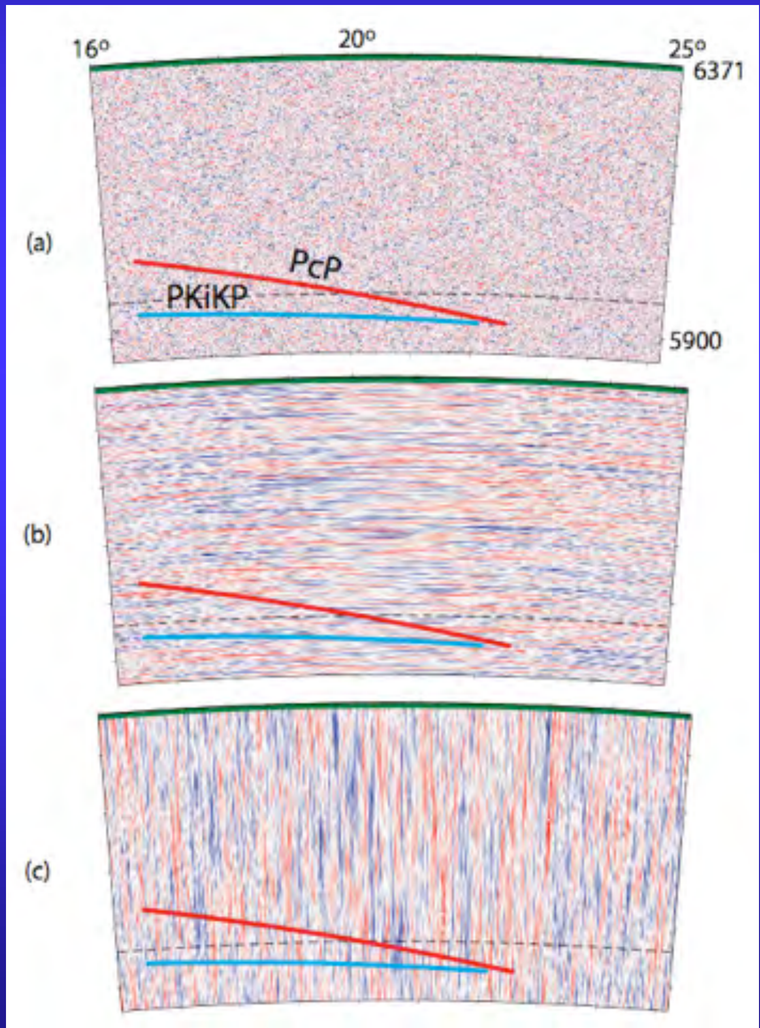
Event	Station	Distance	OBS1	A(PcP)	Quality	OBS2	B(PKiKP)	Quality	B/A	A/P	B/P
010207	ASHI	11.35	**signal**	86.579	A	**signal**	28.081	A	0.324	0.028	0.088
010207	AIB	11.50	**signal**	17.749	A	NOISE	3.560	C	0.201	0.032	0.157
010207	ERIM	12.88	NOISE	74.352	C	early	9999	B	9999	9999	0.069
010207	TNMA	14.74	**signal**	112.859	B	**signal**	25.386	A	0.225	0.030	0.130
010207	AOB	17.03	**signal**	115.525	B	NOISE	6.058	C	0.052	0.014	0.258
010207	MARU	17.39	NOISE	103.810	C	**signal**	16.733	B	0.161	0.022	0.137
010207	SBT	17.80	**signal**	21.711	C	**signal**	2.045	A	0.094	0.012	0.131
010207	YHJ	18.26	**signal**	17.466	B	NOISE	3.746	C	0.214	0.025	0.116
010207	SEK	18.56	NOISE	10.340	C	**signal**	1.493	A	0.144	0.015	0.103
010207	HIT	18.57	NOISE	33.080	C	**signal**	3.091	B	0.093	0.025	0.263
010207	KZK	18.75	**signal**	29.523	A	NOISE	2.157	C	0.073	0.025	0.341
010207	GNZ	18.97	NOISE	4.144	C	**signal**	1.003	A	0.242	0.035	0.145
010207	KUJ	19.34	**signal**	32.197	B	**signal**	3.903	A	0.121	0.033	0.270
010207	DDR	19.63	NOISE	9.848	C	**signal**	0.385	B	0.039	0.016	0.419
010207	KWI	19.88	NOISE	13.942	C	**signal**	1.306	A	0.094	0.006	0.069
010207	ASI	20.03	NOISE	11.550	C	**signal**	1.064	B	0.092	0.029	0.313
010207	AKY	20.06	NOISE	25.532	C	**signal**	2.456	B	0.096	0.014	0.147
010207	OKY	20.60	NOISE	14.321	C	**signal**	2.372	A	0.166	0.015	0.089
010207	KURK	20.69	NOISE	43.429	C	**signal**	7.163	C	0.165	0.013	0.076
010207	ITD1	20.80	NOISE	13.130	C	**signal**	1.895	A	0.144	0.008	0.056
010207	WACH	21.76	NOISE	39.883	C	**signal**	10.350	B	0.260	0.033	0.127
010207	SHK	23.59	**signal**	12.128	B	NOISE	3.434	C	0.283	0.045	0.159
010207	MONO	23.74	**signal**	84.315	A	**signal**	18.683	A	0.222	0.080	0.363
010207	MRMJ	24.03	**signal**	5.242	C	NOISE	3.018	C	0.576	0.159	0.277
010207	TUSI	25.14	**signal**	59.725	C	NOISE	30.408	C	0.509	0.215	0.422
010207	TITI	27.02	**signal**	199.914	A	NOISE	48.079	C	0.240	0.104	0.433
010207	SUZY	27.14	**signal**	58.304	A	NOISE	13.911	C	0.239	0.092	0.387
010207	KUNK	32.12	**signal**	243.076	A	NOISE	31.340	C	0.129	0.016	0.127
010207	YONA	36.61	**signal**	260.963	A	NOISE	106.959	C	0.410	0.594	1.449

Earthquake:
24 out of 29!

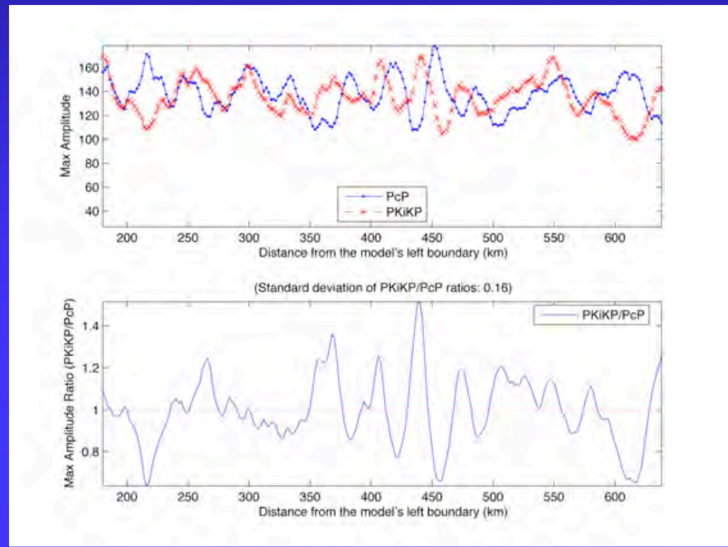
Explosion:
30 out of 39!

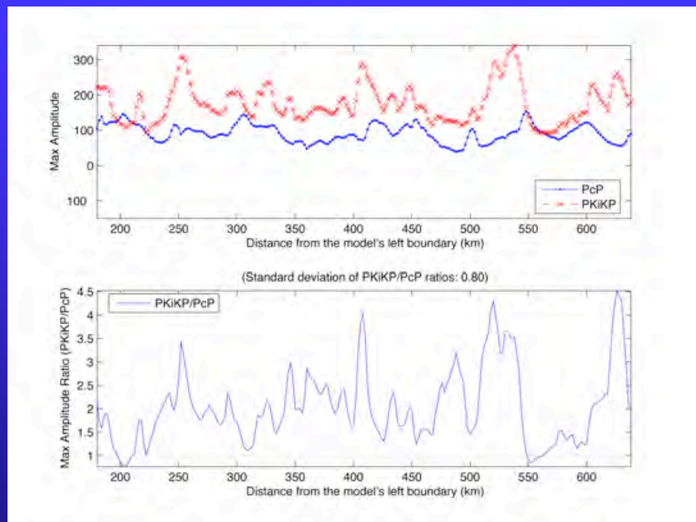
Tkalčić, Cormier, Kennett & He; submitted to PEPI

Simulations of inhomogeneities in the upper mantle confirm anti-correlation of PKiKP and PcP amplitudes



Horizontally Stretched heterogeneities





Vertically Stretched heterogeneities

Tkalčić, Cormier, Kennett & He; submitted to PEPI

ICB density jump - summary

- PKiKP/PcP data indicate (using the seismic noise as a measure of uncertainty) density contrast at the ICB that is similar to PREM and the ak135 model predictions. The seismic noise could be one of the reasons for previous discrepancies in results.

- The uncertainties are conservatively high, yet the upper bound does not exceed 1200 kg/m^3
  Some measurements indicate a very low density jump (200-300 kg/m^3).
  This might be a direct observation of less solidified texture regions at the top of the inner core

- Observed anti-correlation between the observations of PcP and PKiKP waves; e.g. in a number of cases, PcP is buried in noise, and PKiKP is not (and vice versa).
  This is likely a result of heterogeneity in the upper mantle on the receiver side

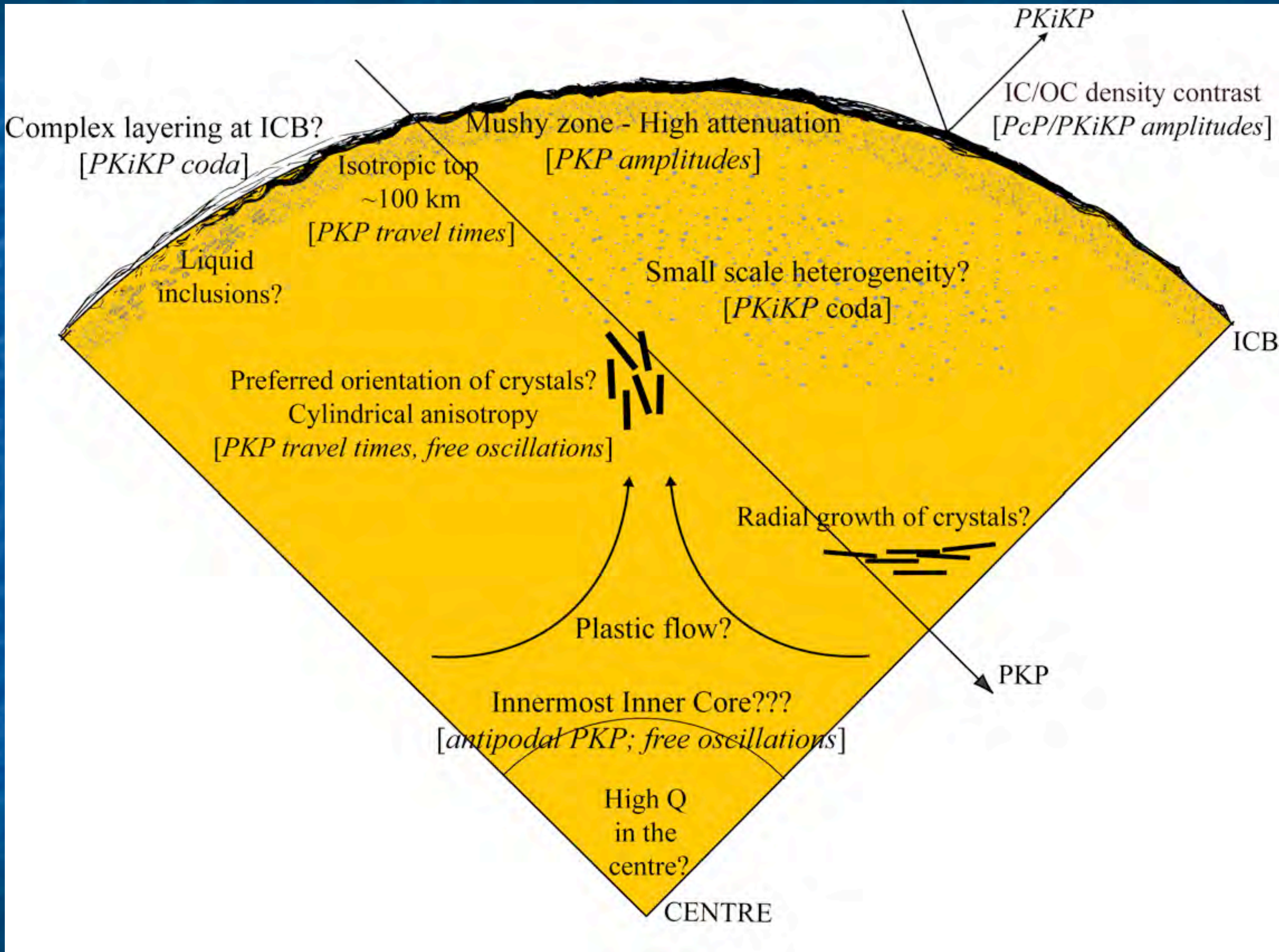
- If heterogeneity is such an efficient mechanism for decreasing and increasing amplitudes of body waves, we have to be cautious and honest about the limitations of ray theory approach in inferring the ICB properties.
  Only in cases when both PcP and PKiKP are affected similarly by heterogeneity in the upper mantle, their amplitudes can be used to infer the ICB density contrast.

Future observations - Earth's Core

Better spatial sampling

- Collecting more PKP (absolute and differential) travel time data with existing and new deployments of instruments
- Developing novel observational techniques
- Observing and analyzing PnKP, PKPPKP and other "exotic" seismic phases with unique spatial sampling

Inner core: a simple world or a microcosm?



from Tkalčić and Kennett, AJES 2008