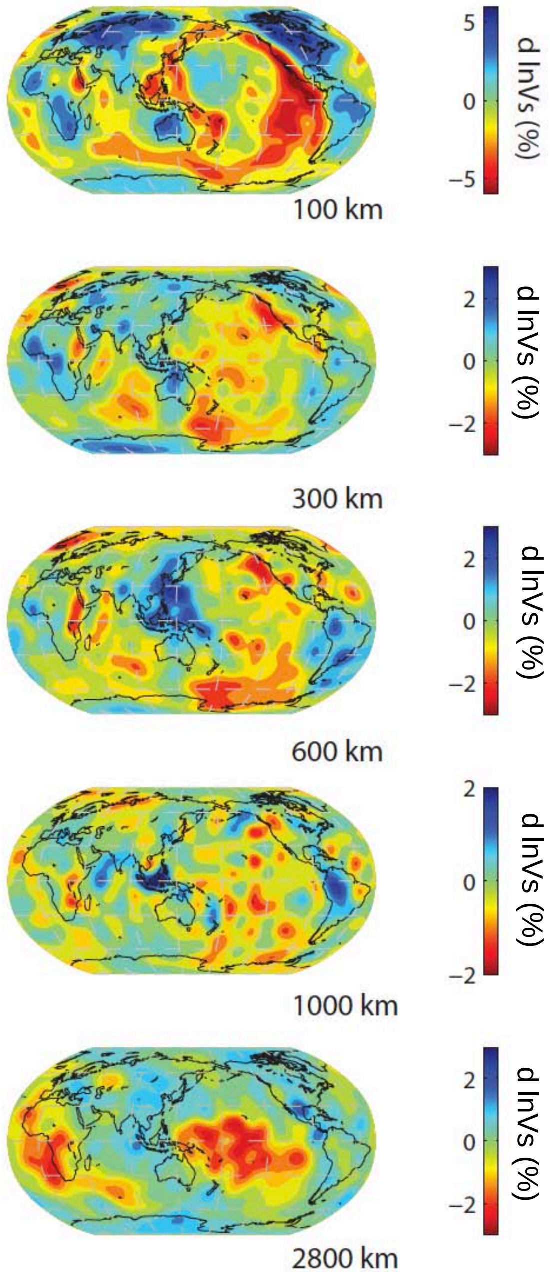
New Ways of Constraining Seismic Attenuation in the Deep Mantle

Jan Matas

Stéphanie Durand, Ved Lekic
Yanick Ricard, Barbara Romanowicz



Ritsema et al. (2011)

What are the red and blue regions made of?

How can we improve constraints on the structure of the Earth's mantle from interpretations of modern tomographic images?

From

Seismic velocities
(observations)

To

Density
Temperature
Composition
(model parameters)

Su & Dziewonski (1997), Masters et al. (2000) … and many others

One needs to accurately know the « conversion factors »

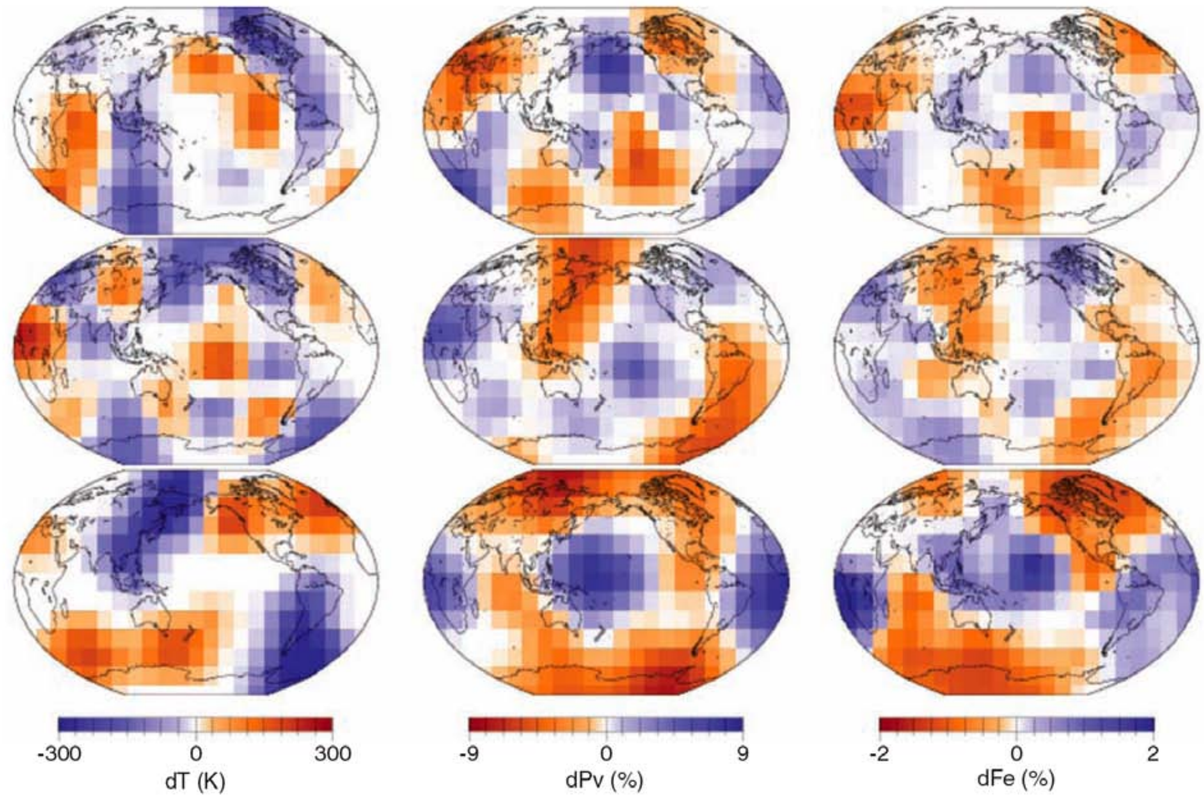
(i.e. partial derivatives of seismic velocities)

$$\frac{\Delta v}{v} \longrightarrow \left(\frac{\partial \ln v}{\partial T}\right)_{P,\chi} \Delta T + \left(\frac{\partial \ln v}{\partial \chi}\right)_{P,T} \Delta\chi$$

670-2000 km

1200-2000 km

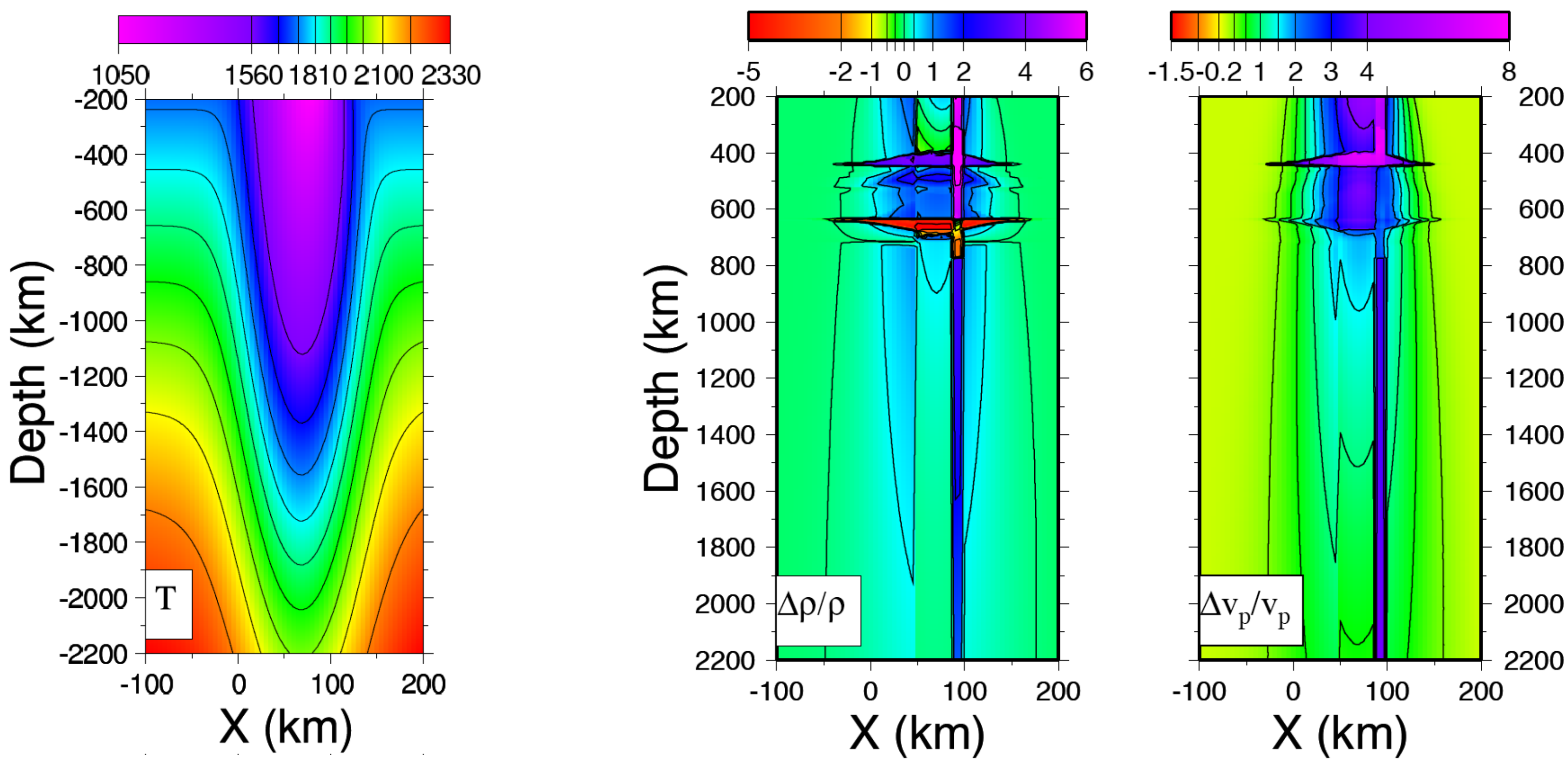
2000-2890 km



Trampert et al. (2004)

… including effects od phase transitions

$$\left(\frac{\partial \ln v}{\partial T}\right)_{P,\chi} \Delta T + \left(\frac{\partial \ln v}{\partial \chi}\right)_{P,T} \Delta \chi \quad \longrightarrow \quad \frac{\Delta v}{v}$$



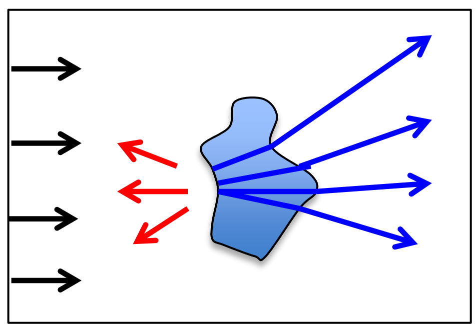
synthetic models from Ricard et al. (2005)

However in the real mantle : seismic attenuation

Extrinsic attenuation
incoming elastic energy
is conserved

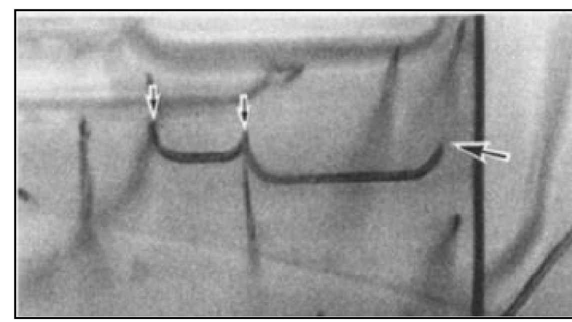
Geometrical
spreading

Focusing/Defocusing
Scattering



Intrinsic attenuation
incoming elastic energy
is transformed

Anelasticity
(dislocations, diffusion, ...)



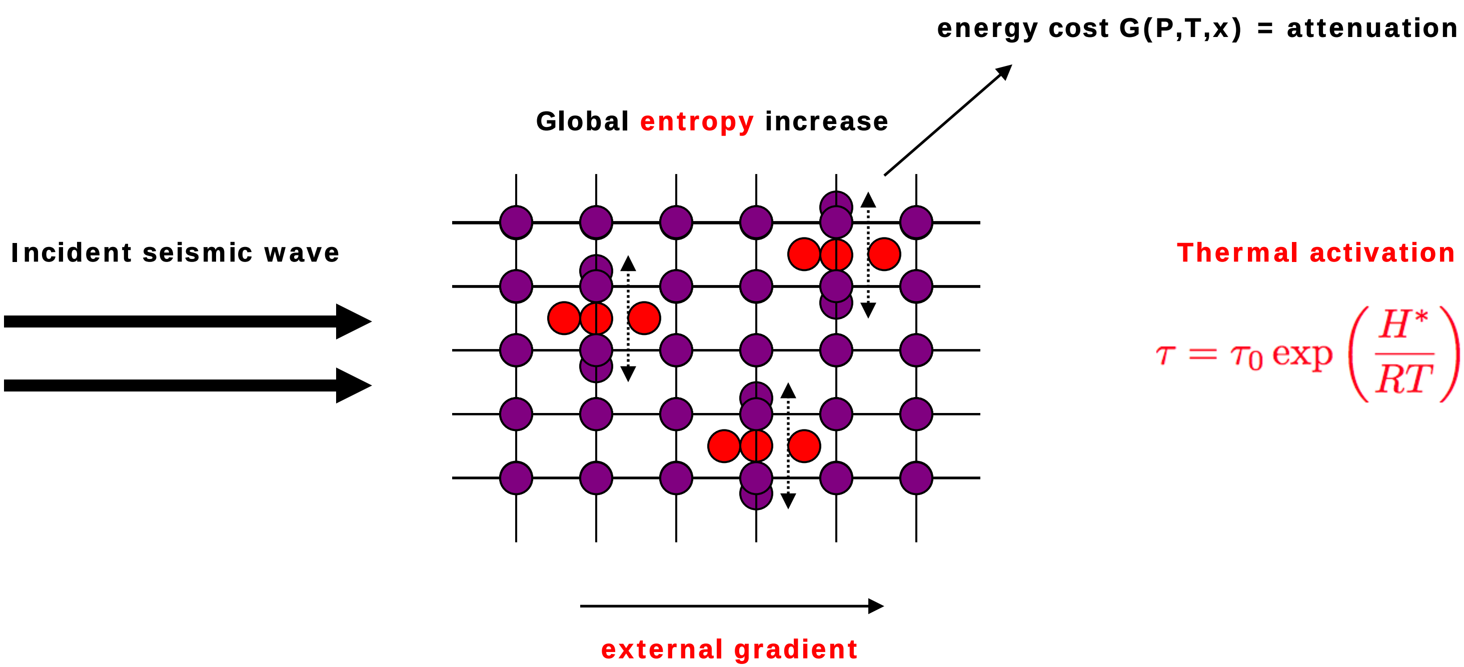
Karato & Spetzler [1990]

Intrinsic attenuation

Elastic energy of waves is consumed dissipative processes (*Knopoff, 1964*)

Many different dissipation mechanisms exist in the mantle
(e.g. Jackson and Anderson 1970)

Example of the diffusion



Thermal activation

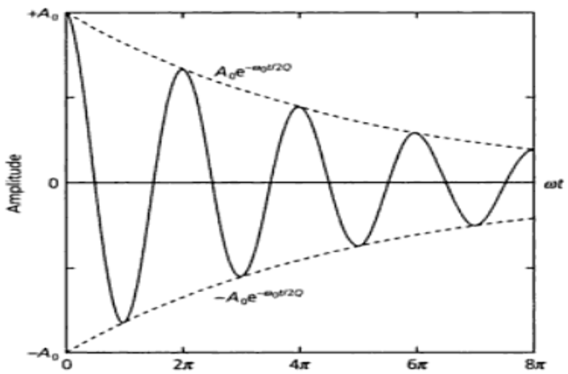
$$\tau = \tau_0 \exp\left(\frac{H^*}{RT}\right)$$

Characterization of the intrinsic attenuation (anelasticity)

Q *(quality factor)* or q *(absorption)*

$$q = 1/Q = -\Delta E/2\pi E = -\Delta A/\pi A$$

$A=A_0 \exp(-\omega_0 t/2Q)$



Frequency dependence

$$Q \sim \omega^{\alpha}$$

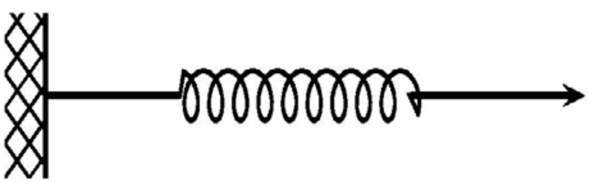
Often assumed thermal activation

$$Q = Q_0 \exp\left(\frac{\alpha H^*}{RT}\right)$$

Modeling of the intrinsic attenuation

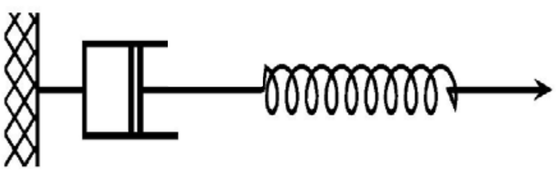
Elasticity

κ, μ

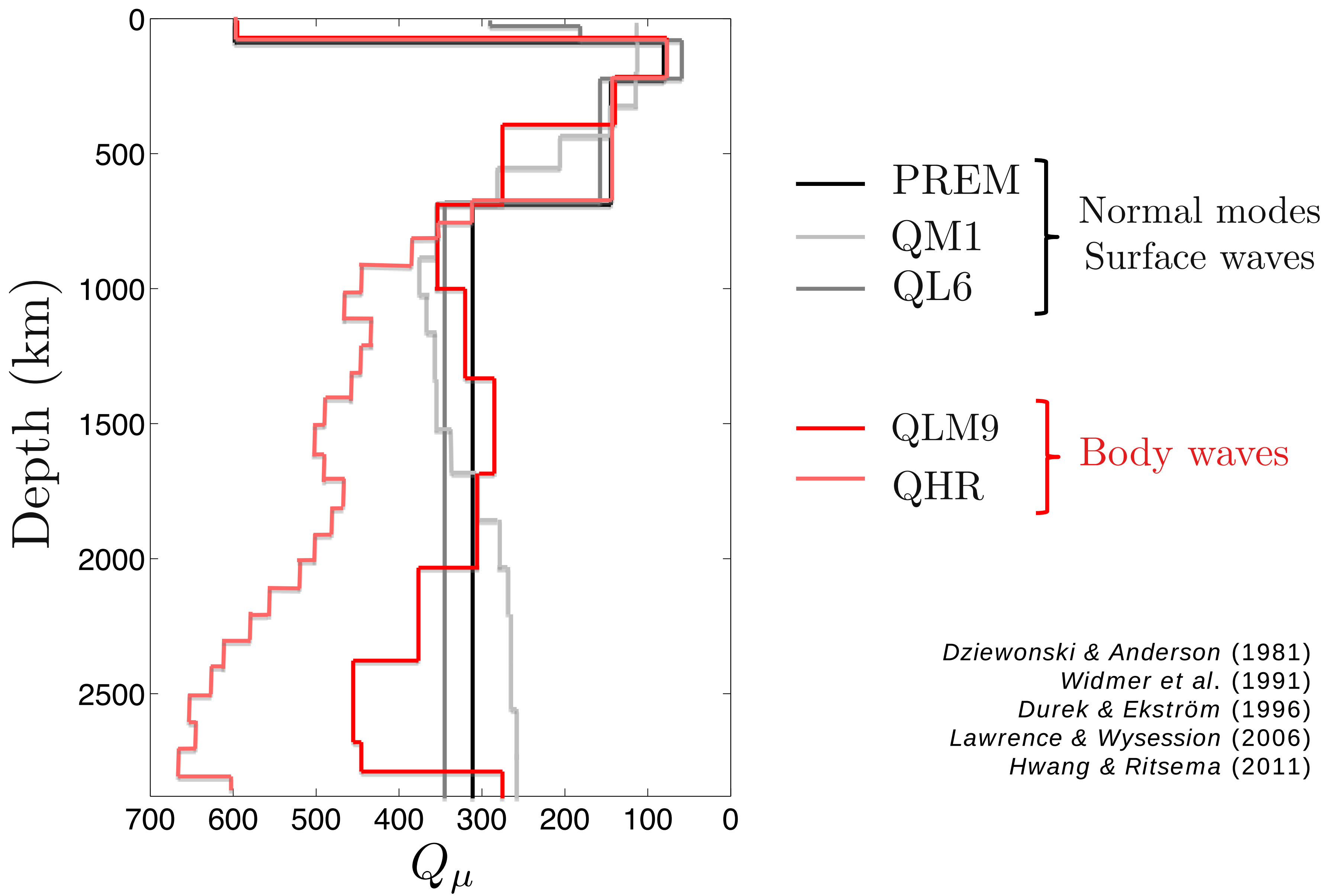


Anelasticity

$Q_\kappa(\omega) >> Q_\mu(\omega)$

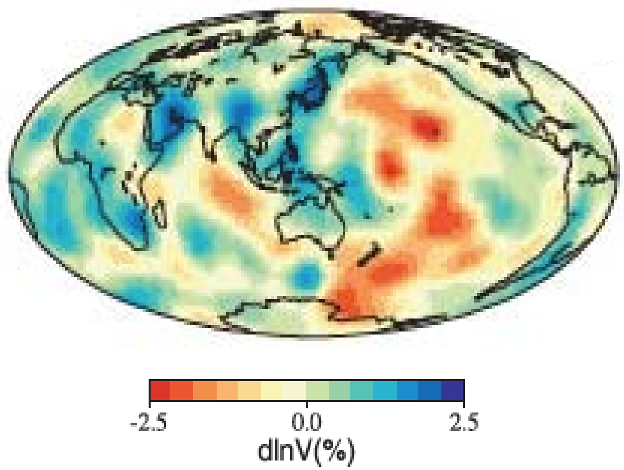


What do we (think to) know:
Global radial attenuation structure



Dziewonski & Anderson (1981)
Widmer et al. (1991)
Durek & Ekström (1996)
Lawrence & Wysession (2006)
Hwang & Ritsema (2011)

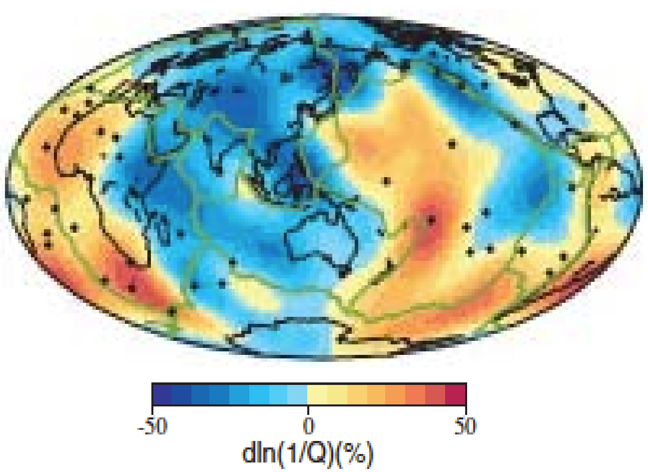
450 km



Recent tomographic images also reveals

lateral variations of attenuation

Mapped mostly the upper part of the mantle: Romanowicz (1994), Gung & Romanowicz (2004), Lekic et al. (2011) ...



Gung & Romanowicz (2004)

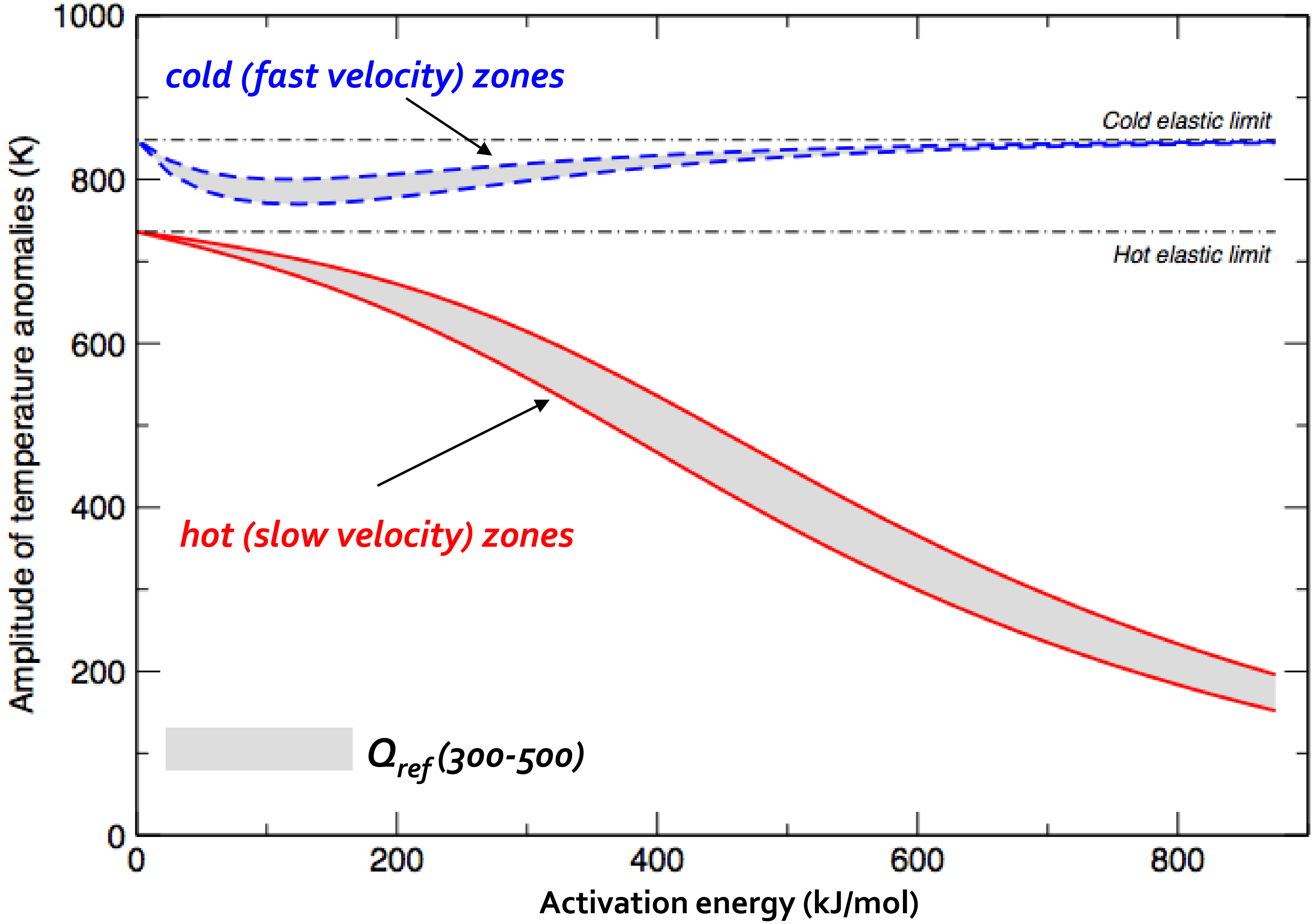
Self-consistent anelastic conversion factors are needed

$$\left(\frac{\partial \ln V_{s,p}}{\partial T}\right)_{\chi,P} = \left(\frac{\partial \ln V^{\mathrm{el}}_{s,p}}{\partial T}\right)_{\chi,P} - \frac{1}{\pi}\frac{F(\alpha)}{Q(\omega,T)}\frac{G*}{RT^2}$$

Karato (1993), Karato & Karki (2001), Trampert et al. (2001), **Matas & Bukowinski (2007)**, Brodholt et al. (2007), ...

Effects of attenuation: an enhancement of slow anomalies

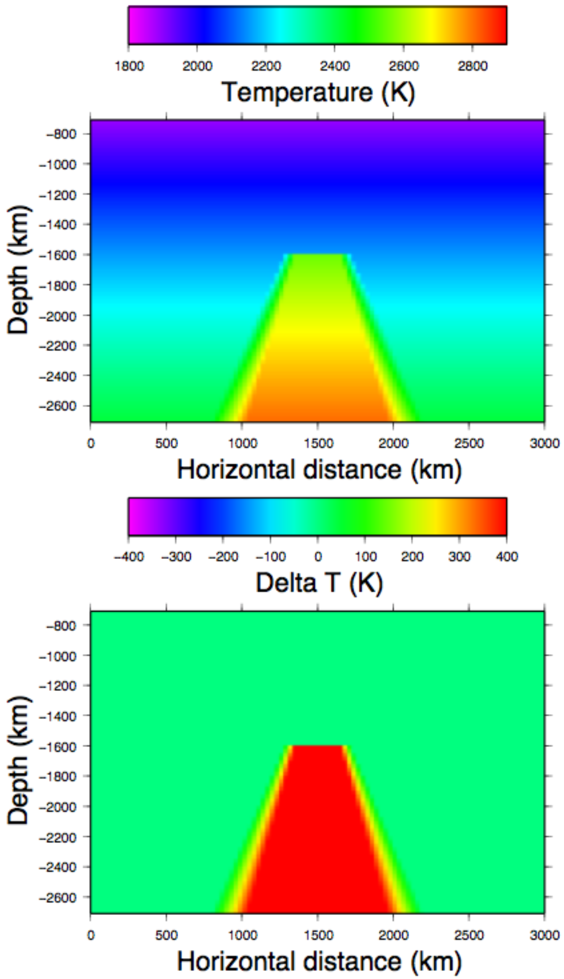
(example with assuming a 2% seismic anomaly)

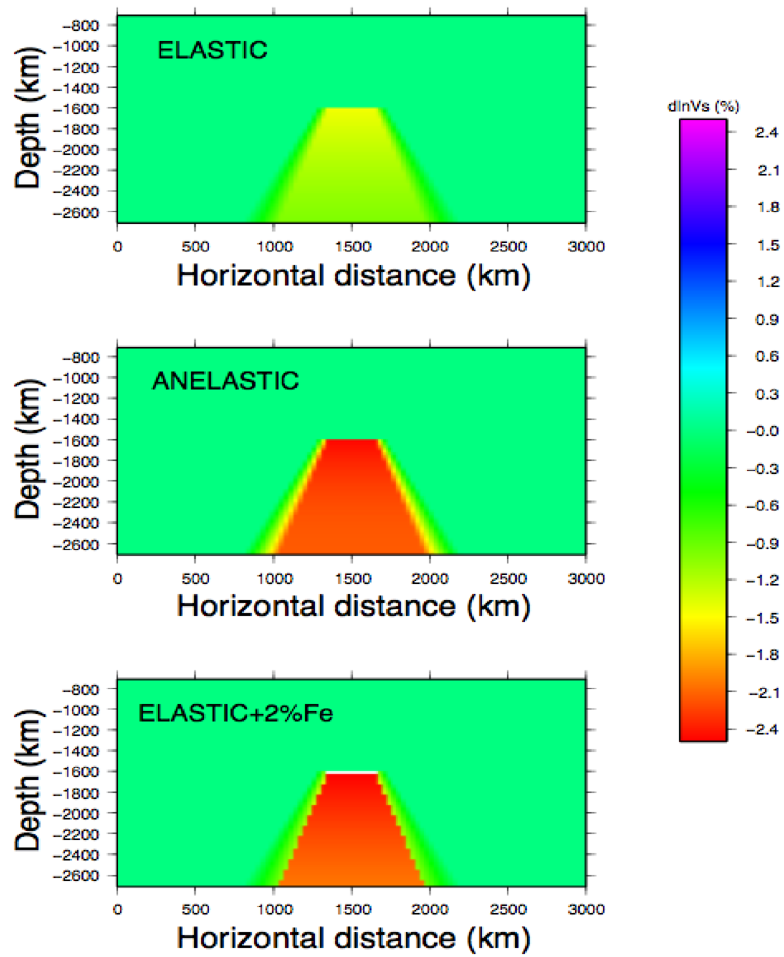


Matas & Bukowinski (2007)

Effects of attenuation: a trade-off between chemistry and attenuation

(example with assuming a simplified rising plume model)





work in progress ...

Conclusions

1) Intrinsic attenuation in the mantle cannot be neglected

2) More robust constraints on Q are required in the lower mantle

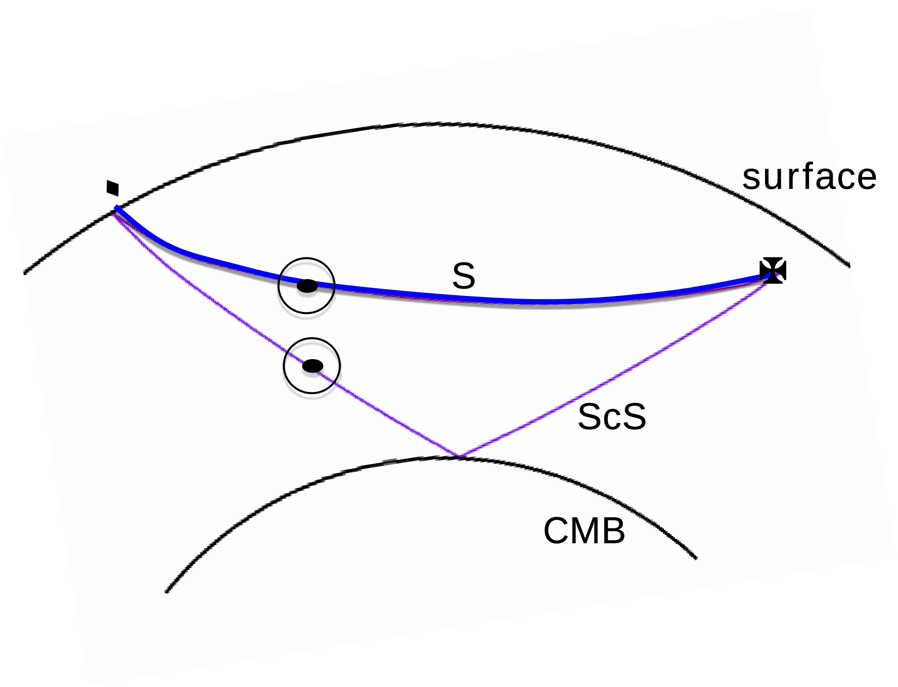
How can we obtain it ?

Two suggestions

a) From differential ScS-S measurements *(Durand et al., submitted)*

b) From analysis of distribution of velocity anomalies *(Lekic & Matas, in prep)*

Differential ScS-S measurements



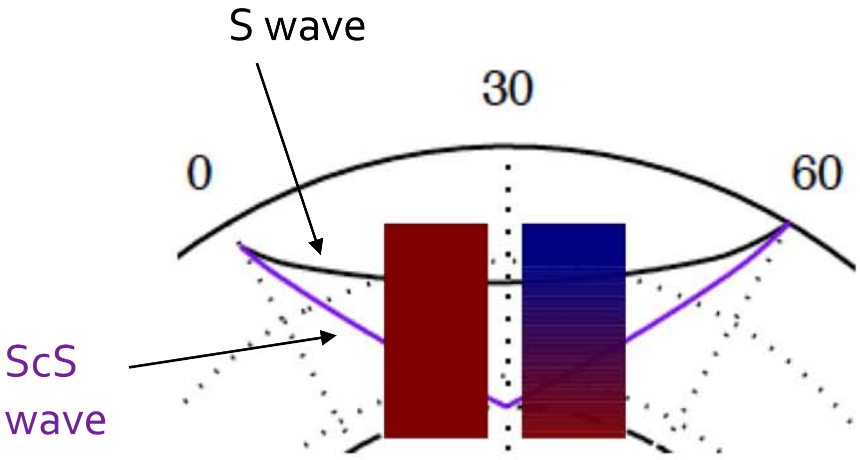
For each wave screening the mantle attenuation structure

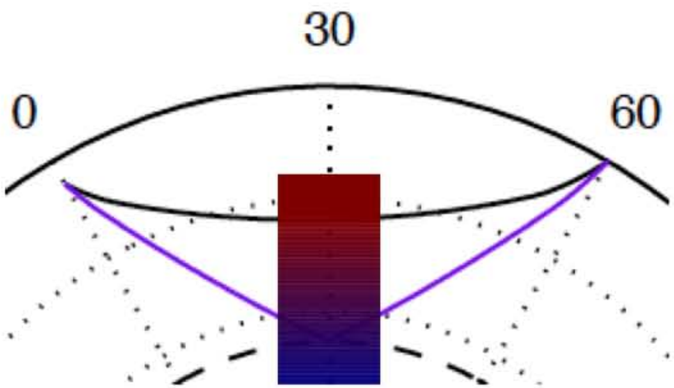
$$t^* = \int_{\text{path}} \frac{ds}{Q_\mu(s)V_s}$$

and, in our case,

$$\delta t^*_{ScS-S} = t^*_{ScS} - t^*_S$$

$$\delta t^*_{ScS-S} = t^*_{ScS} - t^*_S$$





$\delta t^*_{ScS-S} > 0$

$\delta t^*_{ScS-S} < 0$

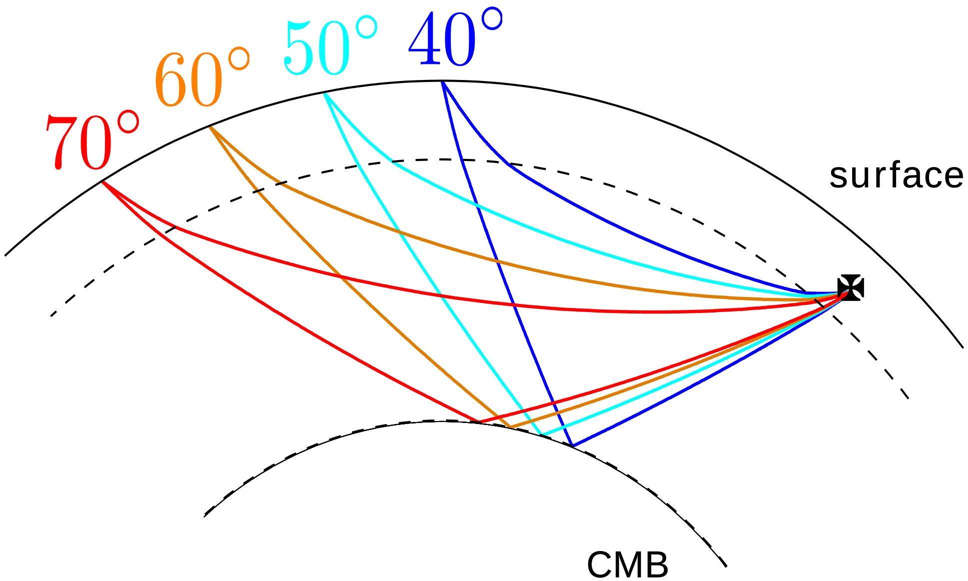
Low Q at the CMB

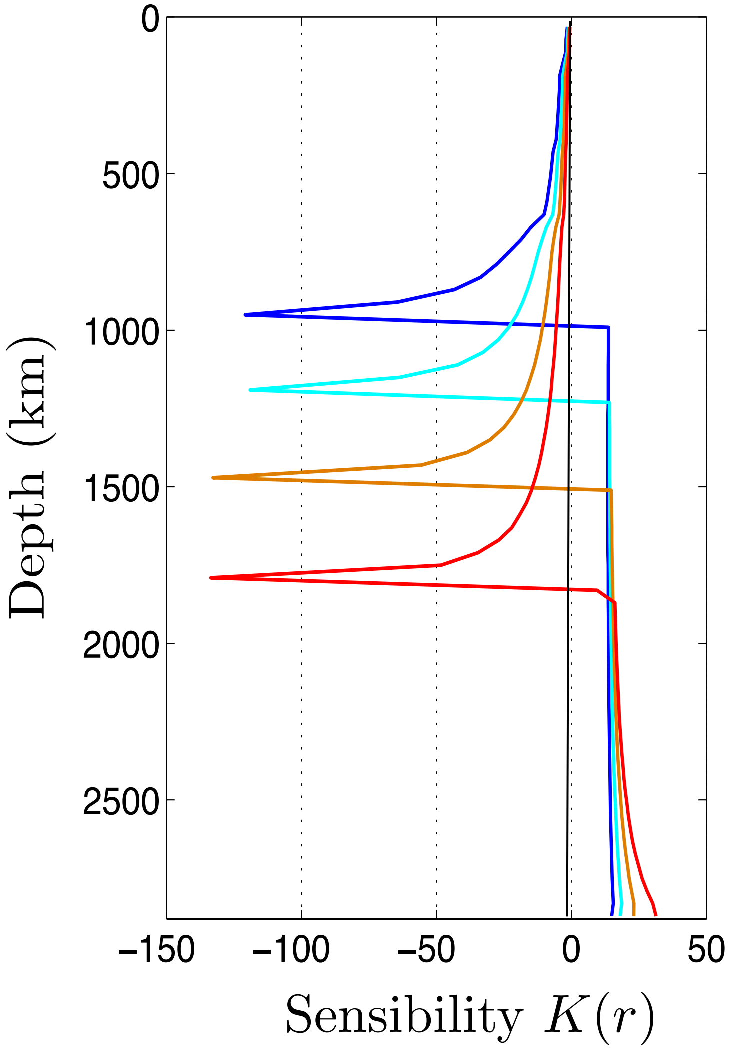
High Q at the CMB

δt^*_{ScS-S} **is a differential measurements integrated along the two ray-paths**

Assuming a radial attenuation structure

$$\delta t^{\star}_{ScS-S} = \int K(r)q(r)dr$$





How we measure method for δt^*_{ScS-S}

Filtered sismogram
[0.018 – 0.2]s

Enveloppe

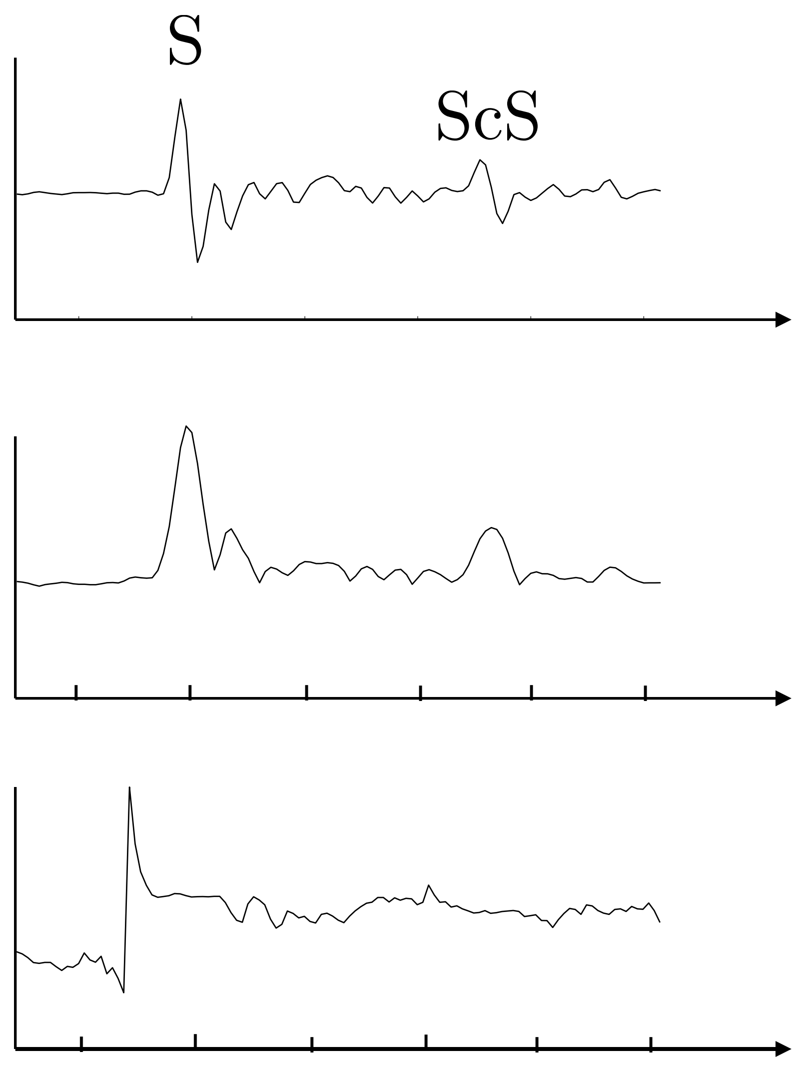
Spectral ratio method

Kovach & Anderson [1964], *Jordan &Sipkin* [1977], *Bhattacharya* [1996]

Instantaneous frequency

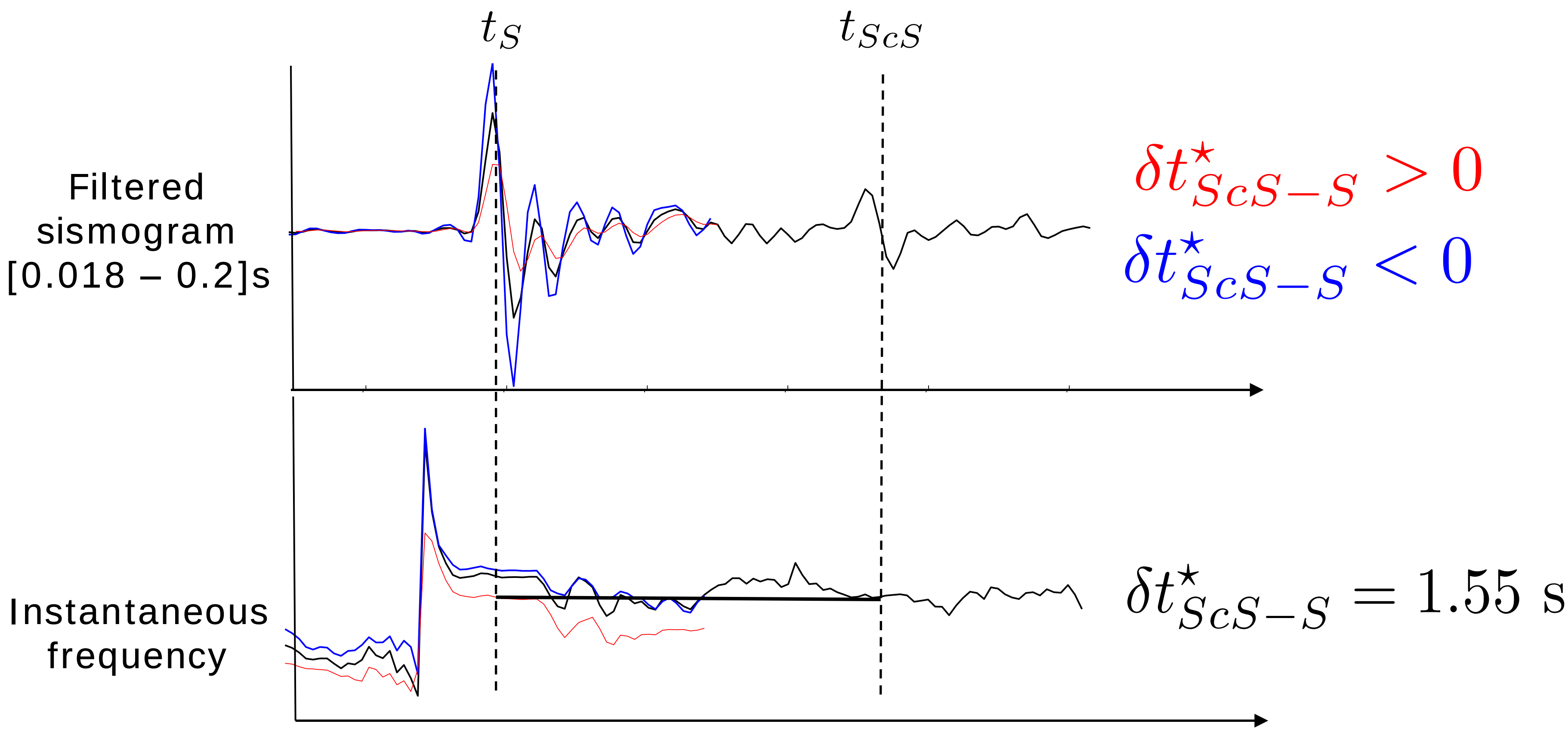
Instantaneous Frequency Matching method

Matheney [1995], *Ford et al*. [2012]

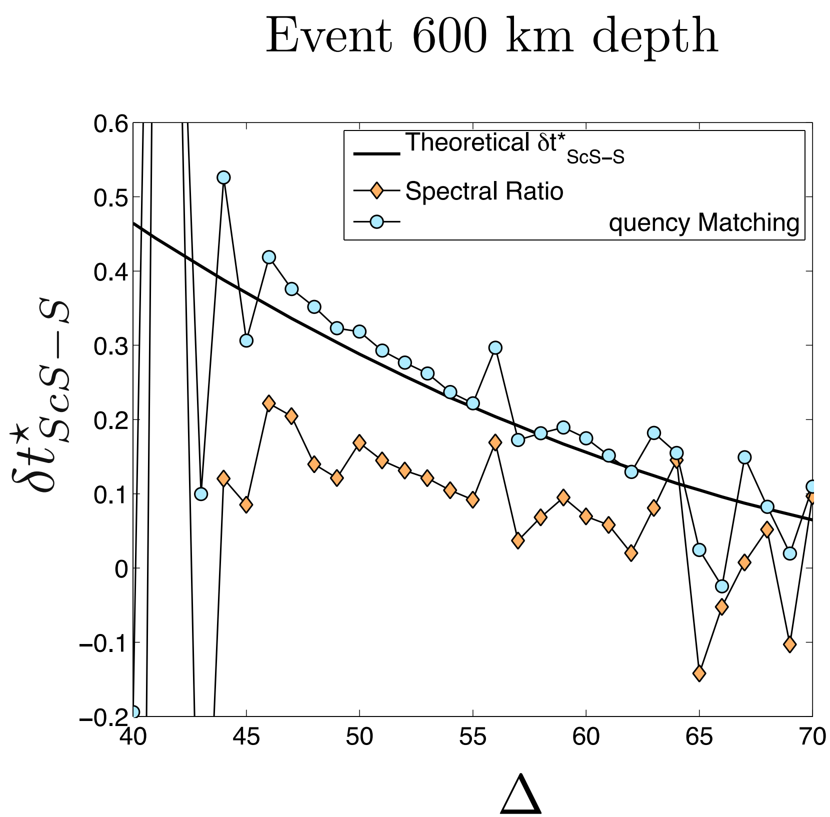


IFM measurement procedure

$$D(\omega) = \exp\left[-\delta t^{*}_{ScS-S}\frac{\omega}{2}\left(1 - \frac{2i}{\pi}\ln\frac{\omega}{\omega_r}\right)\right]$$



Data selection

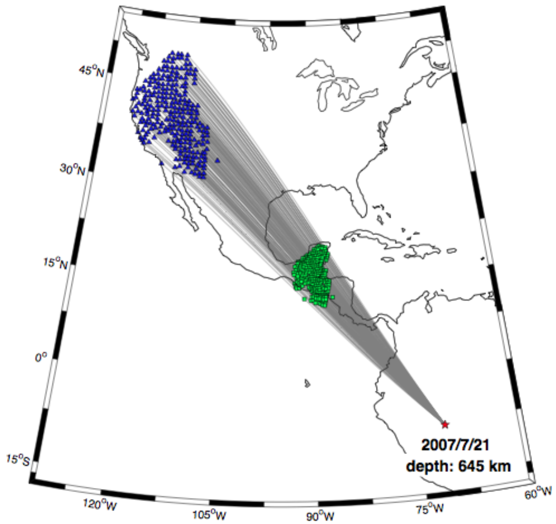


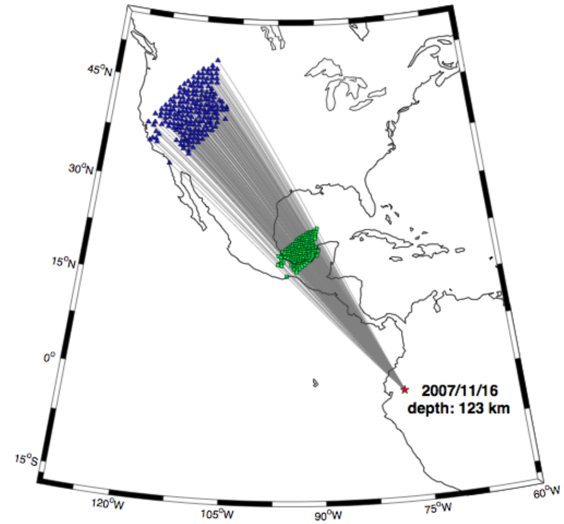
Selection criteria taking into account:

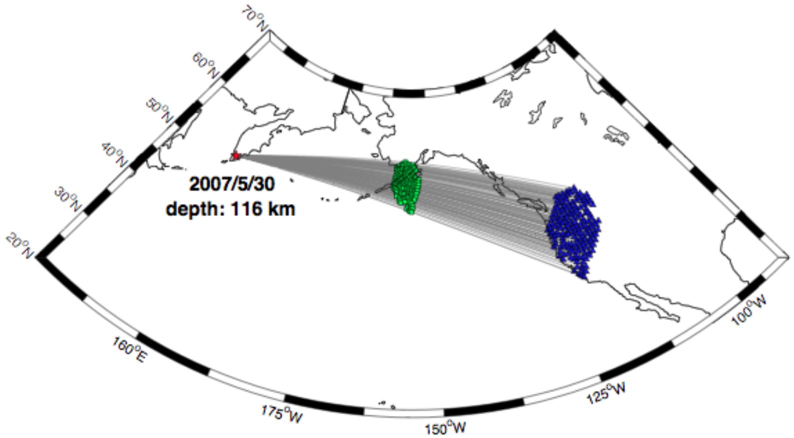
- **phase interference (restricted epicentral distance)**
- **event depth**
- **path azimuth with respect to the source mechanism**

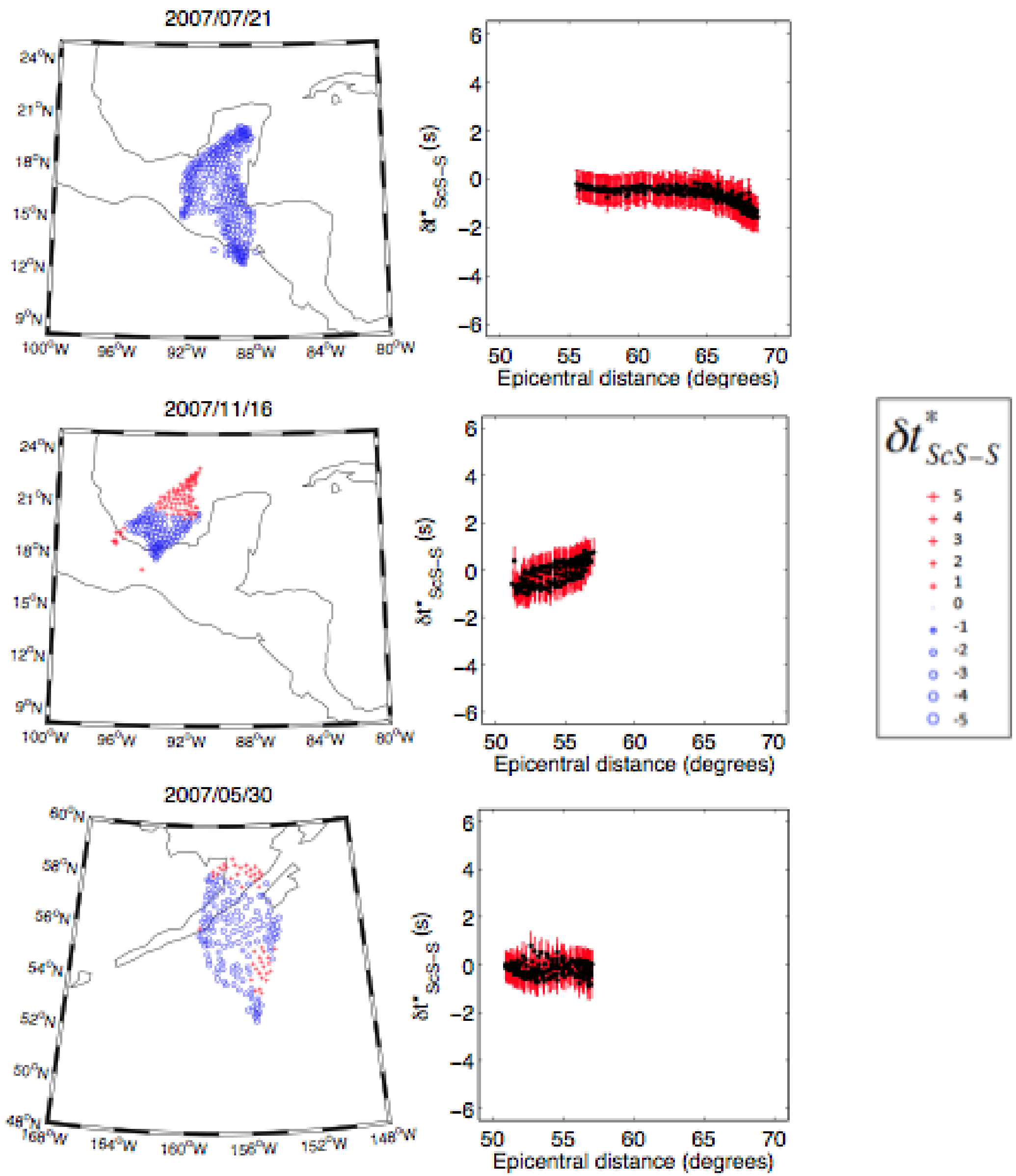
High-quality recordings only

(a regional study)





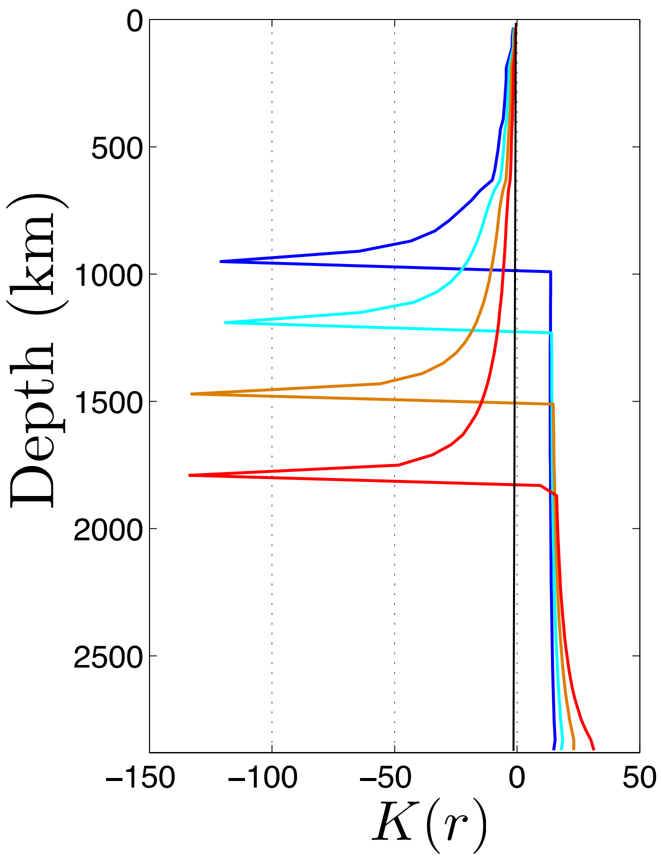


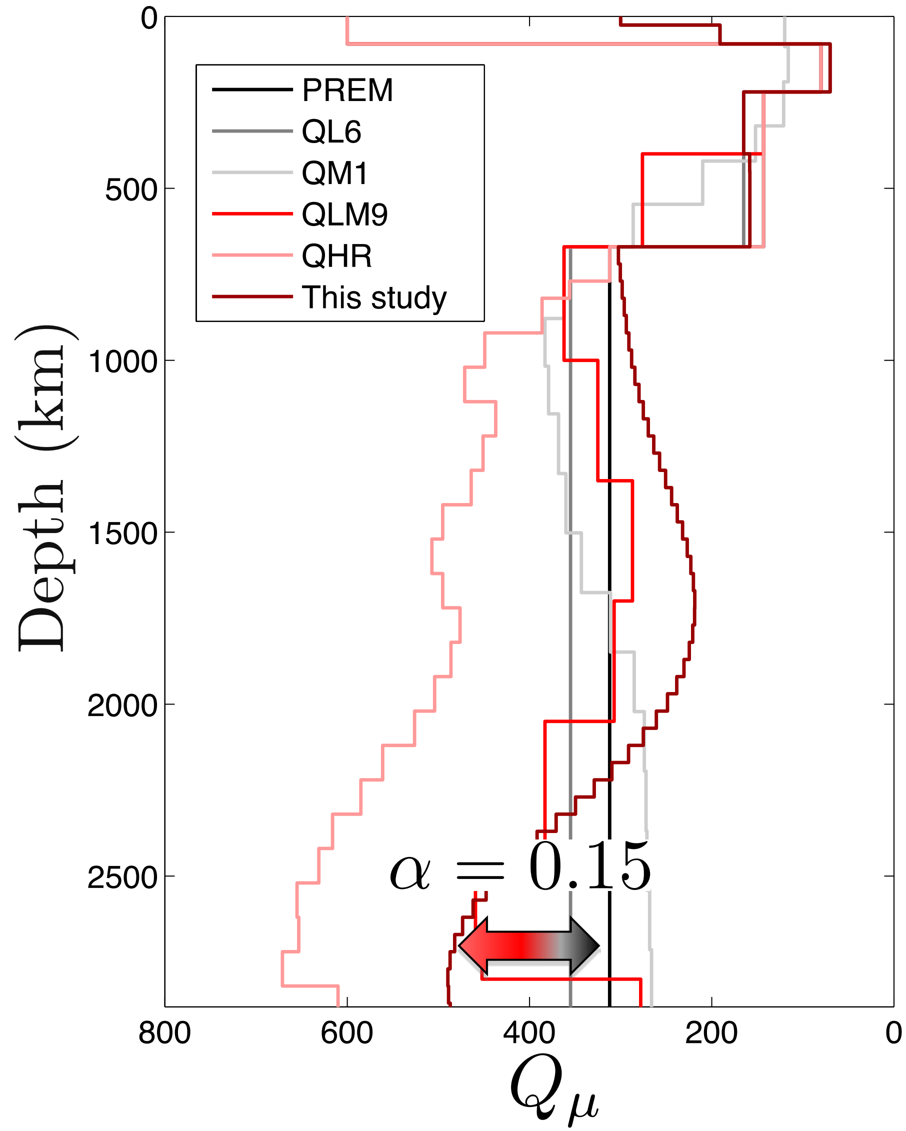


2007/07/21
2007/11/16
2007/05/30
Epicentral distance (degrees)
Epicentral distance (degrees)
Epicentral distance (degrees)
δt*ScS-S (s)
δt*ScS-S (s)
δt*ScS-S (s)
δt*ScS-S
5
4
3
2
1
0
-1
-2
-3
-4
-5

1-D inversion

$$\delta t^{\star}_{ScS-S} = \int K(r) q_\mu(r) dr$$





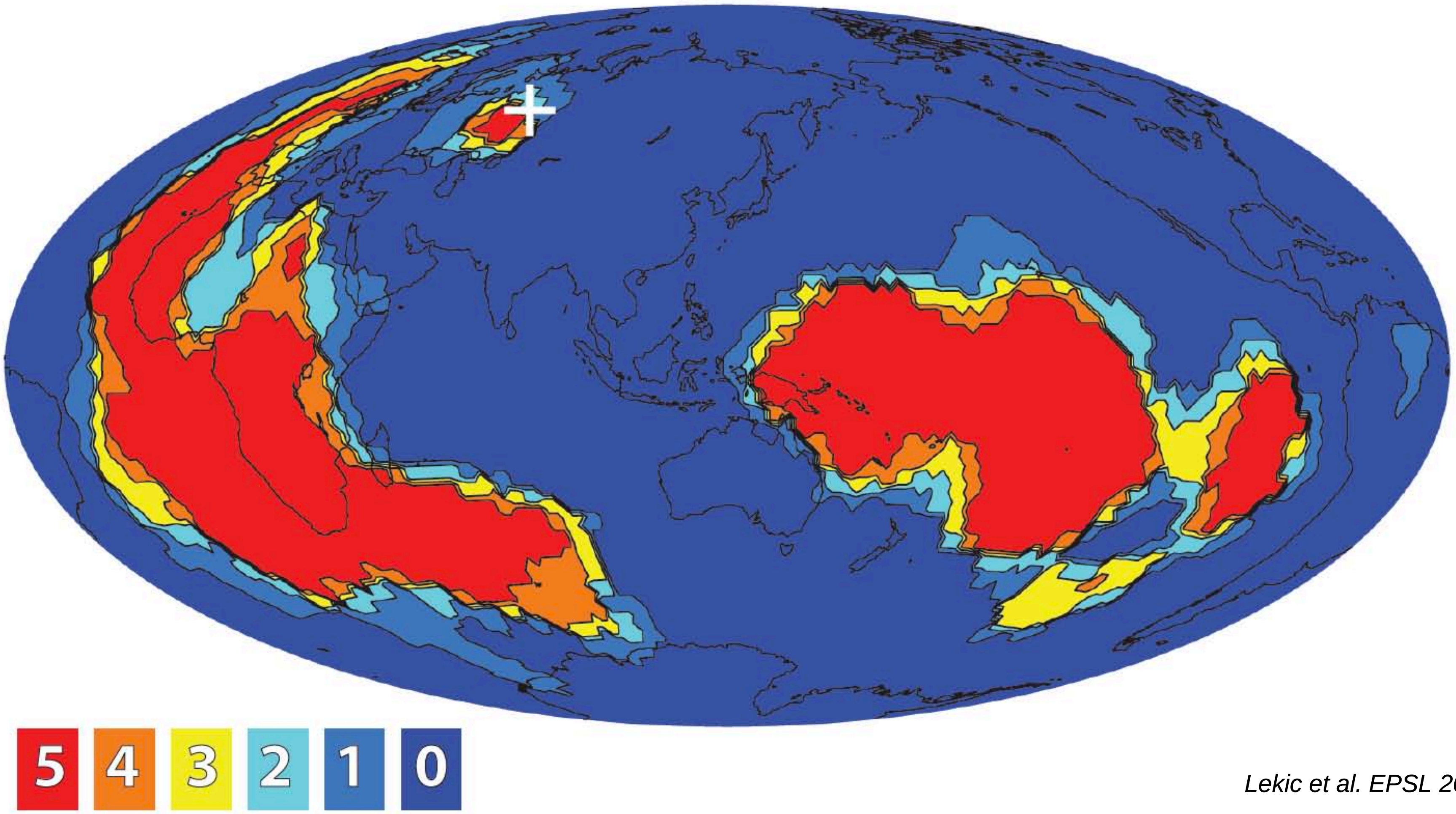
Frequence dependence of attenuation

Lekic et al. 2009

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

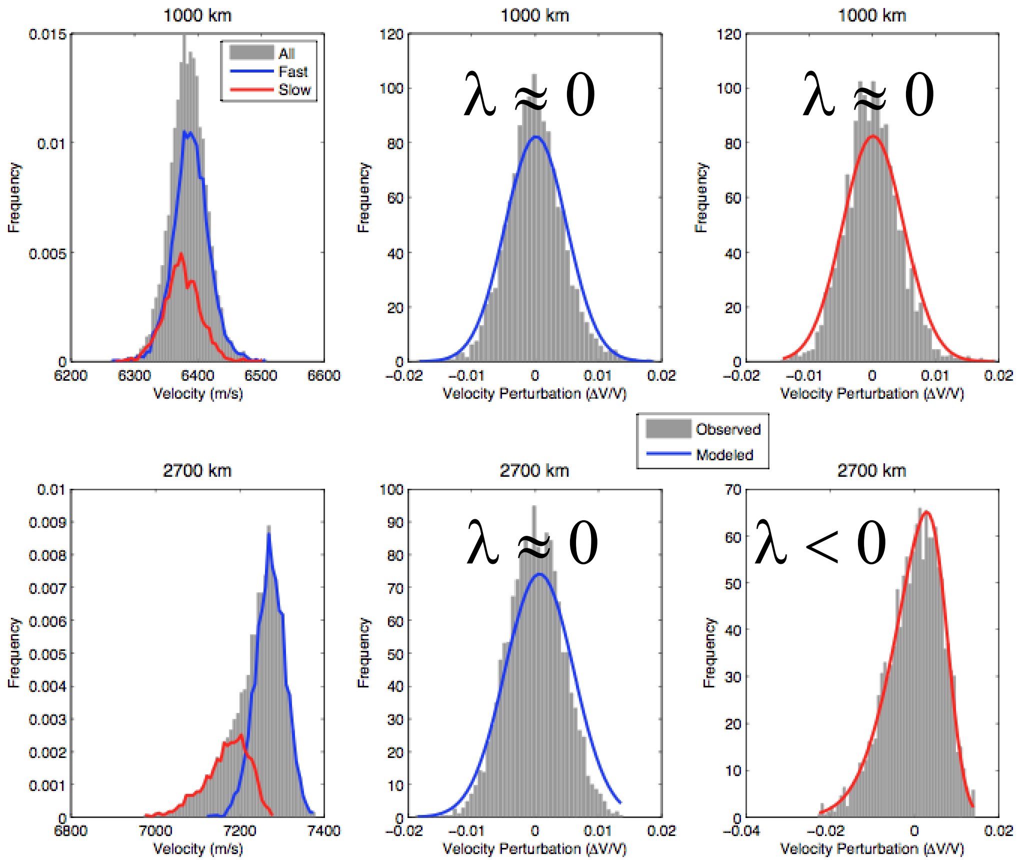
Cluster analysis of lower mantle

All models agree that there is only a single exception to the neat separation of structure into one fast and two slow regions.



Lekic et al. EPSL 2012

Distribution of velocity anomalies (fast & slow clusters)
mid and deep mantle



Normal distribution

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-x_0)^2}{2\sigma^2}}$$

σ – width

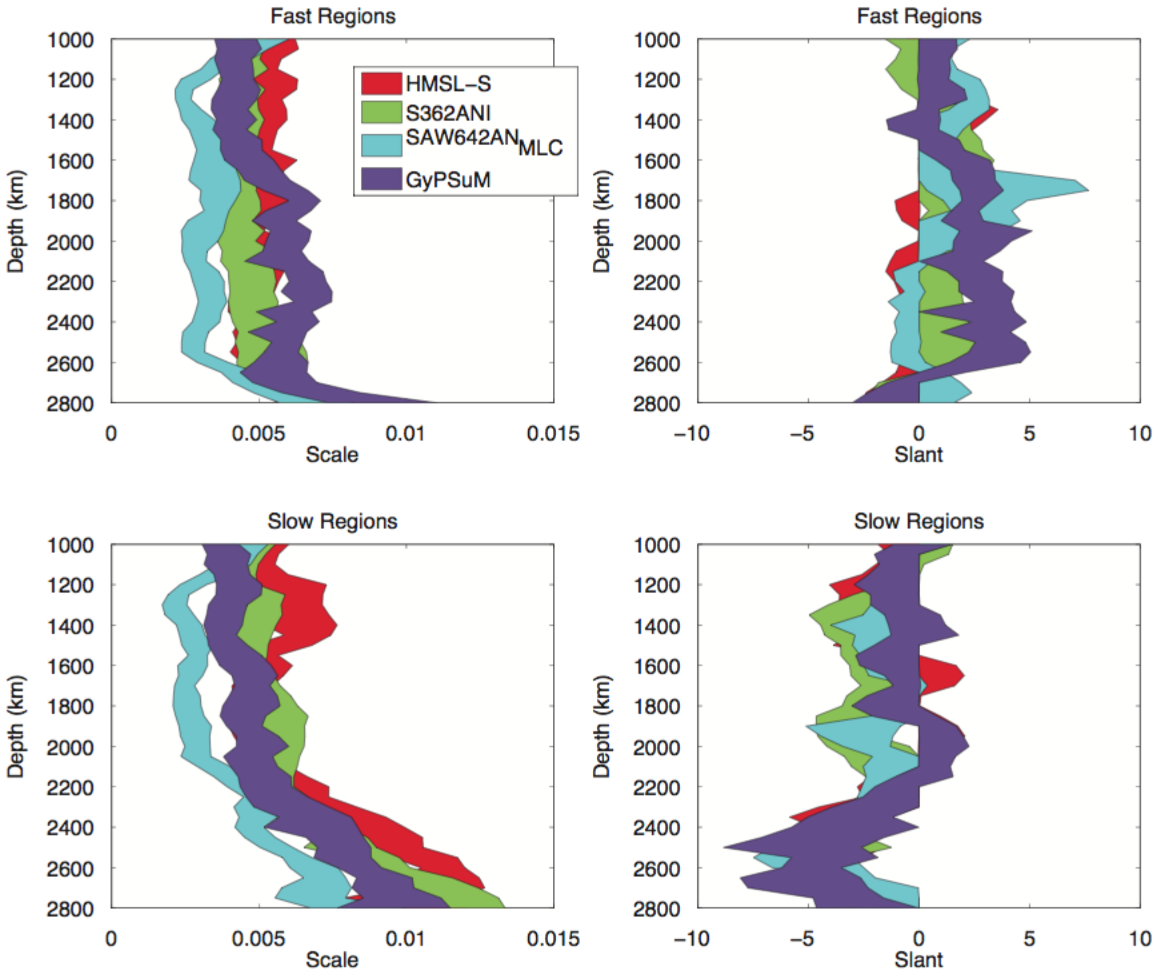
Skew-Normal distribution

$$f(x) = \frac{1}{\sigma\pi} e^{-\frac{(x-x_0)^2}{2\sigma^2}} \int_{-\infty}^{\lambda(x-x_0)/\sigma} e^{-\frac{t^2}{2}}$$

λ- slant (skewness)
additional parameters

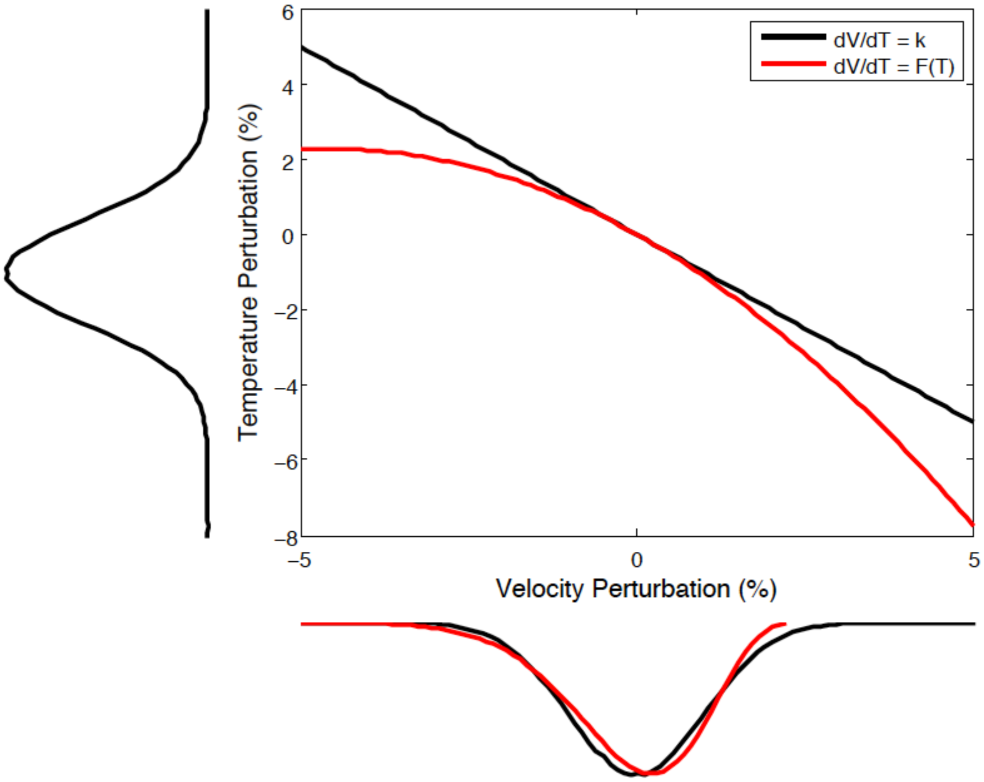
Lekic & Matas … work in progress

Slant & scale profiles



Lekic & Matas … work in progress

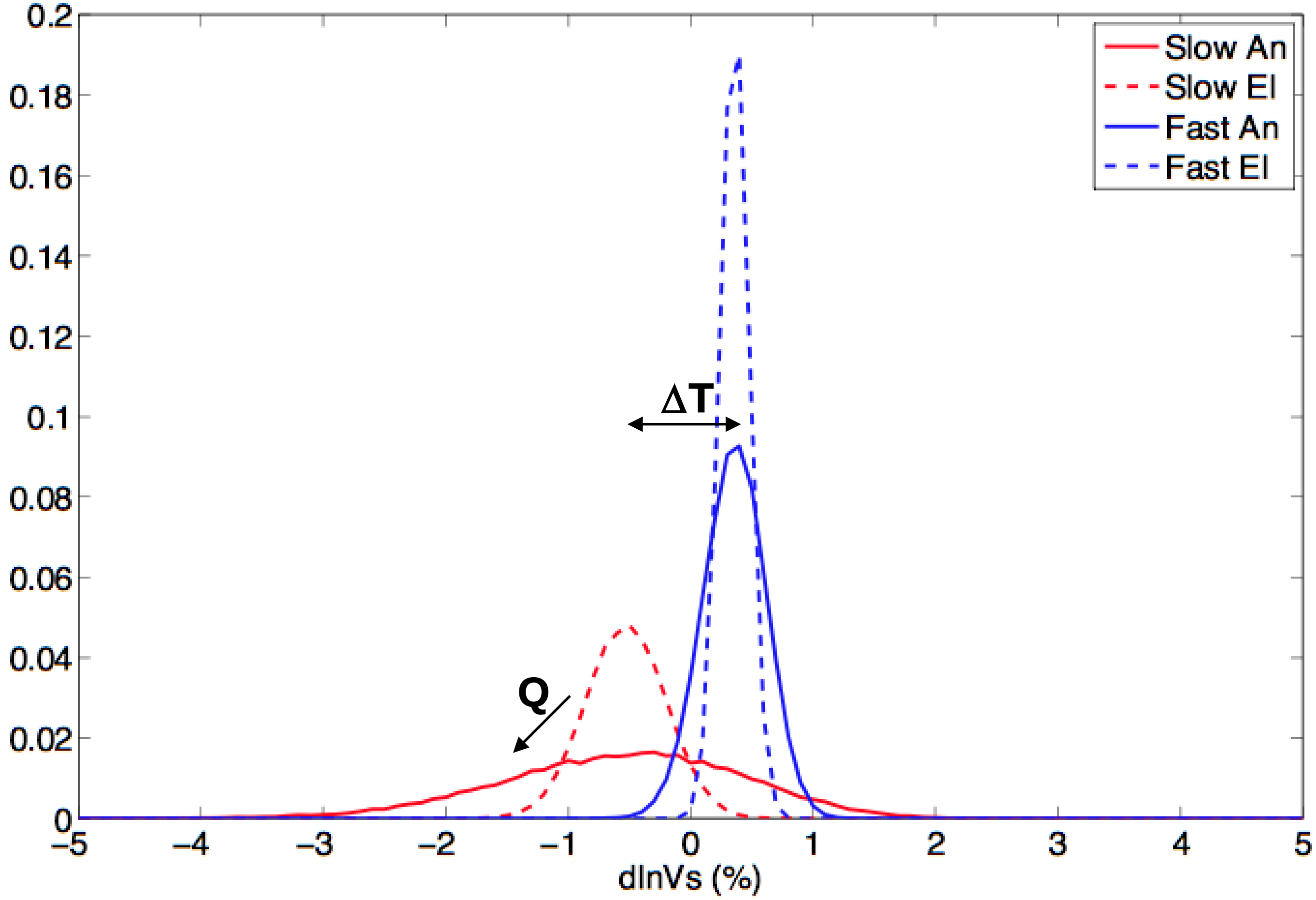
Effect of anelasticity on distribution of velocity perturbations



Anelastic conversion factors

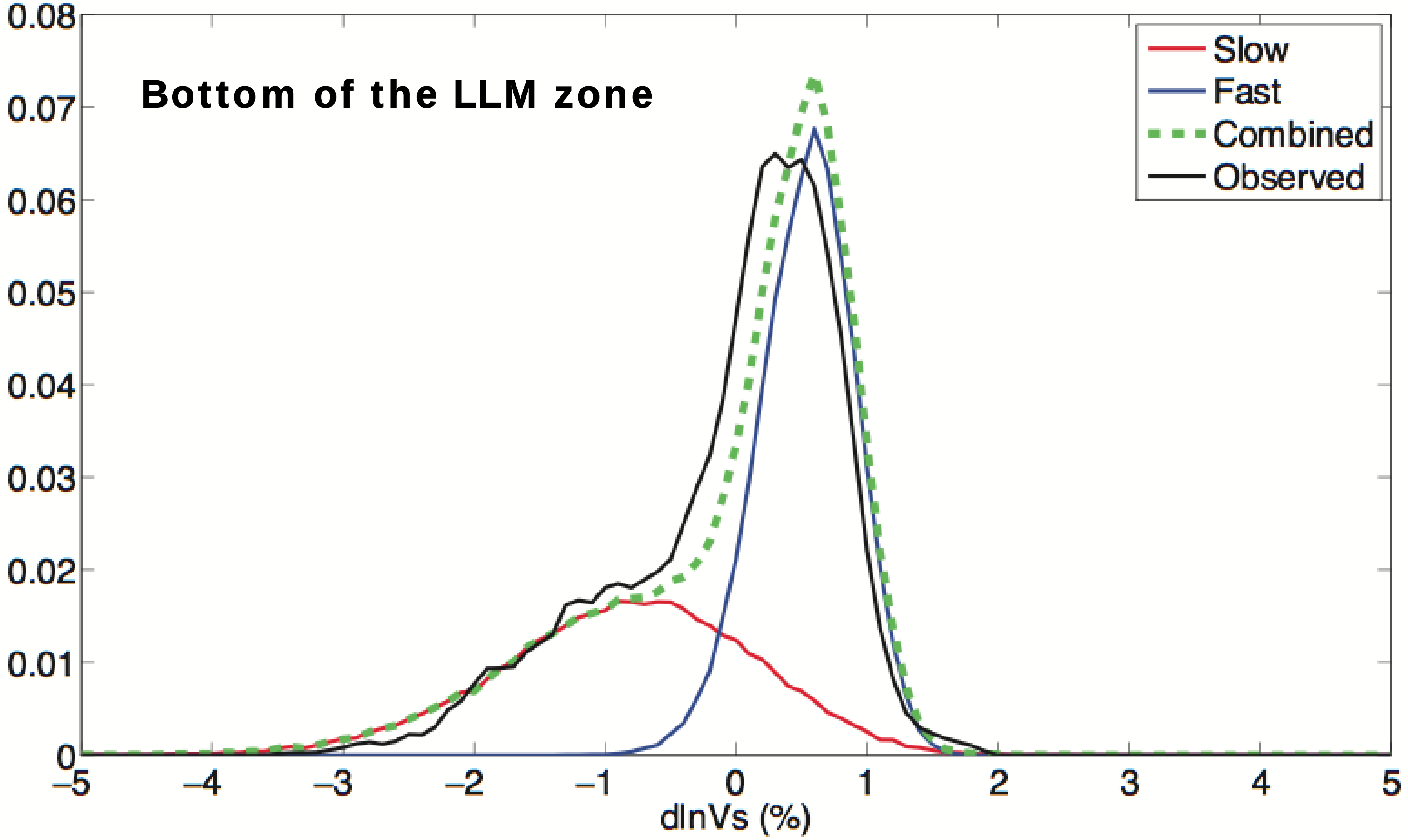
$$\left(\frac{\partial \ln V_{s,p}}{\partial T}\right)_{\chi,P} = \left(\frac{\partial \ln V^{\mathrm{el}}_{s,p}}{\partial T}\right)_{\chi,P} - \frac{1}{\pi}\frac{F(\alpha)}{Q(\omega,T)}\frac{G*}{RT^2}$$

Effect of anelasticity on distribution of velocity perturbations



Matching the observation (just a preliminary test)

Important parameters: ΔT and Q



Take home message

- Our **regional** 1-D attenuation profile confirms a **low attenuating base of the lower mantle** seen by body waves compared to a model based on normal modes.

- It can be partly explained by a **frequency dependent Q_s** with an 〈 of 0.15.

- Further data analysis needed for constraining **lateral variations** of attenuation

- Analyses of distribution of velocity anomalies can bring new constraints for **lower mantle attenuation** and, thus, **thermal structure** related to fast and slow regions

- Look for **more news** during the AGU talk DI44A-02 (Thursday, December 6, 4:15pm - 4:30pm)

Power law Q model

Given & Anderson [1982]