# Seismic structures in the deep mantle

-

# are they due to a phase change?

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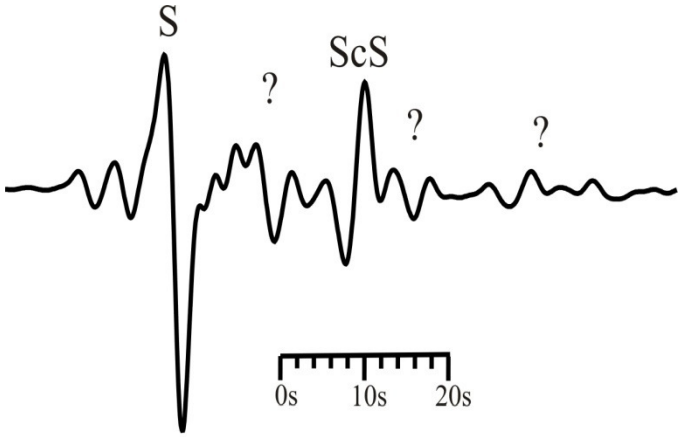
GEOPHYSIK
WWU MÜNSTER

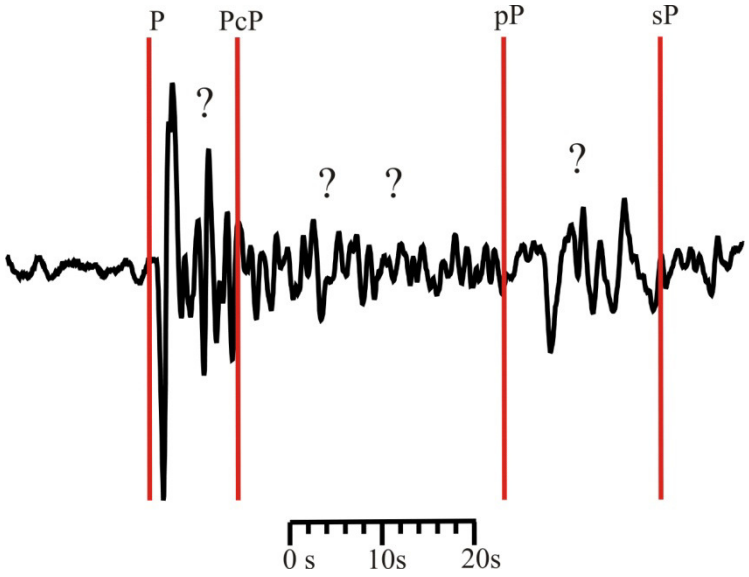
Acknowledgements:

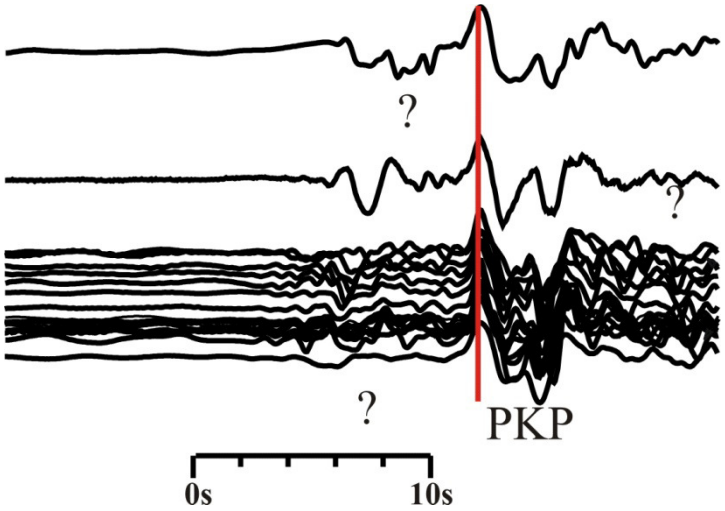
Laura Cobden, Stefanie Hempel, James Wookey, Sebastian Rost, Mike Kendall, Ed Garnero, John Hernlund, Paul Tackley, Thorne Lay, Julian Lowmann, Thomas Fieseler, John Brodholt,

# Seismograms

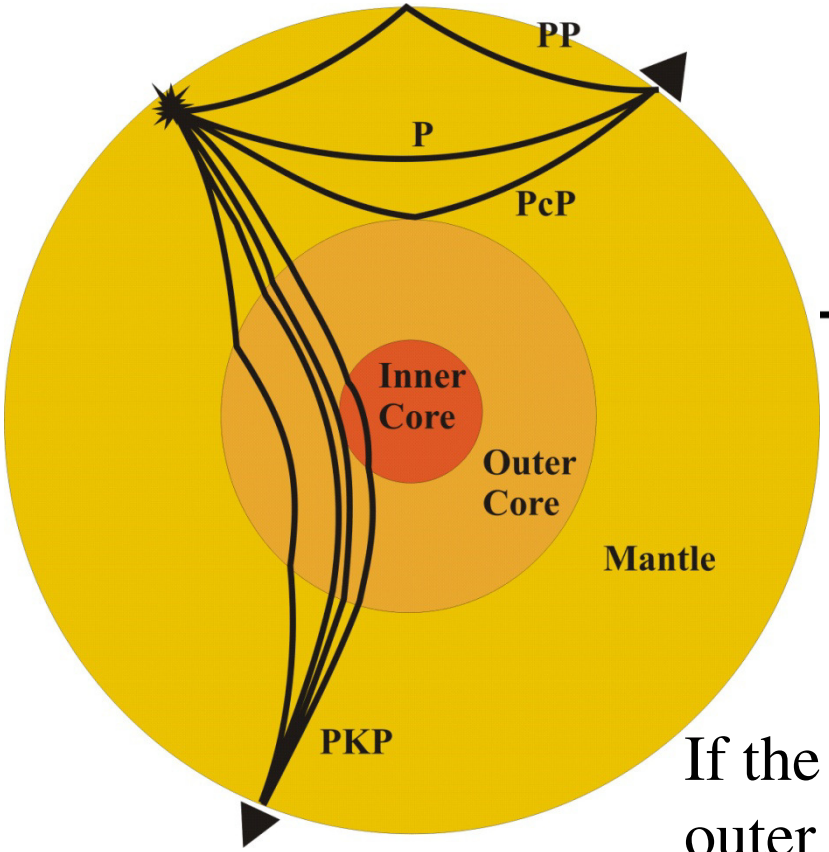
Real seismograms show that the Earth is complex:

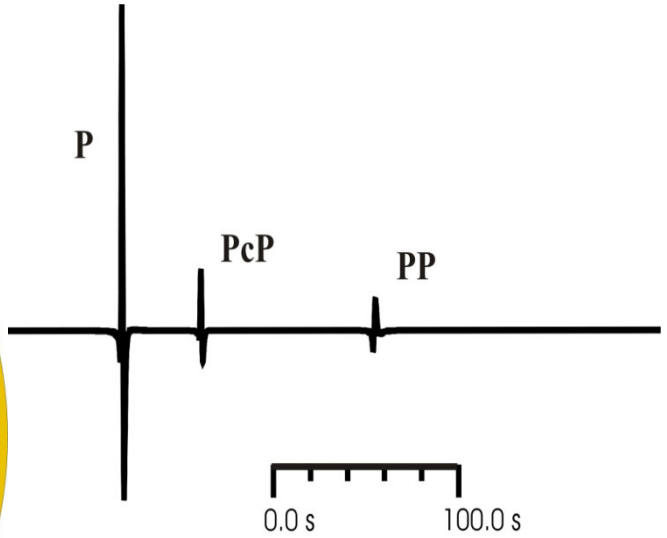


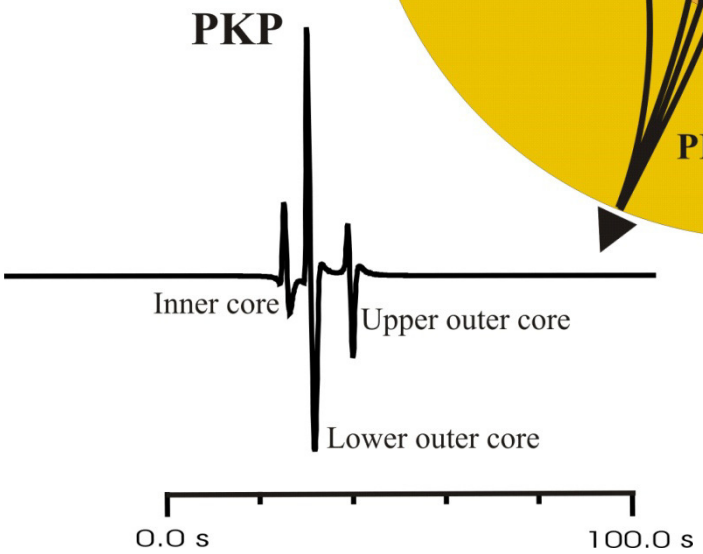



# A simple Earth



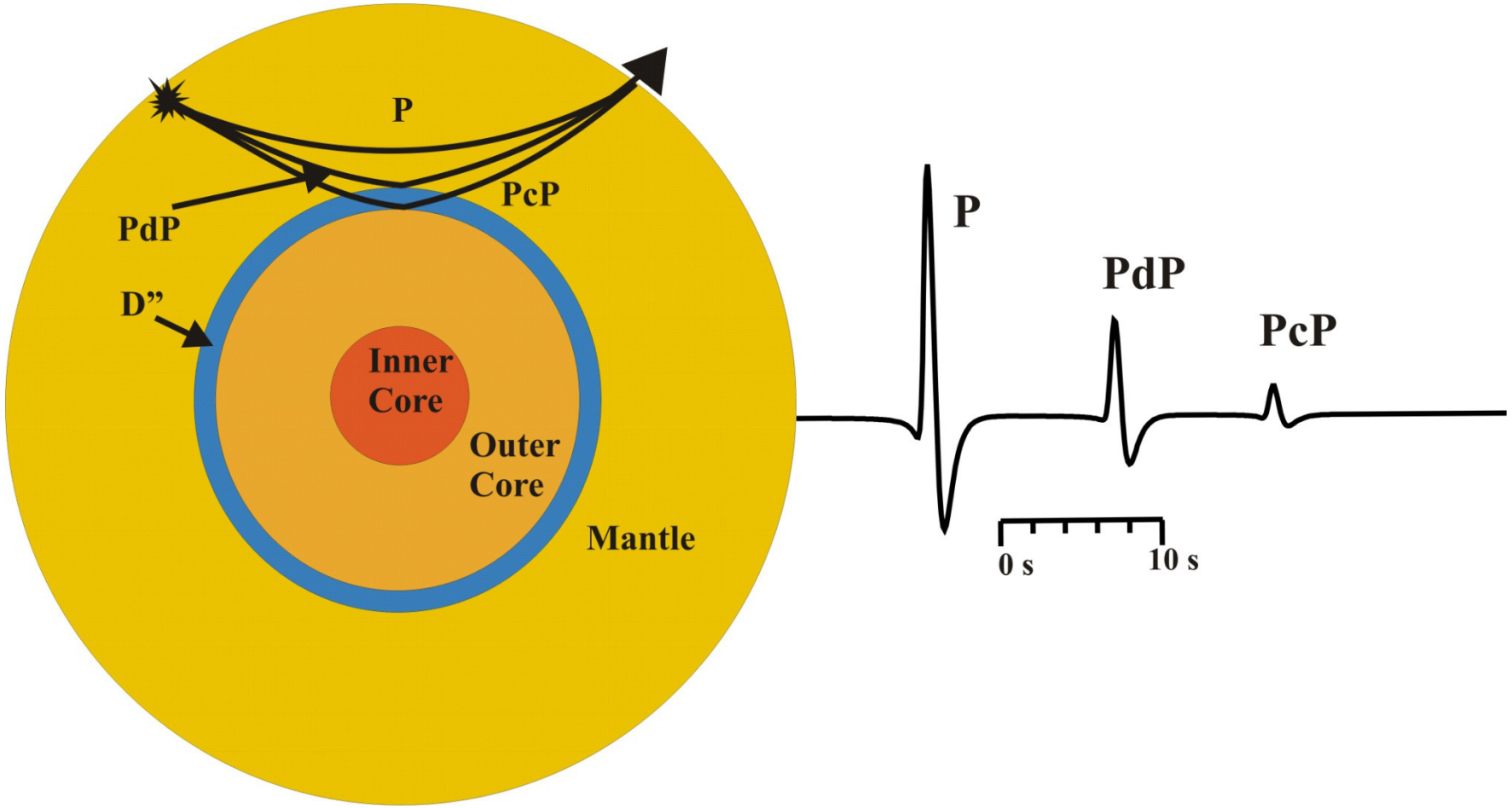




If the Earth only had mantle, outer and inner core (no other layers):

(higher order multiples and depth phases not shown)

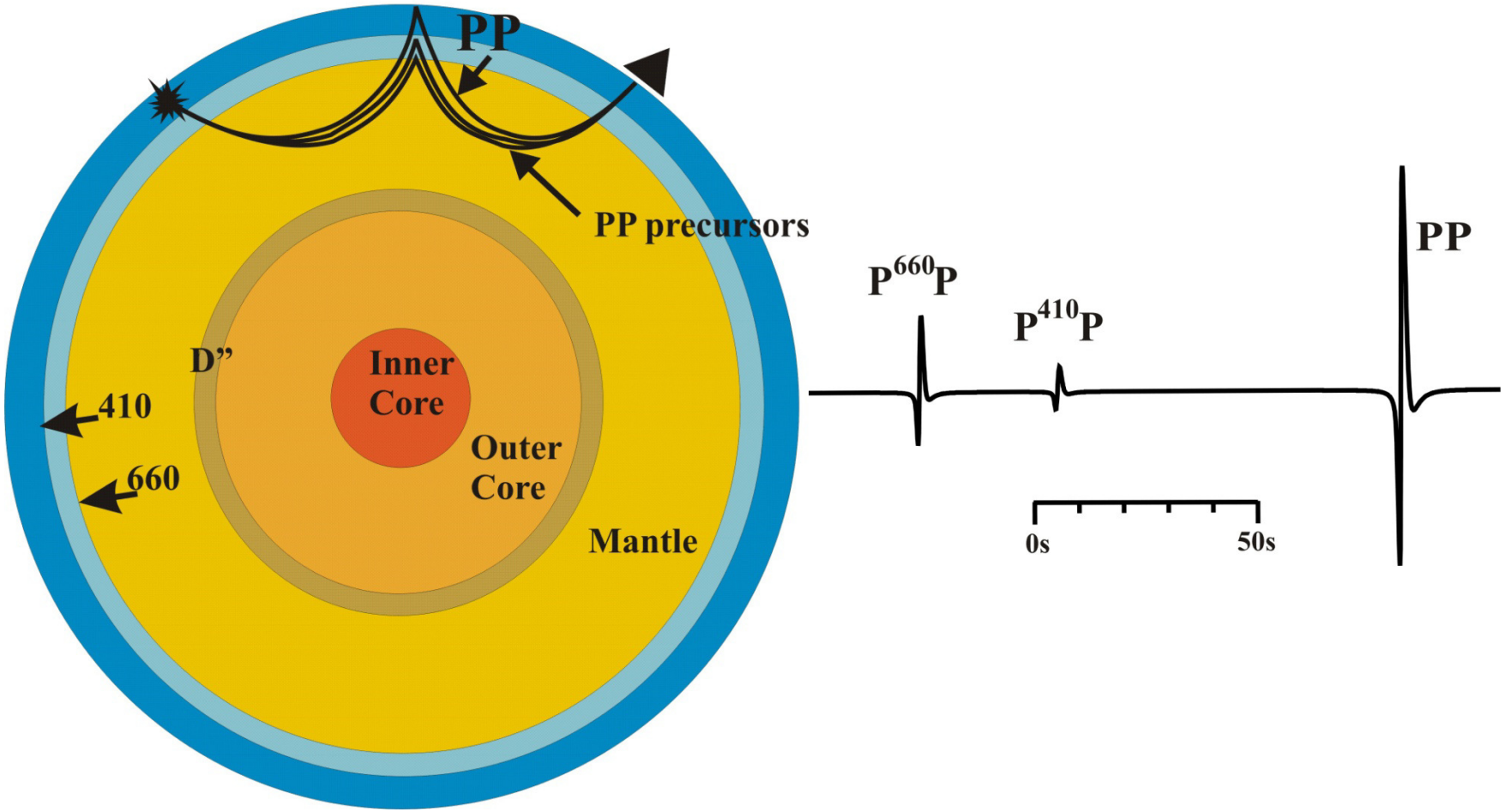
# More layers in our simple Earth

If we add more layers to the simple Earth, we expect more arrivals in the seismogram:

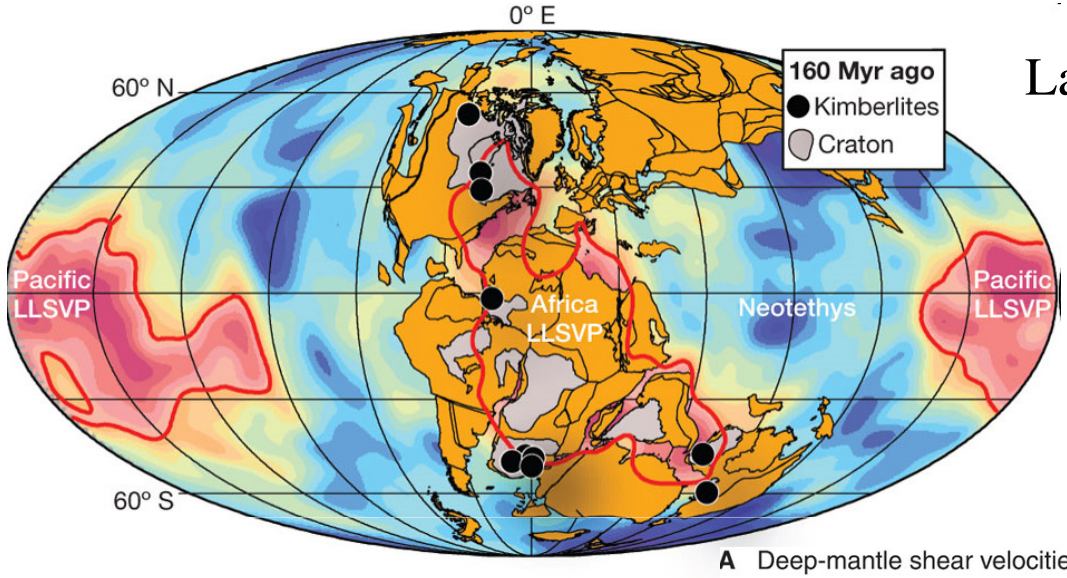


# More layers in our simple Earth

Introducing upper mantle discontinuities
(660 km and 410 km discontinuities):



# D" structures (1)

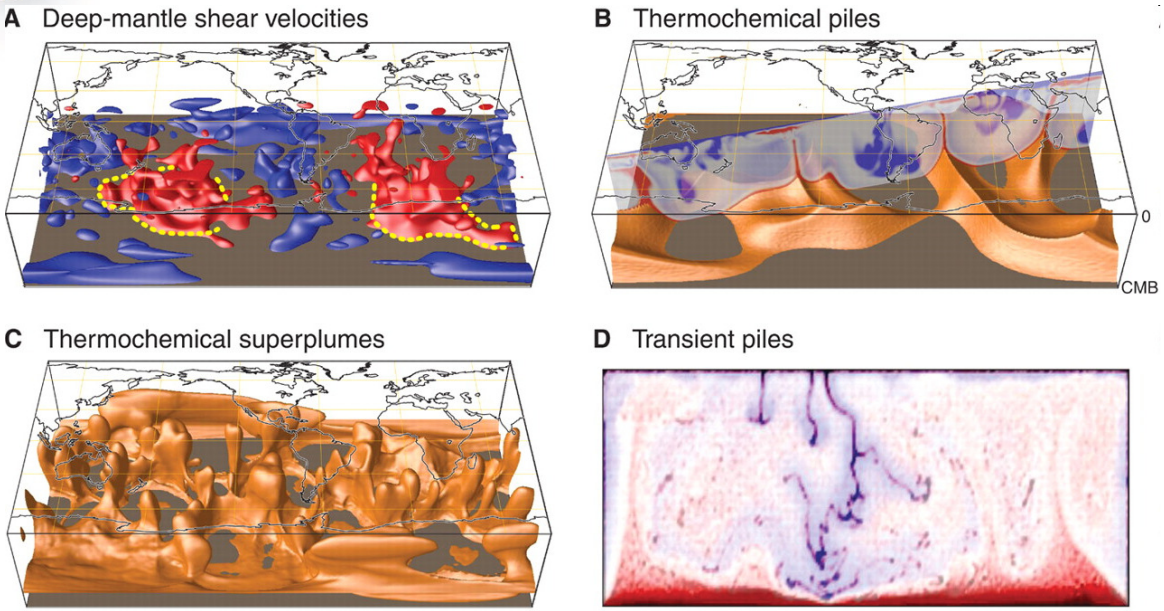



Torsvik et al, 2010

Large Low Shear Velocity Provinces

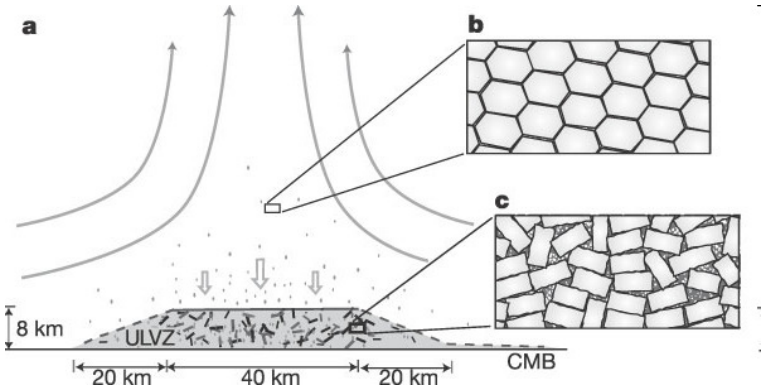
**"LLSVP"**

sharp edges?
flat tops?



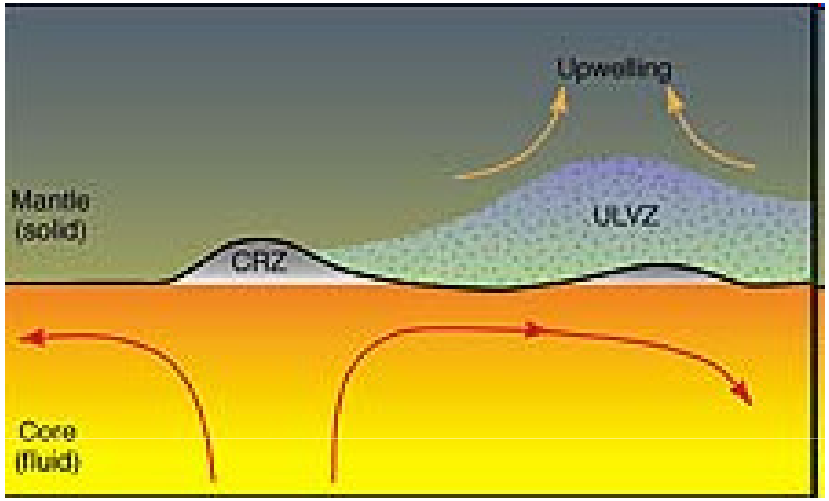

Garnero and McNamara, 2008

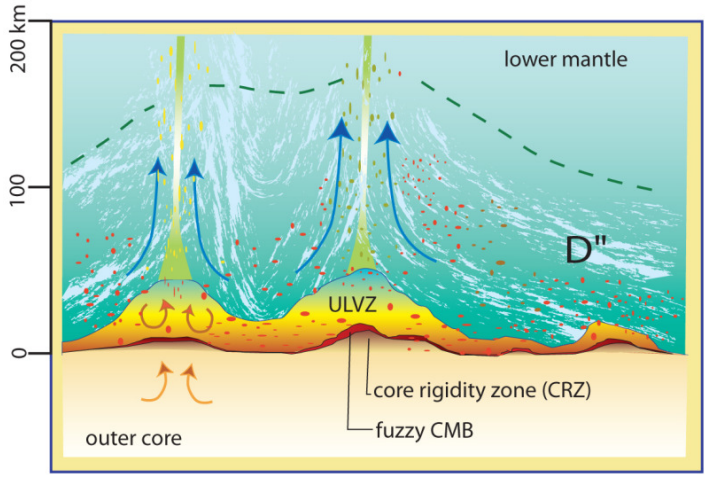
# D" structures (2)




Rost et al., 2005

Rost and Revenaugh, 2003



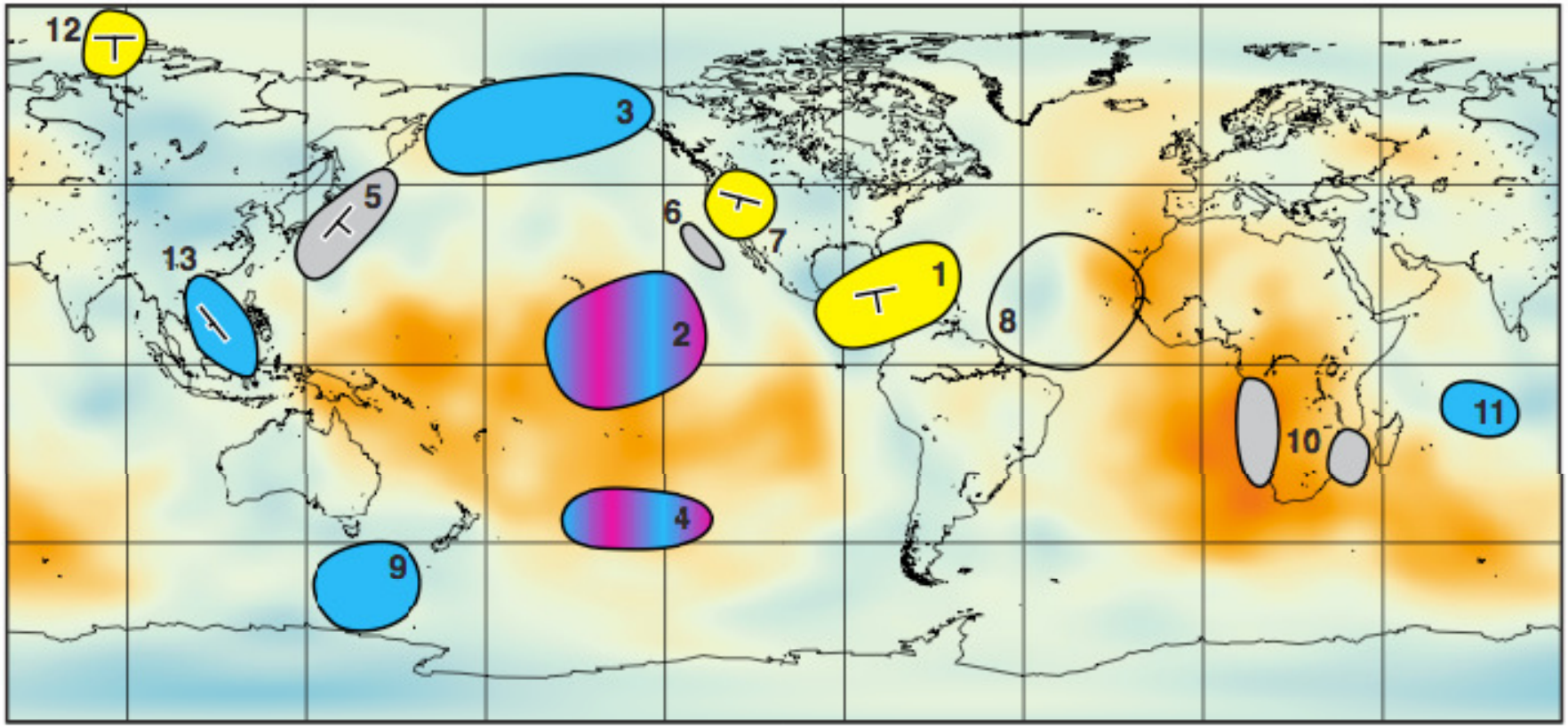

garnero.asu.edu

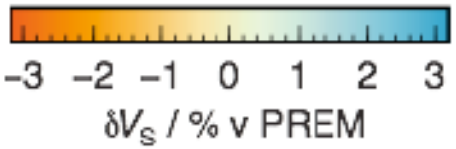
Ultra low velocity zones

**"ulvz"**

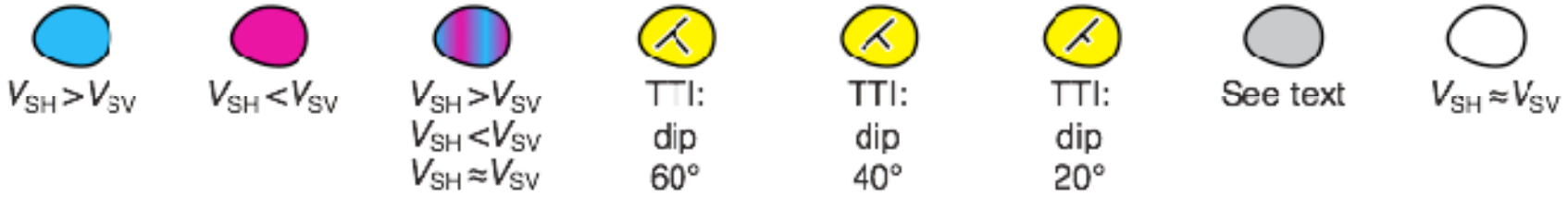
(not Sebastians Rost's talk!)

# Anisotropy in D'' (Mike Kendall's talk)

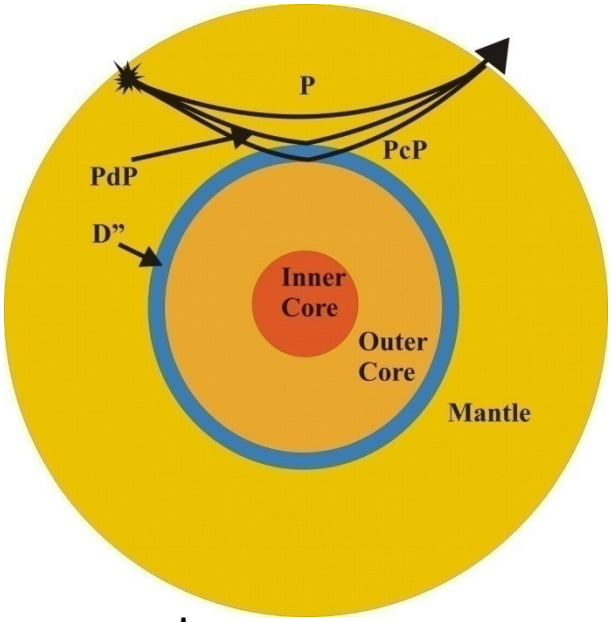


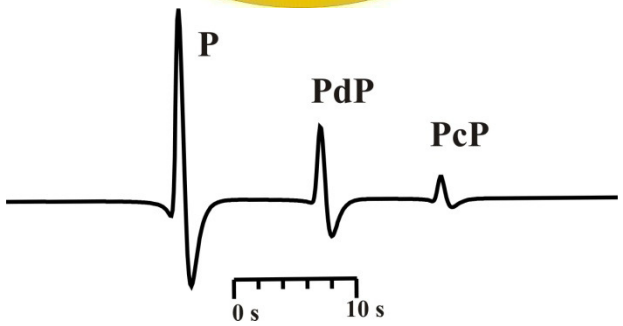




Picture: Mike Kendall

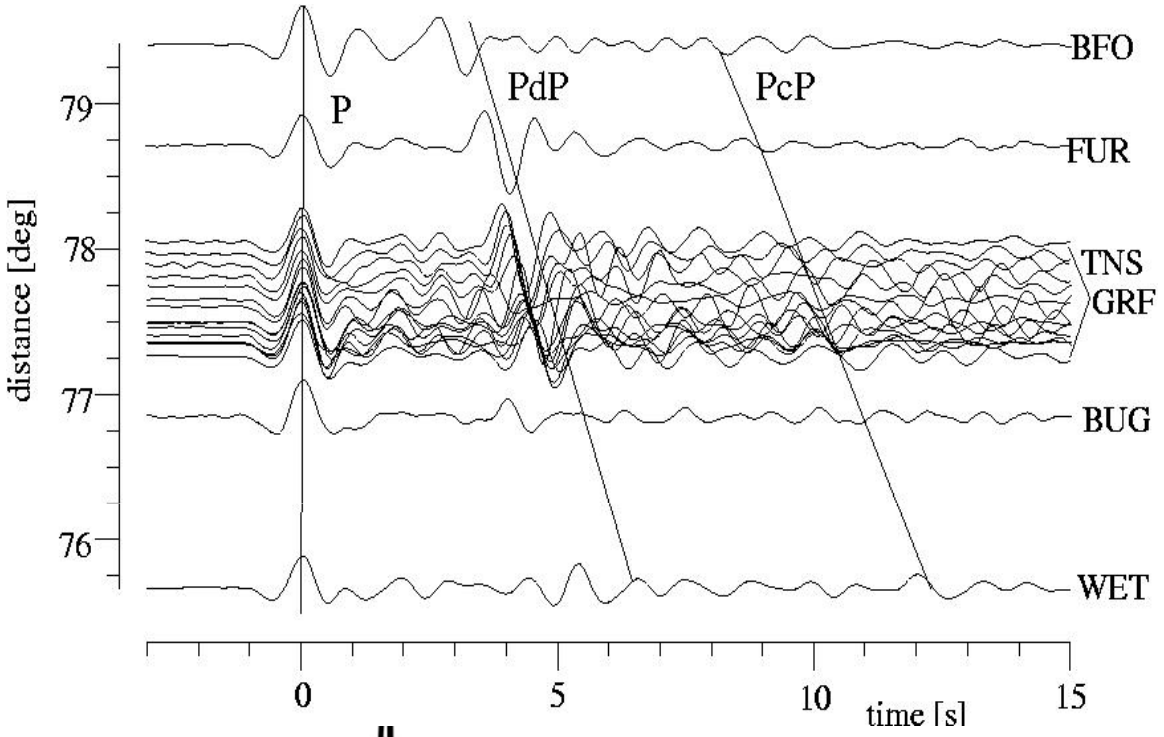


# Reflections from a reflector in D"

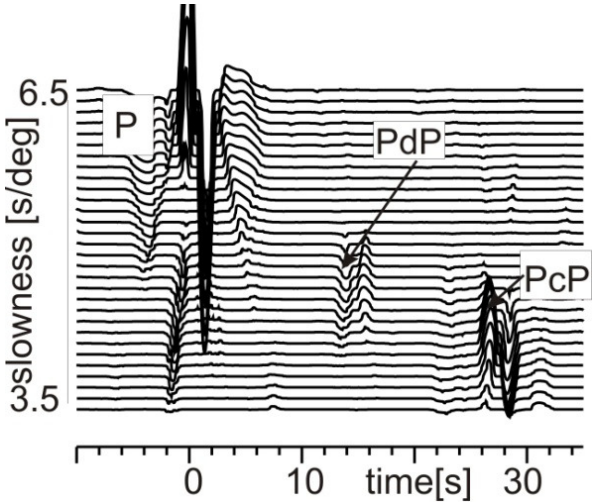



Seismic reflection from D" in P- and S-waves are observed.

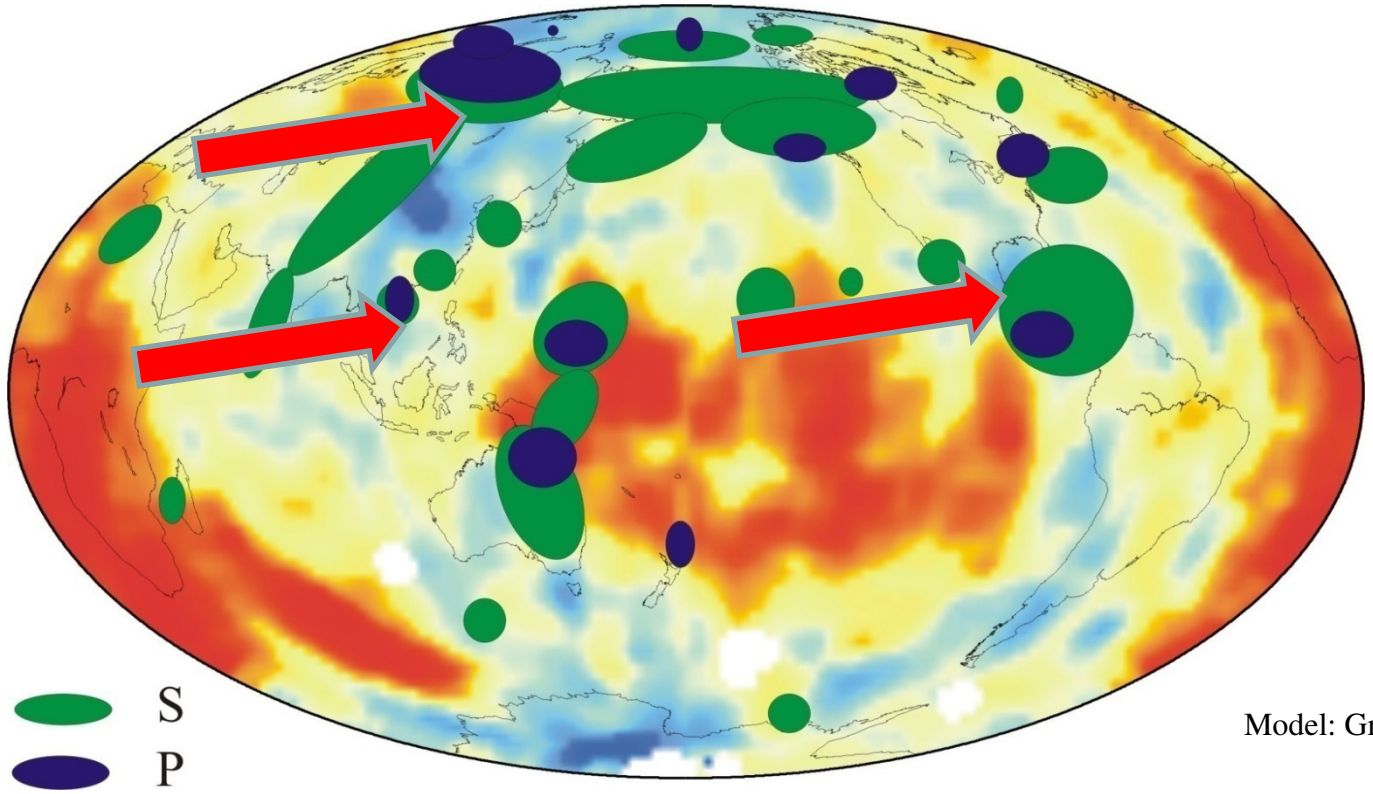



Thomas and Weber 1997




Chaloner, Thomas, Rietbrock, 2009

# High-velocity regions



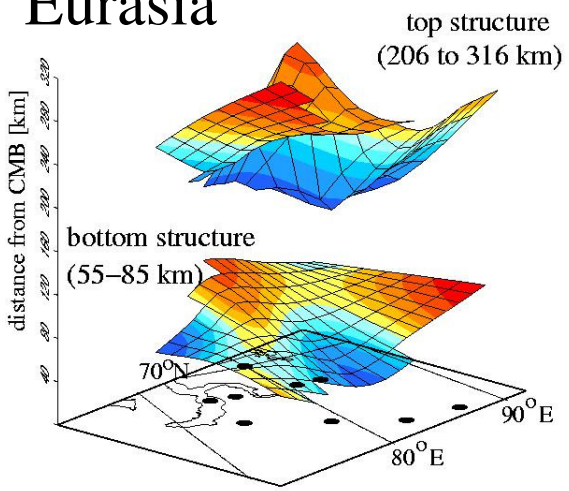

Model: Grand, 2002

Data from: Lay and Helmberger, 1983, Weber and co-workers, 1990s, Kendall and co-wokers, Scherbaum et al, 1997, Lay and co-workers, Houard and Nataf 1990s, Wysession et al., 1998, Kito et al, and many more.

# Observations 1

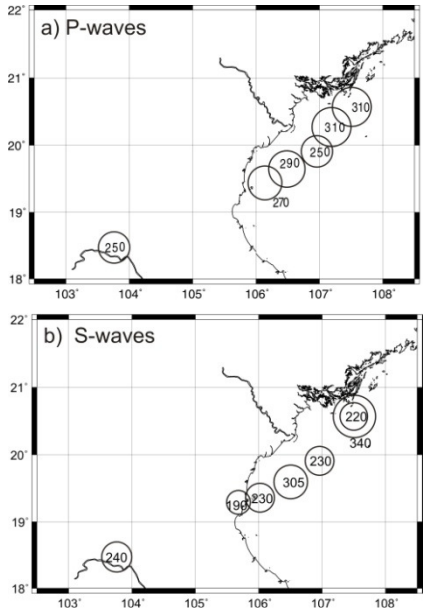
## Eurasia

**S-Waves**




from
Thomas, Kendall, Lowman 2004

## SE Asia




from Chaloner, Thomas, Rietbrock, 2009

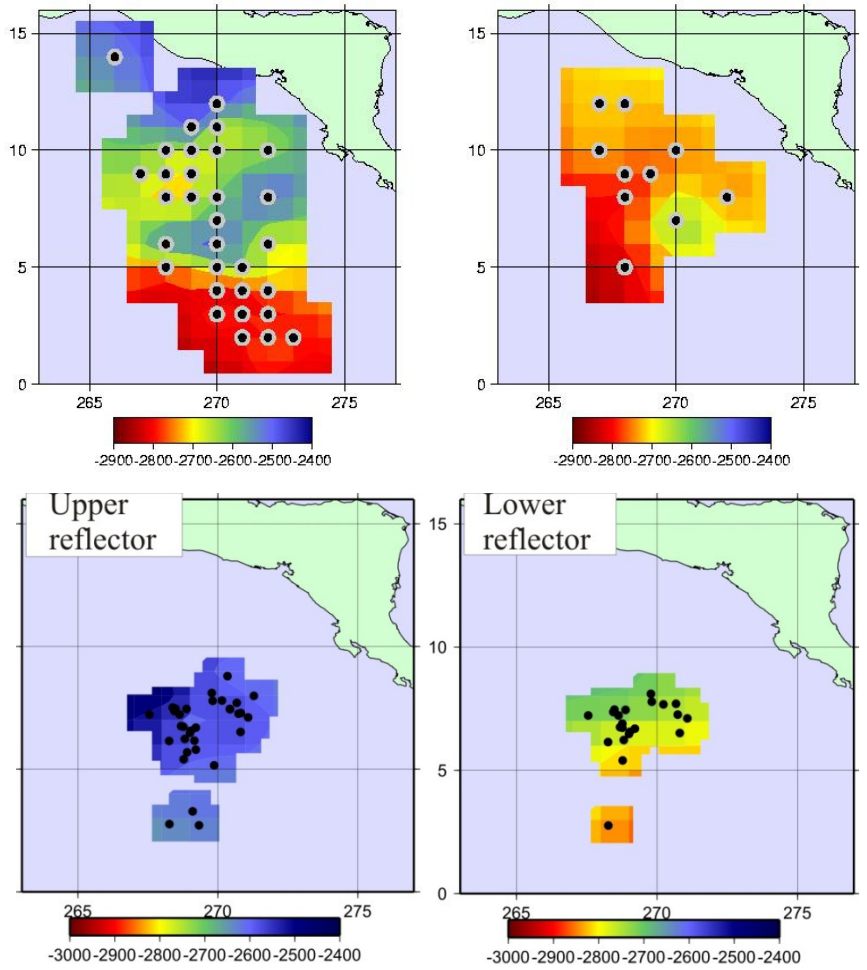
up to **two reflectors** found with P- and S-waves beneath:
Caribbean
SE Asia
Eurasia

## Caribbean

Thomas, Garnero, Lay 2004

**S-Waves**

Migrated reflection points




**P-Waves**

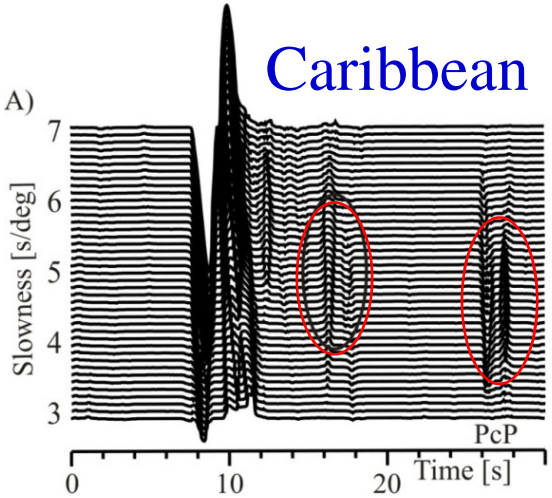
2 reflectors under Caribbean also observed by e.g., Hutko et al. 2006, van der Hilst et al. 2007

Kito, Rost, Thomas, Garnero, 2007

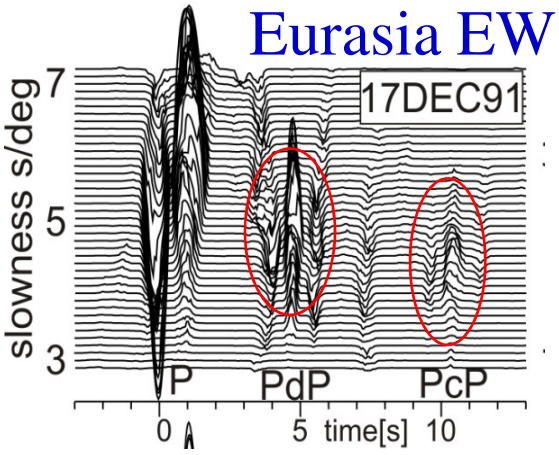
# Observations 2

P-waves

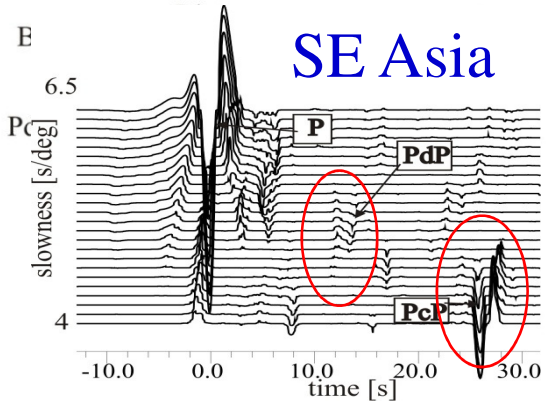
Caribbean




Eurasia EW

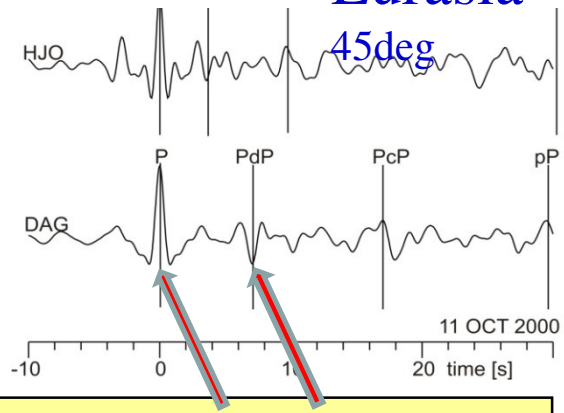



SE Asia




Eurasia

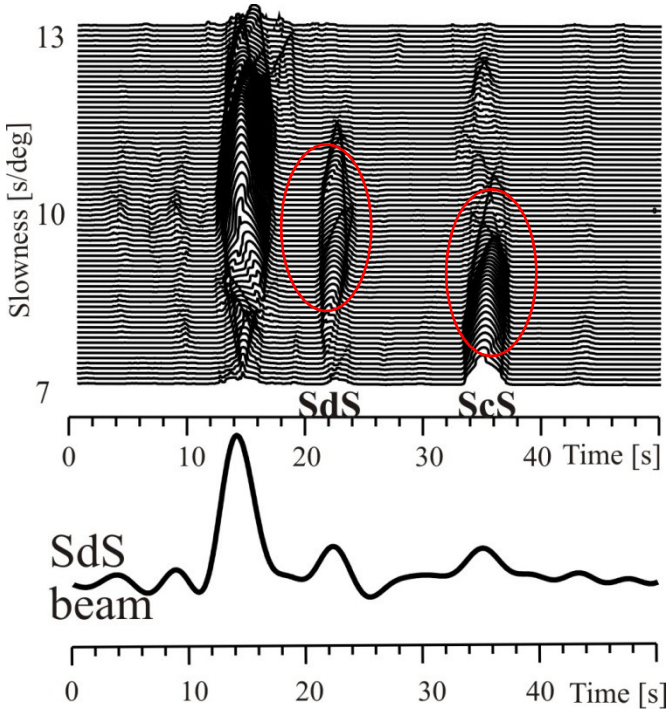
45deg

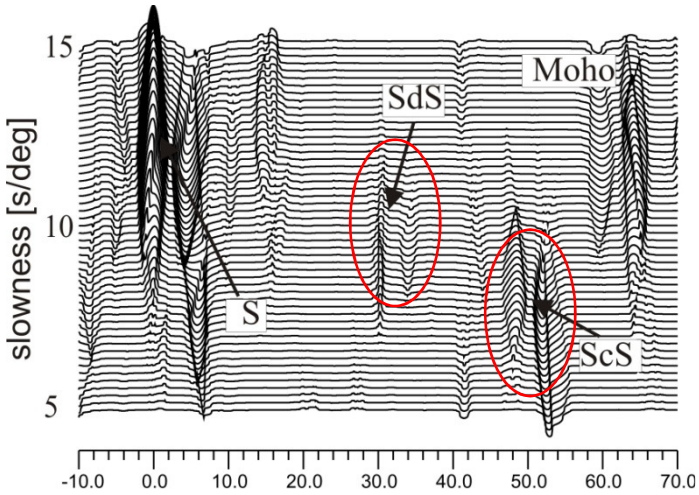



PdP **opposite polarity** to PcP & P; SdS same polarity to ScS & S under Caribbean and SE Asia; **same polarity** for PdP & PcP and SdS & ScS for Eurasia (NS, EW)

S-waves

Caribbean



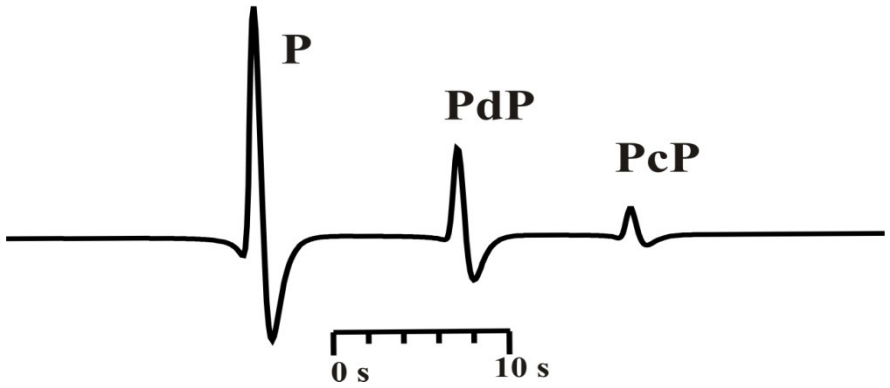



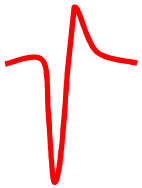

Kito, Rost,, Thomas, Garnero, 2007;
Thomas, Wookey, Brodholt, Fieseler, 2011;
Chaloner, Thomas, Rietbrock, 2009

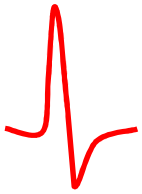
SE Asia

# => Observations 2

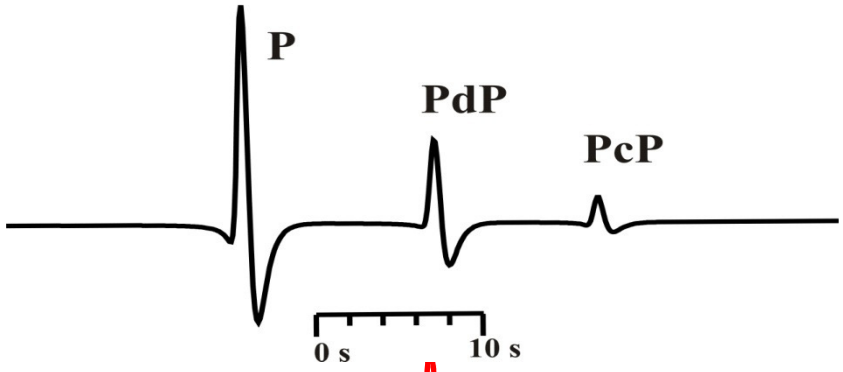
## Caribbean /S.E. Asia




P reflection  neg. impedance

S reflection  pos. impedance

## Eurasia




P reflection  pos. impedance

S reflection  pos. impedance

for 2 perpendicular crossing paths

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P reflection  neg. impedance

for a 45 degrees path

# Two regions

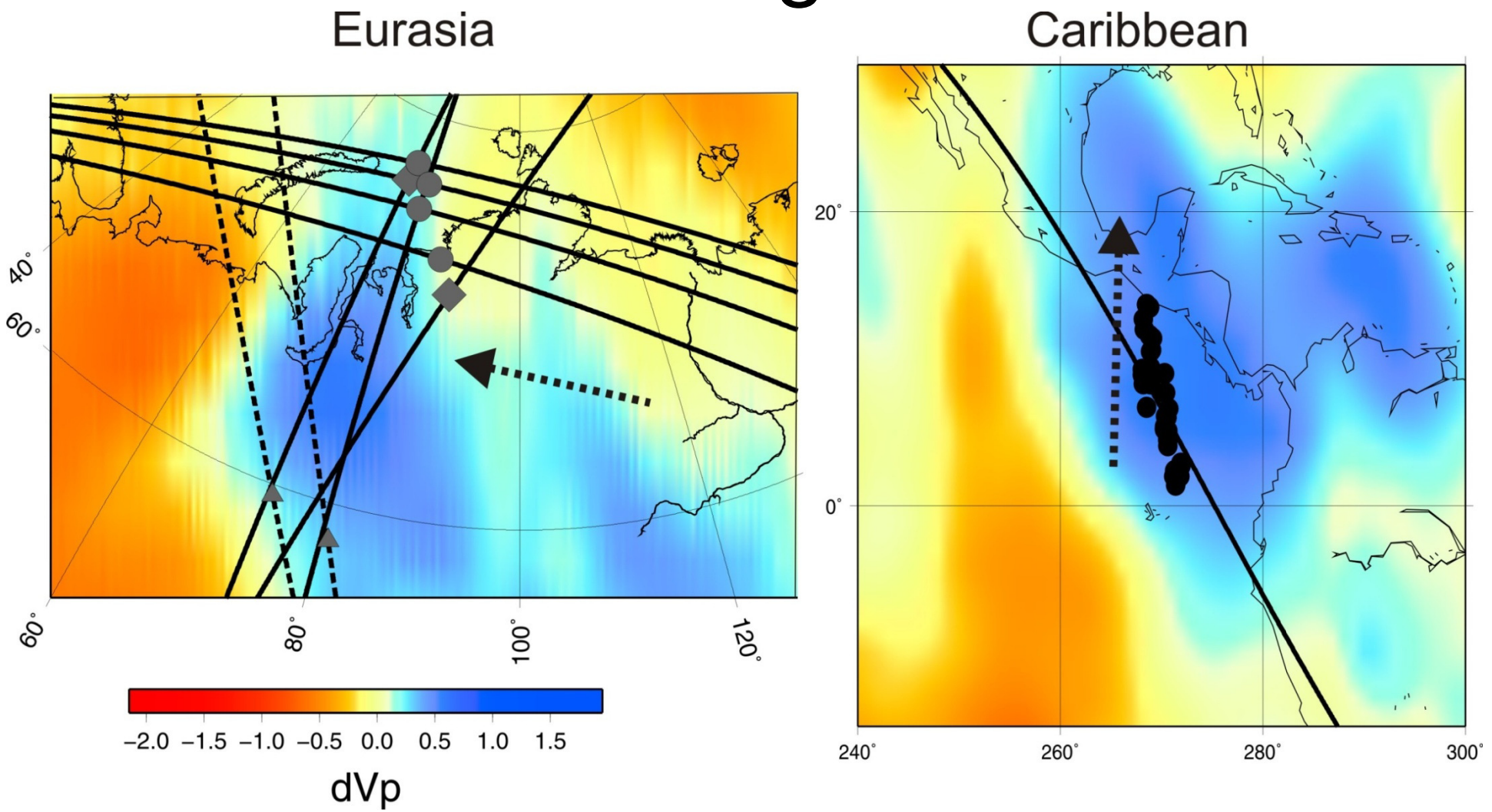
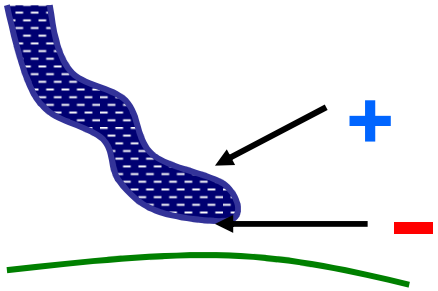


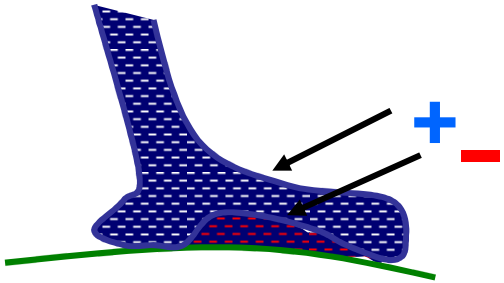

plate motion 80-100 Ma ago

Thomas, Wookey, Brodholt, Fieseler, EPSL2011

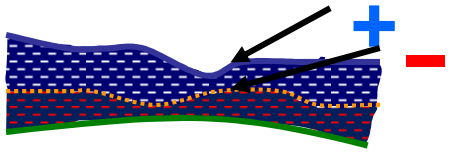
# possible interpretations:



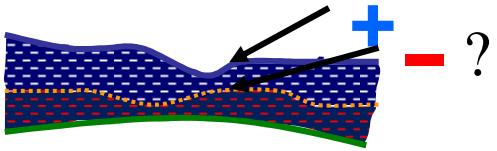
Top and Bottom of a purely thermal slab
*e.g. Thomas et al. 2004*



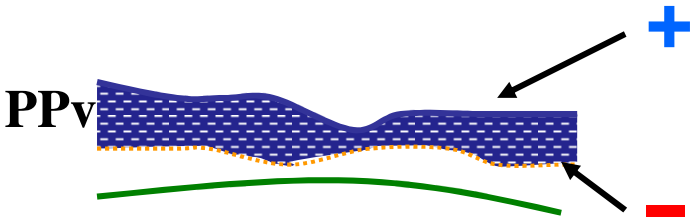
Birth of an upwelling
*e.g. Tan et al. 2002*



Thermo-chemical boundary layer with internal low-velocity zone
*e.g. Lay et al. 2004*



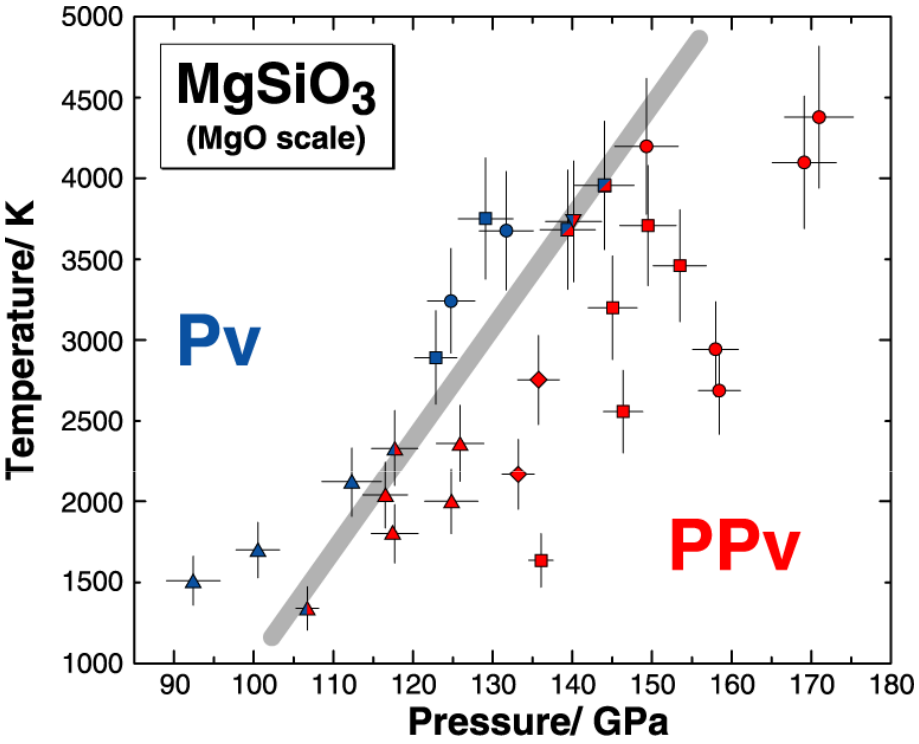
Change of anisotropy with depth



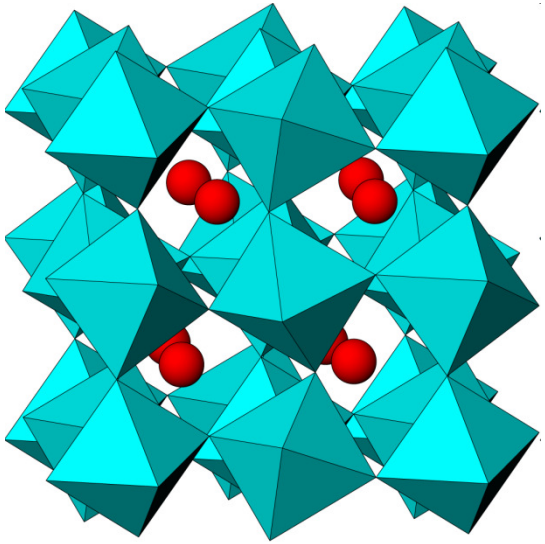

Post-perovskite transition stability field
*e.g. Hernlund et al. 2005*

After Garnero 2005/ Thomas et al 2004

# post-perovskite (ppv)

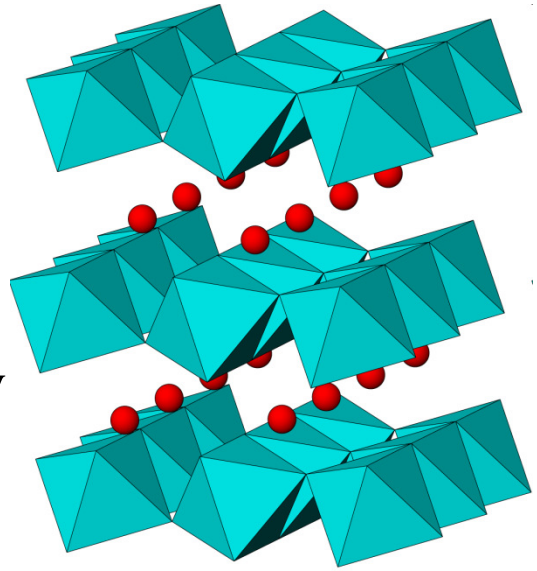



pv



by Dan Shim

ppv



by Dan Shim

post-perovskite: ($MgSiO_3$)

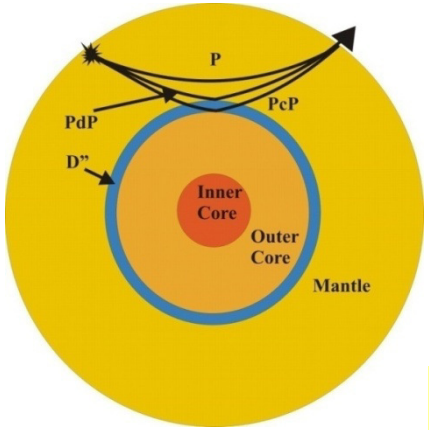
density change (~1%)

velocity change (? %)

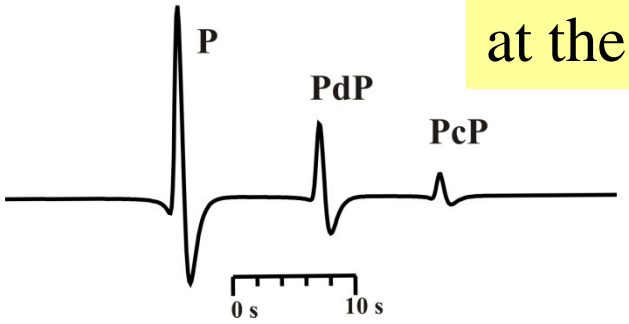
Clapeyron slope (6-13 MPa/K)?

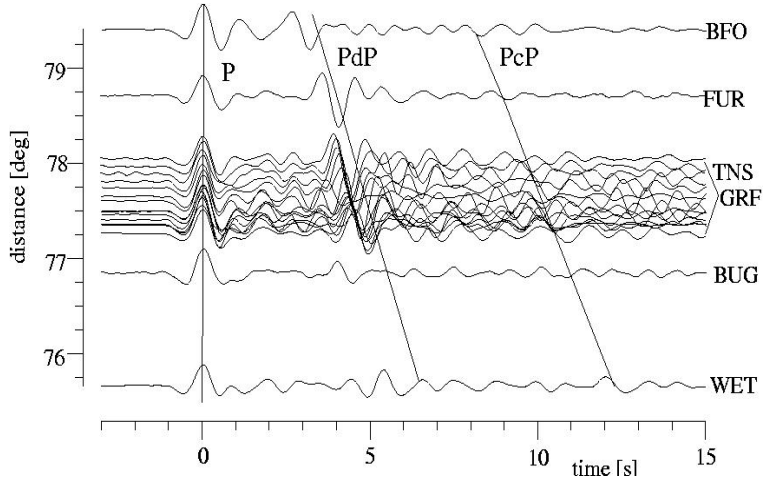
(Dan Shim's talk)

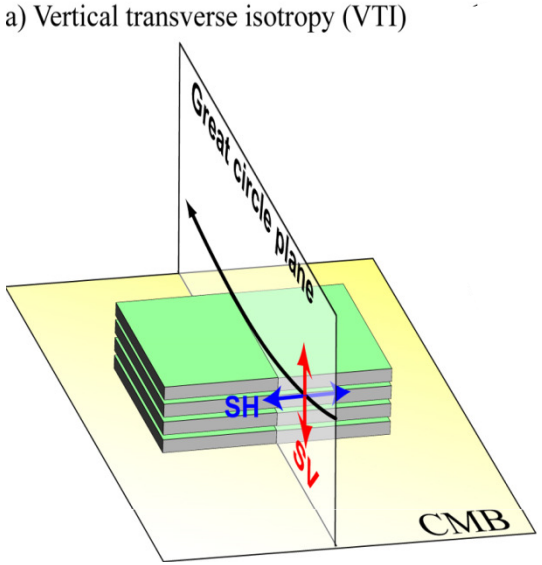
# ppv can explain:

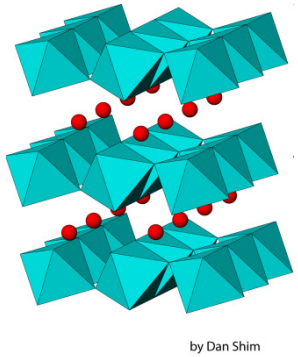



Reflections of seismic waves at the top of D"

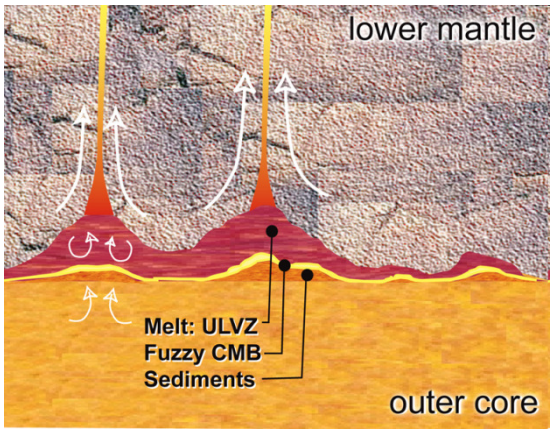



seismic anisotropy through layered structure

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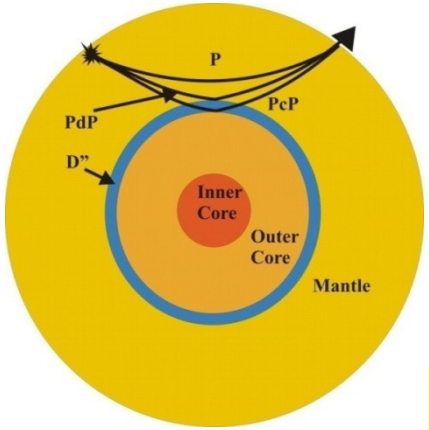
ultra-low velocity zones

# ppv can explain:

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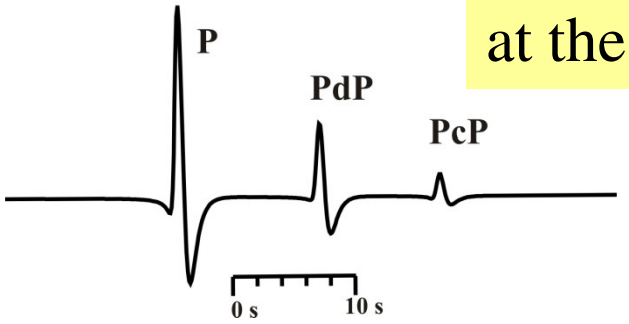
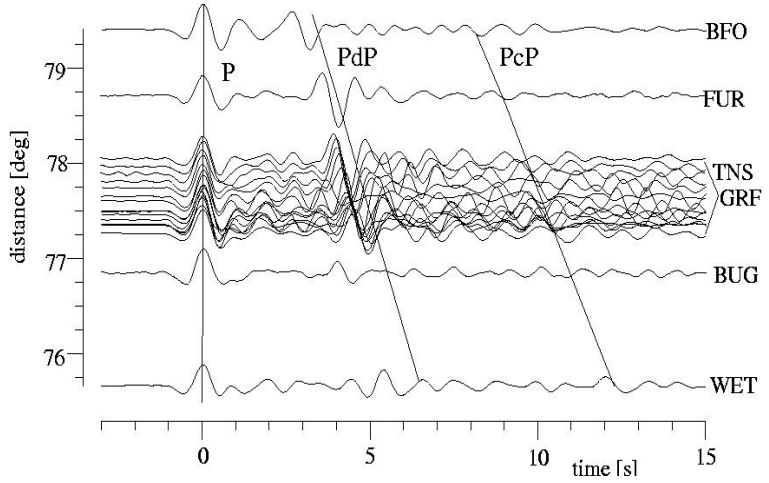
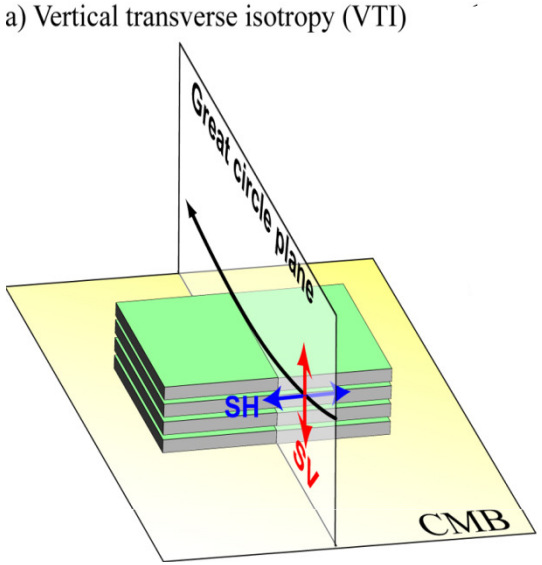
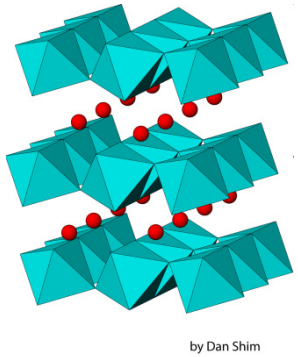
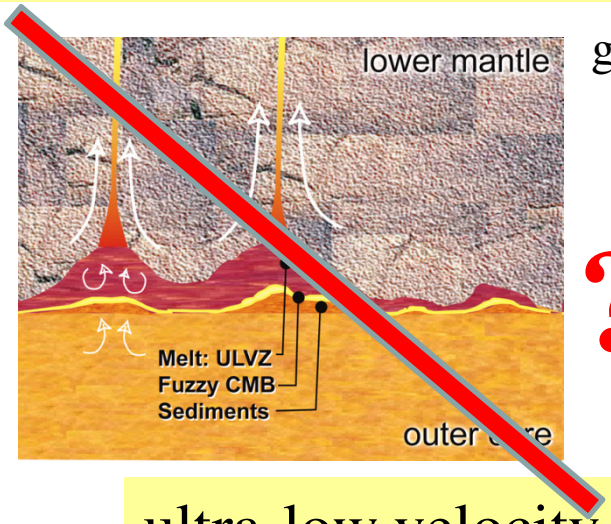



seismic anisotropy through layered structure

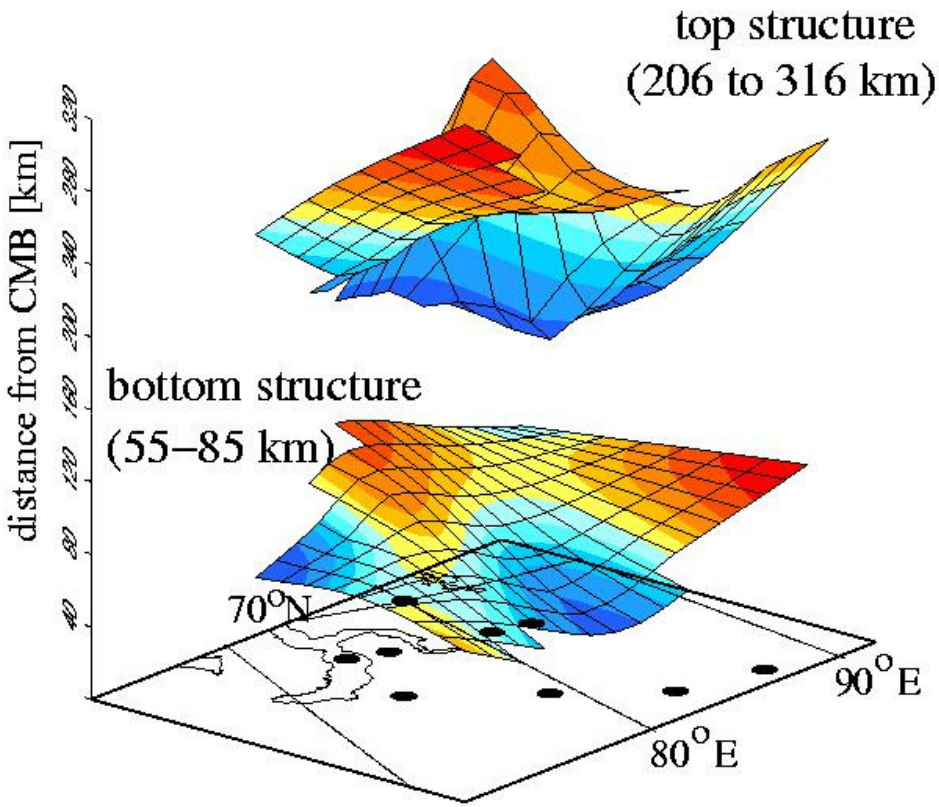



garnero.asu.edu

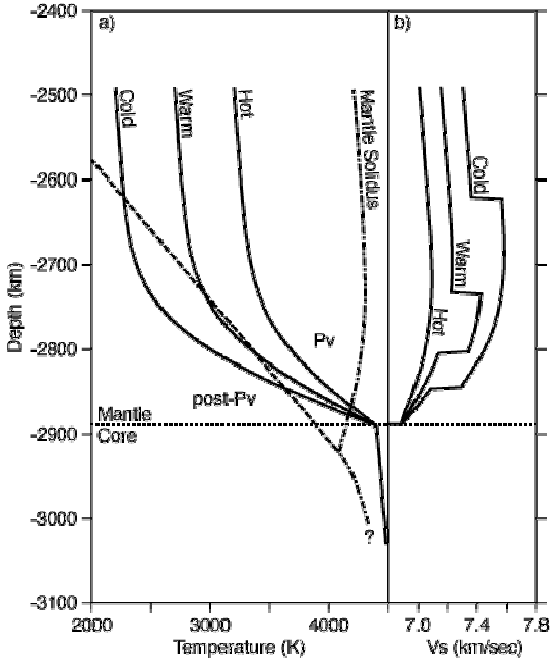
?

ultra-low velocity zones

# … 2 discontinuities ...



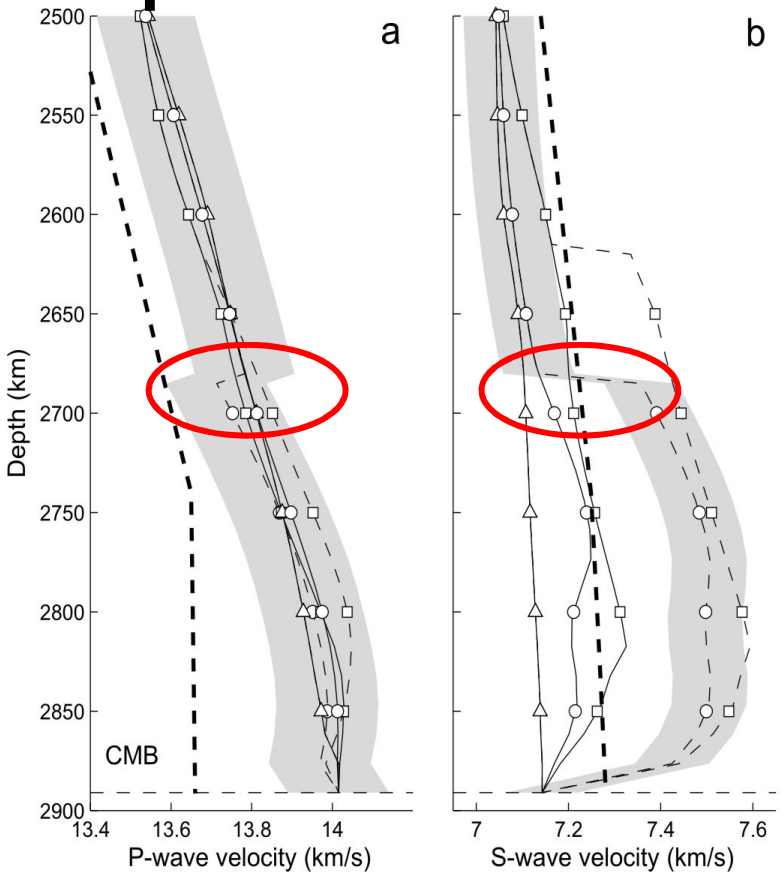

e.g., Thomas et al., 2004a,b Kito et al., 2007,
Hutko et al., 2008, van der Hilst et al., 2007



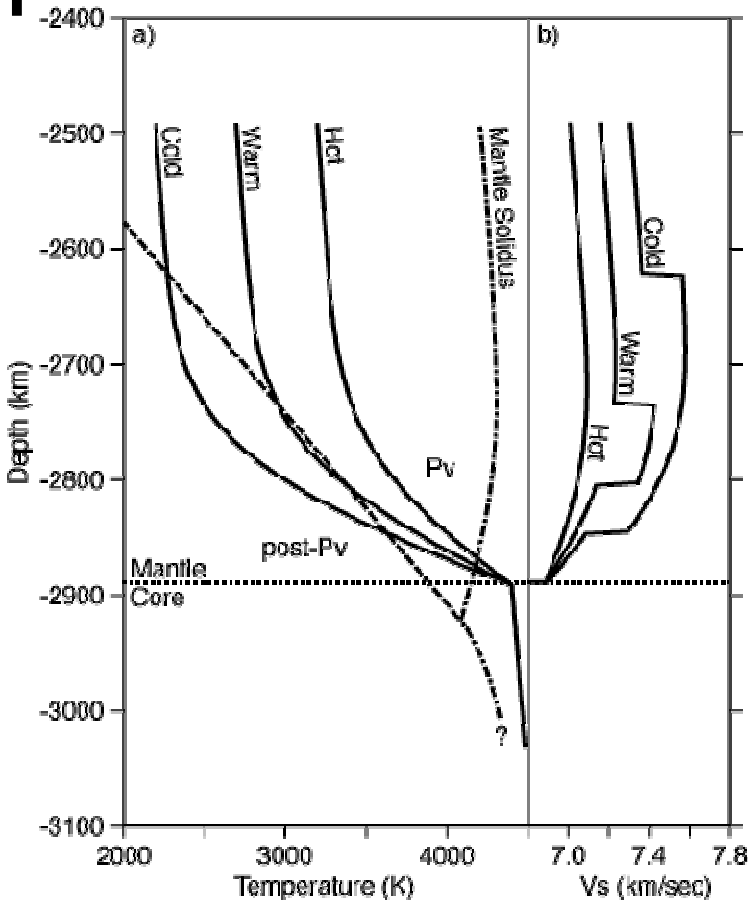

Hernlund et al., 2005

seismically observed two discontinuities in D"
due to "double crossing"

# ... polarities and depth variation ...




*ab initio* calculations (Wookey et al. 2005) predict a positive velocity contrast for S waves and negative for P-waves



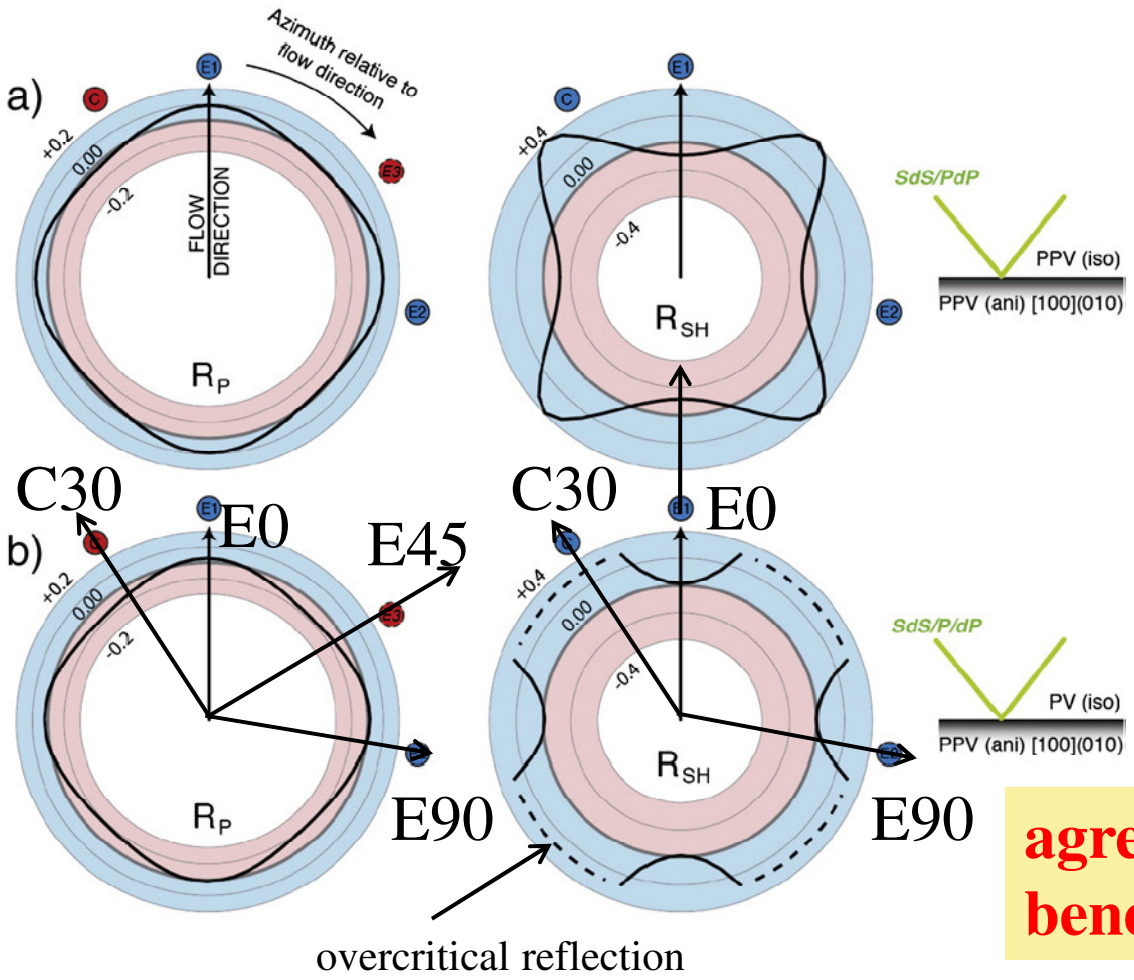

from Hernlund, Thomas and Tackley, 2005

Mantle temperature variation can explain topography

**=> agreement with observations beneath Caribbean and SE Asia**

# ....and directional dependency of polarities

calculated reflectivity:




along alignment direction and perpendicular:
positive P-wave contrast (E0, E90)
positive S-wave contrast

45 deg: neg. P and pos. S contrast (E45)

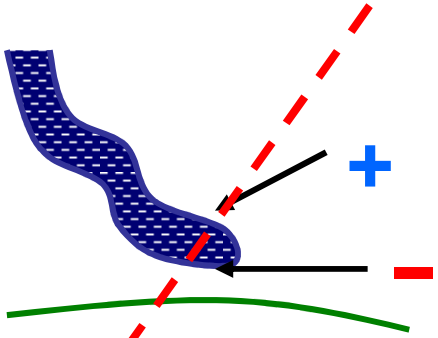
C30: Caribbean

**agreement with observations beneath Eurasia and Caribbean**

red: neg. reflectivity: neg. polarity
blue: pos. reflectivity: pos. polarity

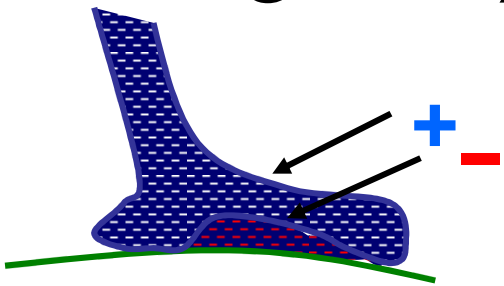
Thomas, Wookey, Brodholt; Fieseler, 2011

# Most likely interpretation (fast regions)



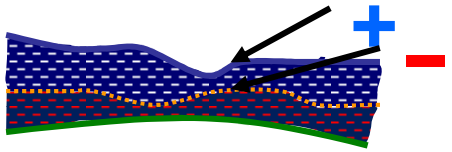
Top and Bottom of a purely themal slab

*e.g. Thomas et al. 2004*



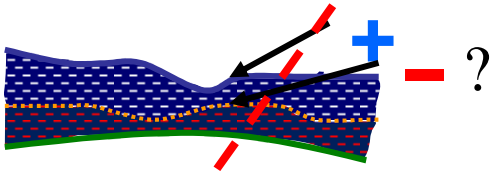
Birth of an upwelling

*e.g. Tan et al. 2002*



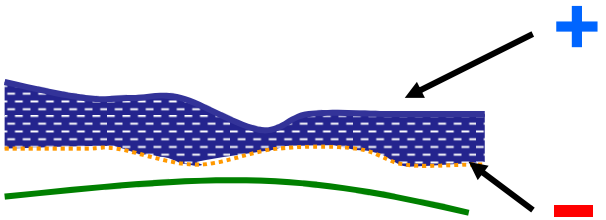
Thermo-chemical boundary layer with internal low-velocity zone

*e.g. Lay et al. 2004*



?

Change of anisotropy with depth



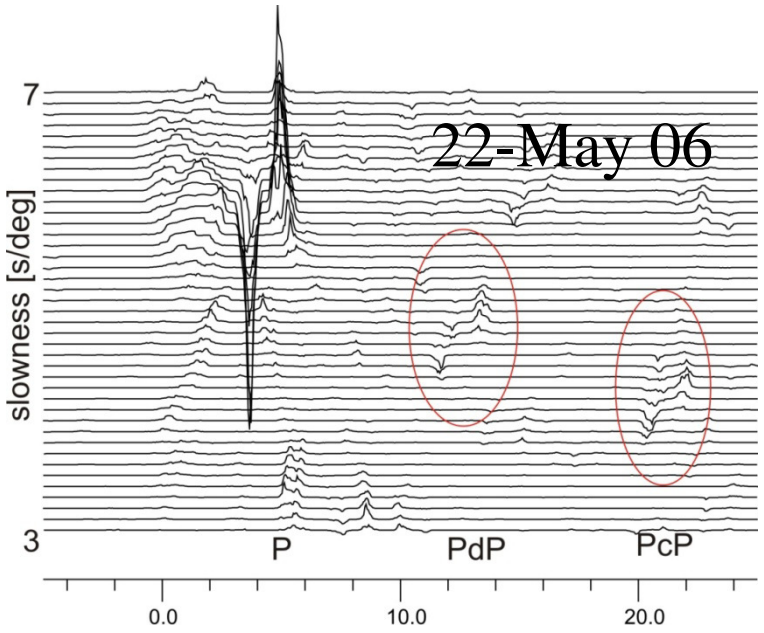

Post-perovskite transition stability field

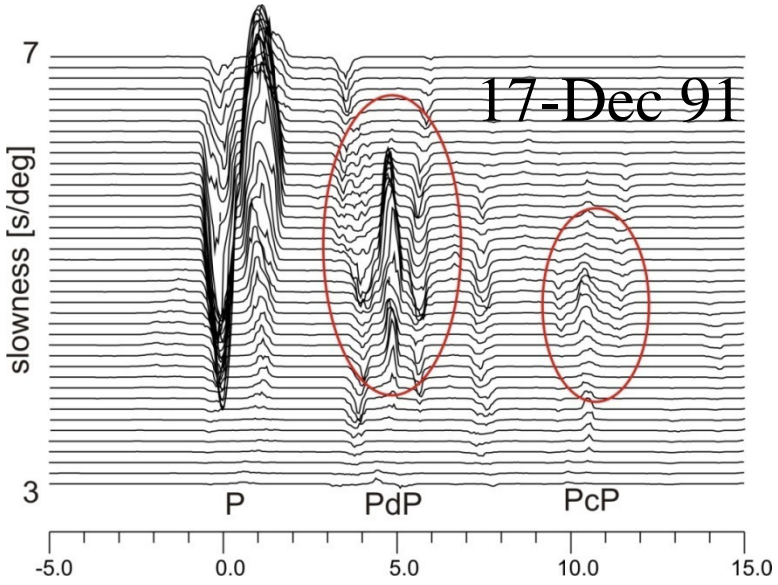
*e.g. Hernlund et al. 2005*

After Garnero 2005/ Thomas et al 2004

# Problems solved??

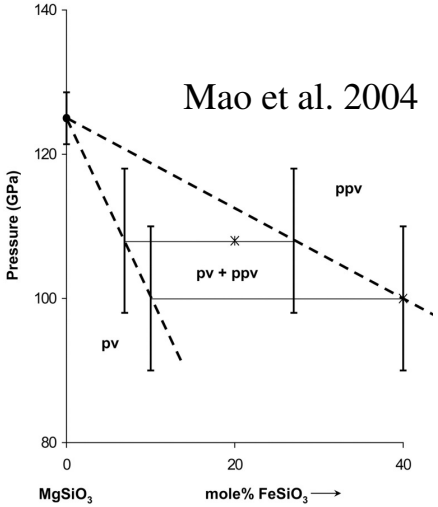
1) "…the aggregate shear wave velocity contrast between MgSiO3 perovskite and post-perovskite is 0.5% at most up to the pressure of 125 GPa. " Murakami et al., 2007.



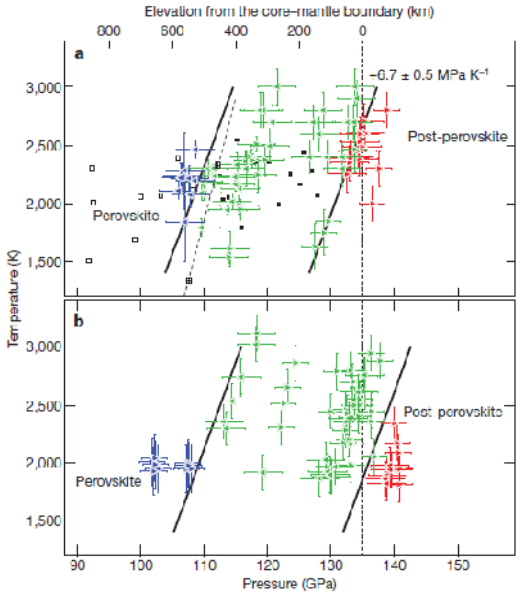




Amplitude of PdP is very large (focussing effect?)
for P waves should be very small for S-waves 0.5%

# 2) sharpness of transition




Schematic phase diagram of the MgSiO3–FeSiO3 binary system at 2,000–2,500 K.




Catalli et al 2009

ppv transition - pyrolite

(John Brodholt's talk)
Ammann et al, 2010

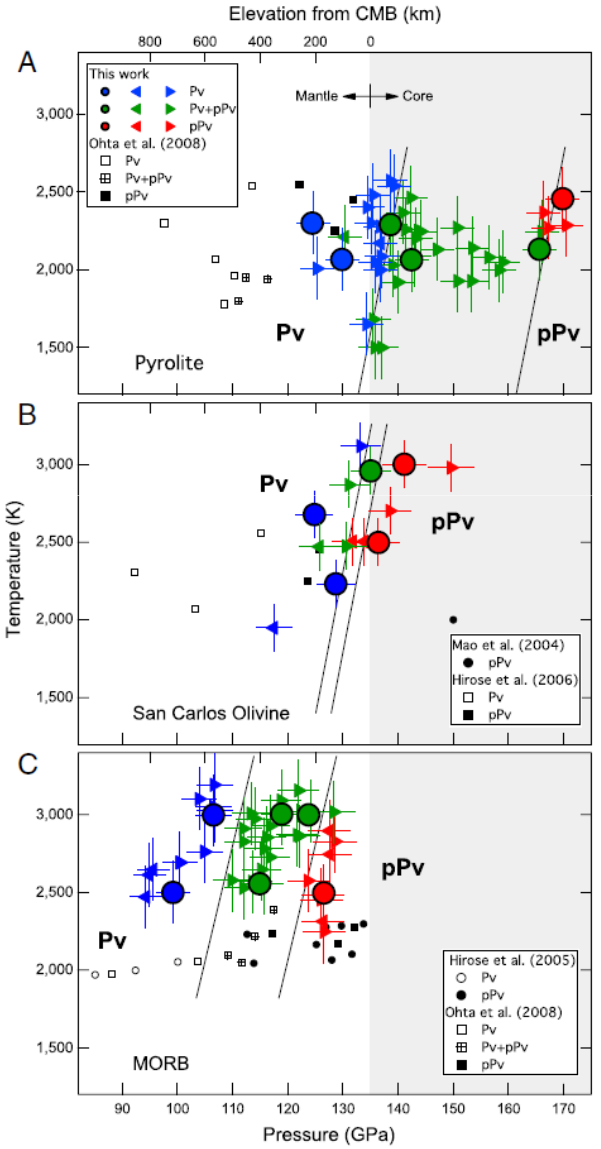
shear induced alignment

---

Grocholski et al. 2012

transition in other minerals can be sharp

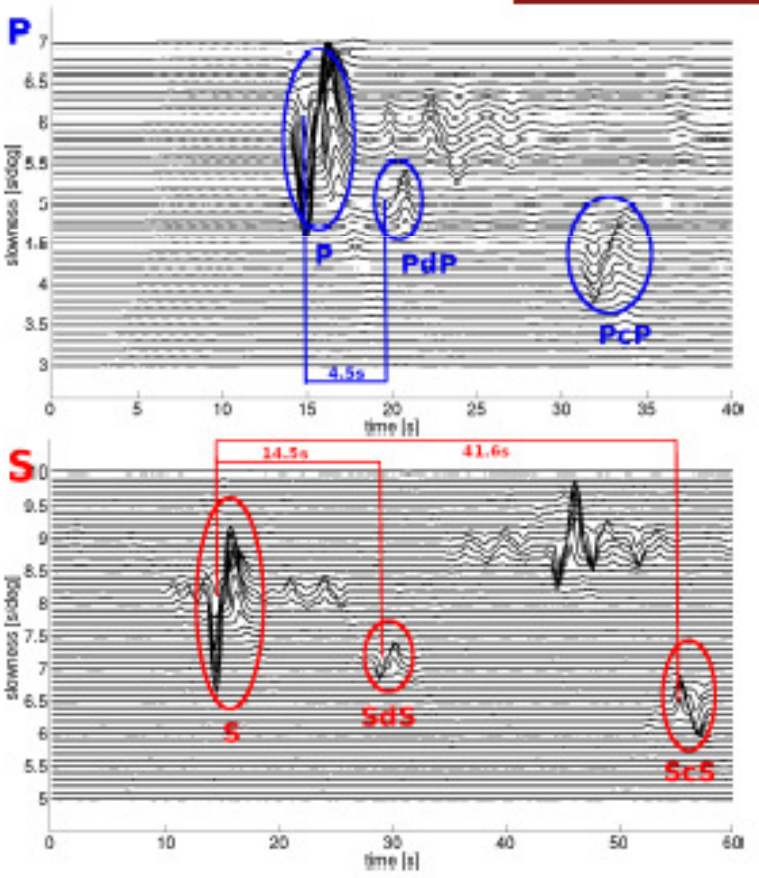
(Dan Shim's talk)



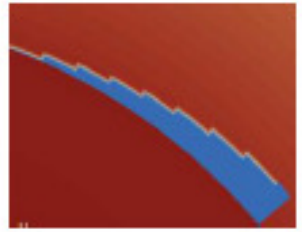
# 3) observed depth of reflection

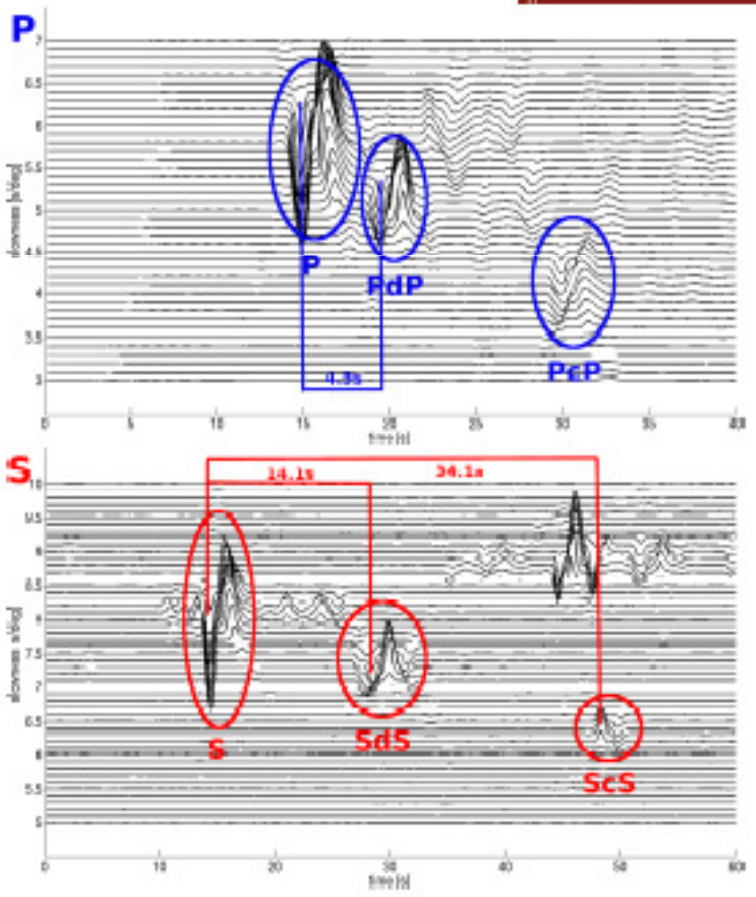
## Depths and inclinations

Flat reflector at 250km above CMB
($d\rho = 1\%, dv_P = 2\%, dv_S = 3\%$)



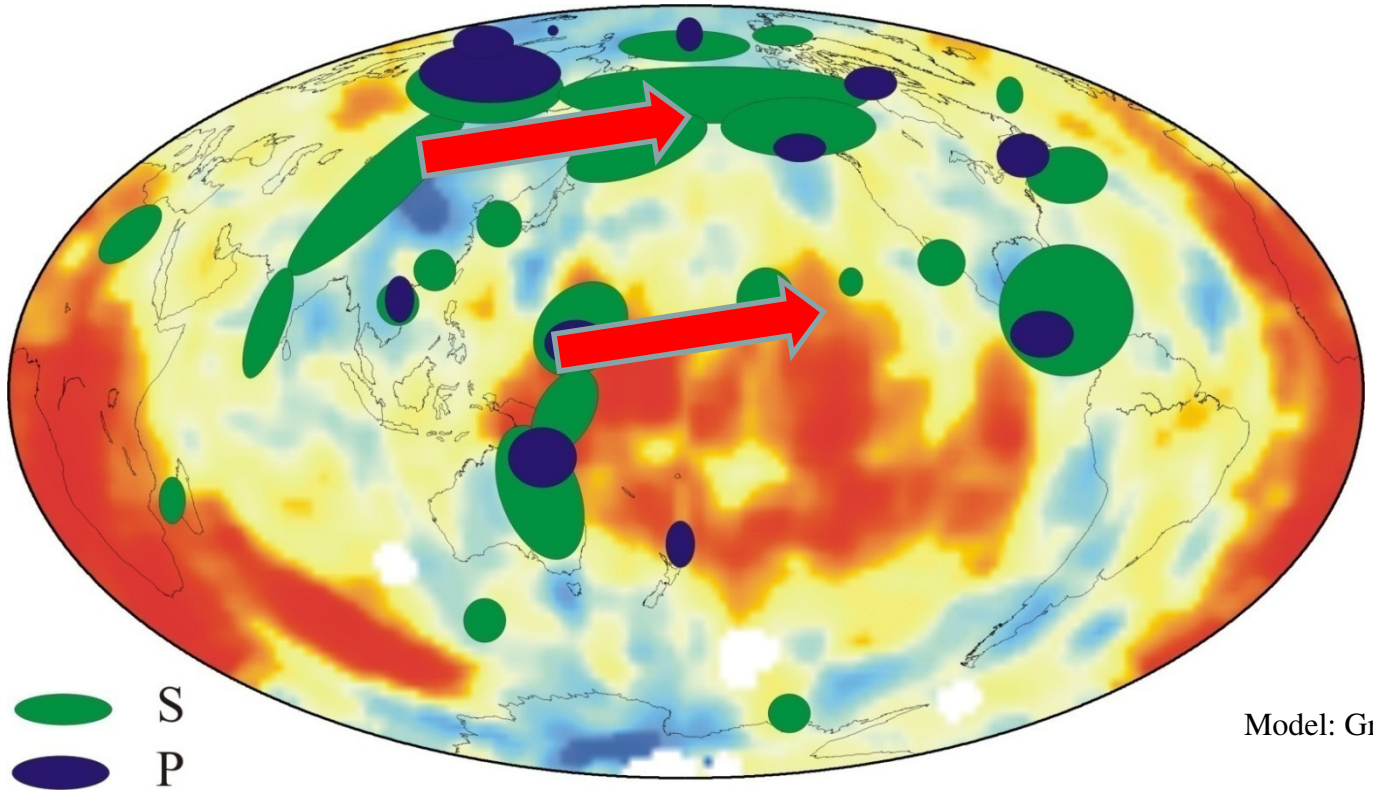

10deg inclined reflector at 140km above CMB
($d\rho = 1\%, dv_P = 2\%, dv_S = 3\%$)






Hempel, Nissen-Meyer, Thomas,

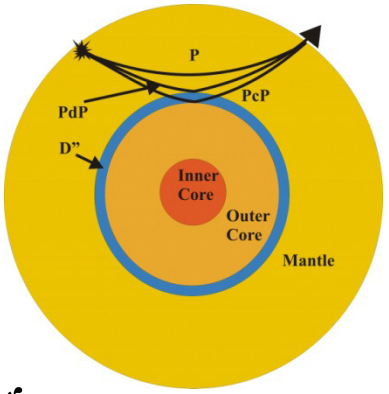
# Low-velocity regions

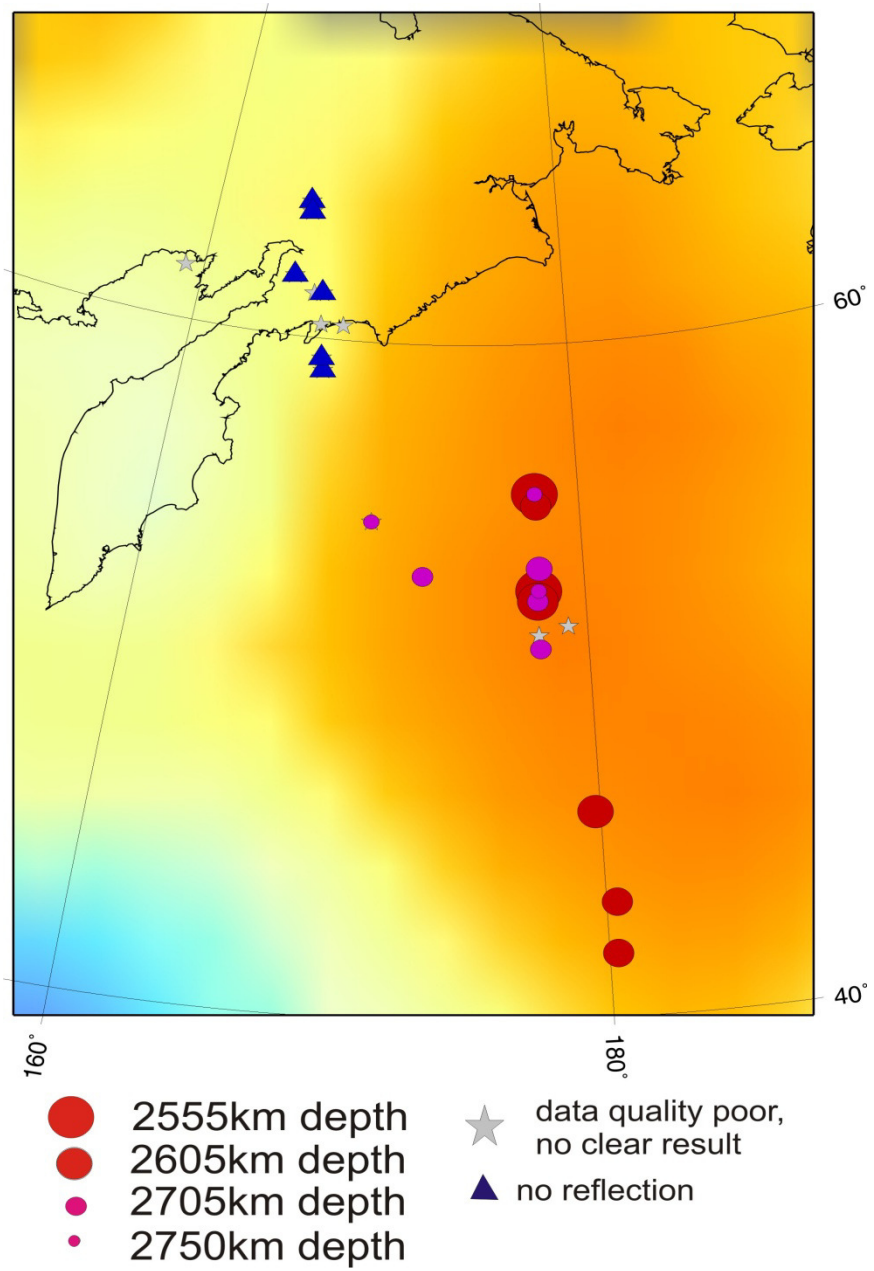



Model: Grand, 2002

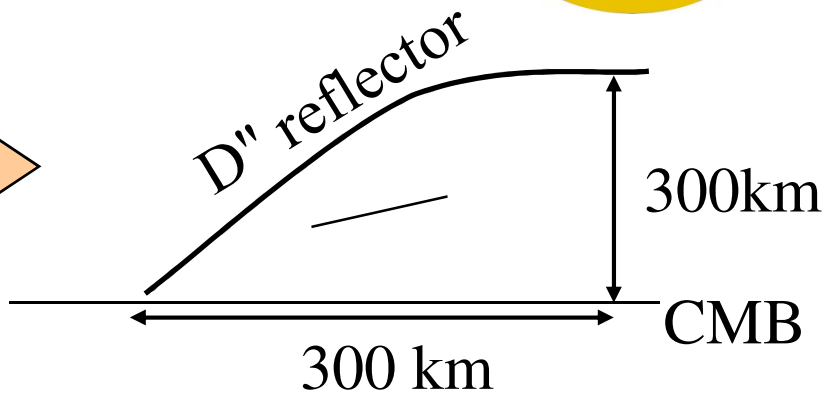
Data from: Lay and Helmberger, 1983, Weber and co-workers, 1990s, Kendall and co-wokers, Scherbaum et al, 1997, Lay and co-workers, Houard and Nataf 1990s, Wysession et al., 1998, Kito et al, and many more.

# Low velocity region



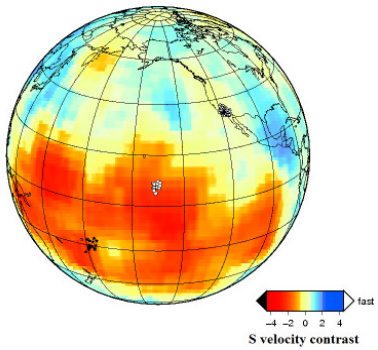

Hempel, Thomas
in prep. 2012

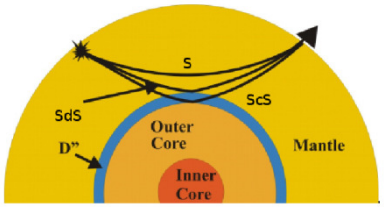


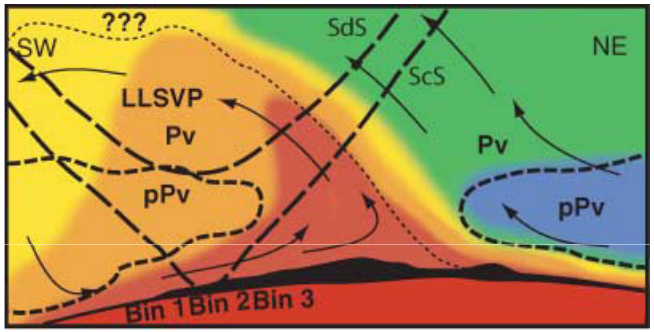

observations:

- low velocity region,
- reflector 40-90 km sharp
- 2nd reflector possible
- positive contrast (? why?)
- steep sides

# low velocity region (Pacific)

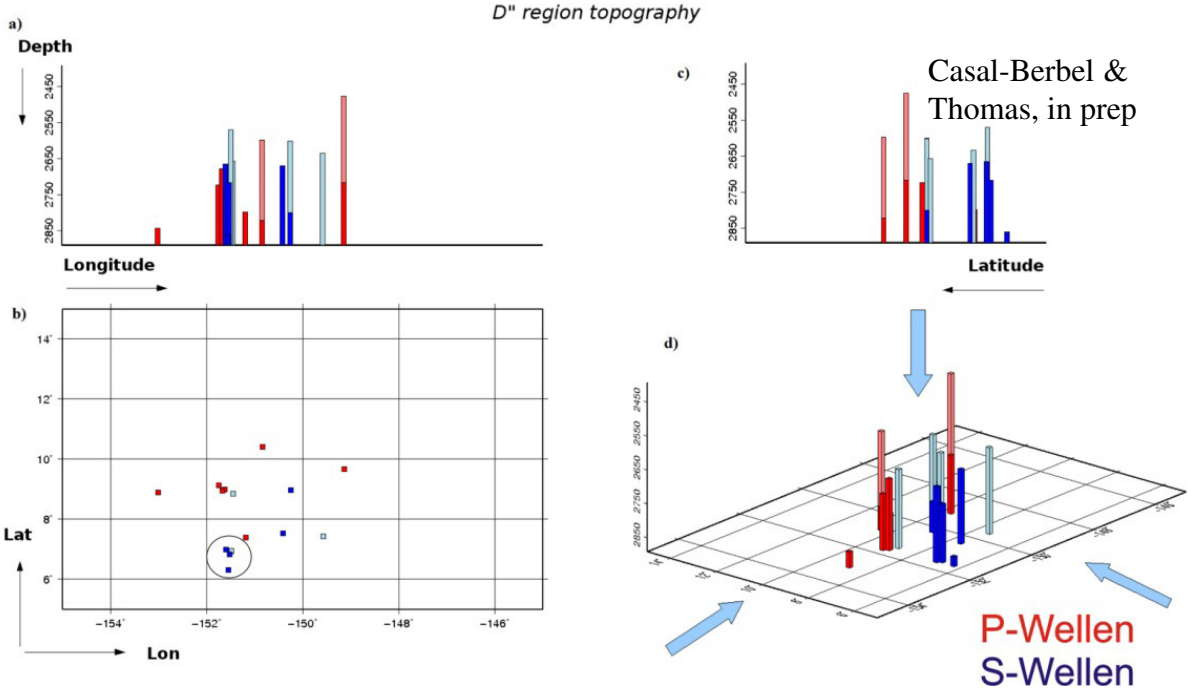



Lay et al., 2006

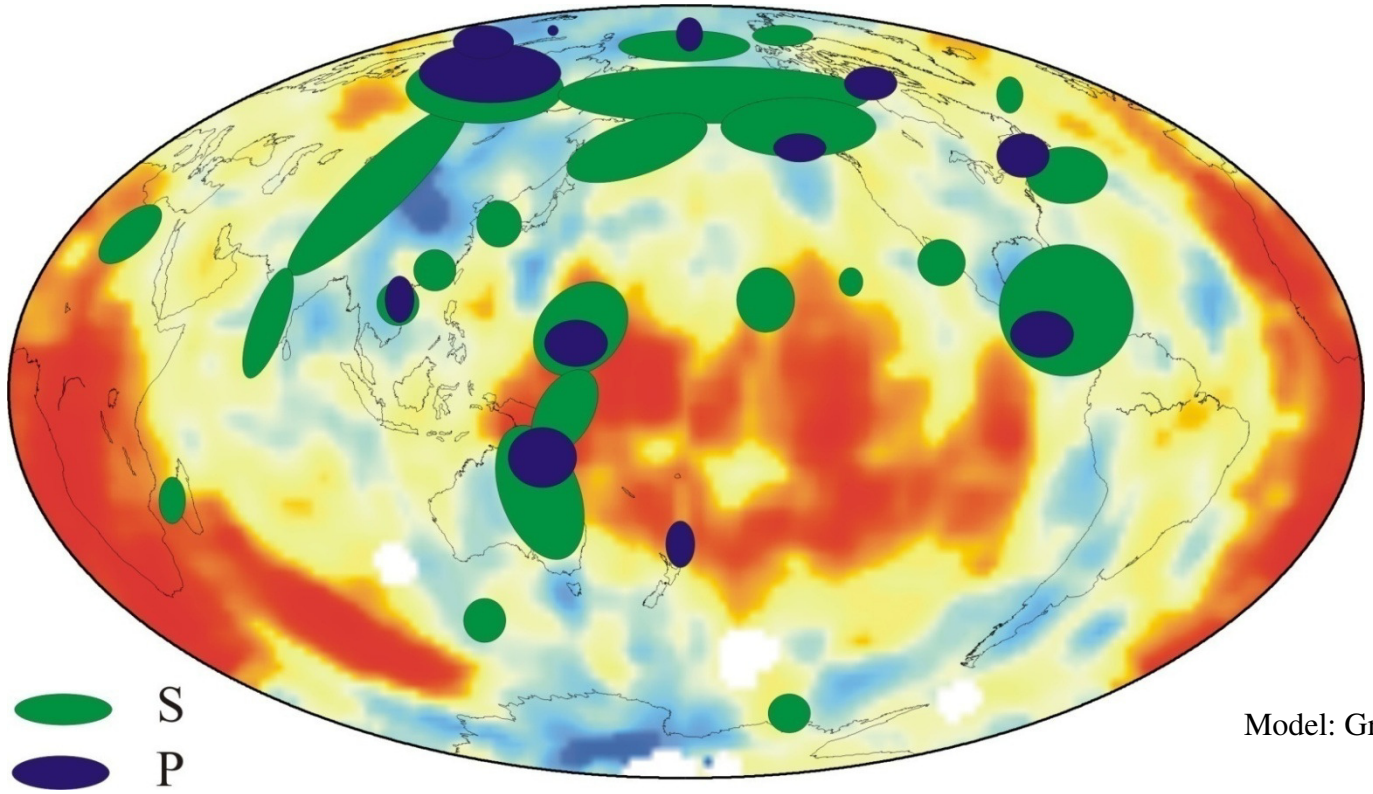
Lay et al. (2006): double crossing observed
and additional two reflectors (A and B).
Pyrolite mantle and MORB ppv transition? (Ohta et al., 2008)
Or top/bottom of LLSVP and ulvz. (Lay et al., 2006)




Casal-Berbel & Thomas, in prep

- Only up to two reflections.
- No clear trend for 'lens' shaped reflector.
- Reflections for S- and P-waves seem to be positive, *inconsistent with neg. velocity change in tomography?*

# "One for all"?

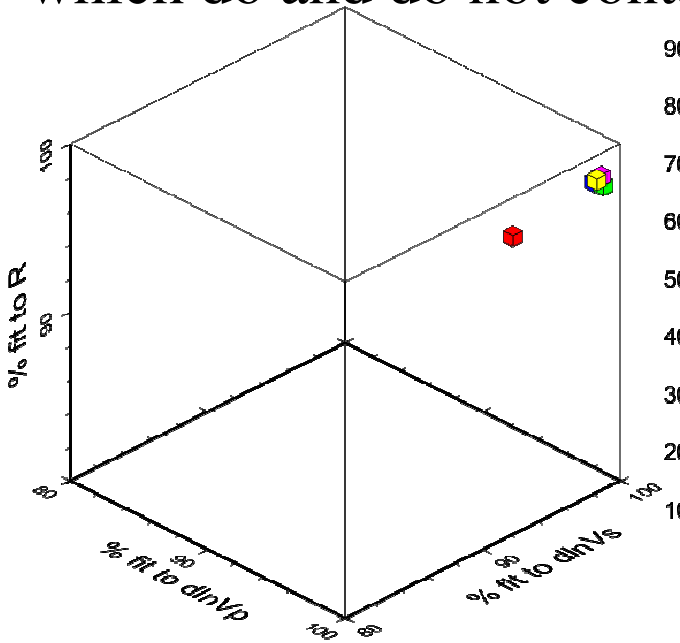



Model: Grand, 2002

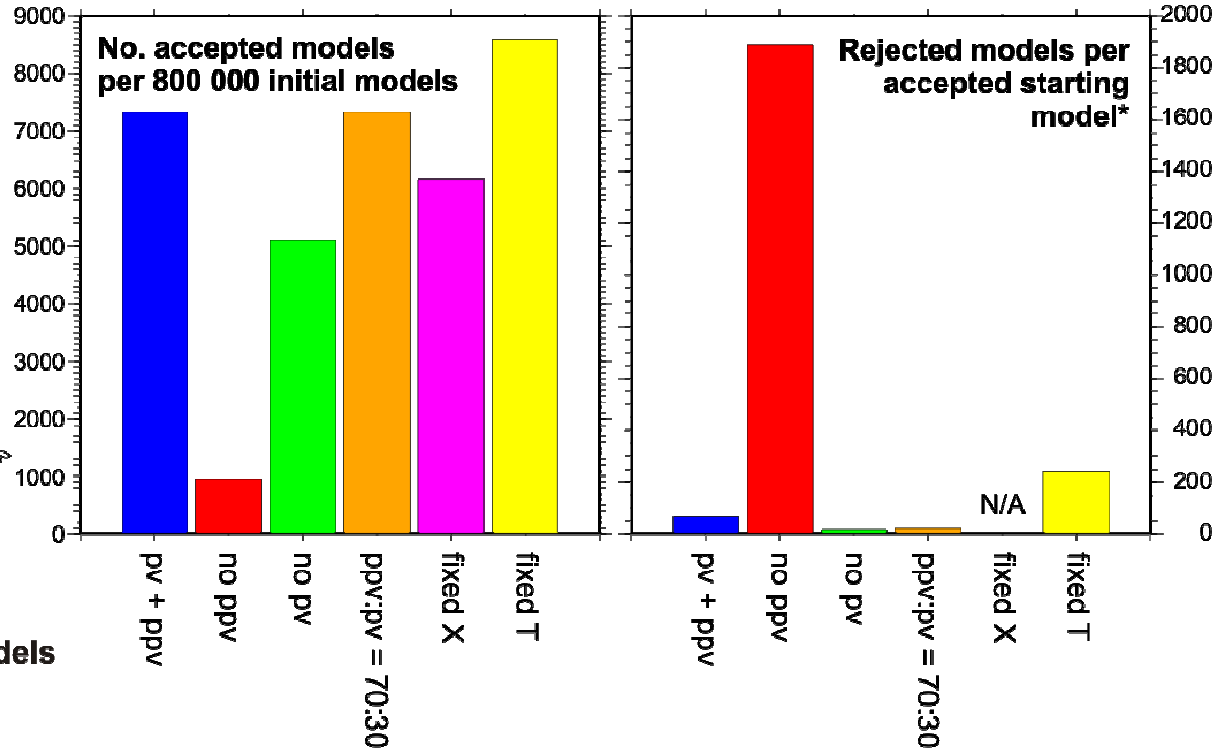
Data from: Lay and Helmberger, 1983, Weber and co-workers, 1990s, Kendall and co-wokers, Scherbaum et al, 1997, Lay and co-workers, Houard and Nataf 1990s, Wysession et al., 1998, Kito et al, and many more.

# Possible scenarios for lower mantle

statistical comparison of the relative fit to seismic data of mantle models which do and do not contain post-perovskite




**% Fit of accepted thermochemical models to seismic data at the CMB. See right for colour key**





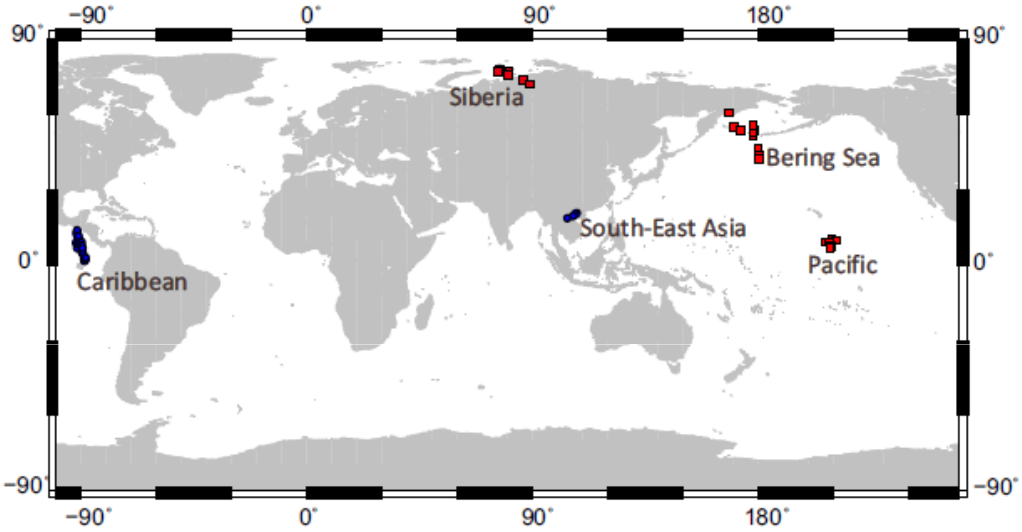


**starting models are rejected if not within 1% of PREM velocity and density*

Cobden et al, 2012

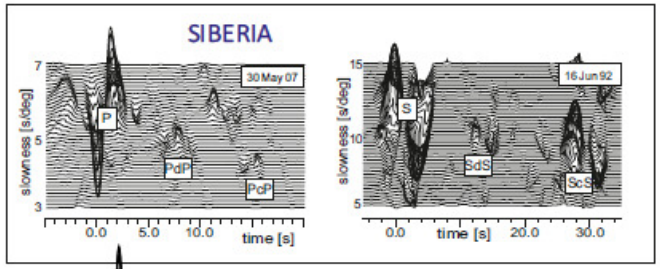
Difficult to distinguish between different scenarios on this evidence alone, although stastically “no post-perovskite” (red) has the worst fit to the data

# Only one explanation for D" reflection?

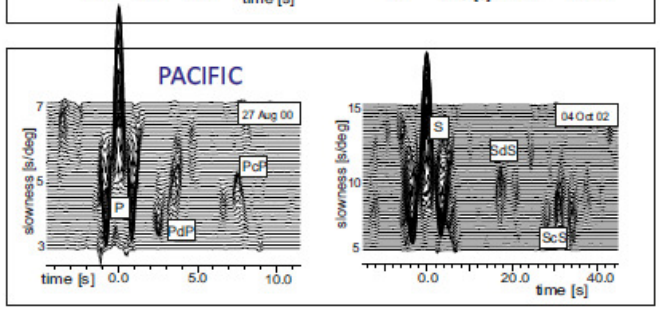



Focus on <u>polarity and amplitude</u>/ velocity contrast.
Fit those with Monte Carlo thermodynamic modelling

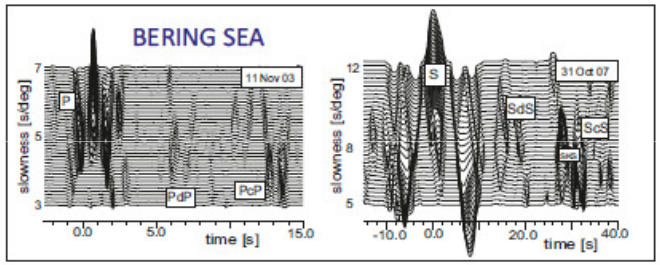
Cobden and Thomas, GJI subm.



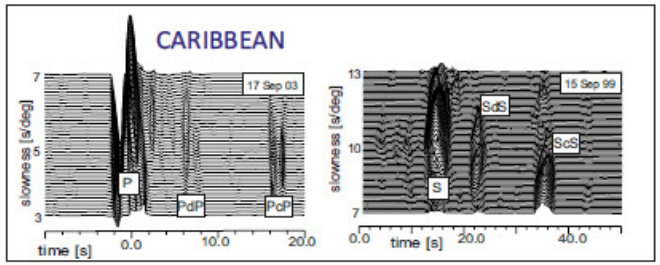

**PdP +** 1-3%
**SdS +** 2-3%



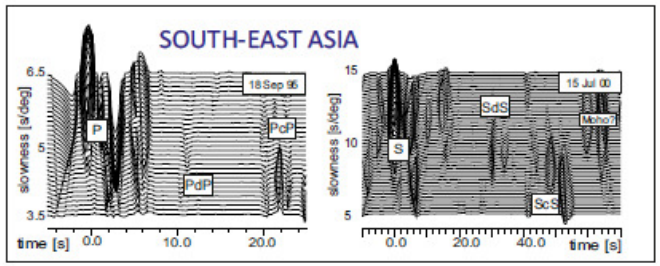

**PdP +** 1-3%
**SdS +** 2-3%




**PdP +** 1-1.5%
**SdS +** 1-2%

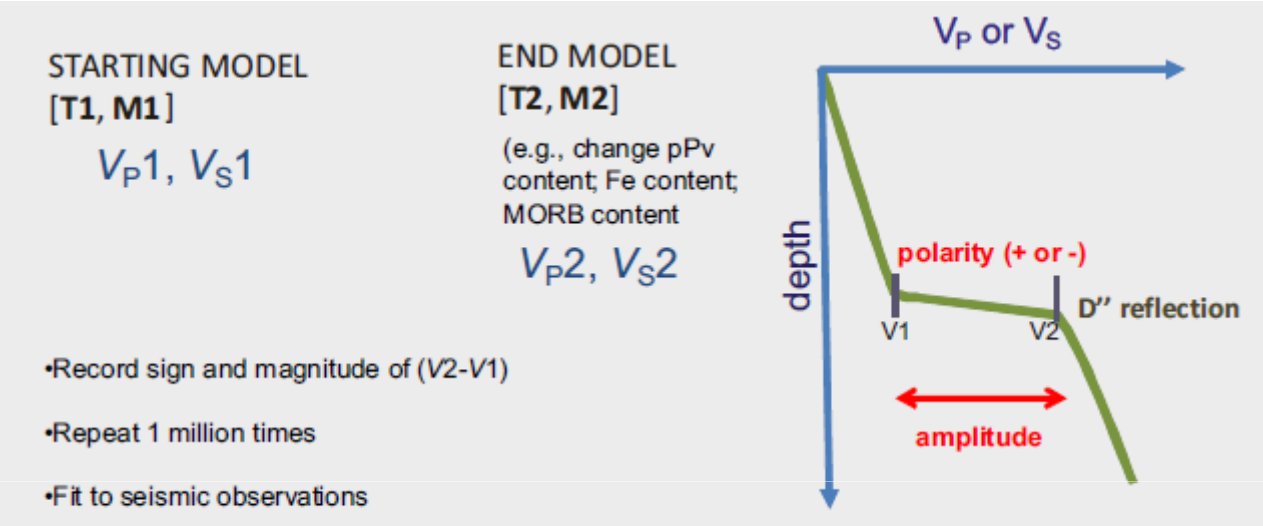



**PdP -** -2- -3%
**SdS +** 2-3%




**PdP -** -1- -2%
**SdS +** 1-3%

# Modelling




Cobden and Thomas, GJI subm.

(1) scattering off thermo-chemical heterogeneity,
(2) a sharp impedance contrast due to a phase change pv-ppv

elastic parameters and thermo-chemical composition vary within specified ranges , create 1Million models

fit polarity and amplitude => gives statistical measure of likelihood for cause of D" reflection

# fit to MORB

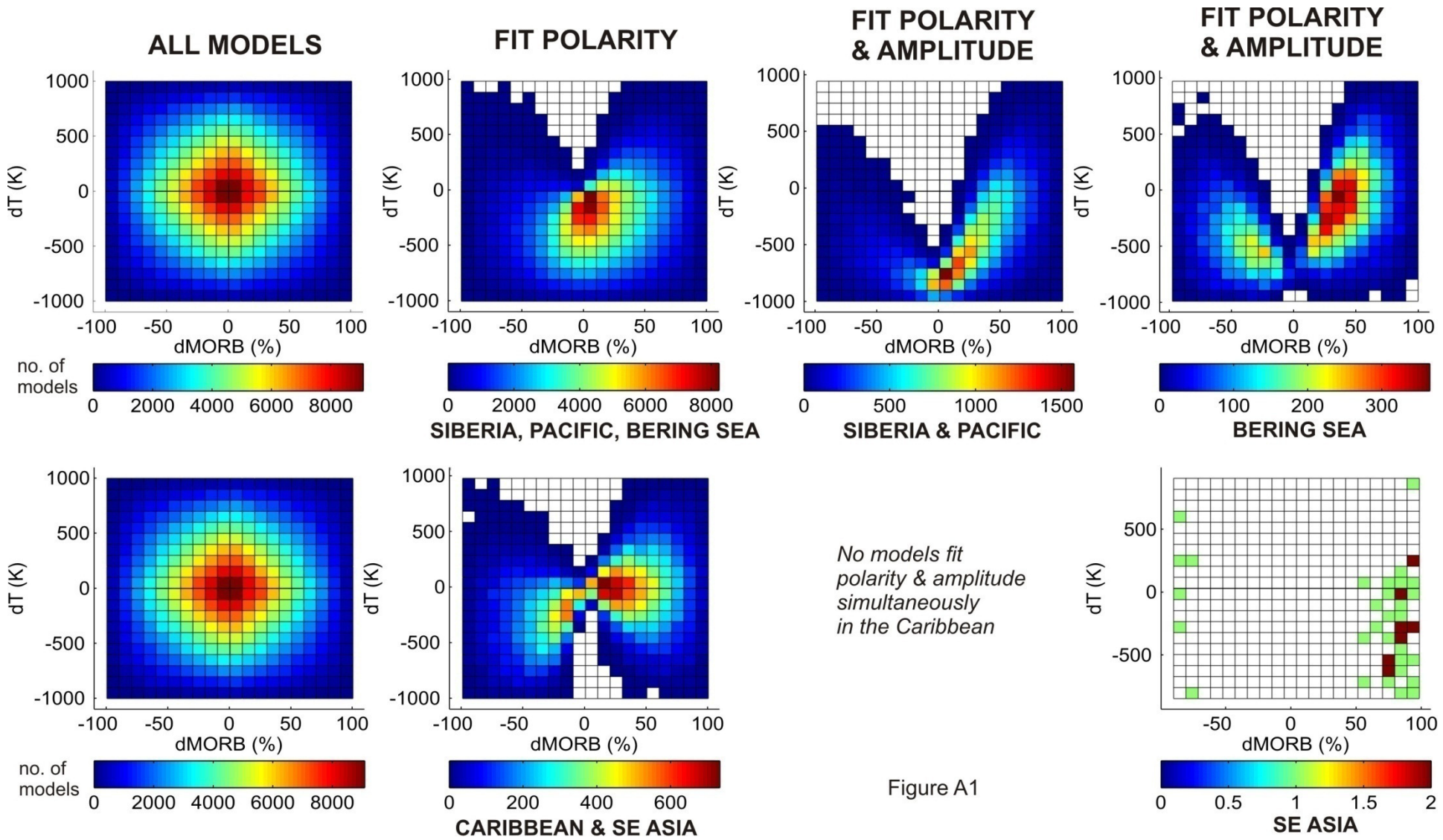
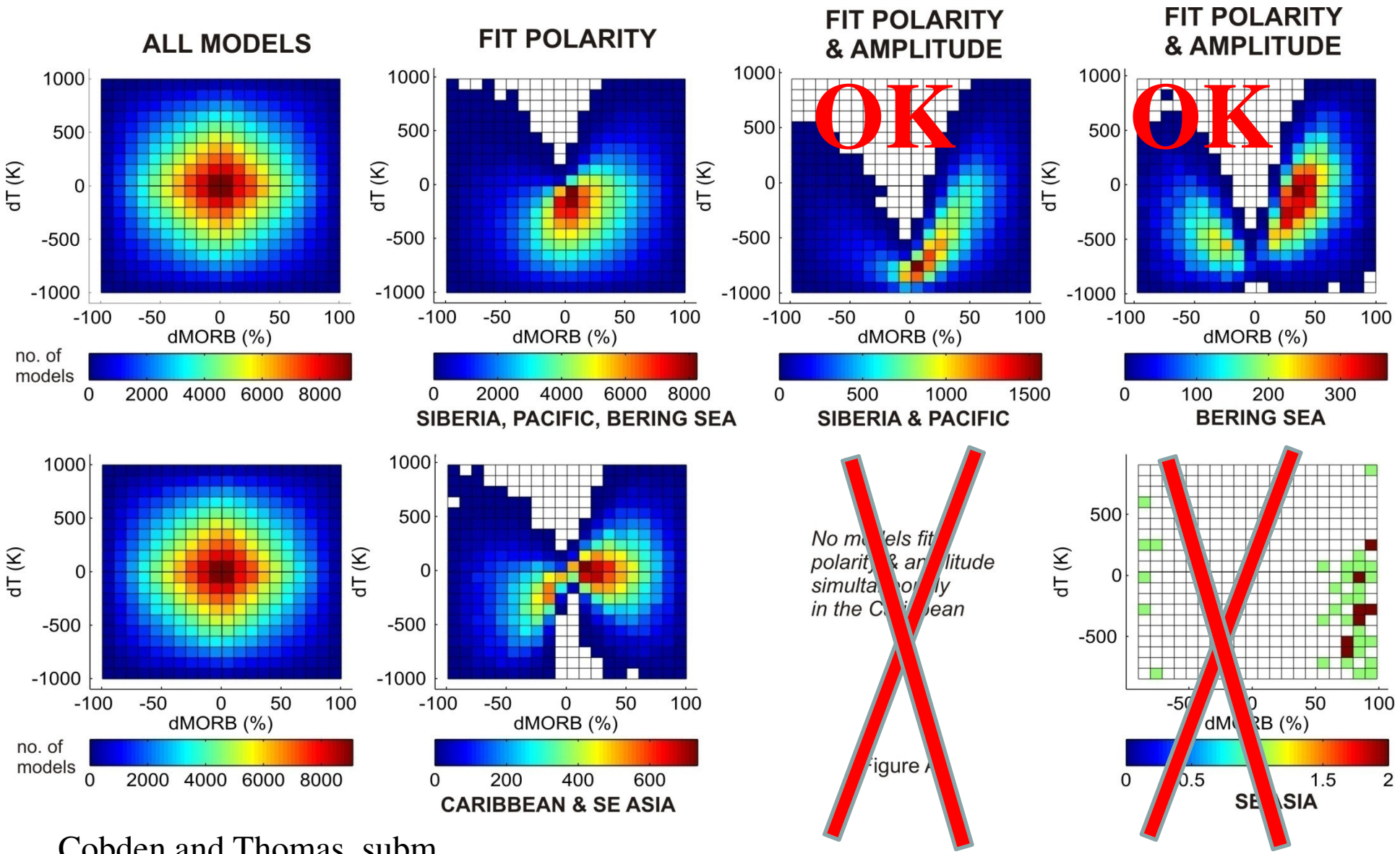



Figure A1

Cobden and Thomas, subm.

# fit to MORB




Cobden and Thomas, subm.

# fit to ppv

Cobden and Thomas, subm.

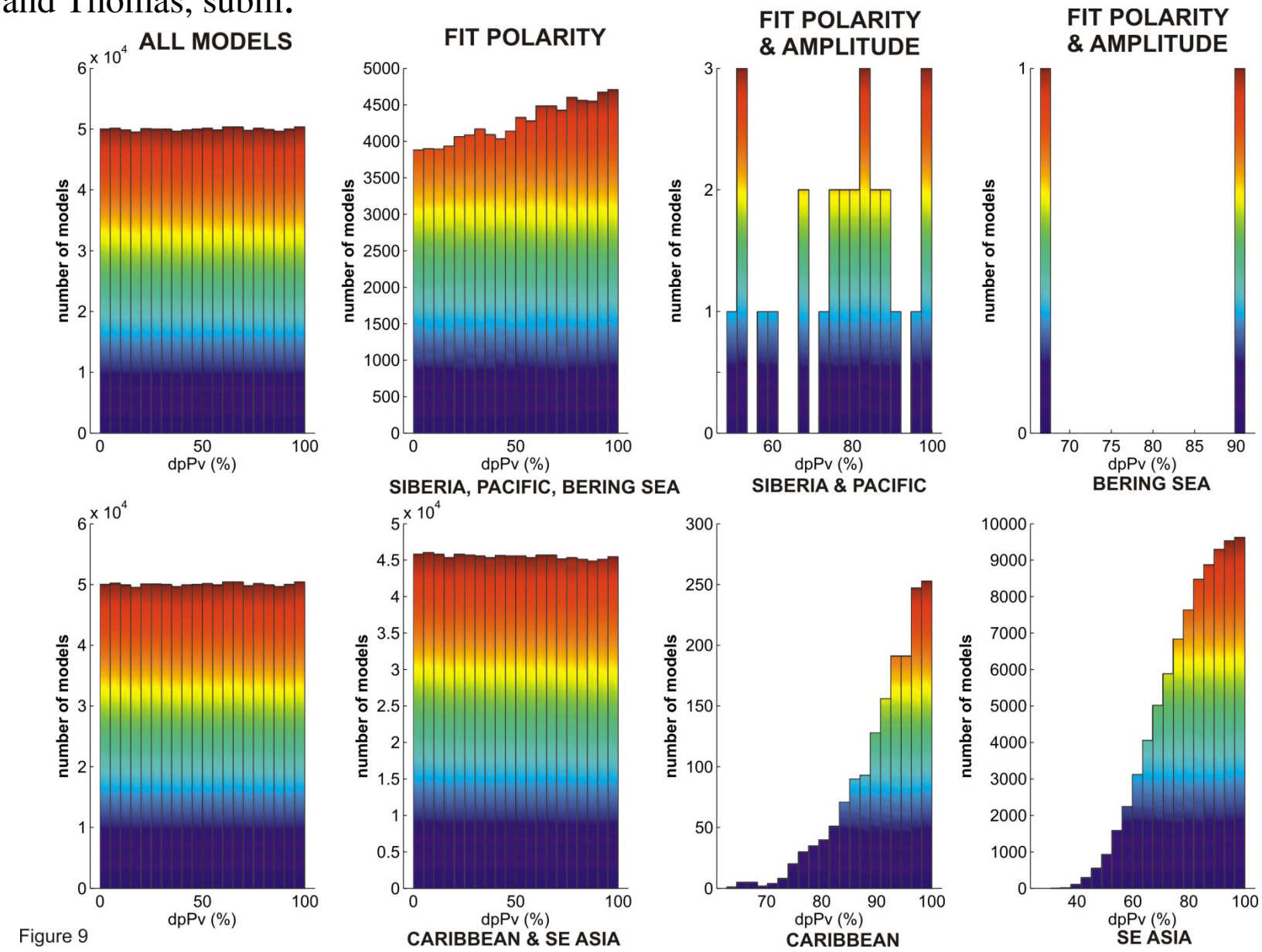



Figure 9

# fit to ppv

Cobden and Thomas, subm.

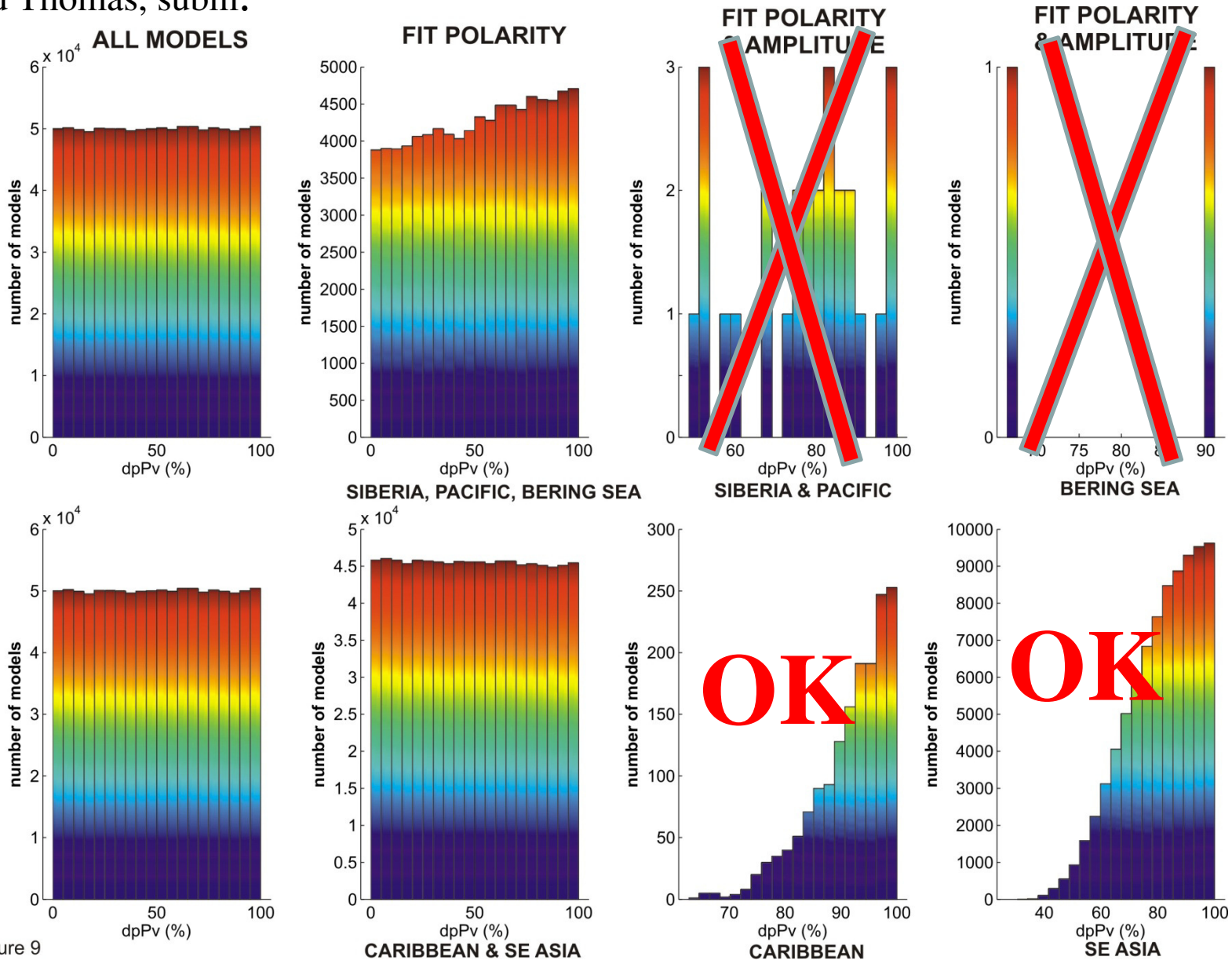
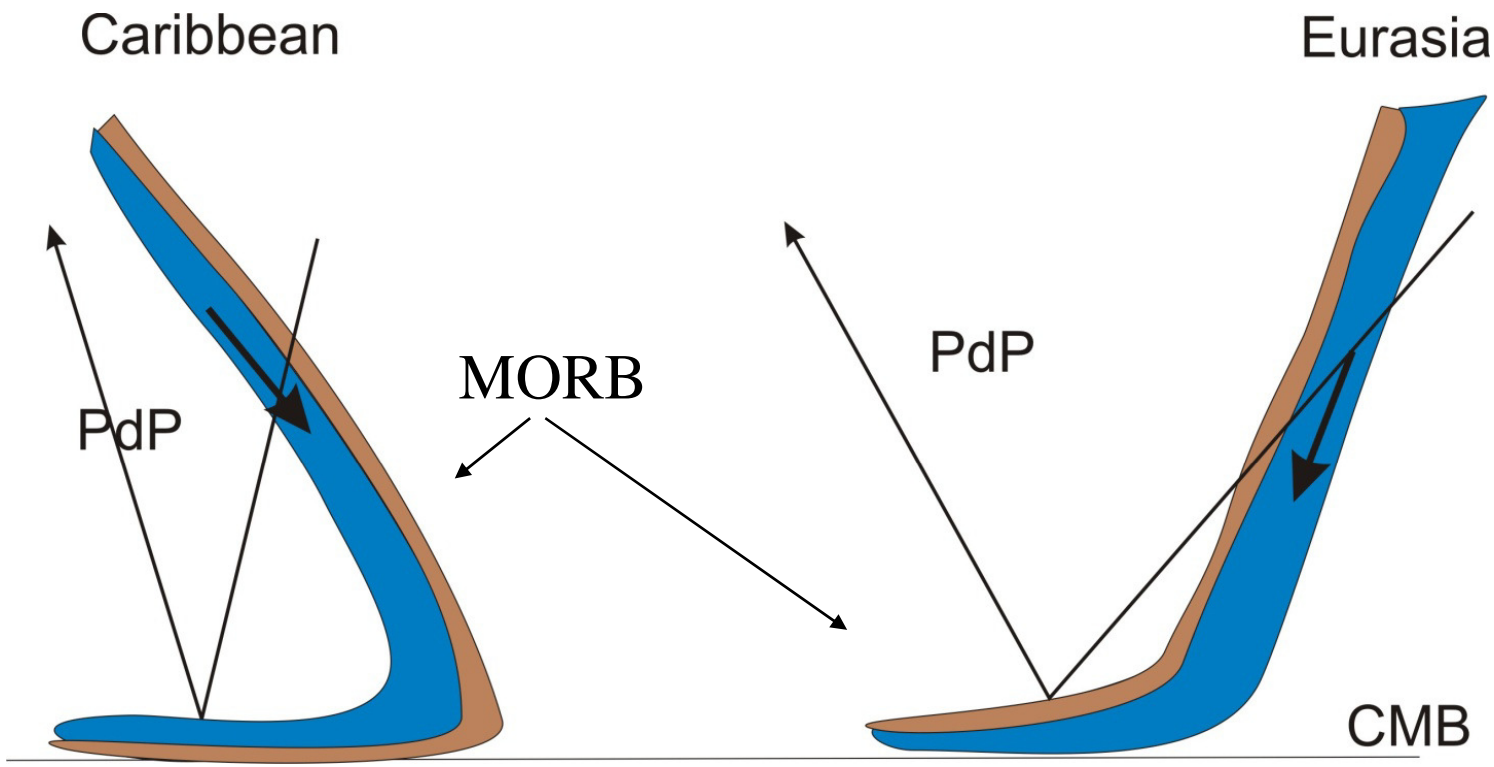



Figure 9

# Possible explanation




Pacific/Bering Sea: reflection off MORB

Cobden and Thomas, GJI subm.

# Conclusions

Seismic structures in D" include up to two reflectors, anisotropy, ulvz etc.

high velocity regions:

*D" reflectors show positive velocity contrast for S-waves*
*varying velocity contrast for P-waves*
*amplitude between 1 and 3% in most regions*

low velocity regions:

*D" reflectors visible, positive P- and S-wave impedance*

Possibility for explanation: *From amplitude and velocity contrasts of D" reflection:*

- *phase change from perovskite to post-perovskite (anisotropic)*

- *different causes: increase in MORB,*
  *post-perovskite phase transition*
  *strong changes in Temperature.*