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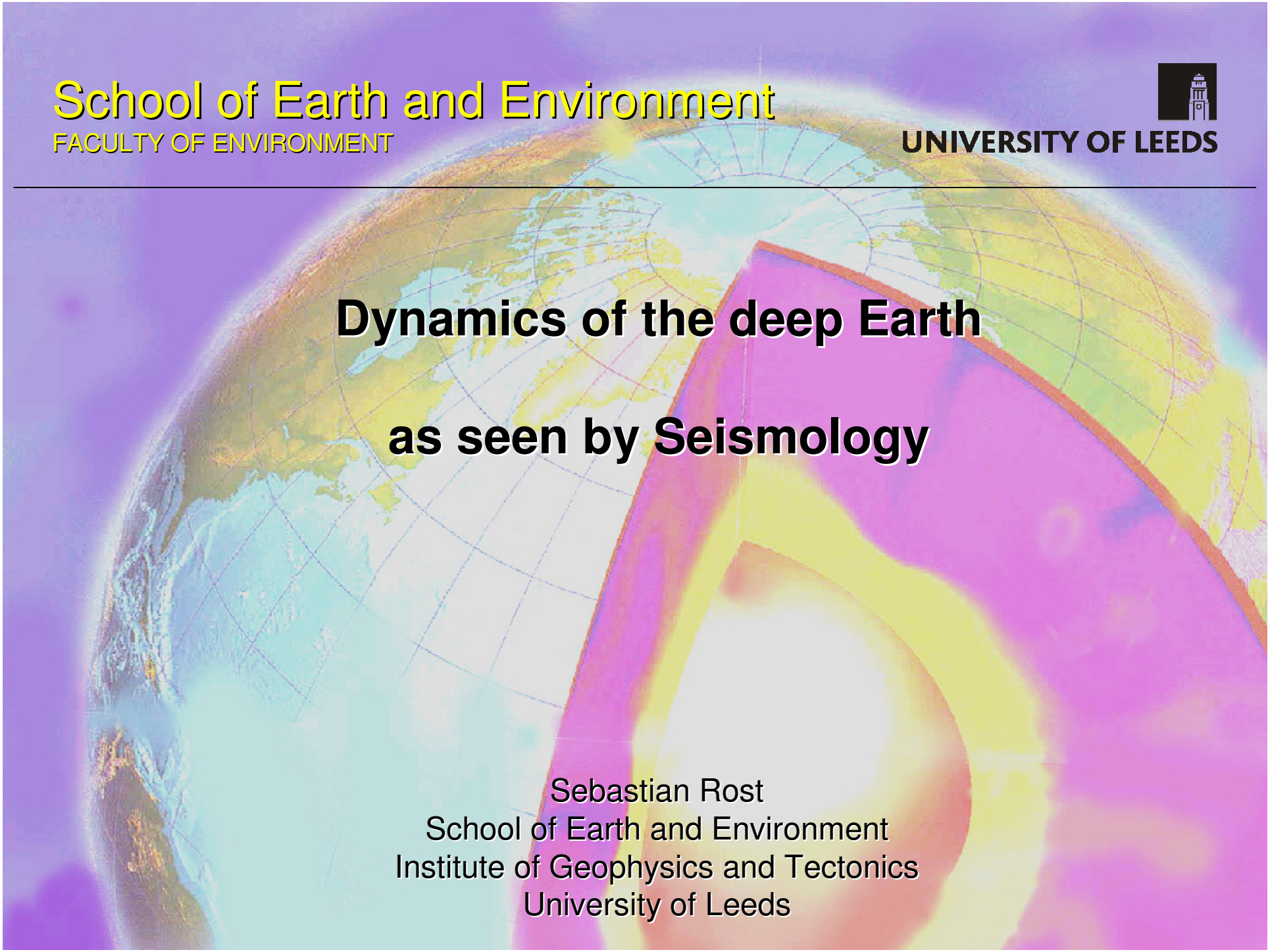

Dynamics of the deep Earth

as seen by Seismology

Sebastian Rost
School of Earth and Environment
Institute of Geophysics and Tectonics
University of Leeds

Contributions by:

Ed Garnero	**Arizona State University**
Tine Thomas	**University of Liverpool**
Quentin Williams	**University of California Santa Cruz**
Tadashi Kito	**University of Liverpool**
Michael Manga	**University of California Berkeley**
Allen McNamara	**Arizona State University**
Paul Earle	**USGS Golden**
Peter Shearer	**Scripps San Diego**

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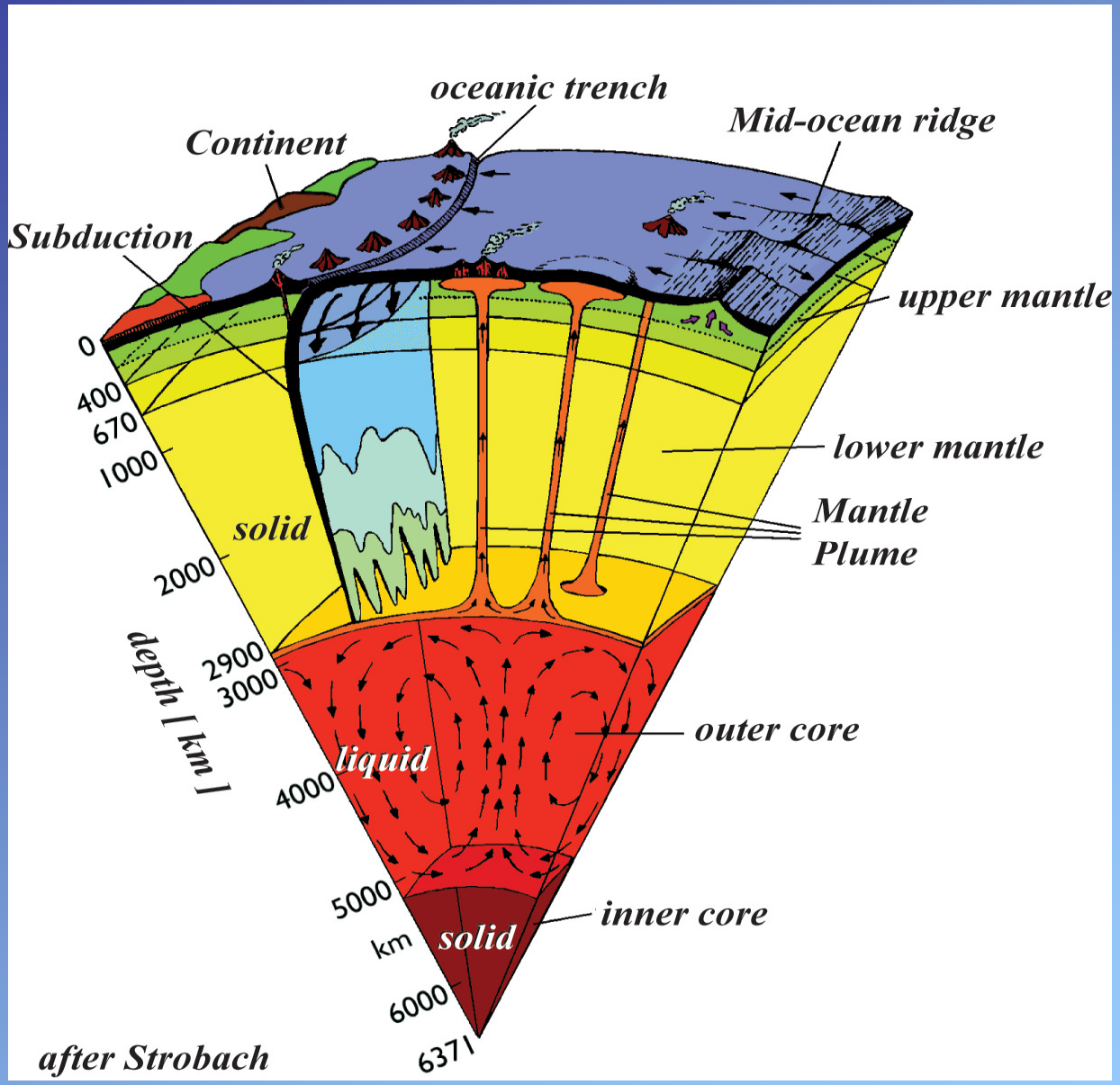
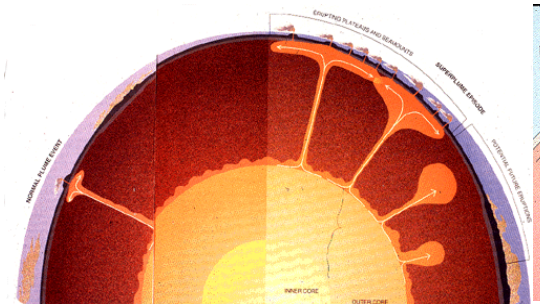
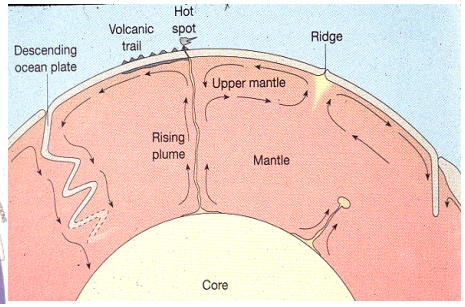
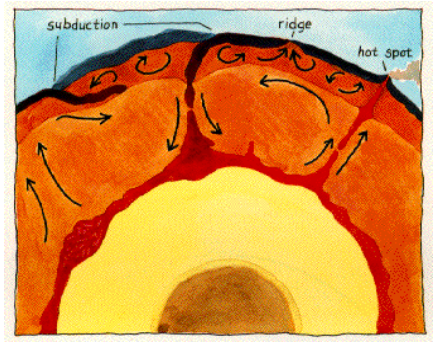
Earth's internal structure – textbook style

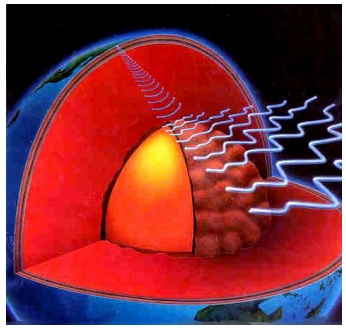


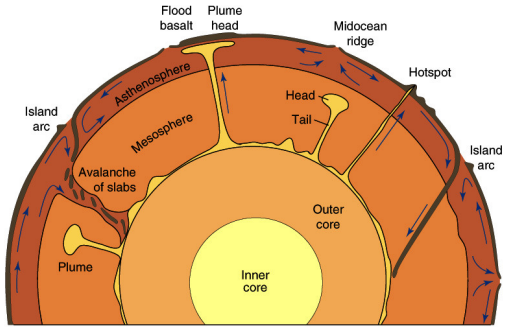
Recent Geophysics/Geochemistry Views

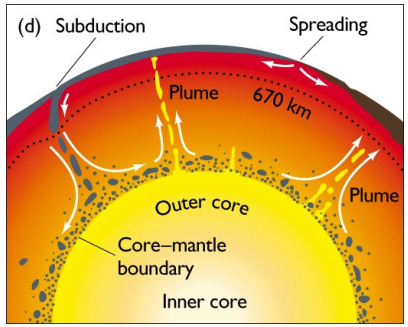


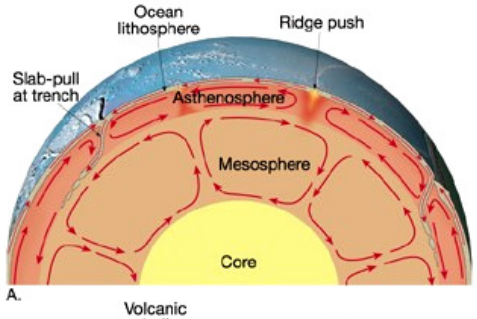


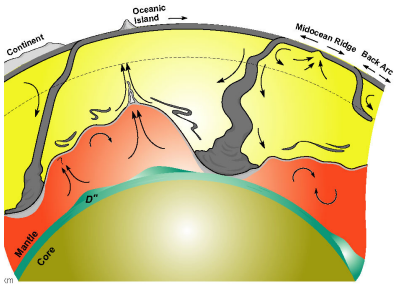


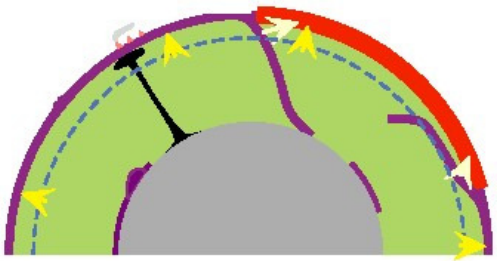


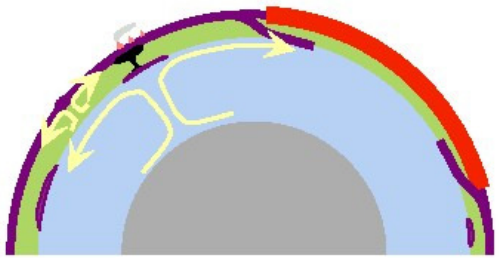


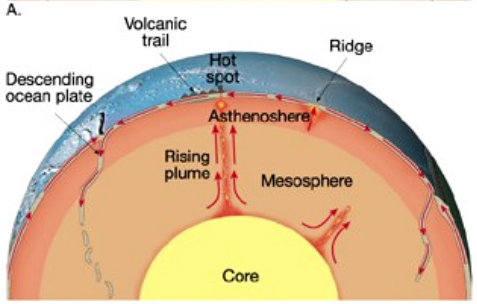




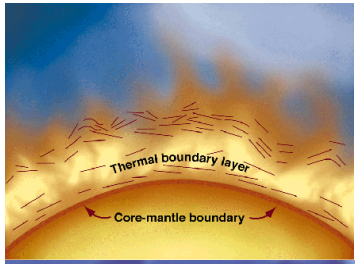


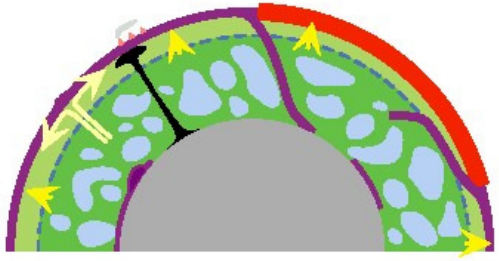


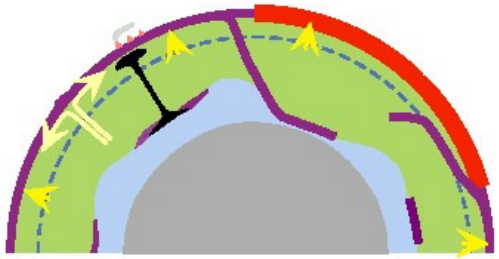


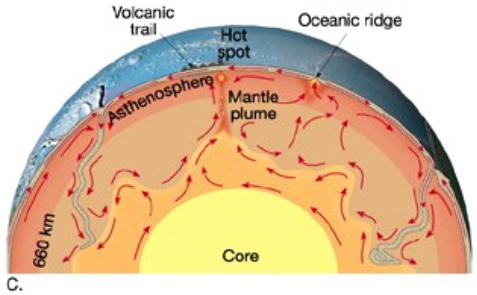


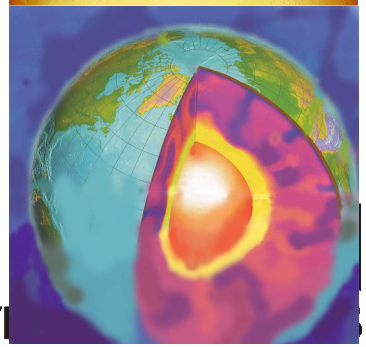
Kellogg, et al 19 MARCH 1999 VOL 283 SCIENCE









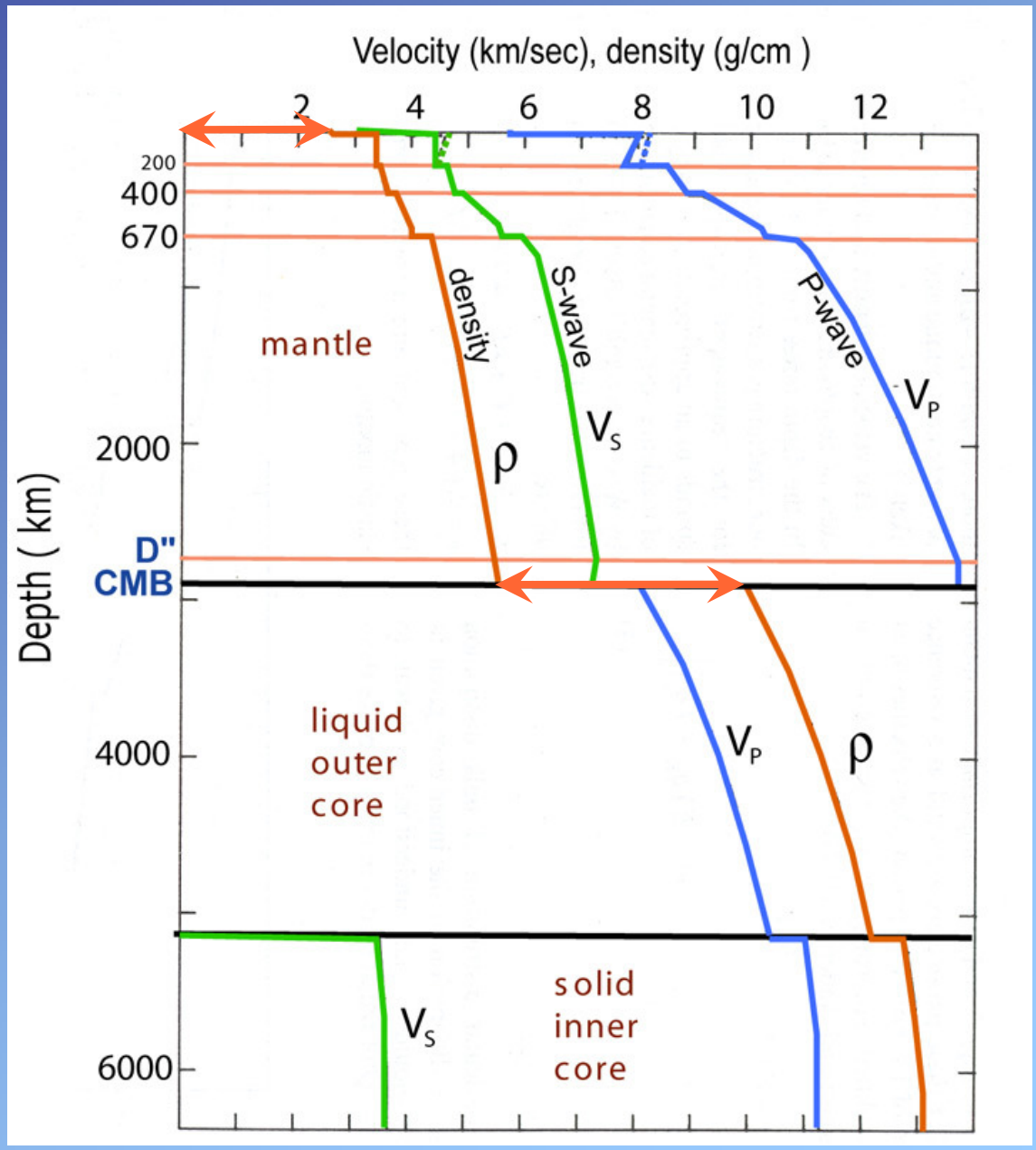


Earth's important boundary layers

Preliminary **R**eference **E**arth **M**odel

PREM

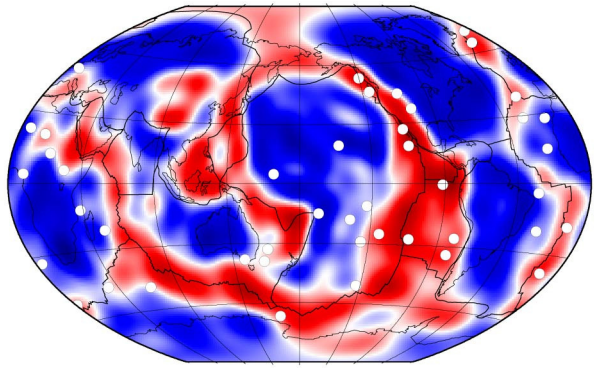
Globally averaged properties with depth



Dziewonski and Anderson [1981, PEPI]

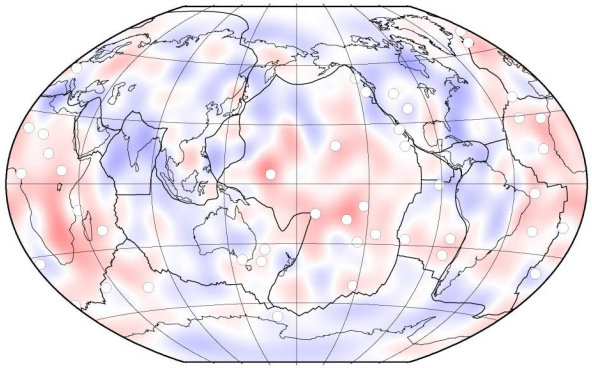
HETEROGENEITY

Z=50 km



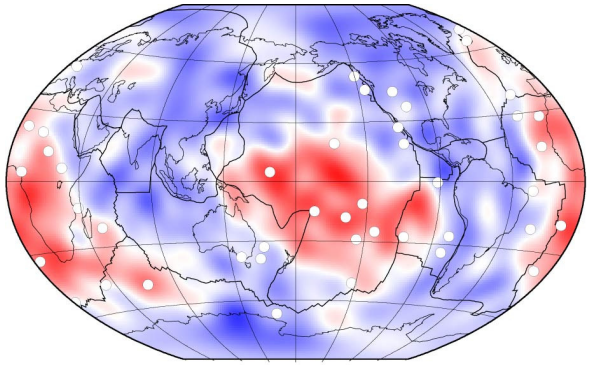
Strongest

Z=1500 km

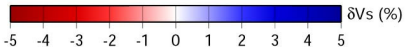


Weakest

Z=2880 km



Strong again



[Tomography Ritsema and van Heijst, 2001]

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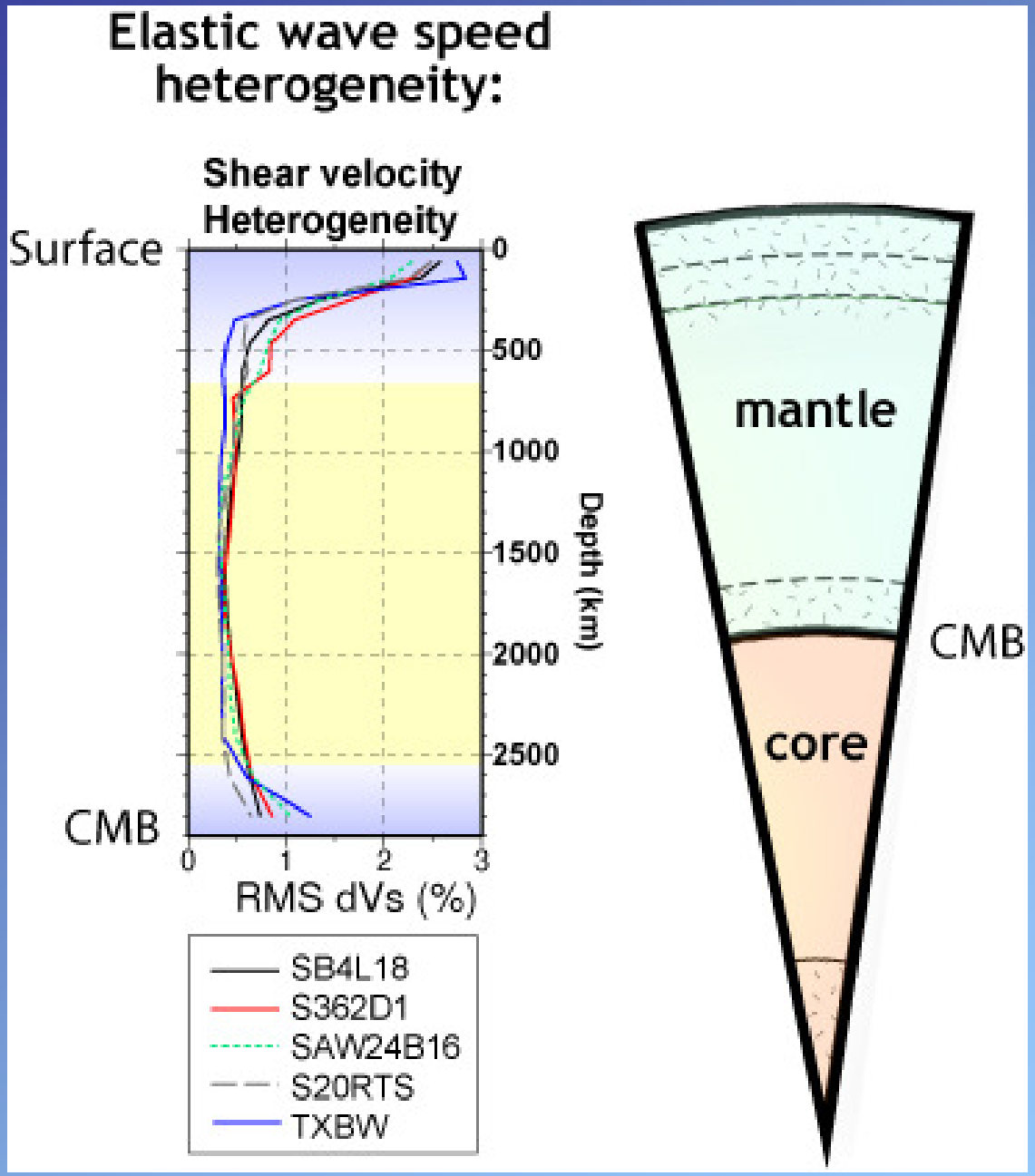
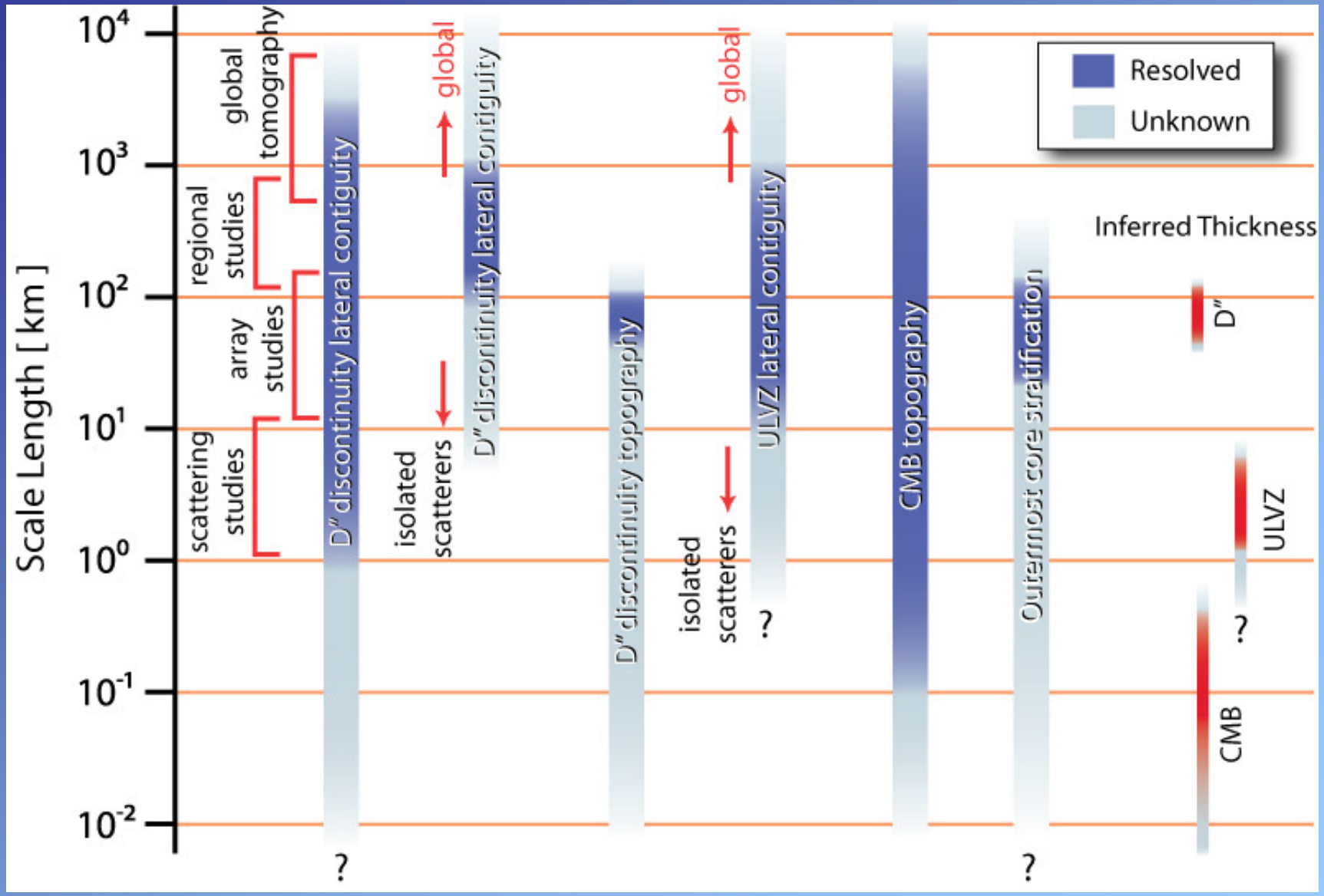
Elastic wave speed heterogeneity:



(adapted from: garnero.asu.edu)

Seismically determined D'' / CMB Phenomena



[after Garnero, 2005]

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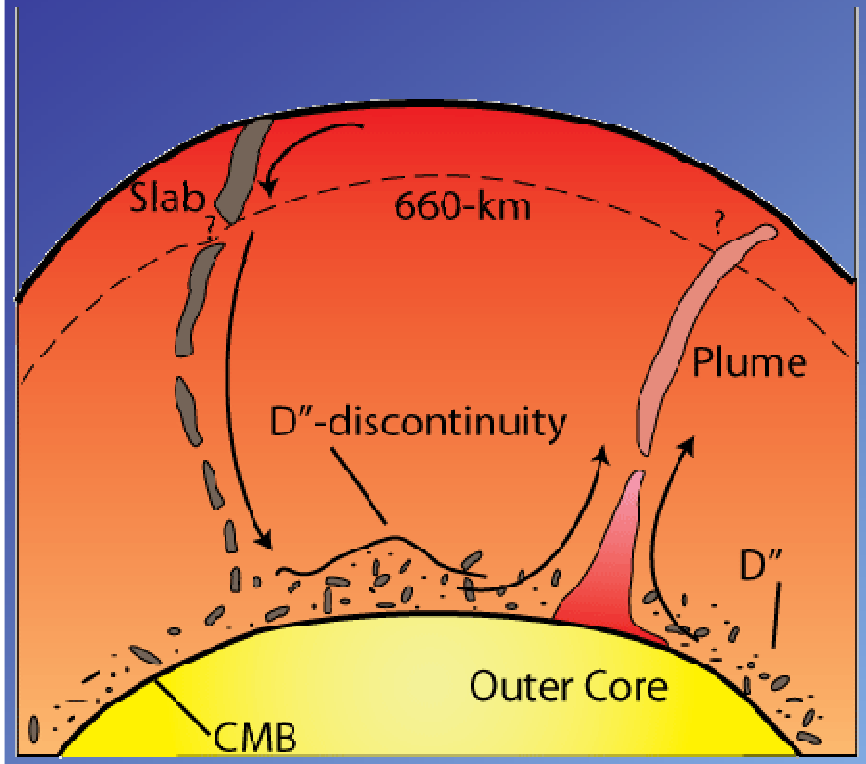
Earth's Deep Interior



CMB: Thermal boundary layer
- Largest density increase
- Huge viscosity contrast
- Chemical heterogeneity

D" Highly heterogeneous
- Anisotropic
- Intermittent Discontinuity
- Scattering

ULVZ Ultra Low Velocity zone
- Extreme velocity reductions
- Dense material
- Partial Melts?

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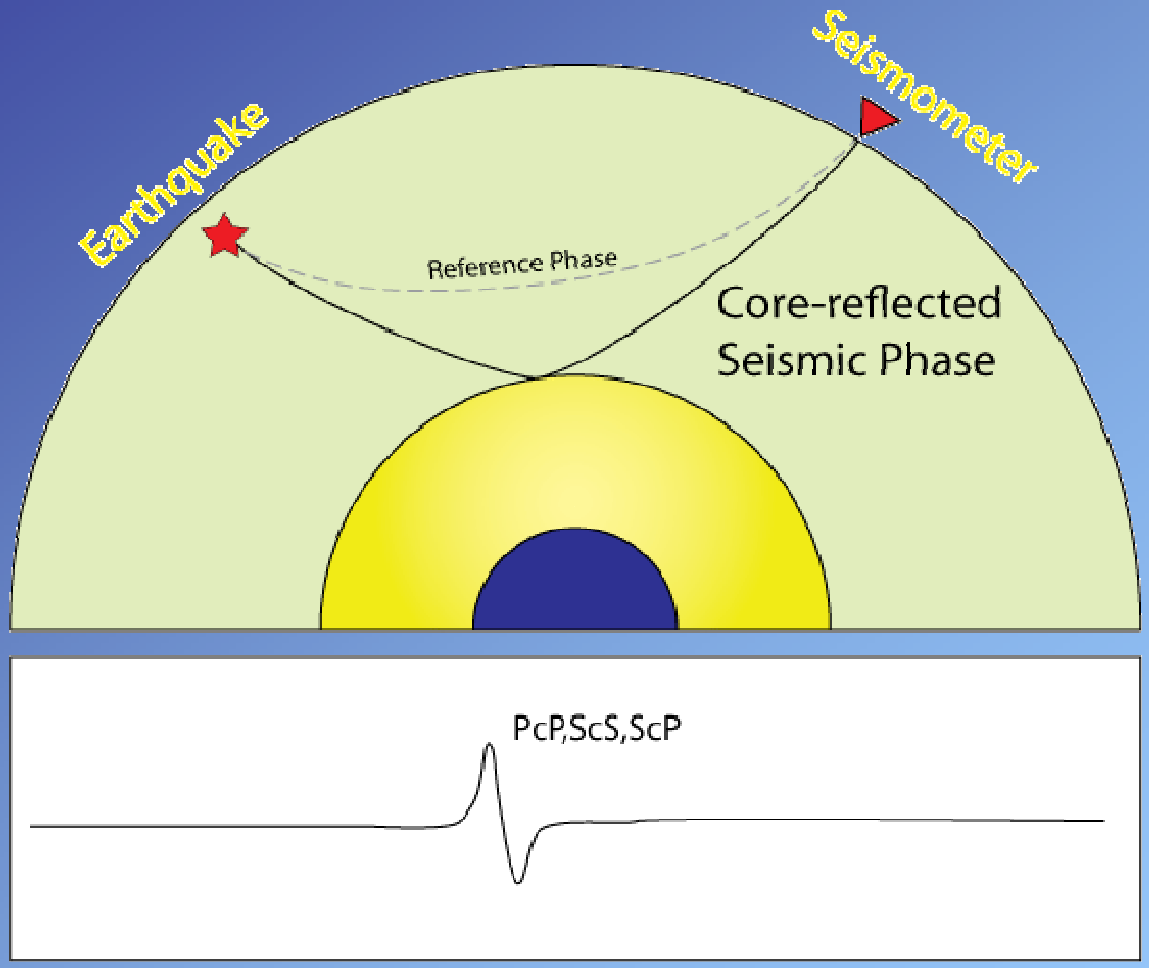
Seismic Sampling of D'' and CMB



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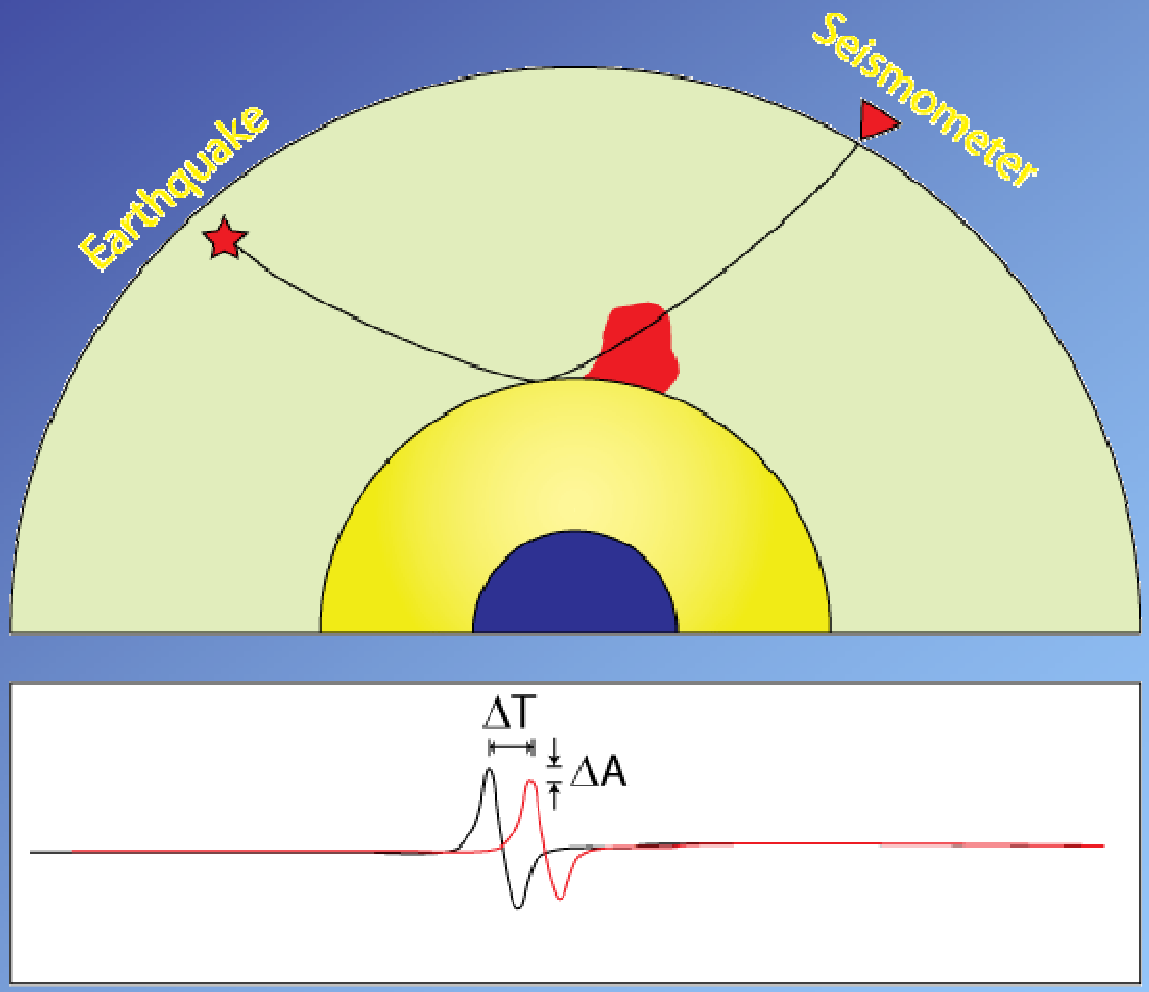
Tomography



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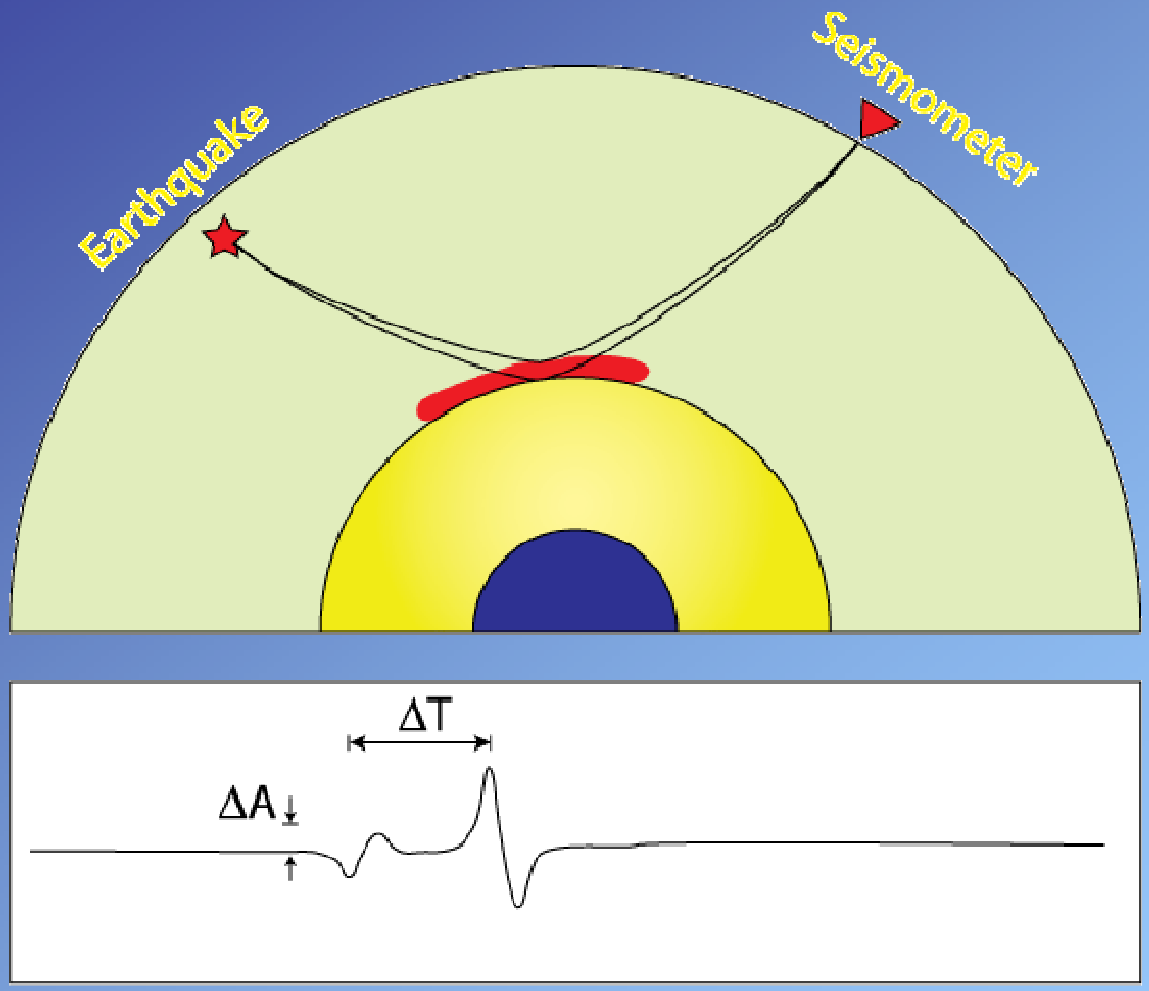
Reflected Phases



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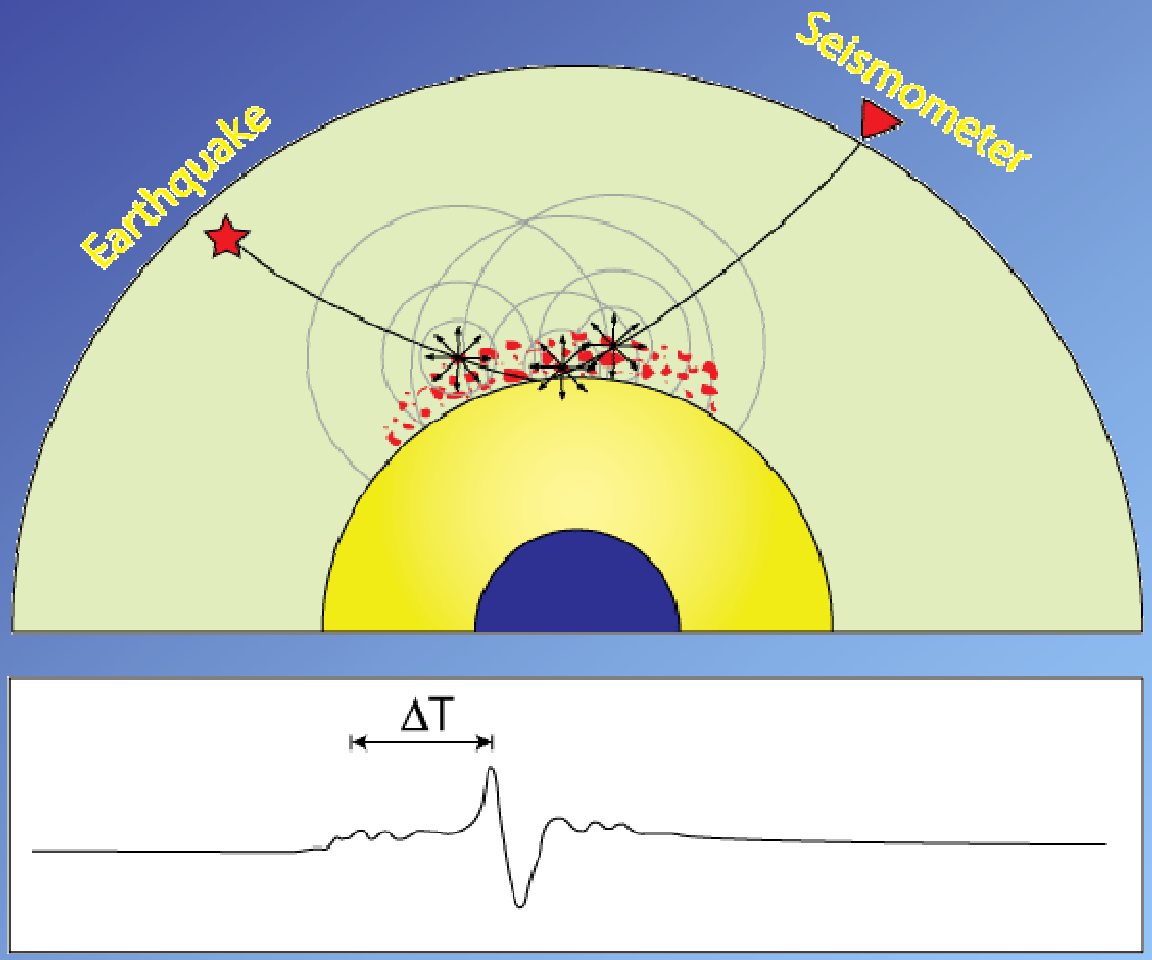
Scattering



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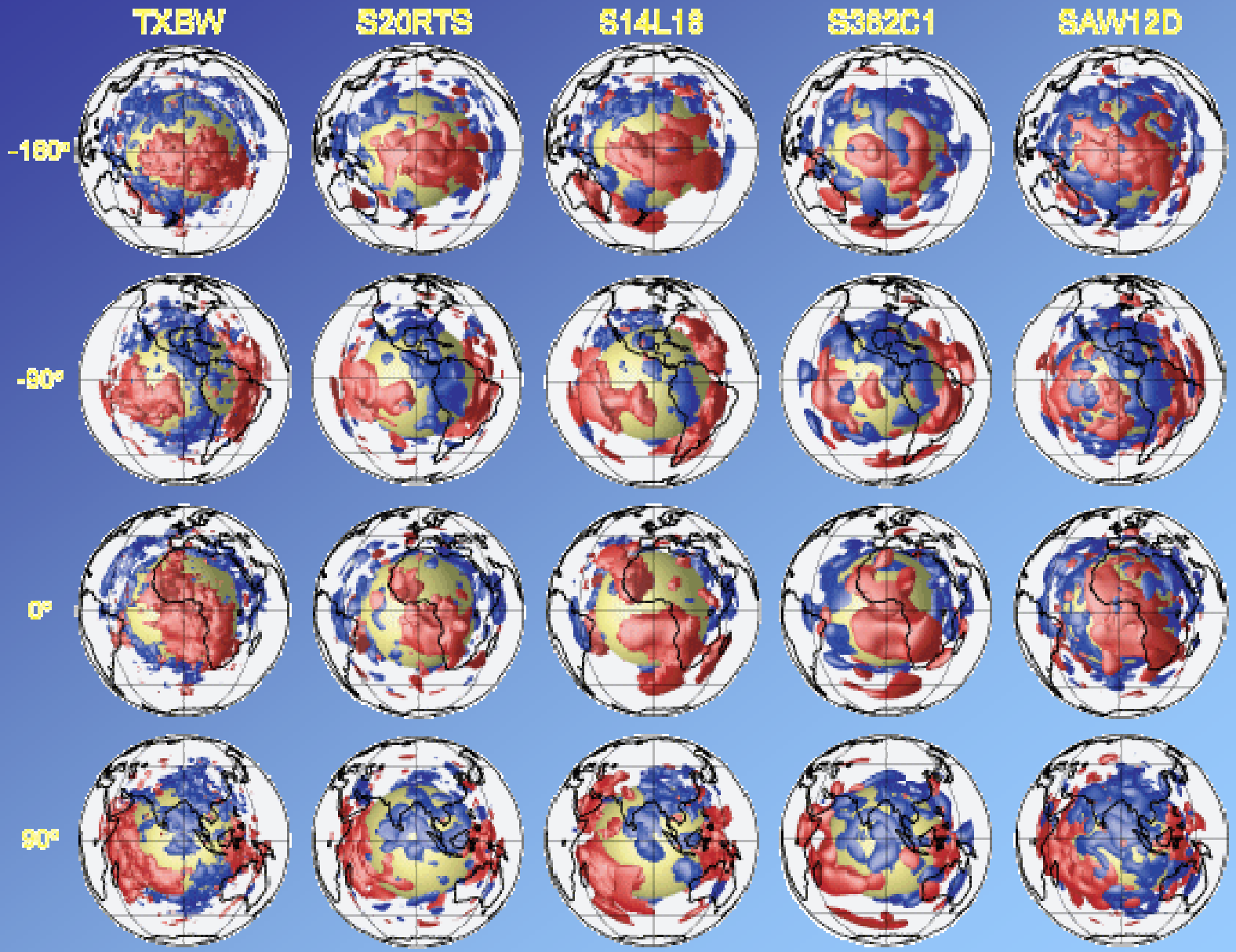
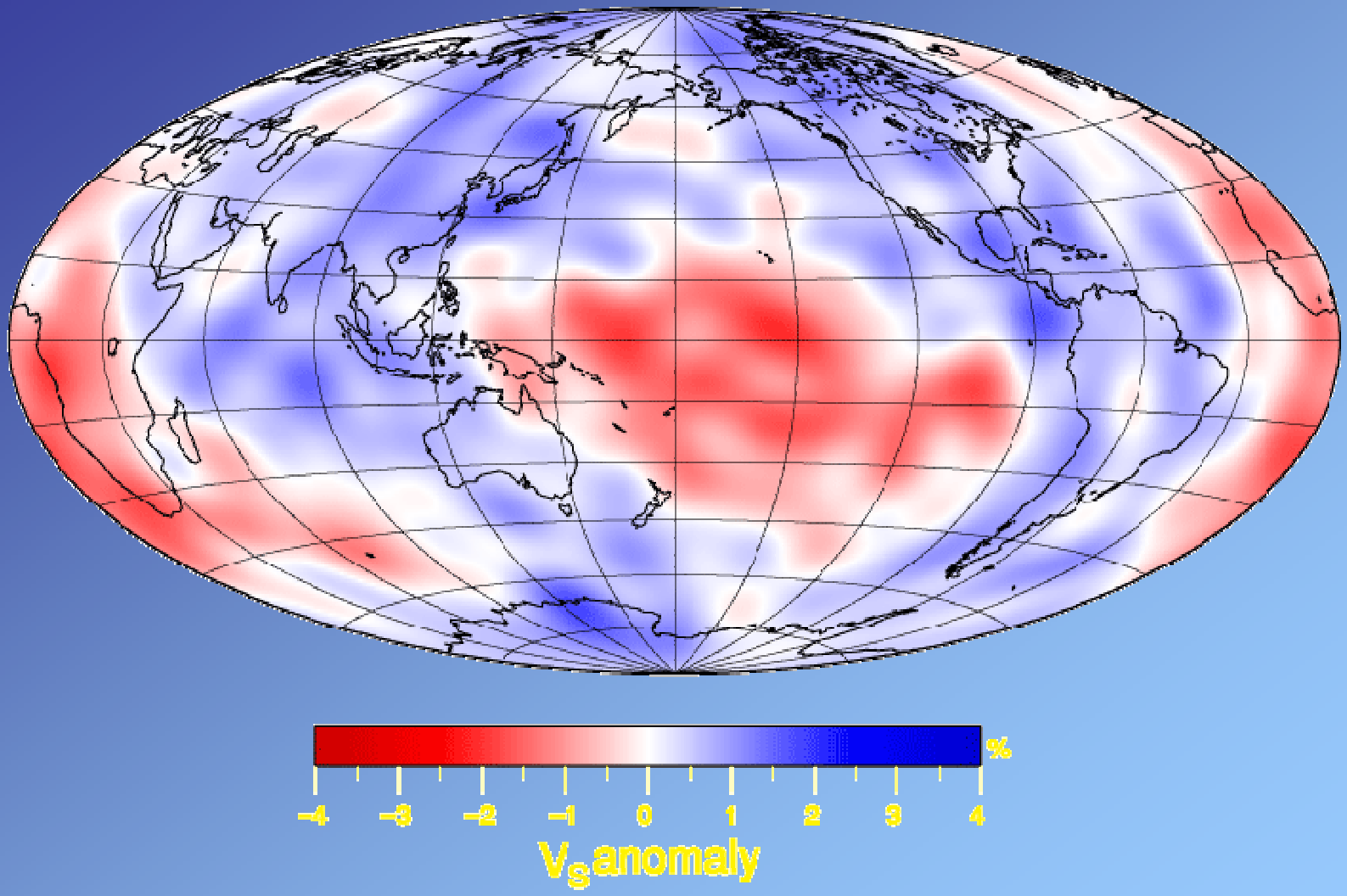
Degree 2 heterogeneity



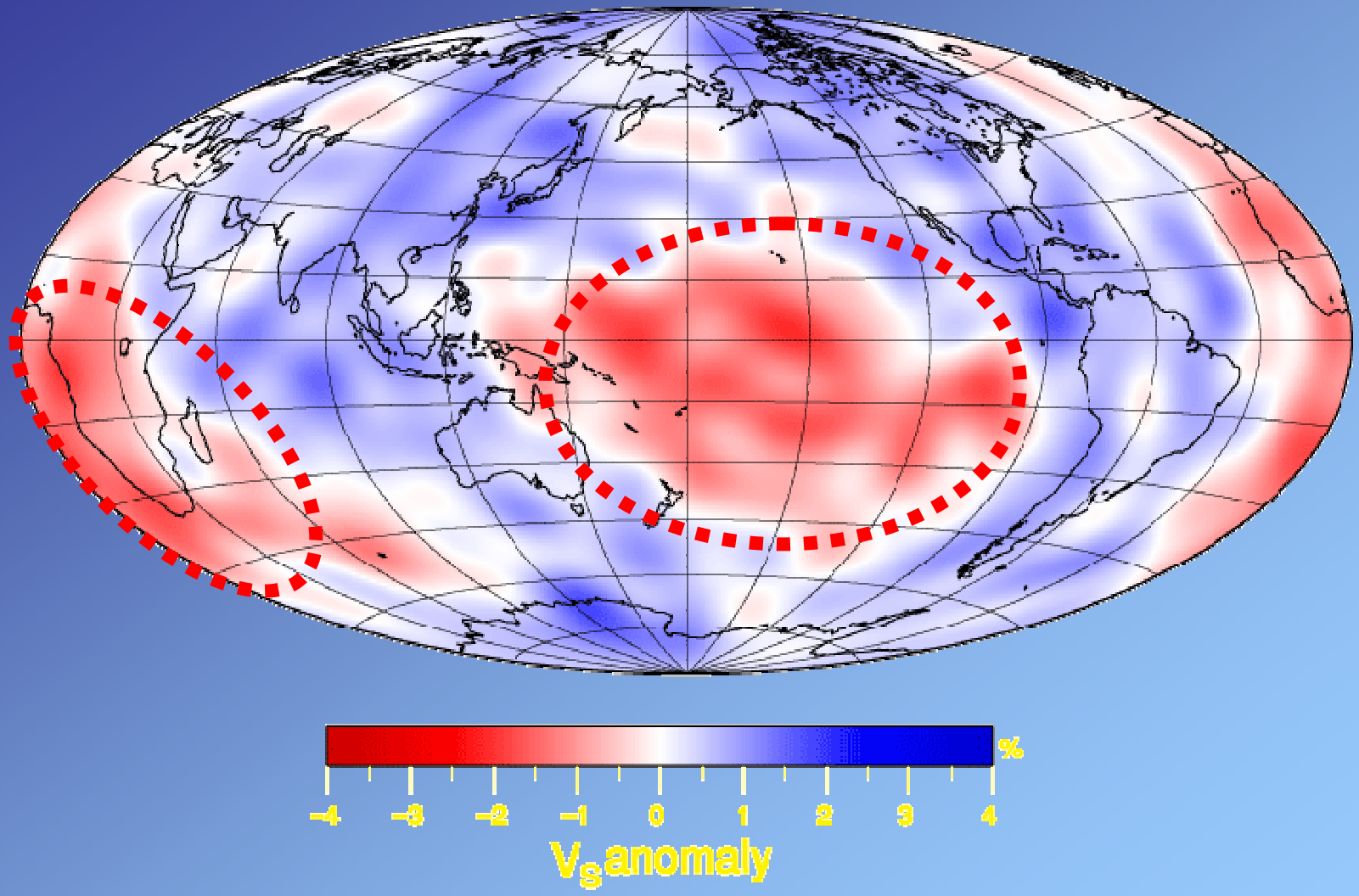
[Garnero et al., Superplumes, 2007]

Degree 2 heterogeneity



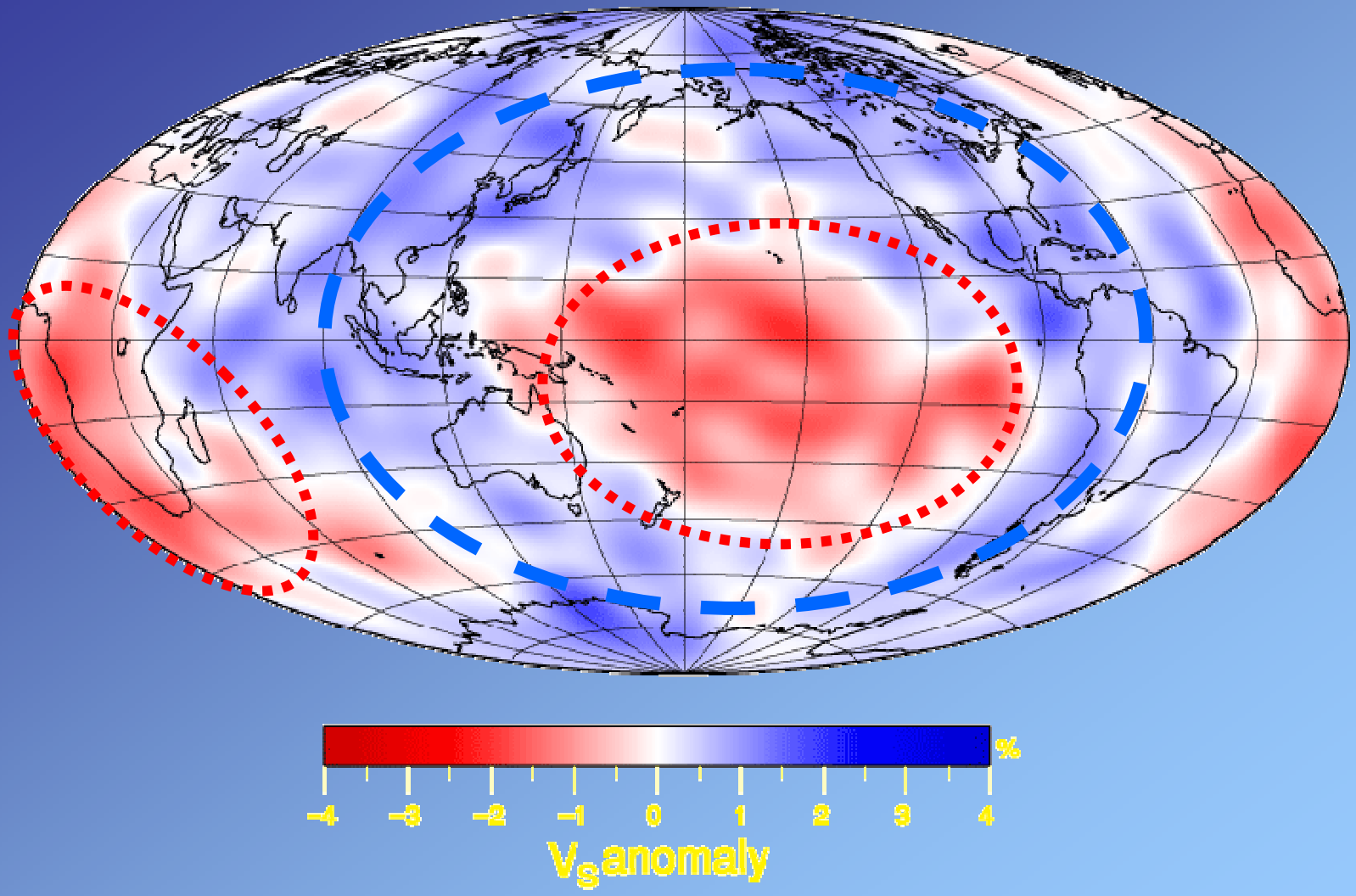
[Ritsema and van Heijst, 2001]

Degree 2 heterogeneity



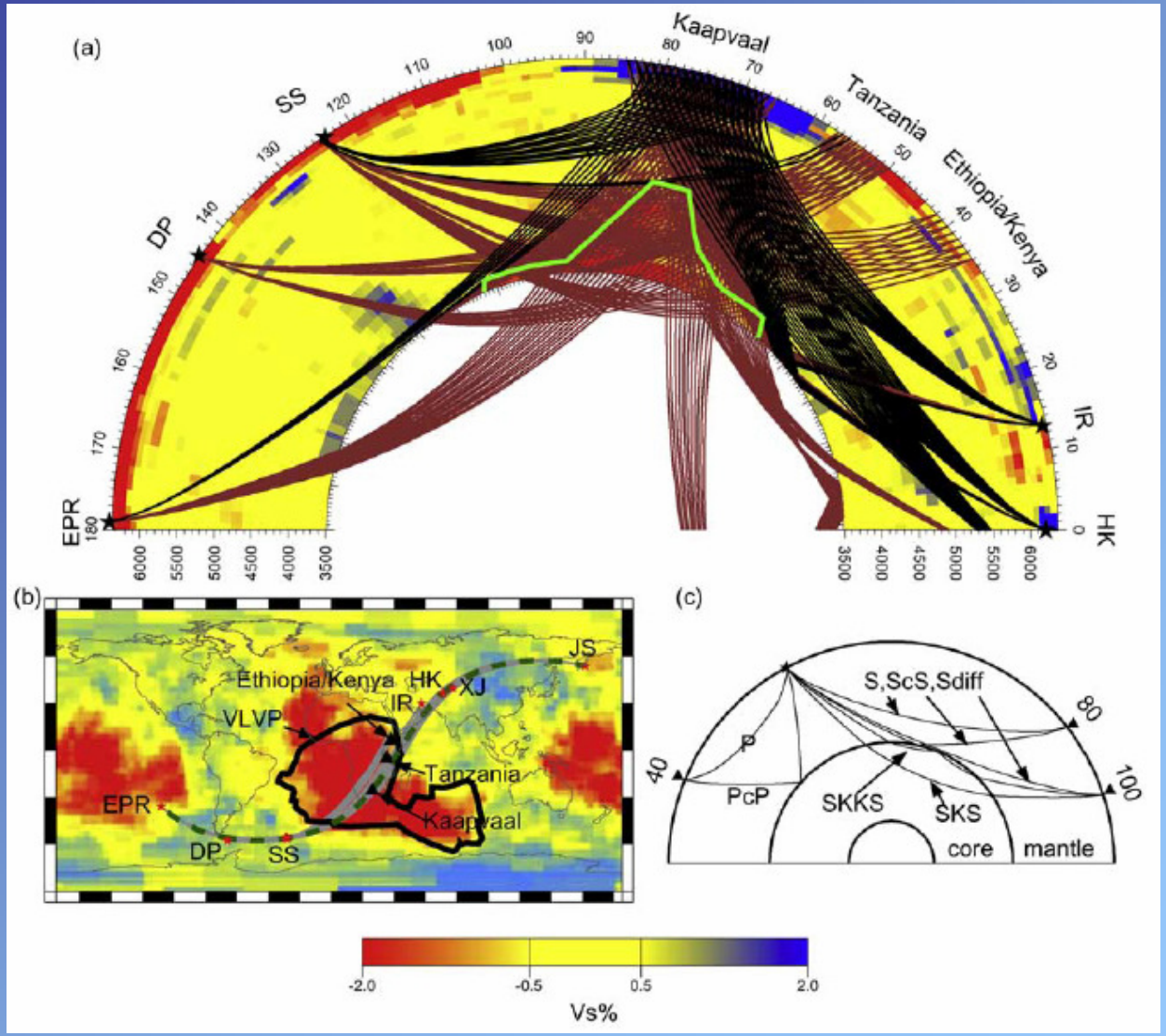
[Ritsema and van Heijst, 2001]

Degree 2 heterogeneity



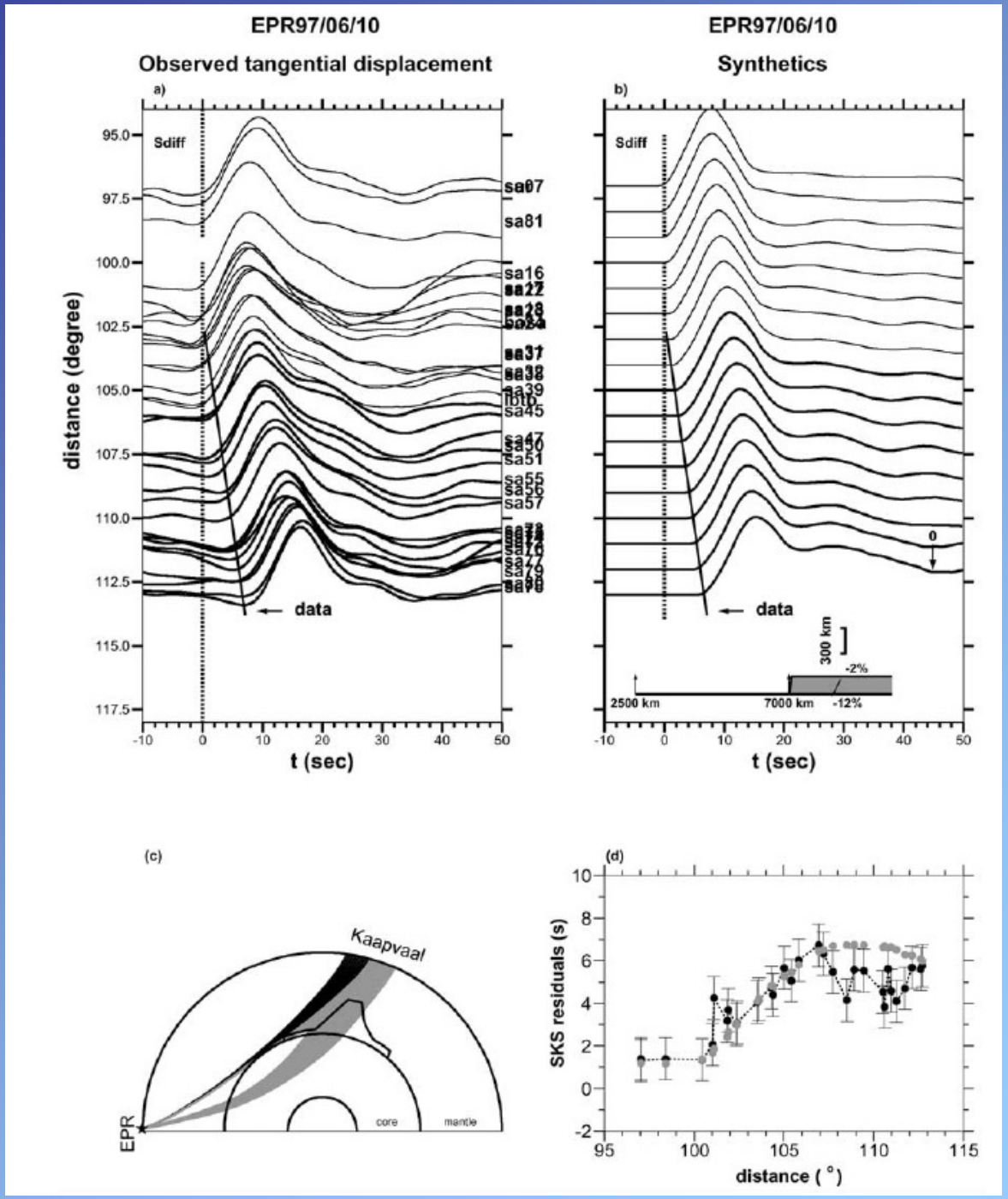
[Ritsema and van Heijst, 2001]

African Anomaly

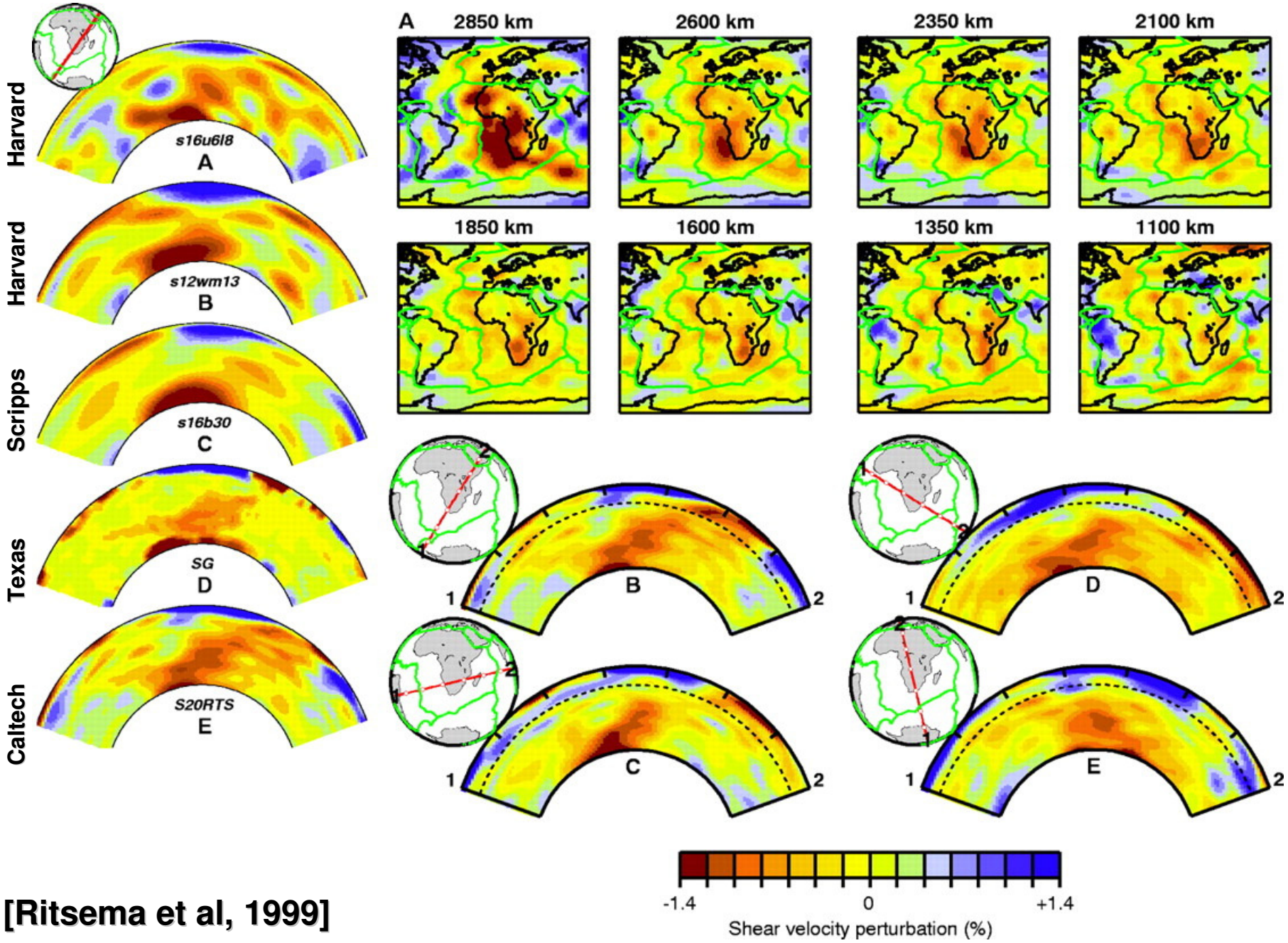


[Wang and Wen, JGR, 2007]

Detailed waveform modeling + Traveltime analysis

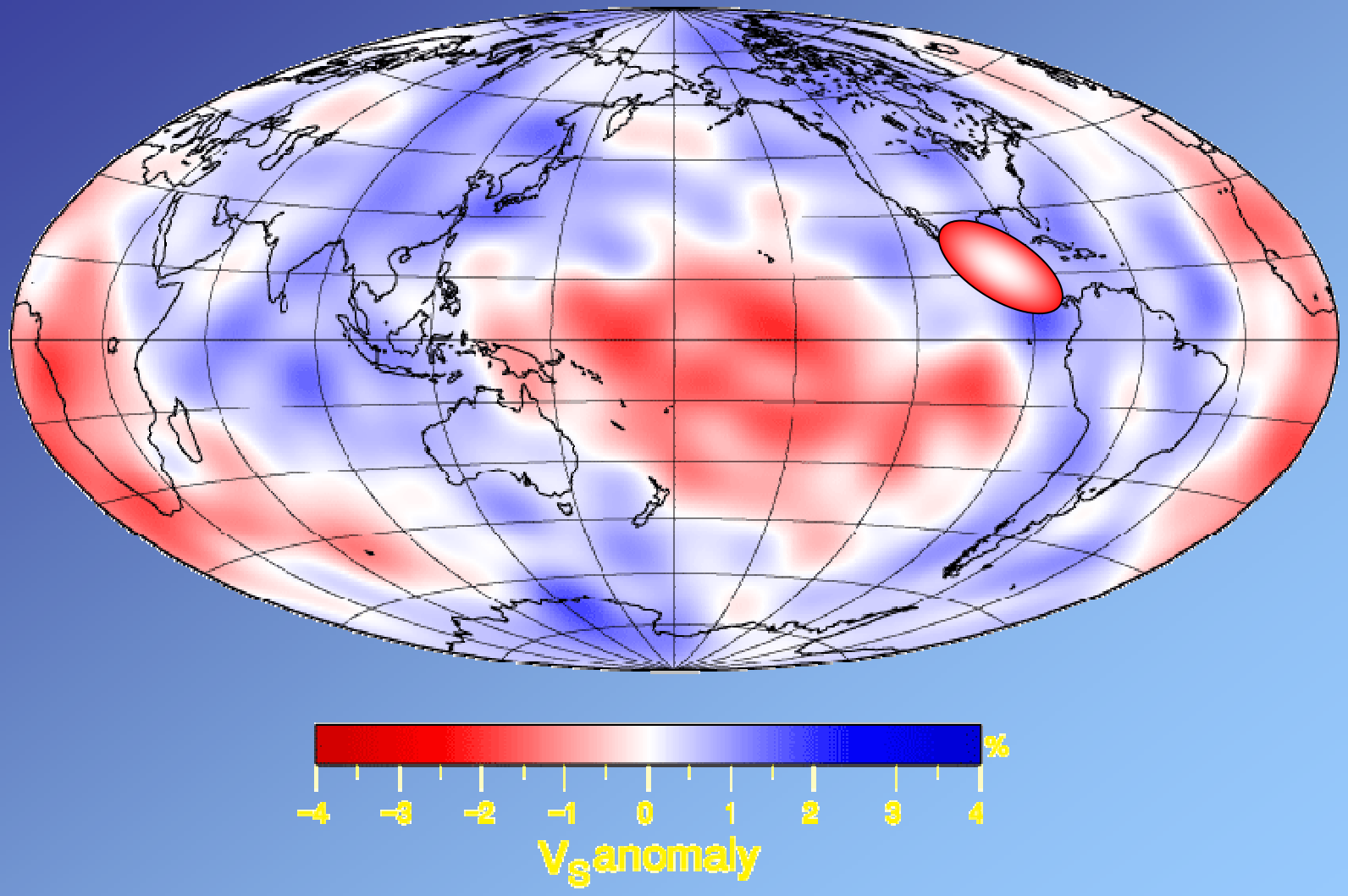


Tomography



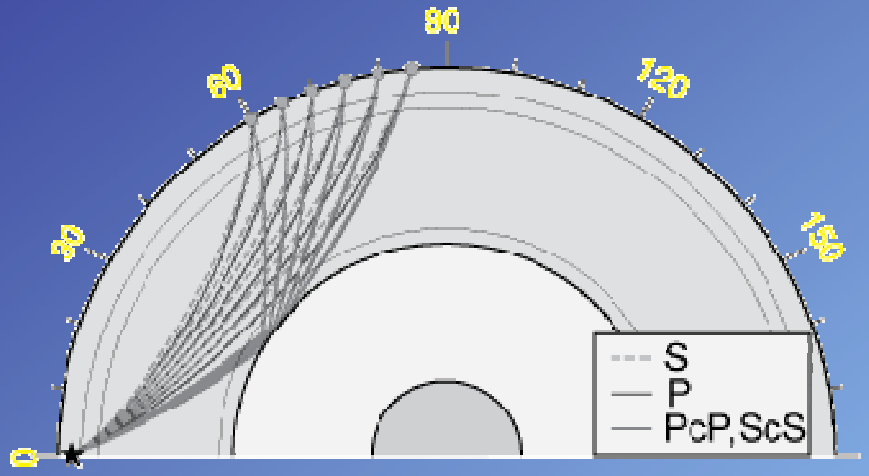
[Ritsema et al, 1999]

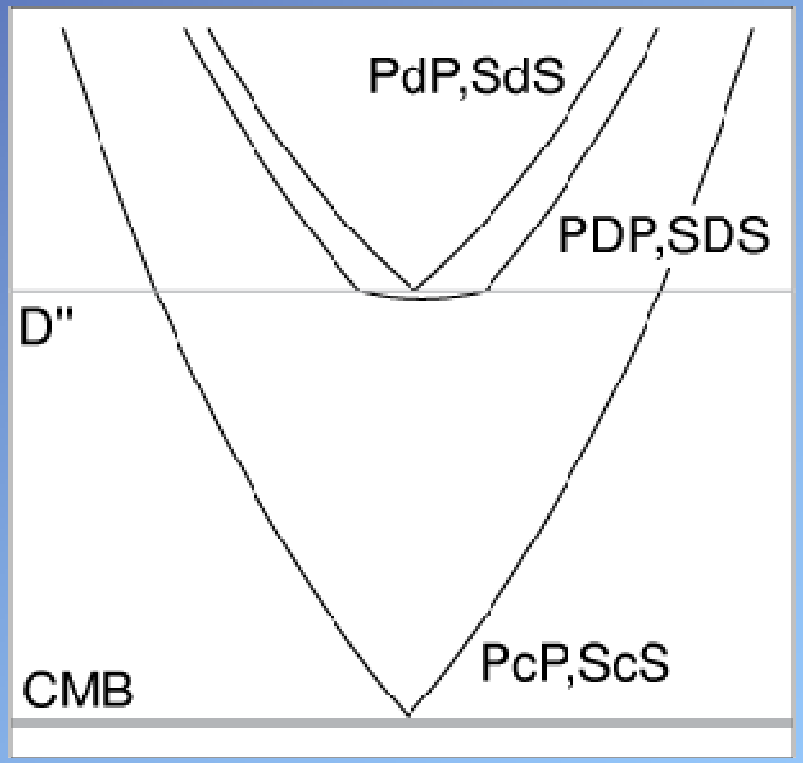
D'' discontinuity structure



[Tomography: Ritsema & van Heijst, 2001]

D'' structure beneath the Cocos plate





Kito, Rost, Thomas & Garnero, GJI, 2007

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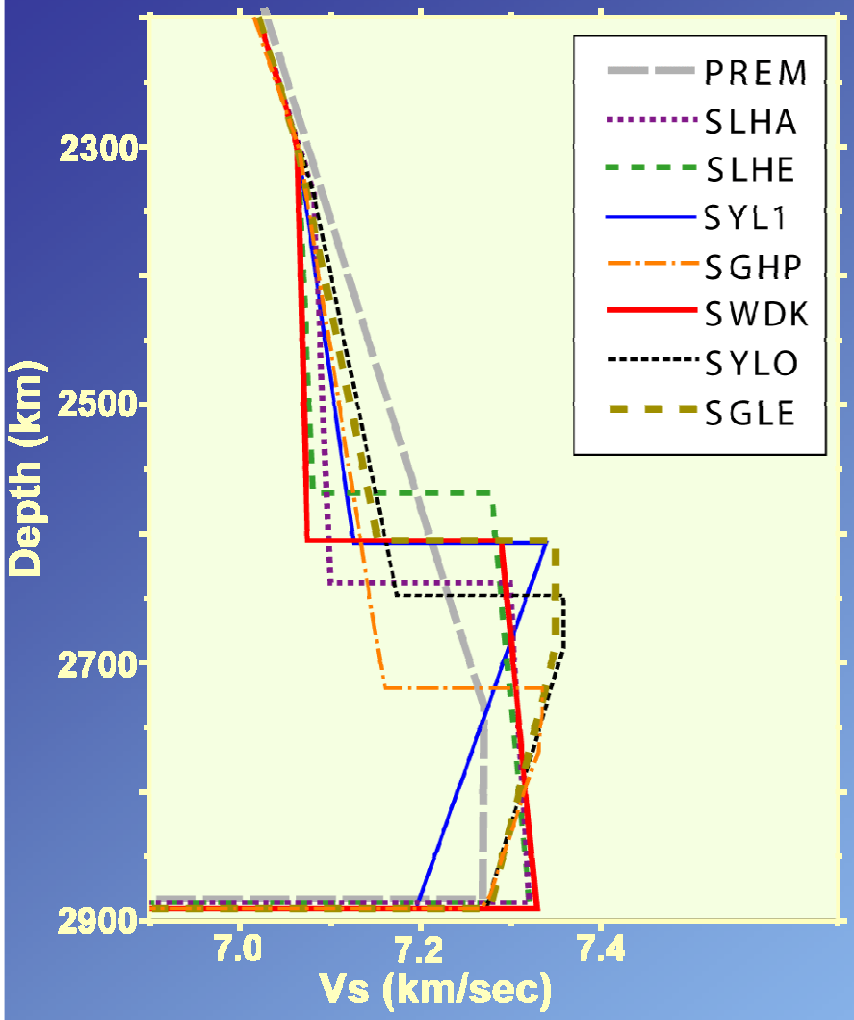
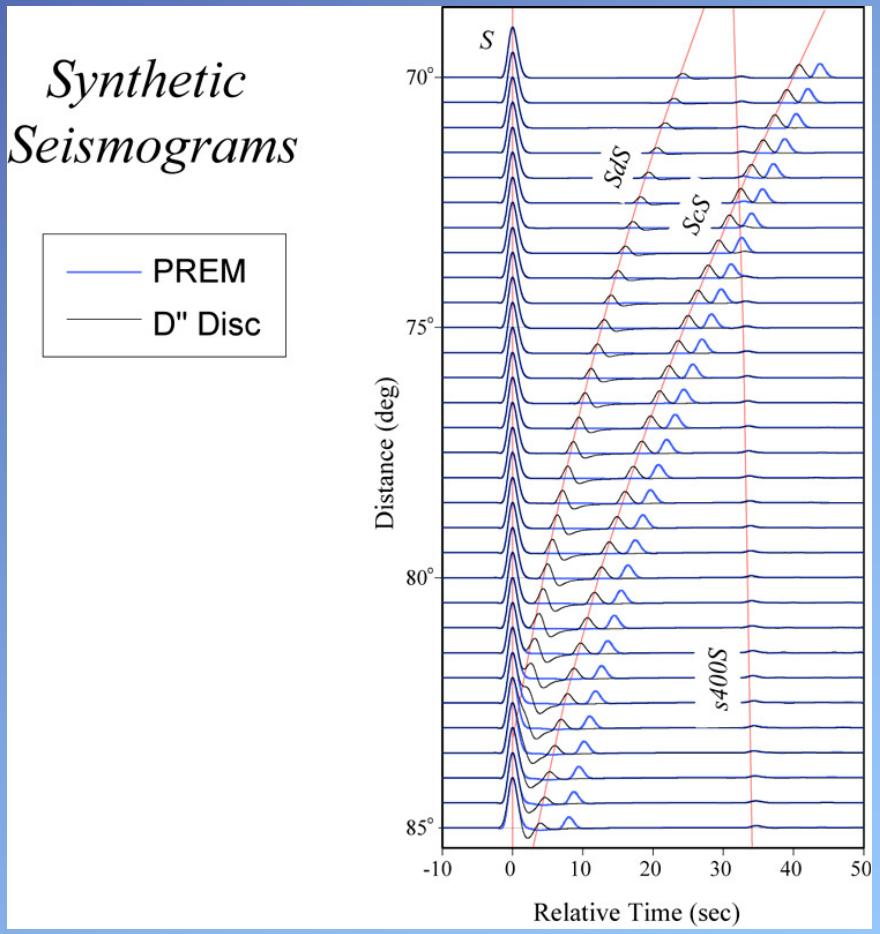
D'' discontinuity



[Lay, Garnero, Williams PEPI, 2004]



Thorne et al., [GJI in press2007]

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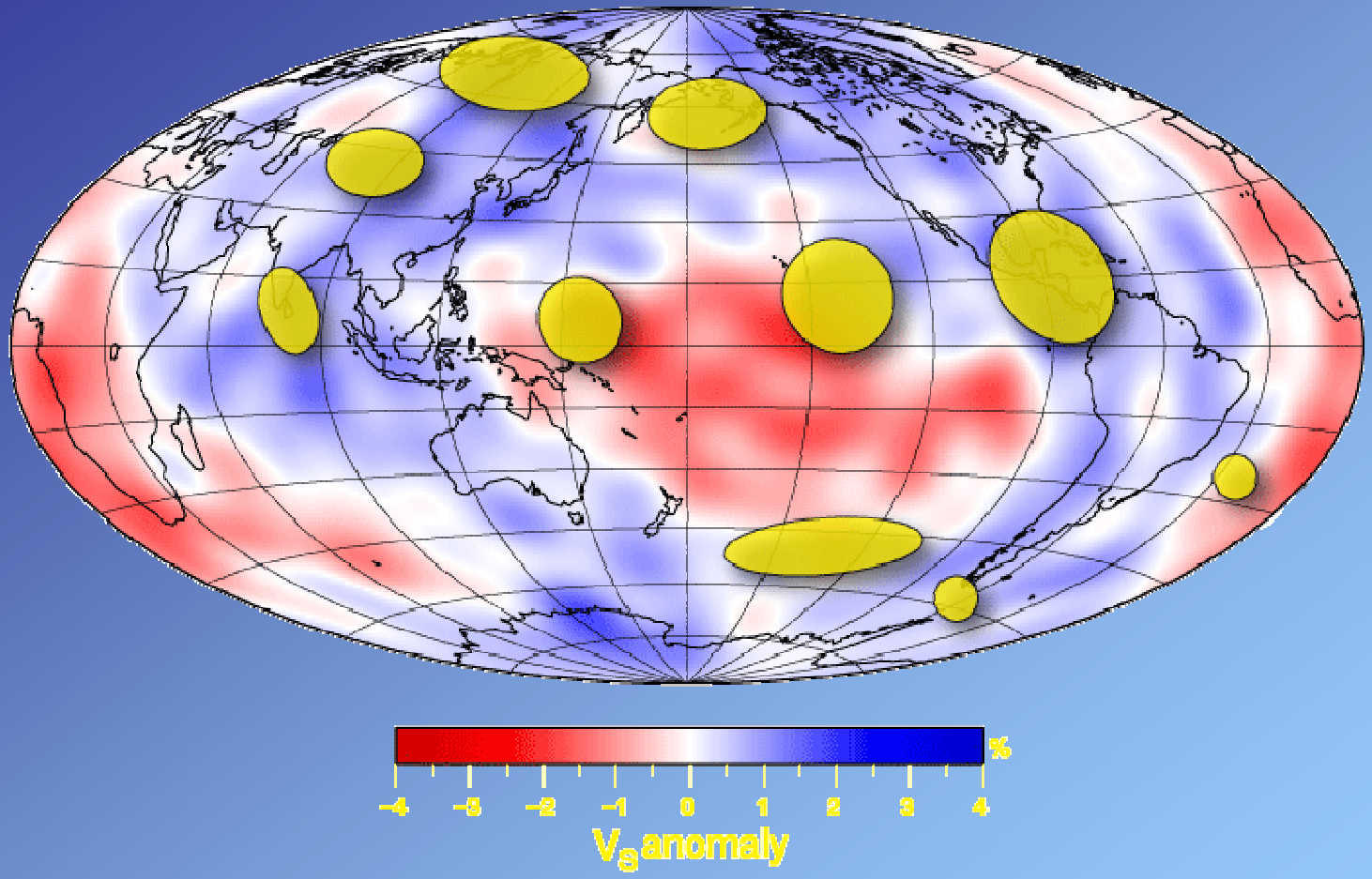
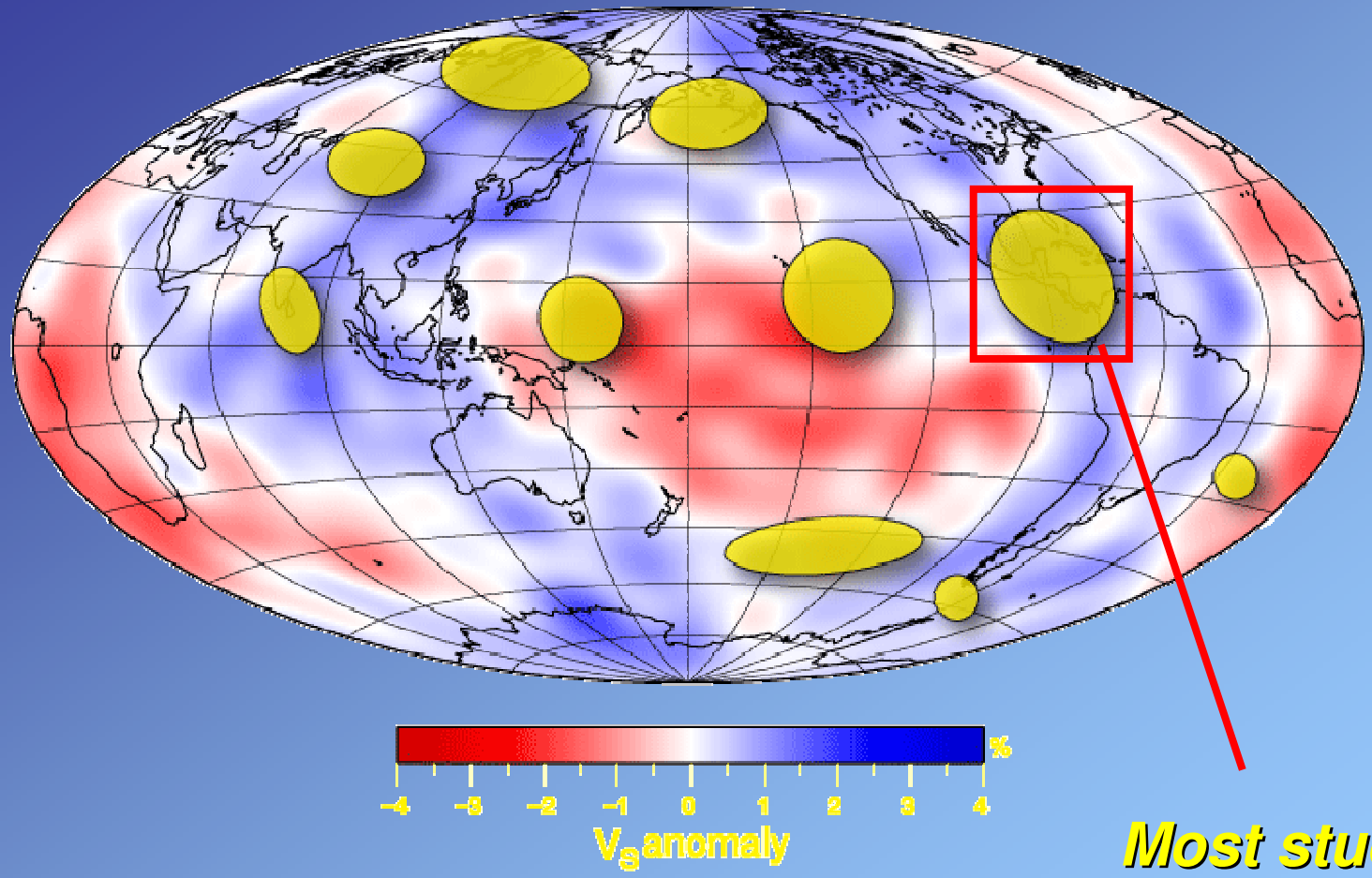
D'' discontinuity Detections from waveforms



Detected D'' discontinuities

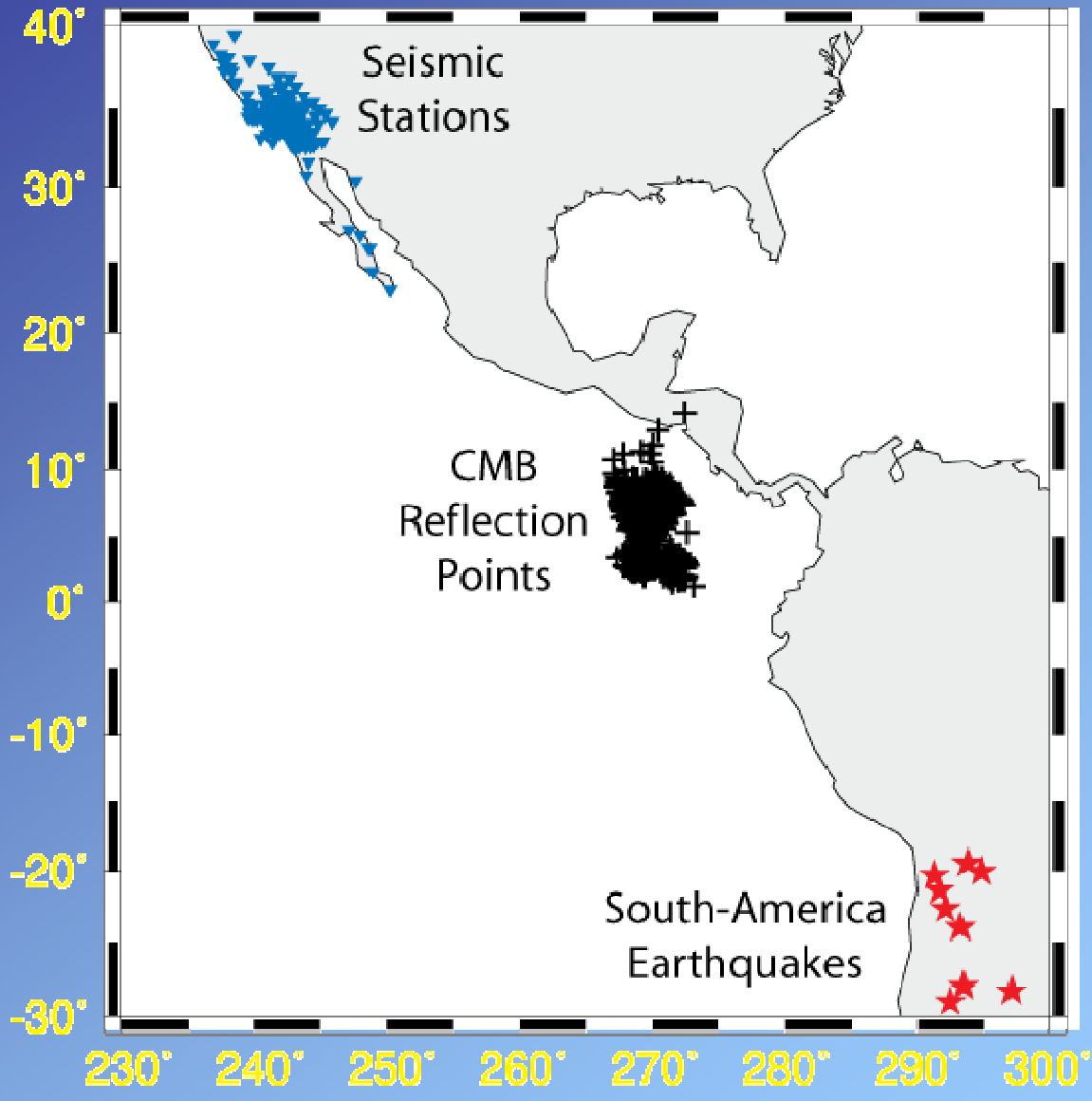
D'' discontinuity Detections from waveforms



Most studied region

Detected D'' discontinuities

D'' discontinuity beneath Cocos plate



[Kito, Rost, Thomas & Garnero, GJI, 2007]

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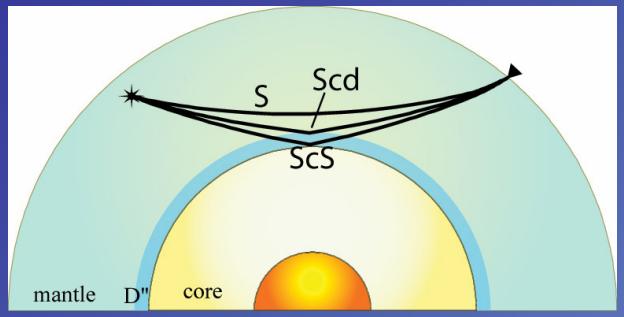
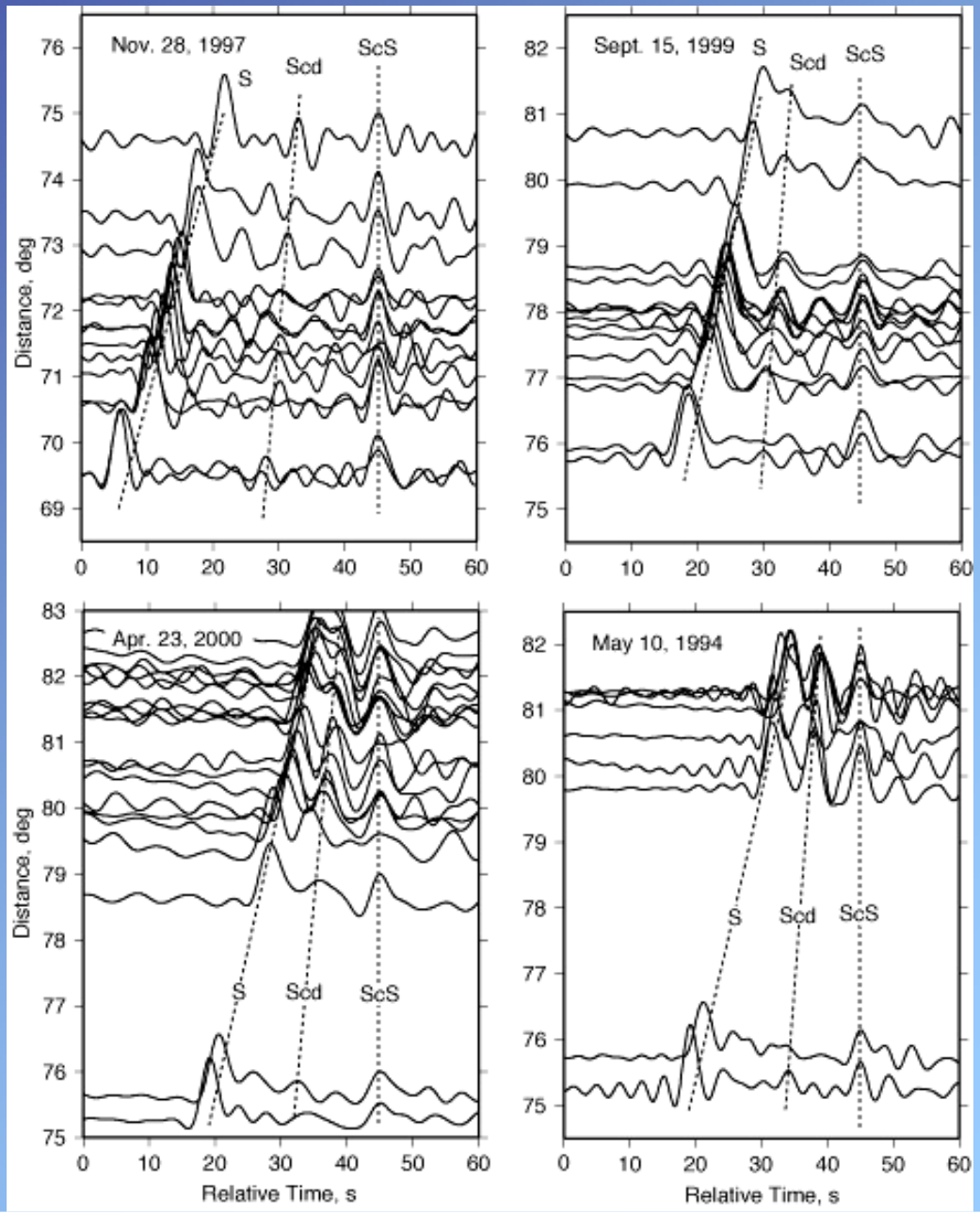
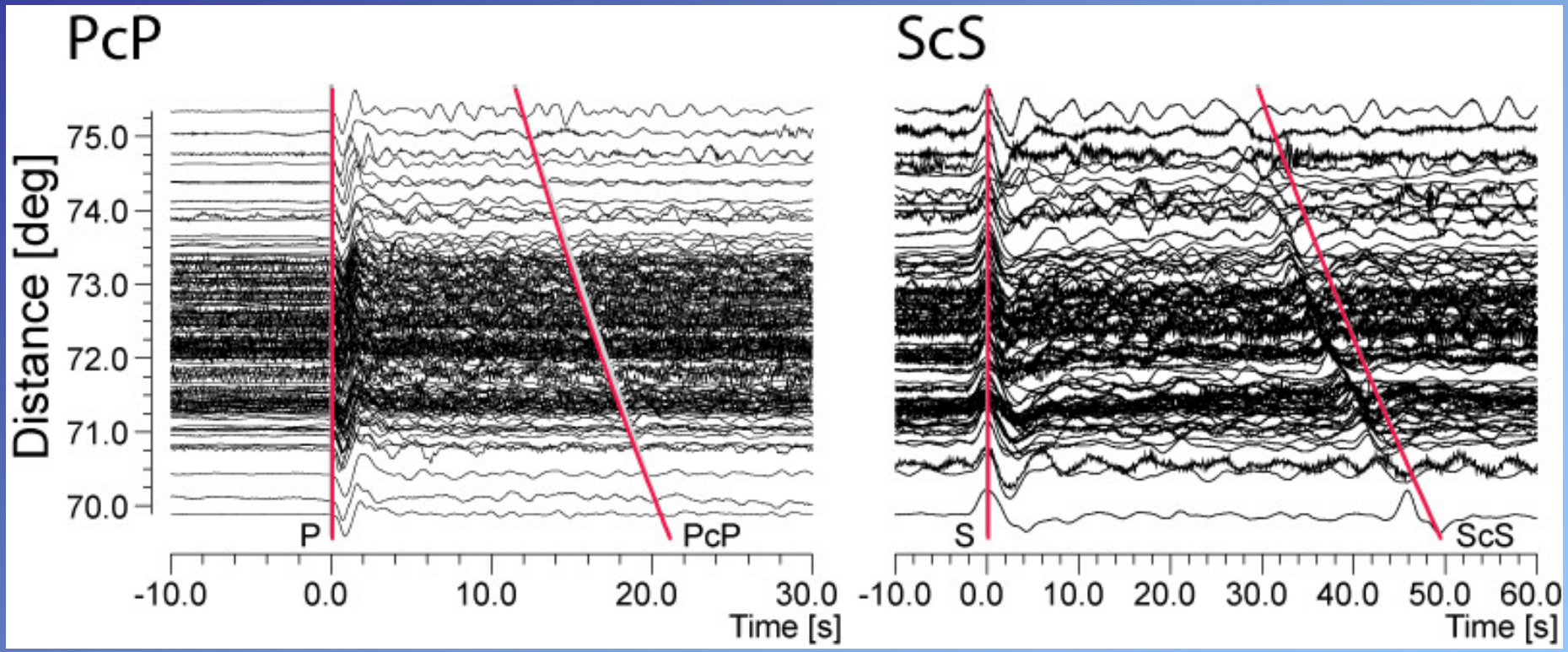
Example event profiles





[Thomas, Garnero, Lay JGR, 2004]



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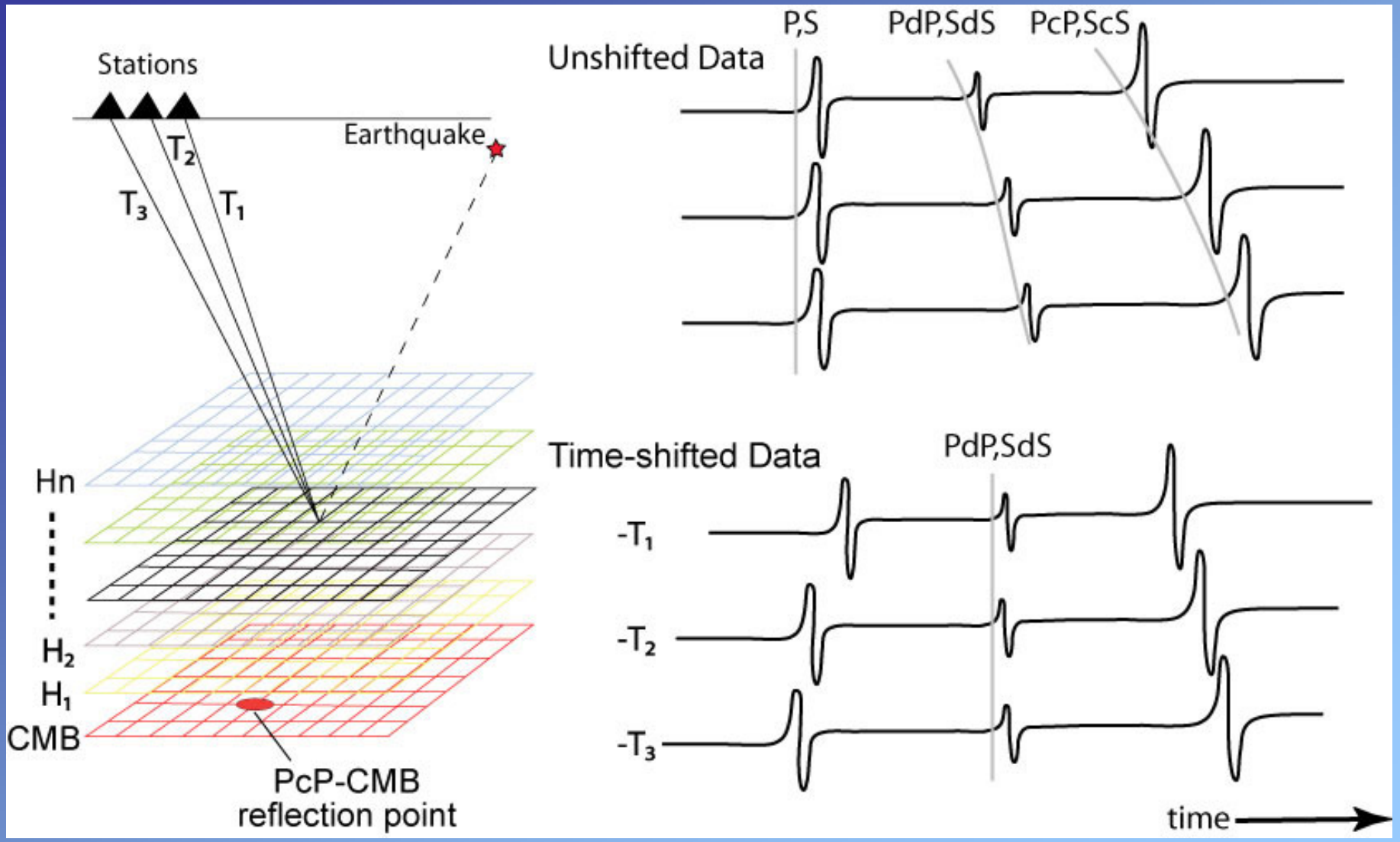
Migration



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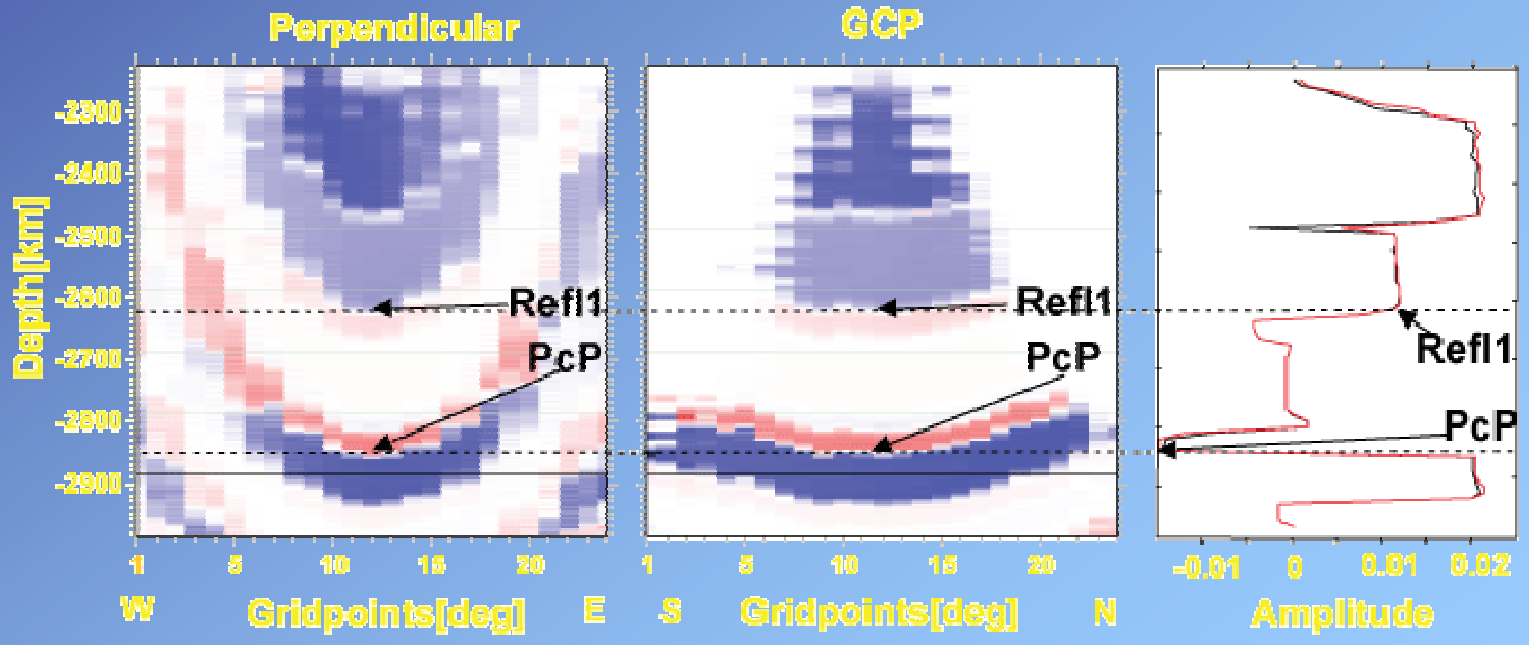

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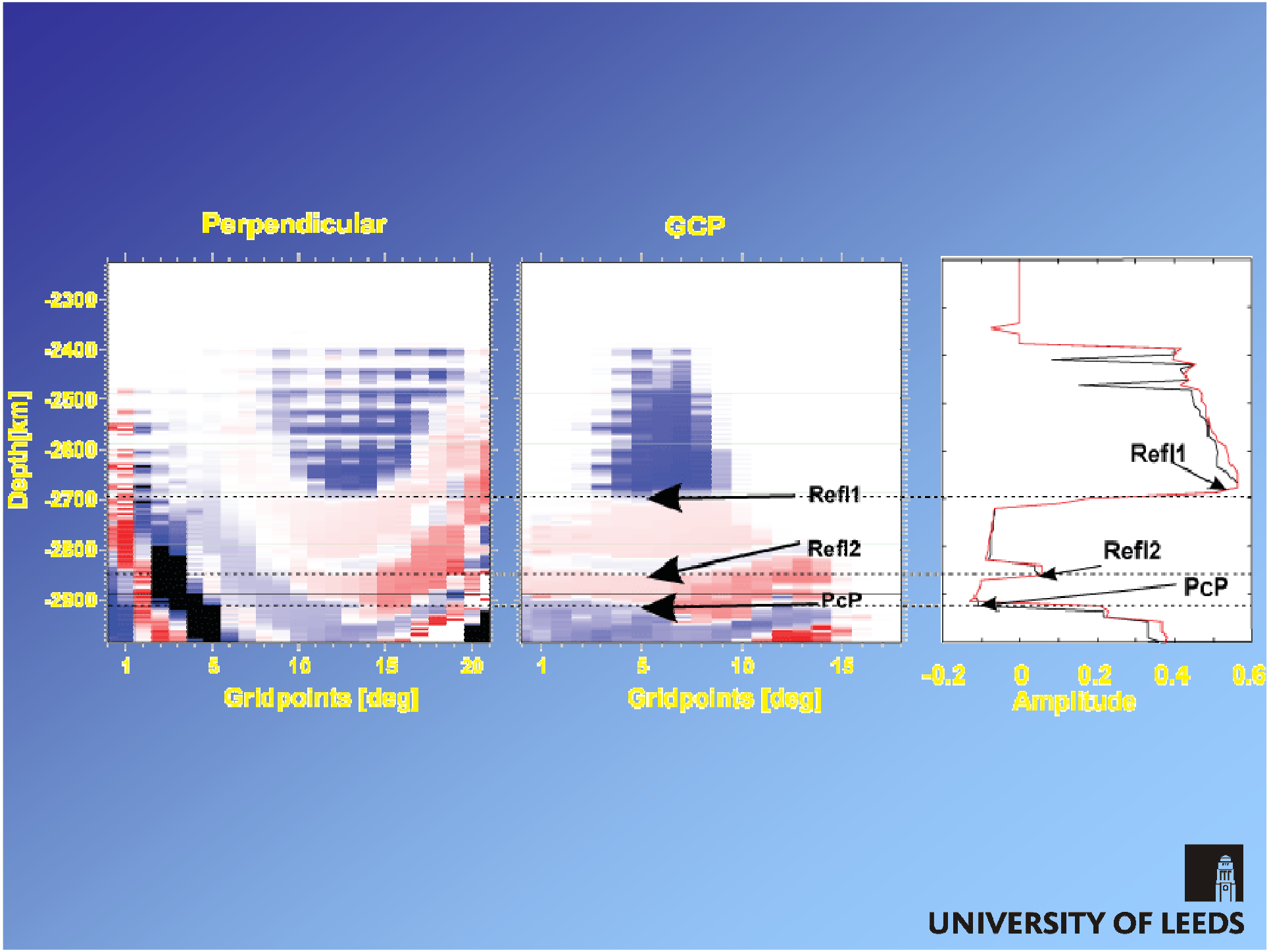

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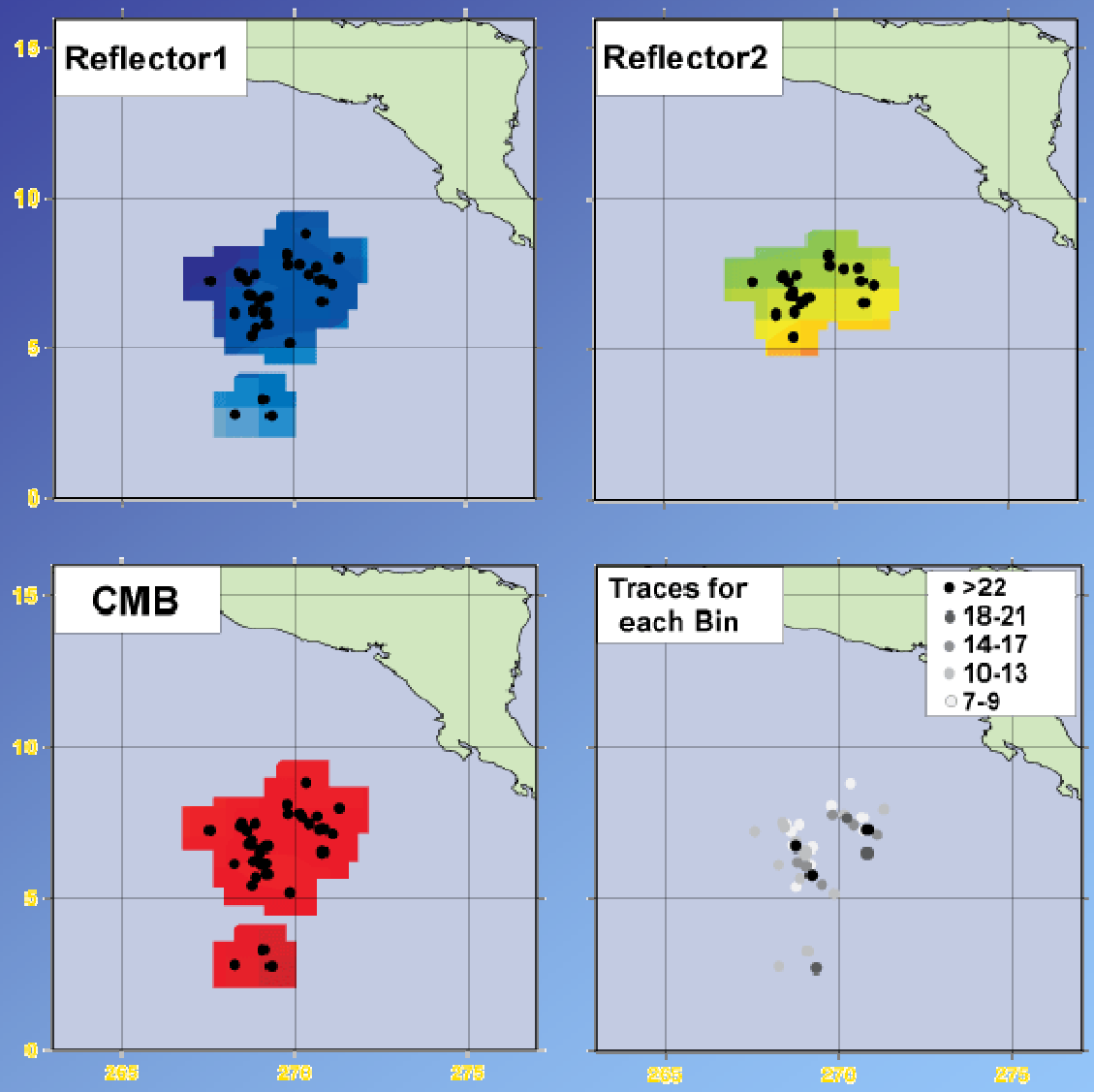
D” discontinuity topography



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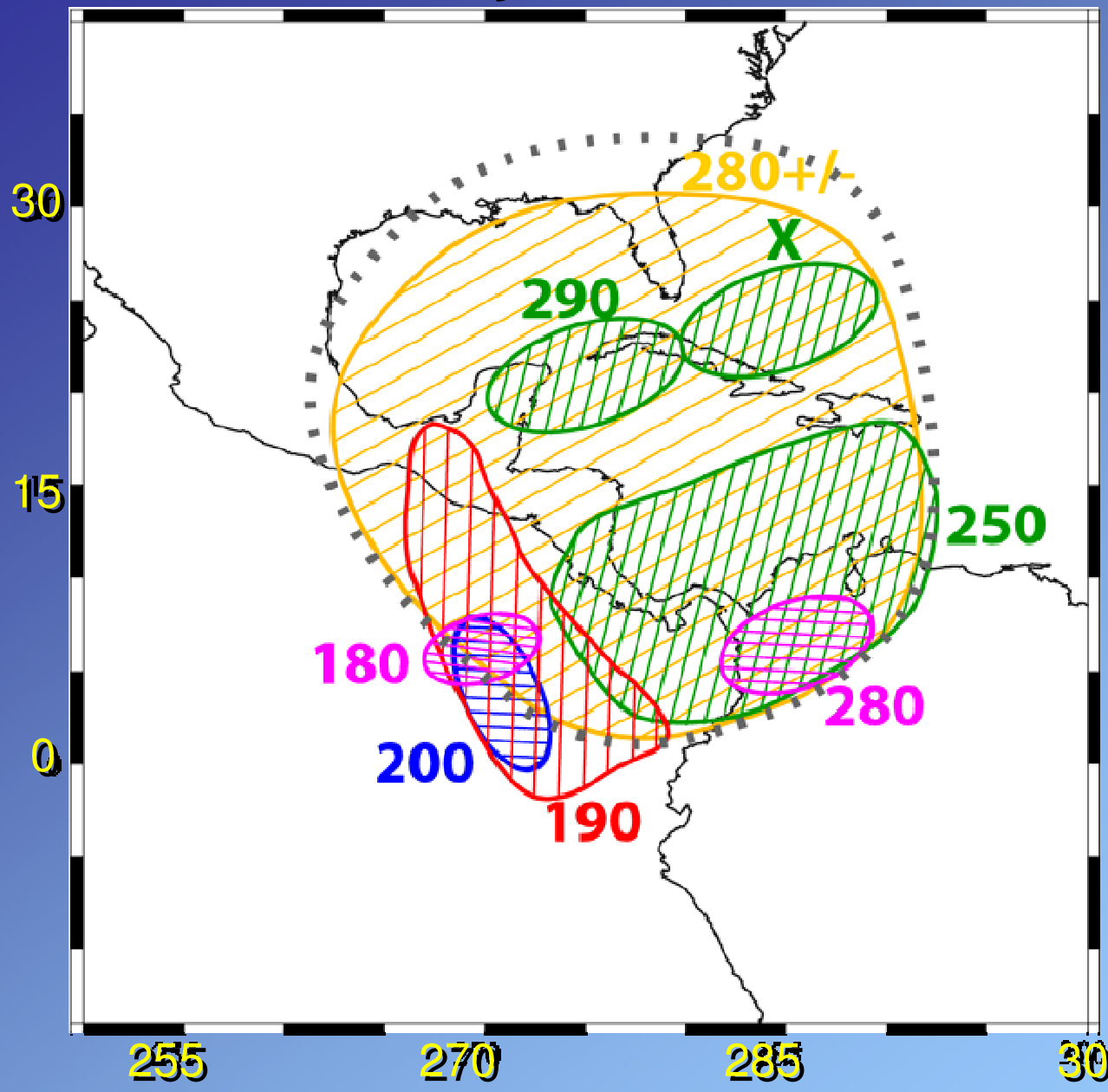
Past D" layer thicknesses



Vs

Lay and Helmberger (1983)

Kendall and Shearer (1994)

Kendall and Nangini (1997)

Ding and Helmberger (1997)

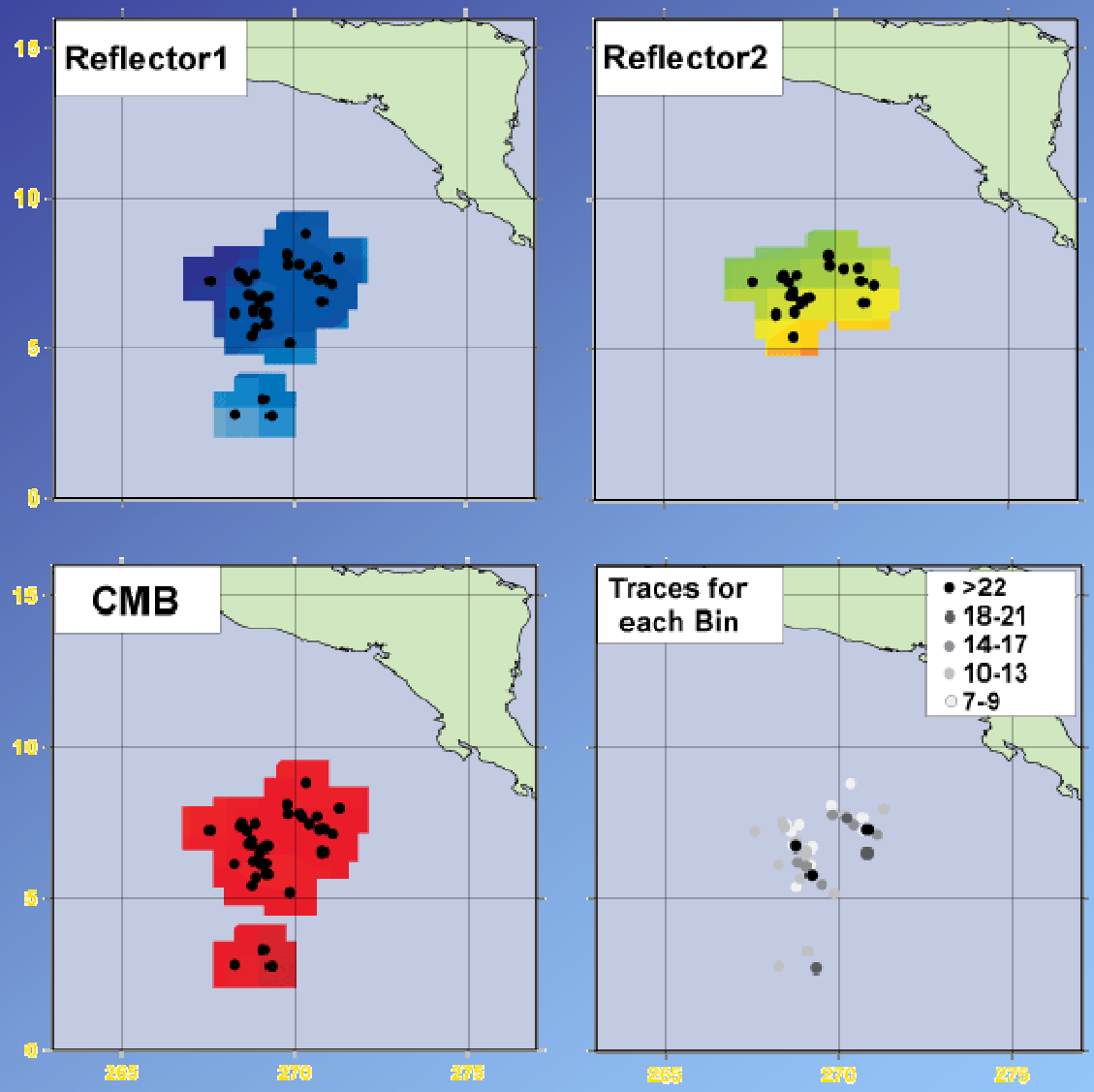
Garnero and Lay (2003)

Vp

Reasoner and Revenaugh (1999)

[Thomas, Garnero and Lay, 2004]

D” discontinuity topography



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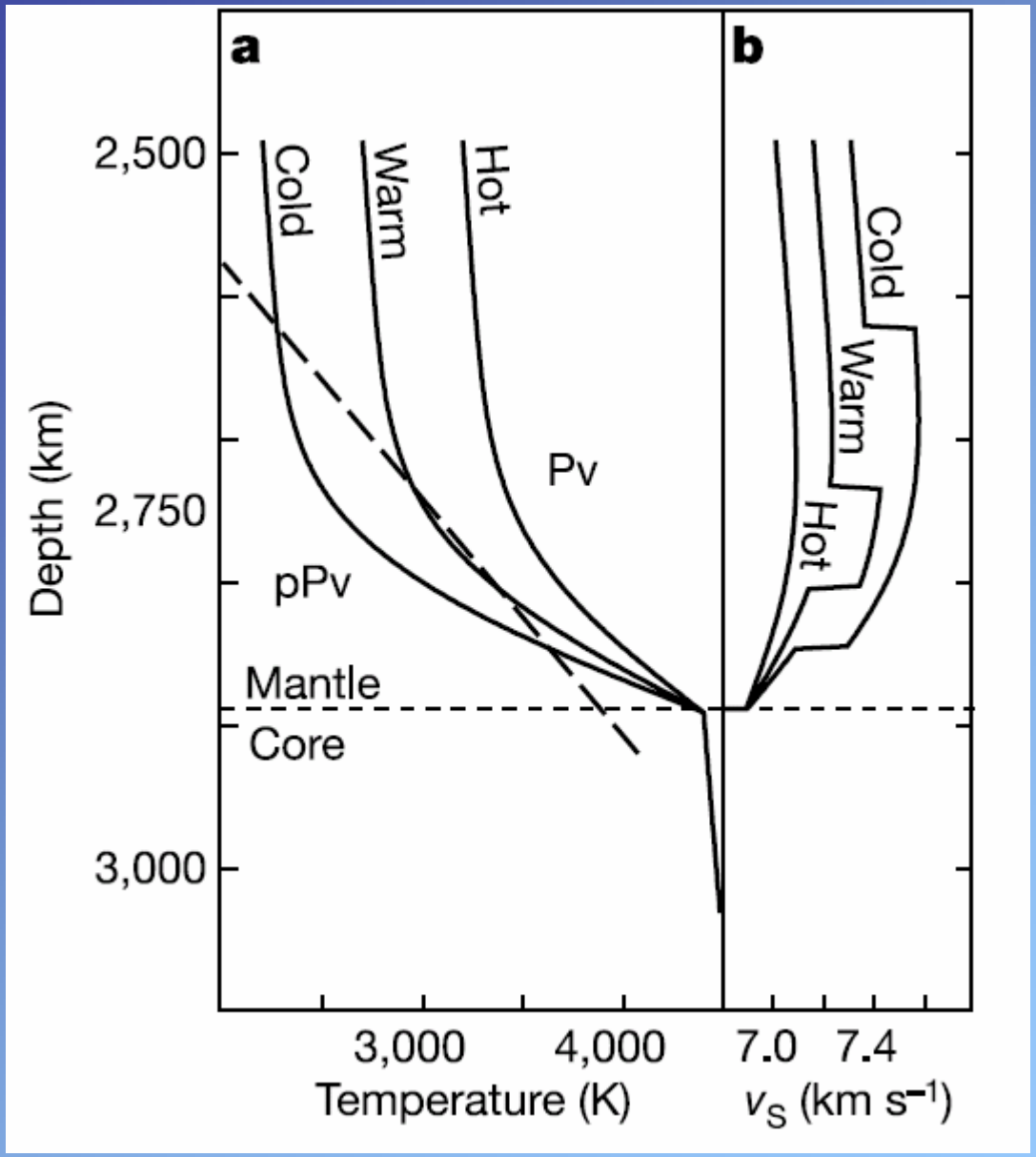
Post-perovskite and D” discontinuity



[Hernlund et al., 2005]

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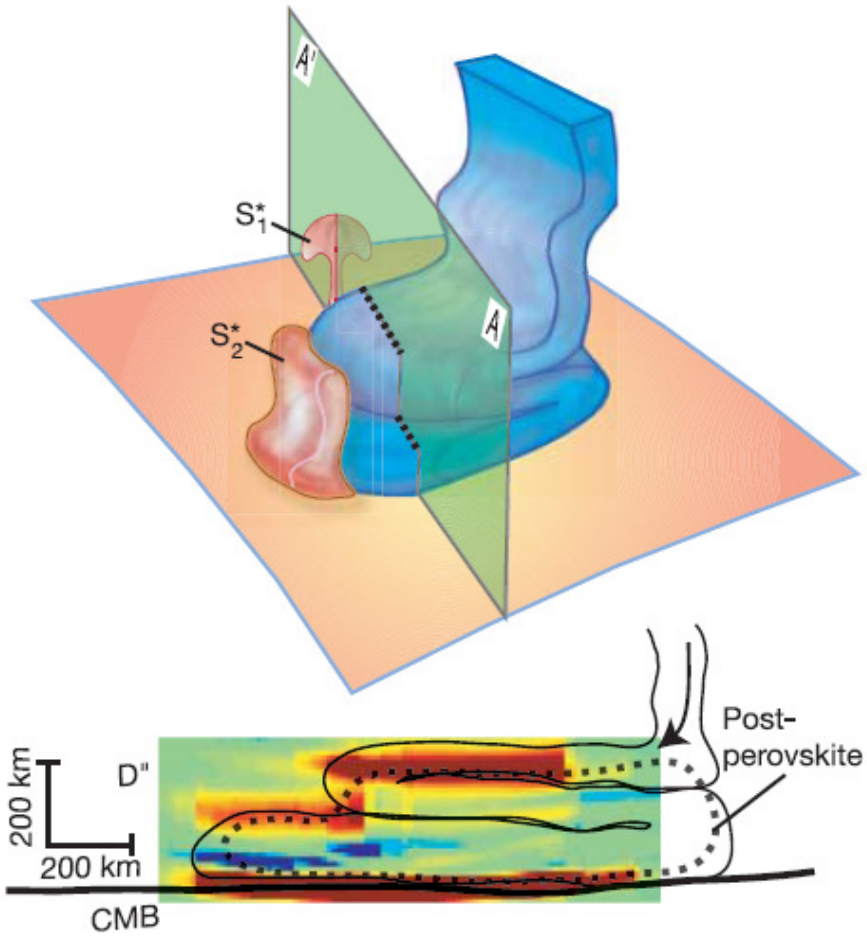
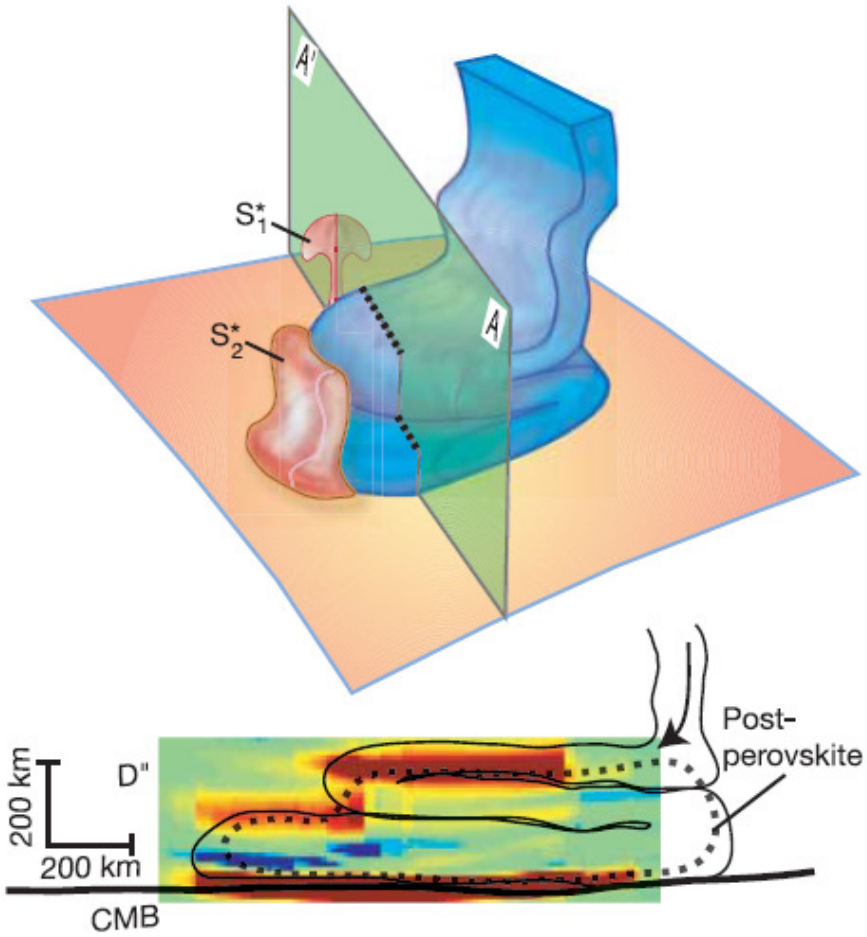
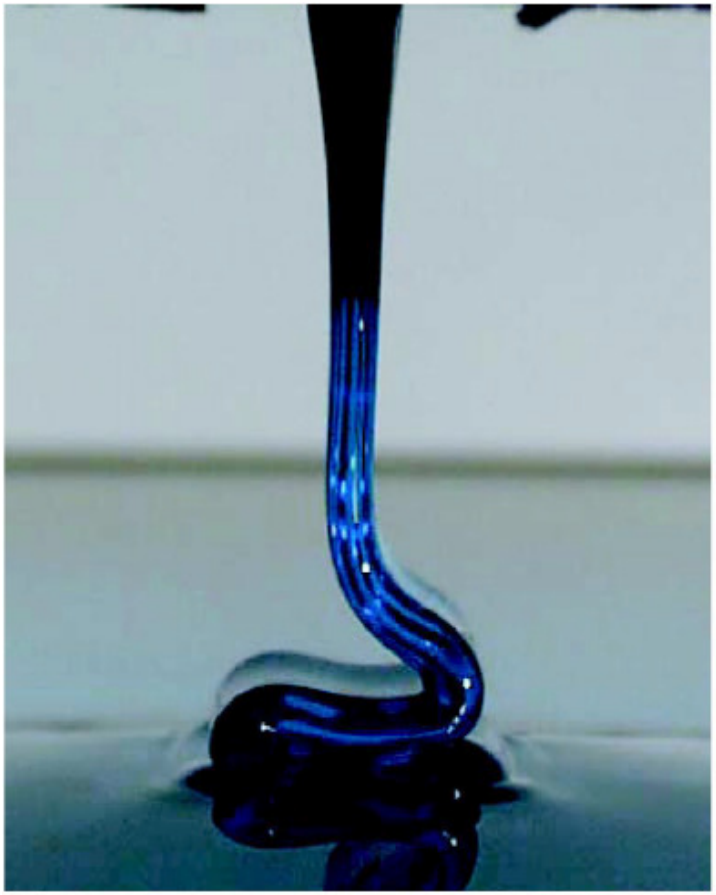
Other interpretations



[Hutko et al., Nature, 2006]

Other interpretations

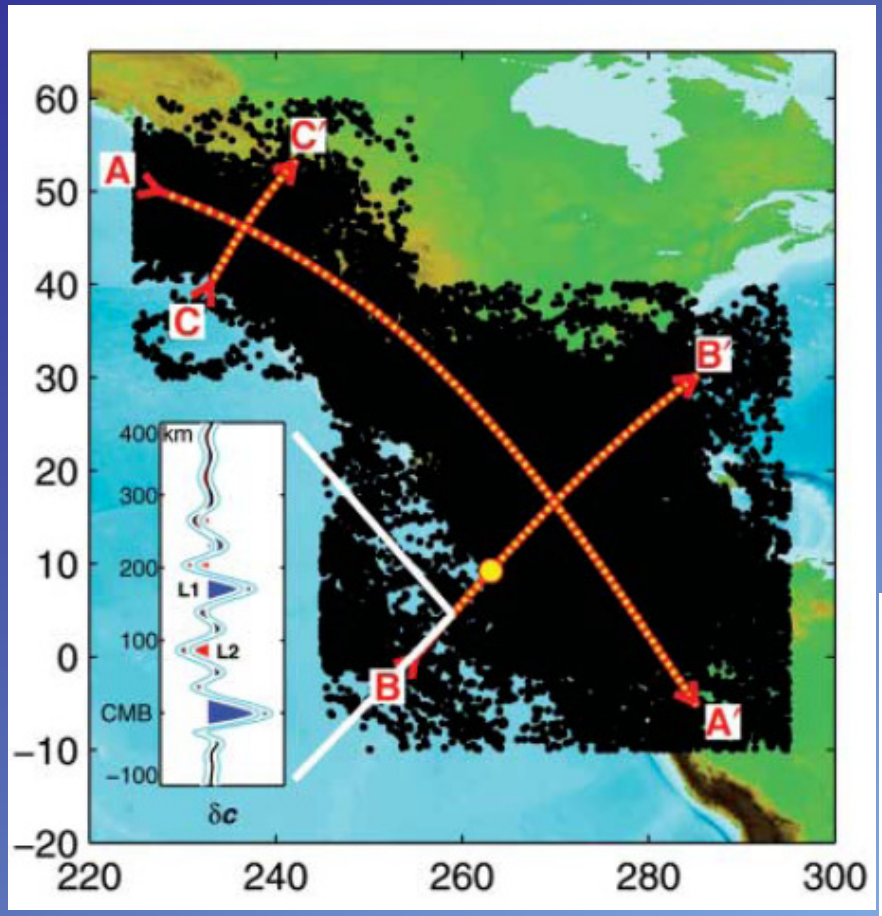




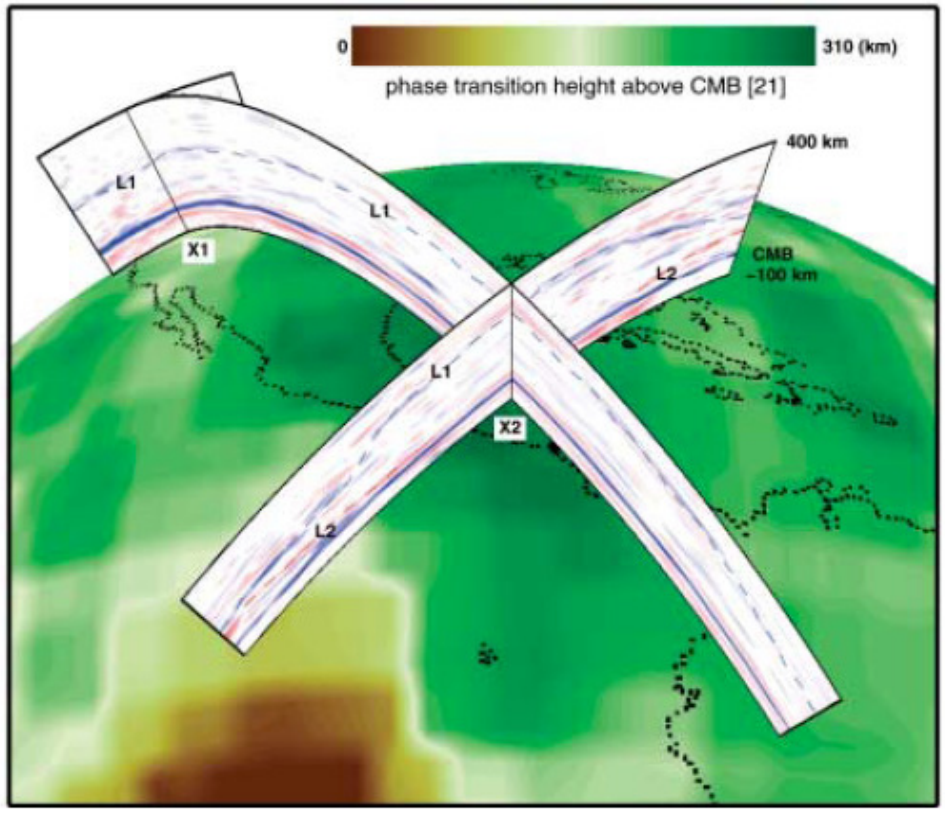
[Hutko et al., Nature, 2006]

[Ribe 2002]

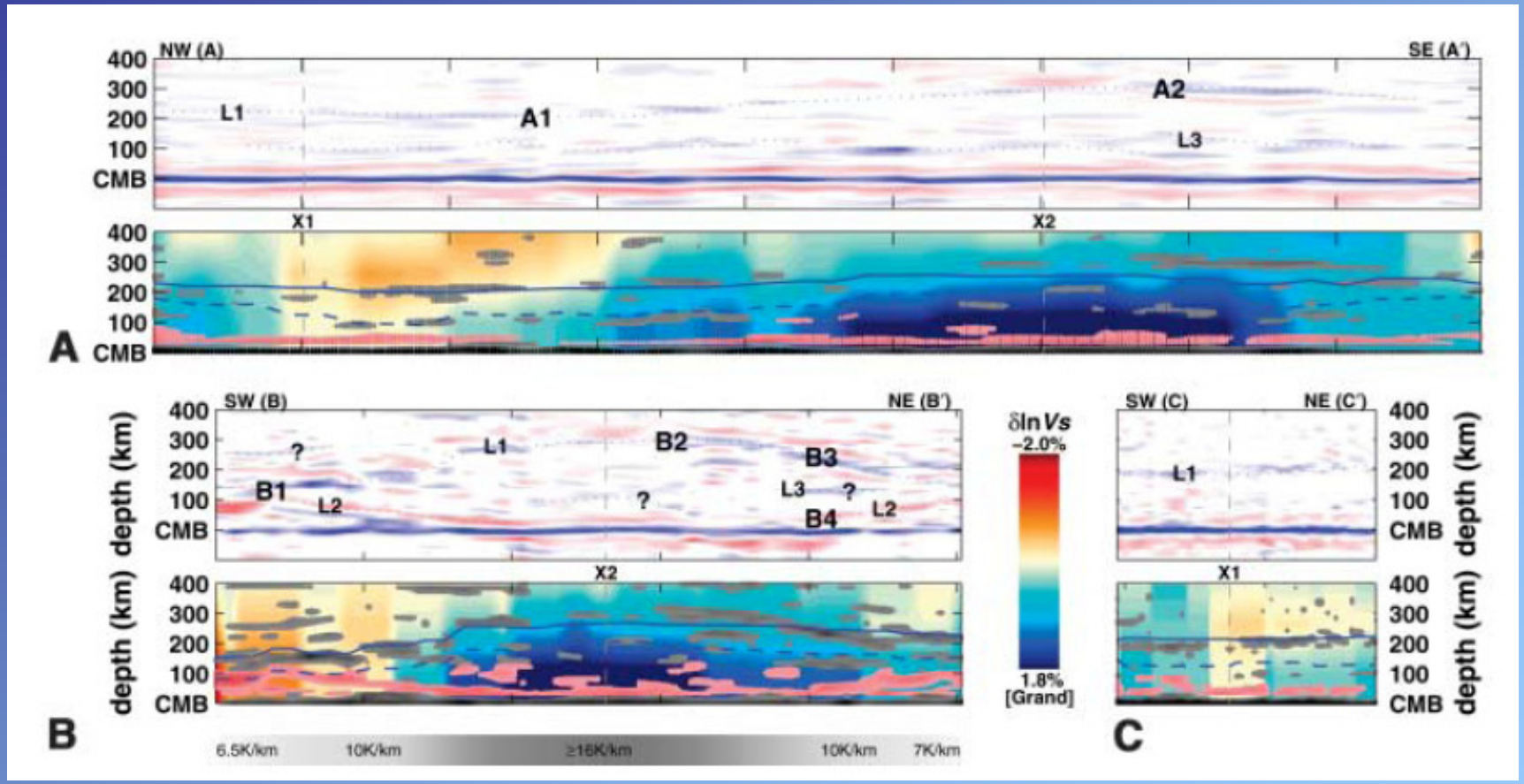
Mapping with GRT



Longitude [°]

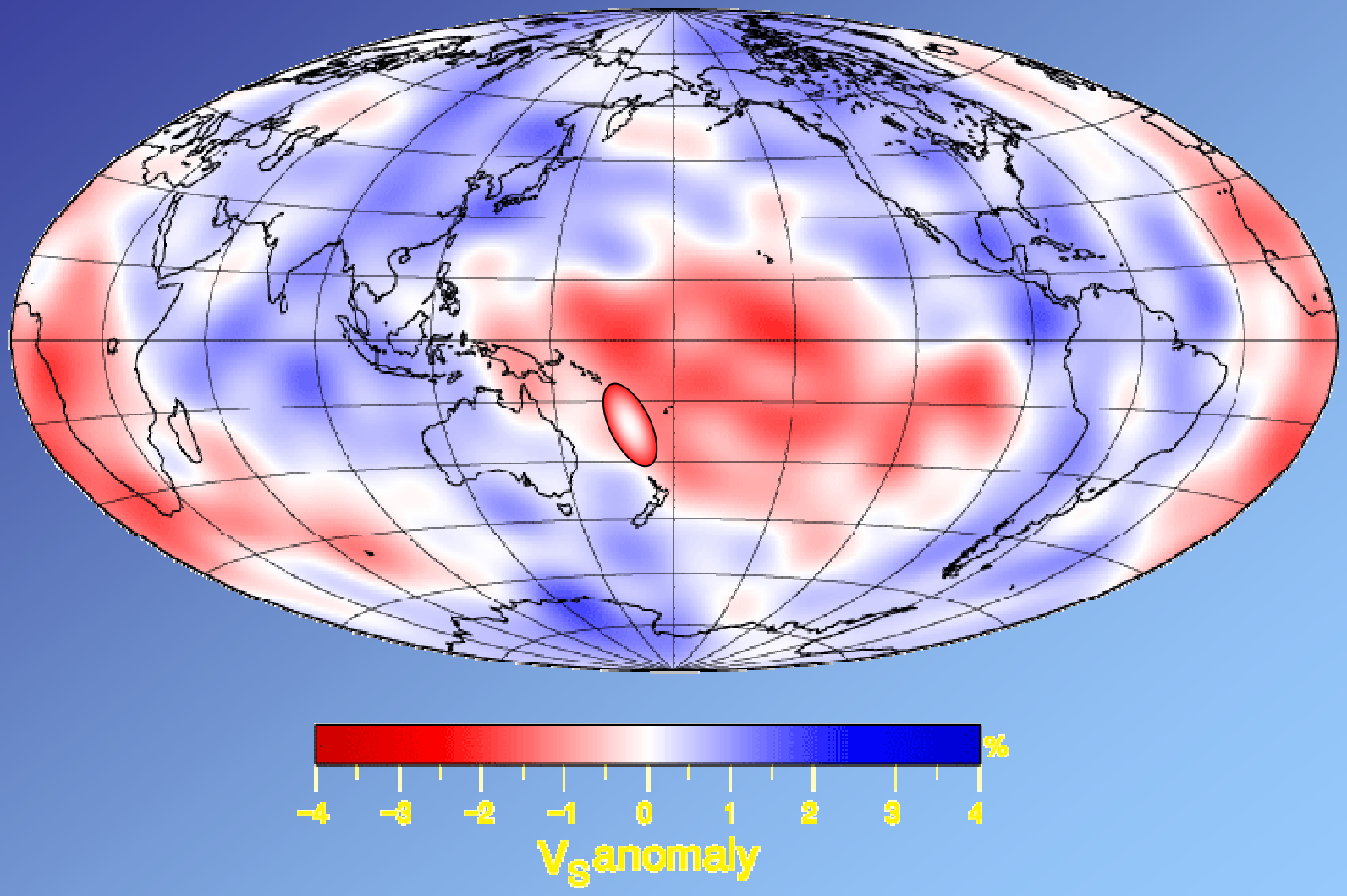


[van der Hilst et al, Science, 2007]



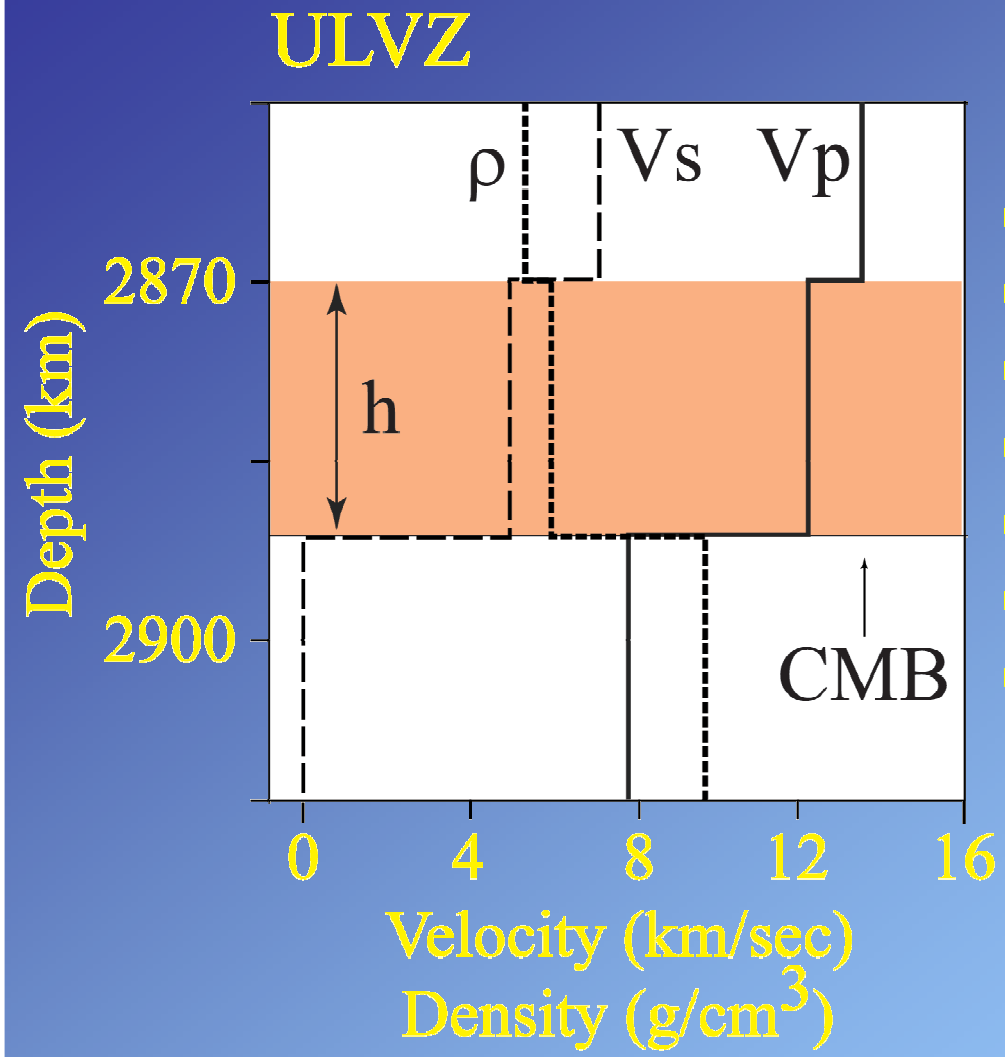
[van der Hilst et al., 2007]

ULVZ structure



[Ritsema and van Heijst, 2001]

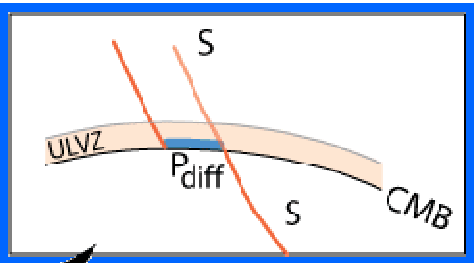
Ultra Low Velocity Zones



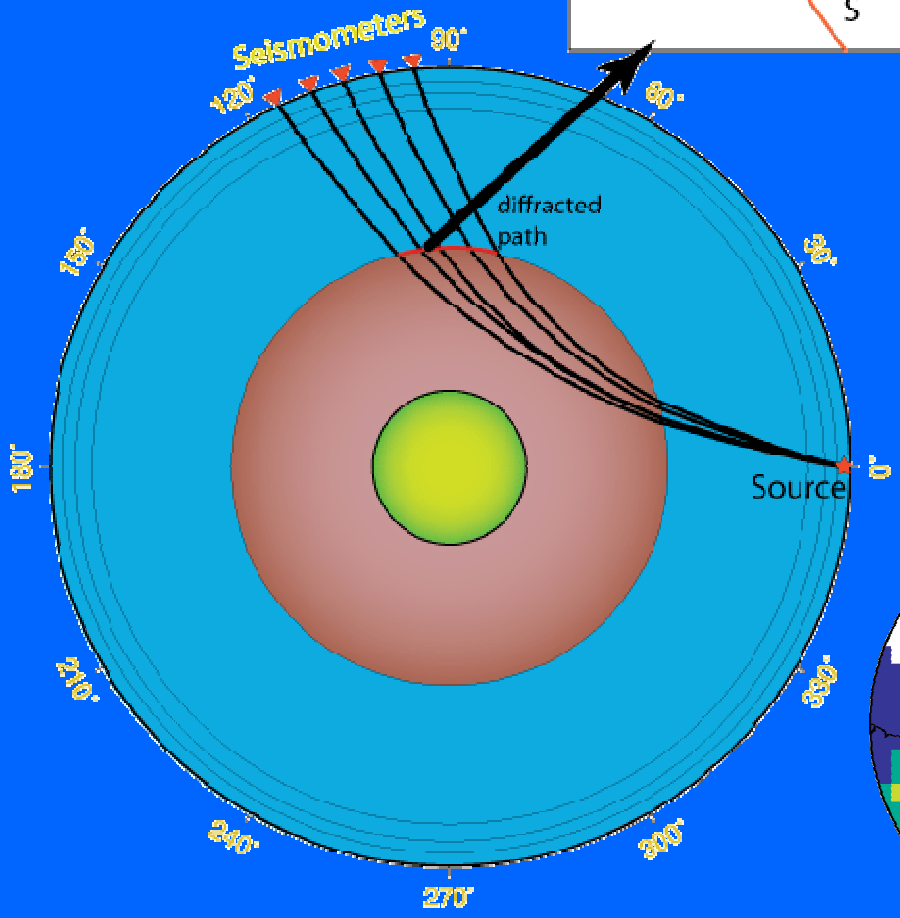
- 0.5 to 10's km thick
- 10 to 30 % velocity decrease
- partially molten material ?
- core entrainment ?
- core-mantle reactants ?
- remnants of magma ocean ?
- density ?

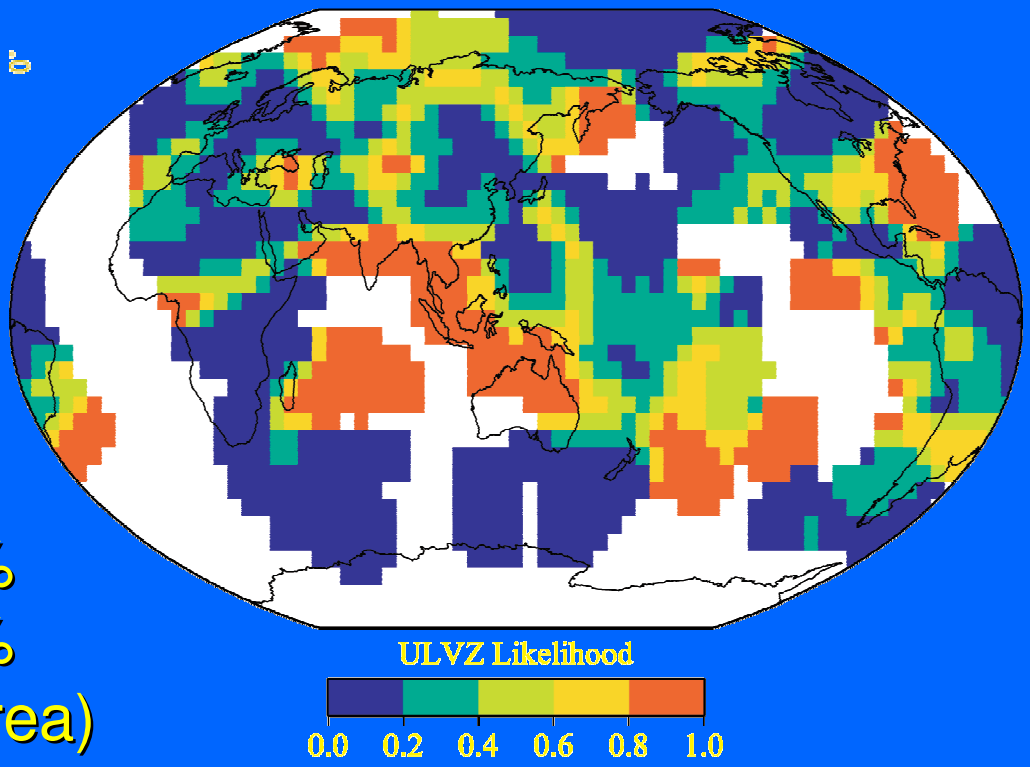
Thorne and Garnero, 2004

ULVZ probes



$SP_{diff}KS$

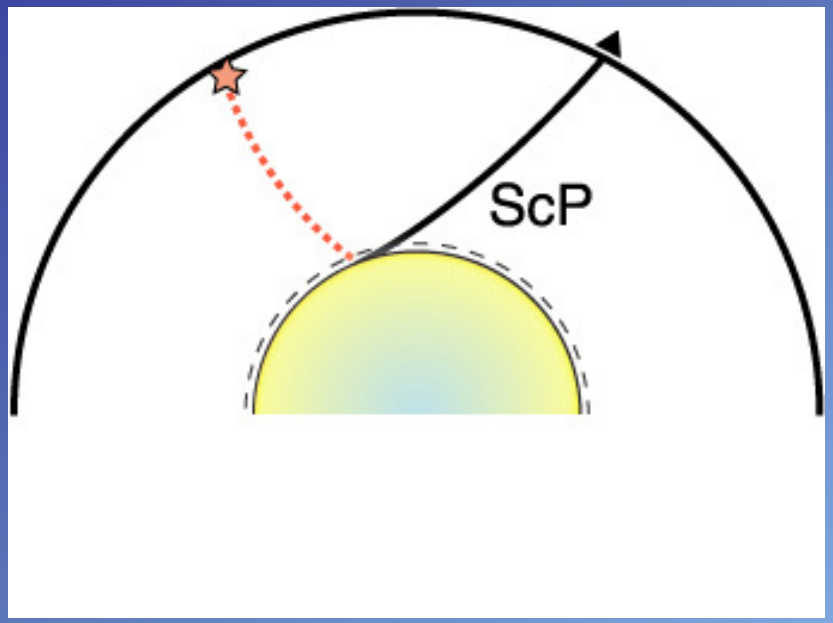


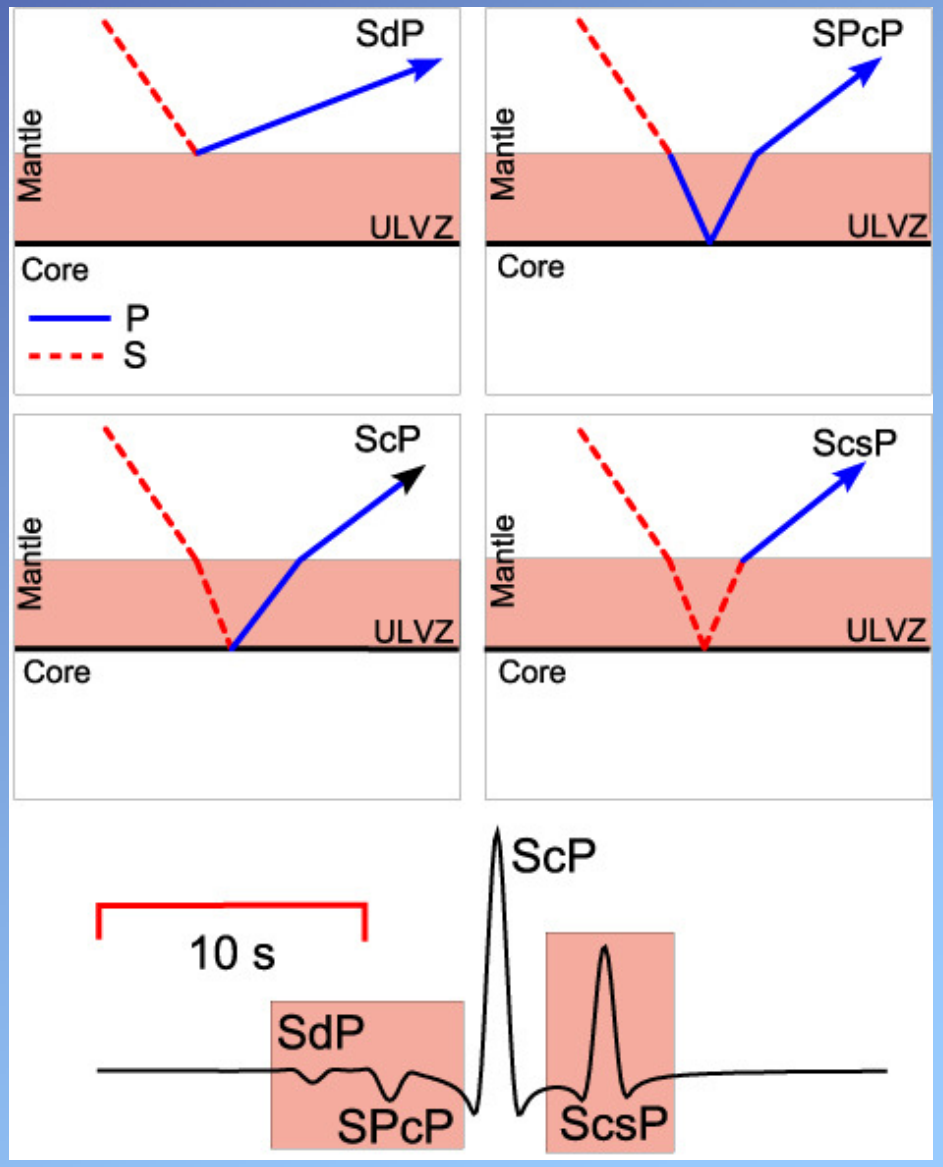


- CMB are probed < 50 %
- ULVZ evidence < 10 %
  (of CMB area)

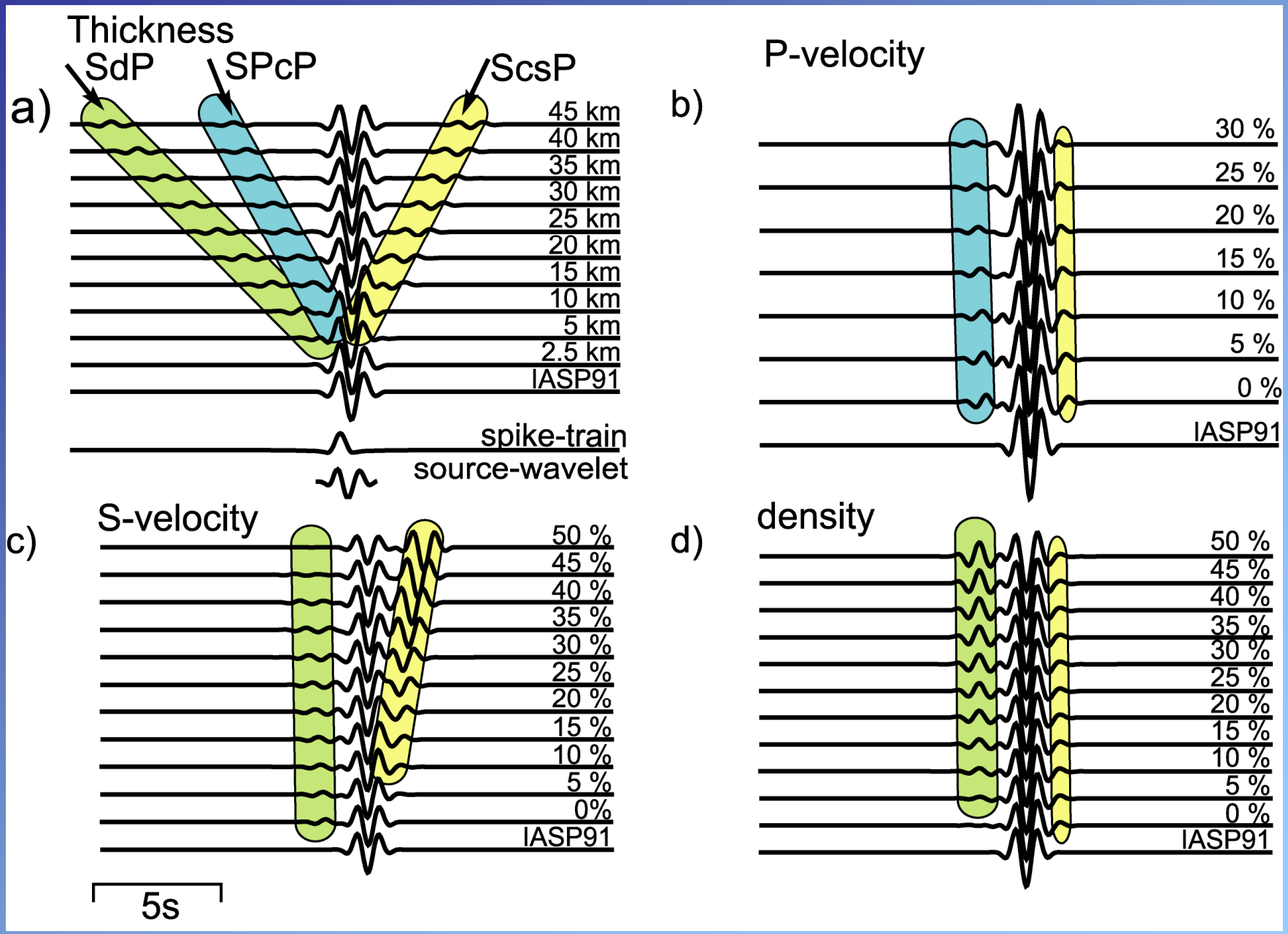
[Thorne and Garnero, 2004]

ULVZ Probes – High resolution

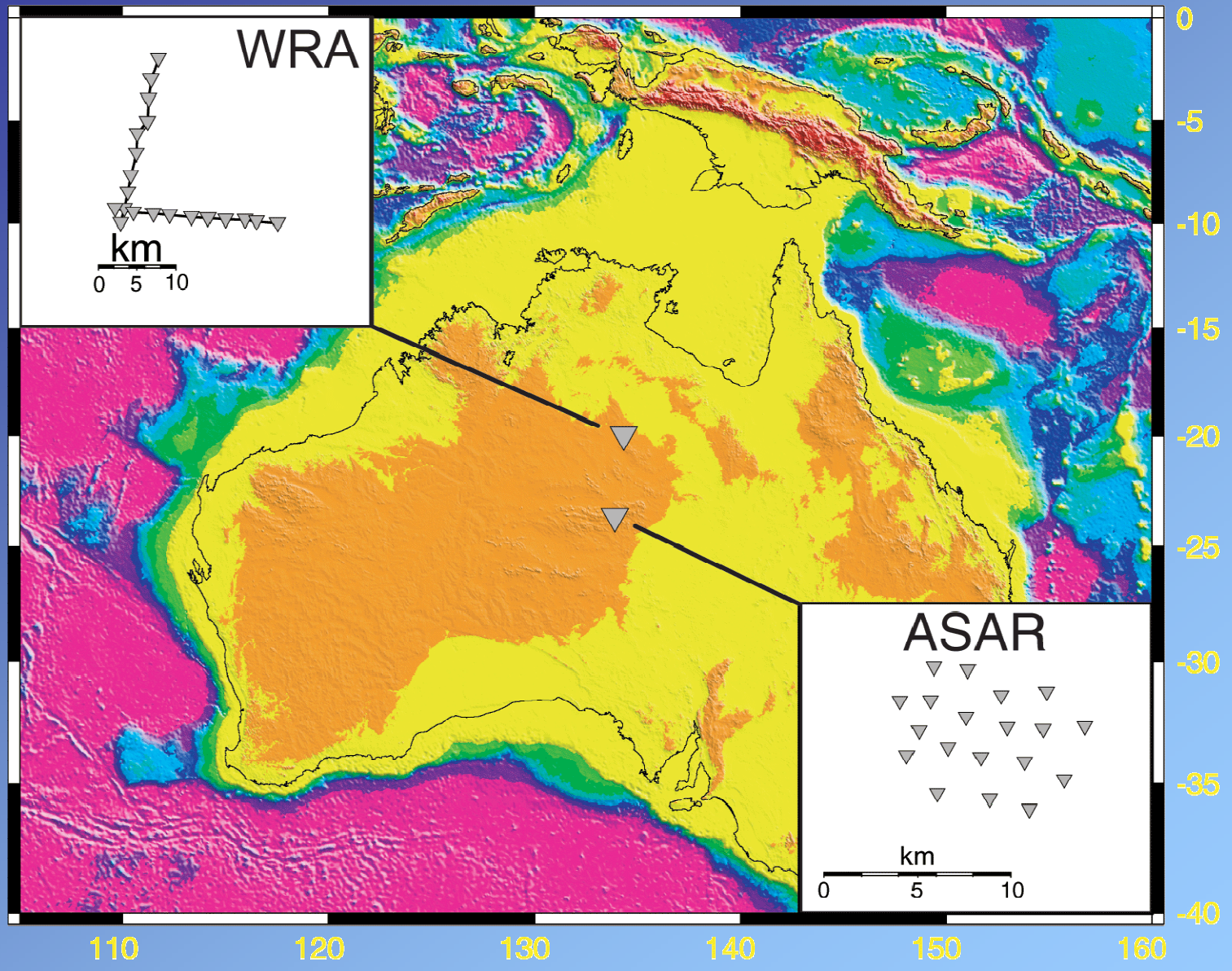




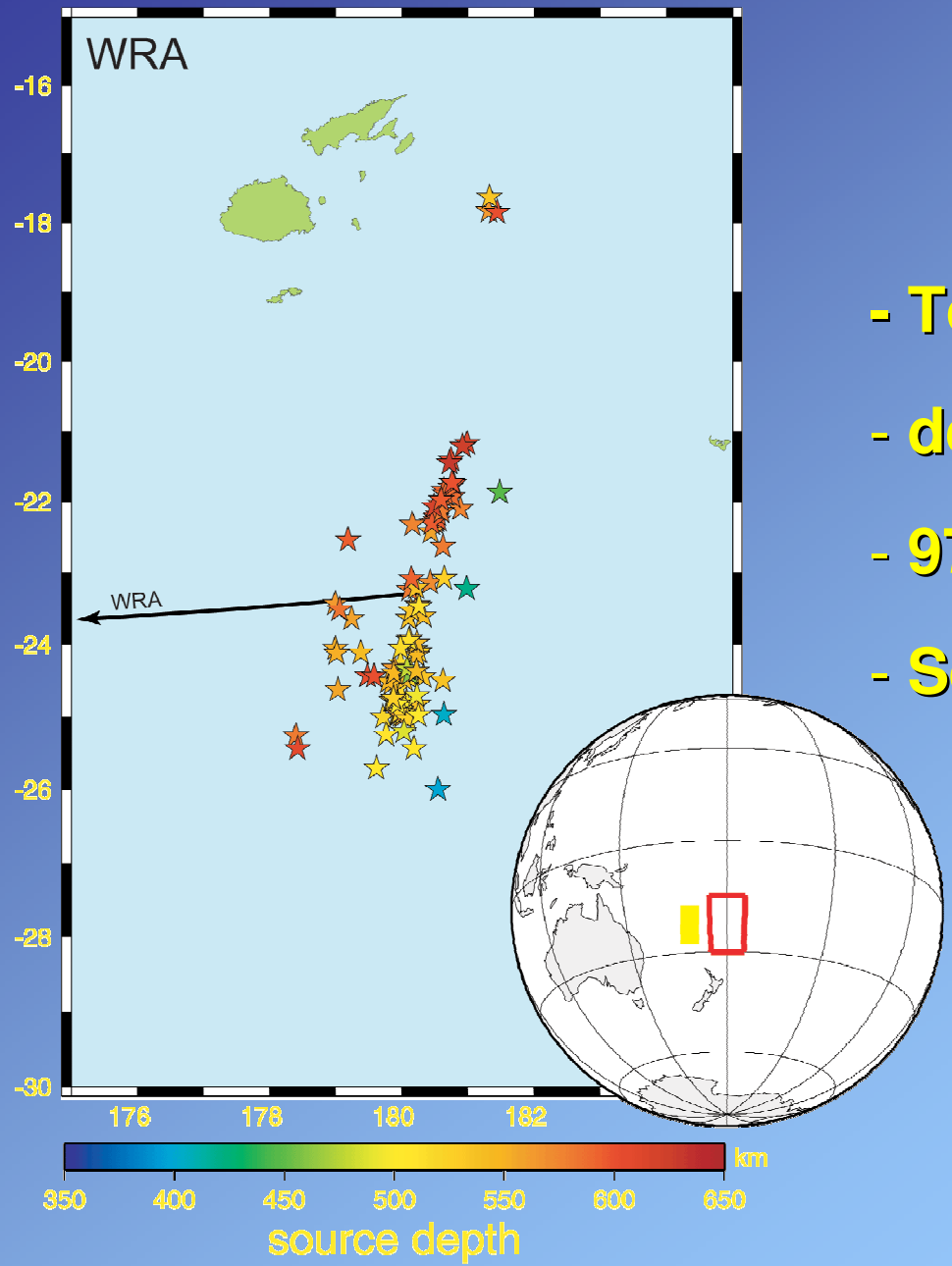
ScP waveforms



Small aperture Arrays



Topography from NOAA 2' dataset



- Tonga-Fiji seismicity
- deep earthquakes
- 97 earthquakes
- Seismicity from:
  10/1990 – 01/1998

[Rost, Garnero, Williams & Manga, Nature, 2005]

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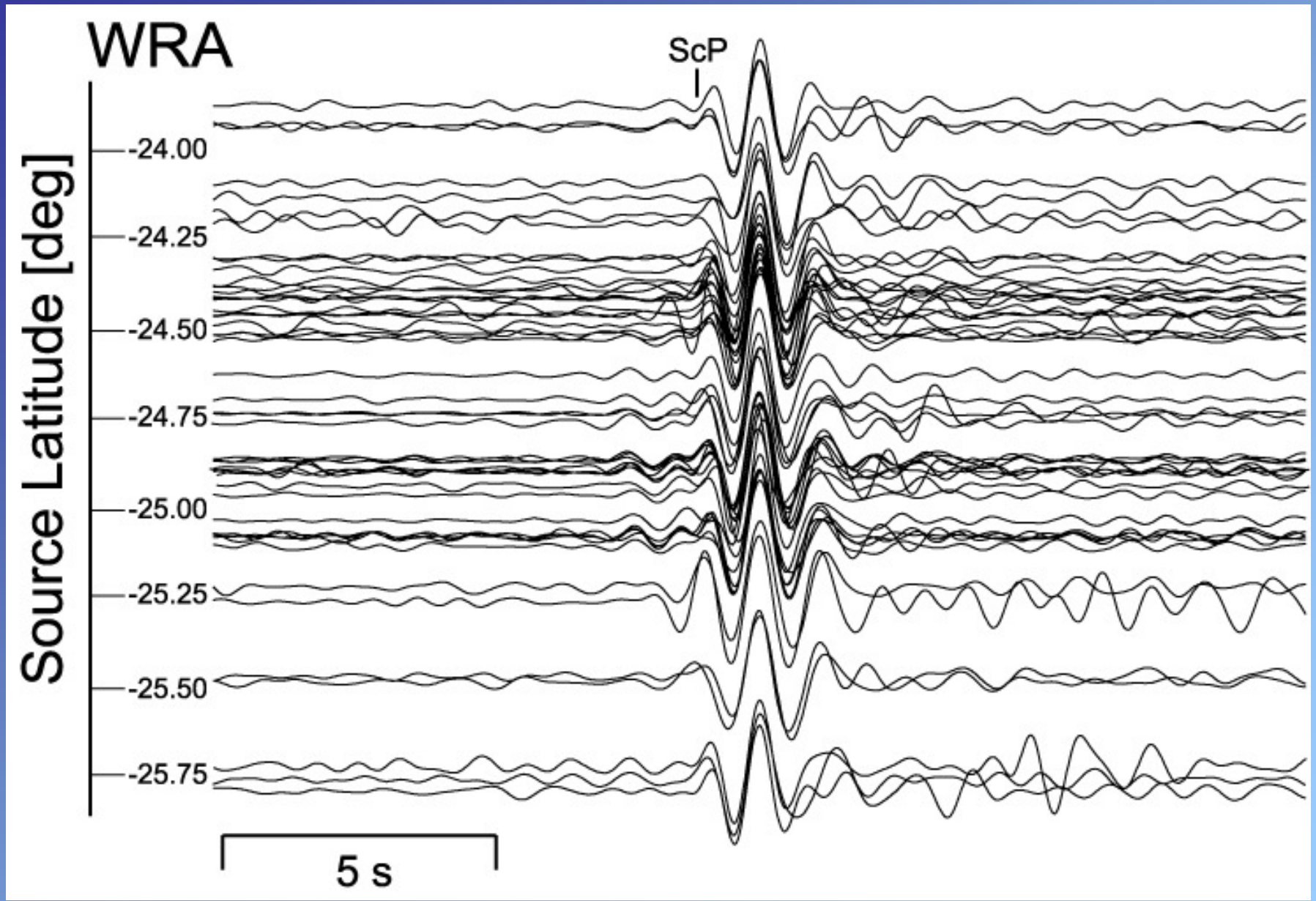
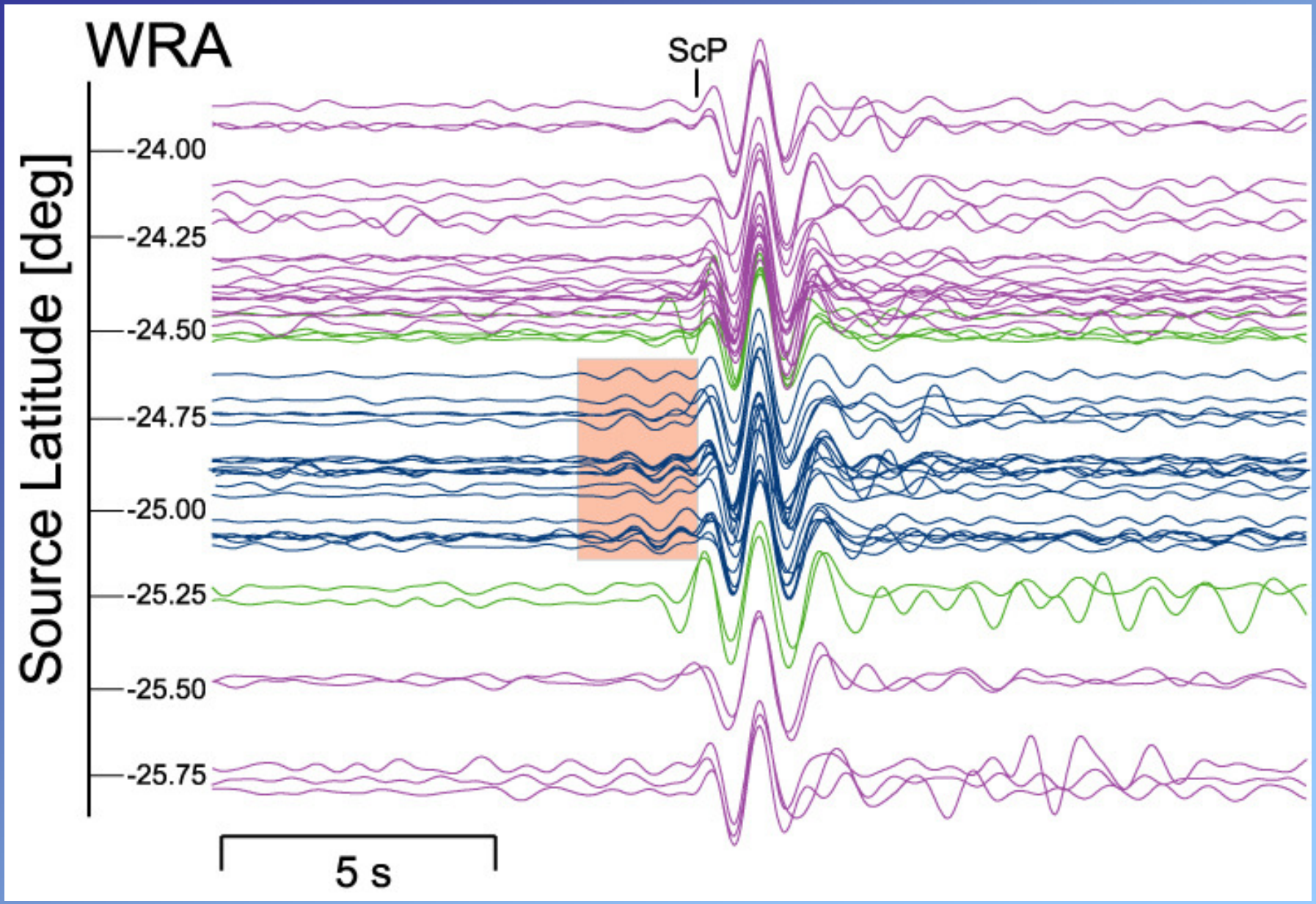
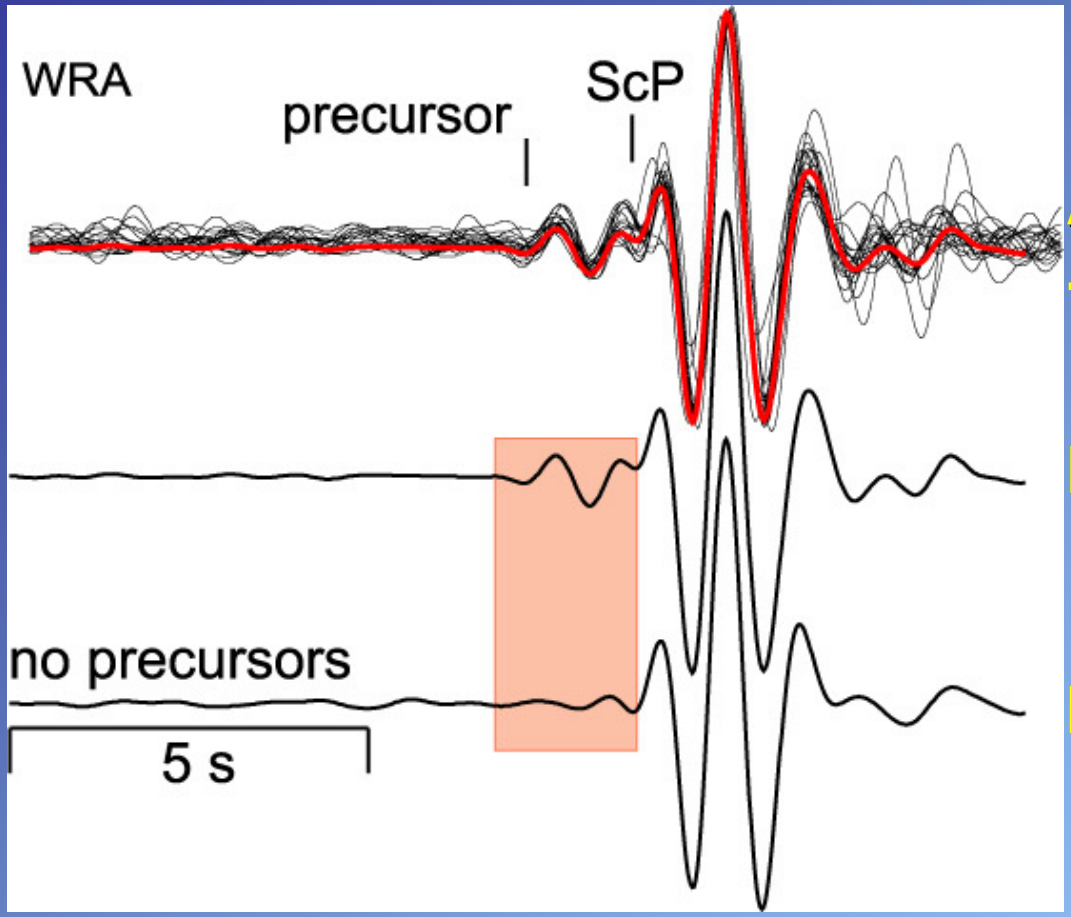

WRA
ScP
Source Latitude [deg]
-24.00
-24.25
-24.50
-24.75
-25.00
-25.25
-25.50
-25.75
5 s



[Rost, Garnero, Williams & Manga, Nature, 2005]



All precursor events
+ summation trace

Precursor summation trace

Non-precursor summation

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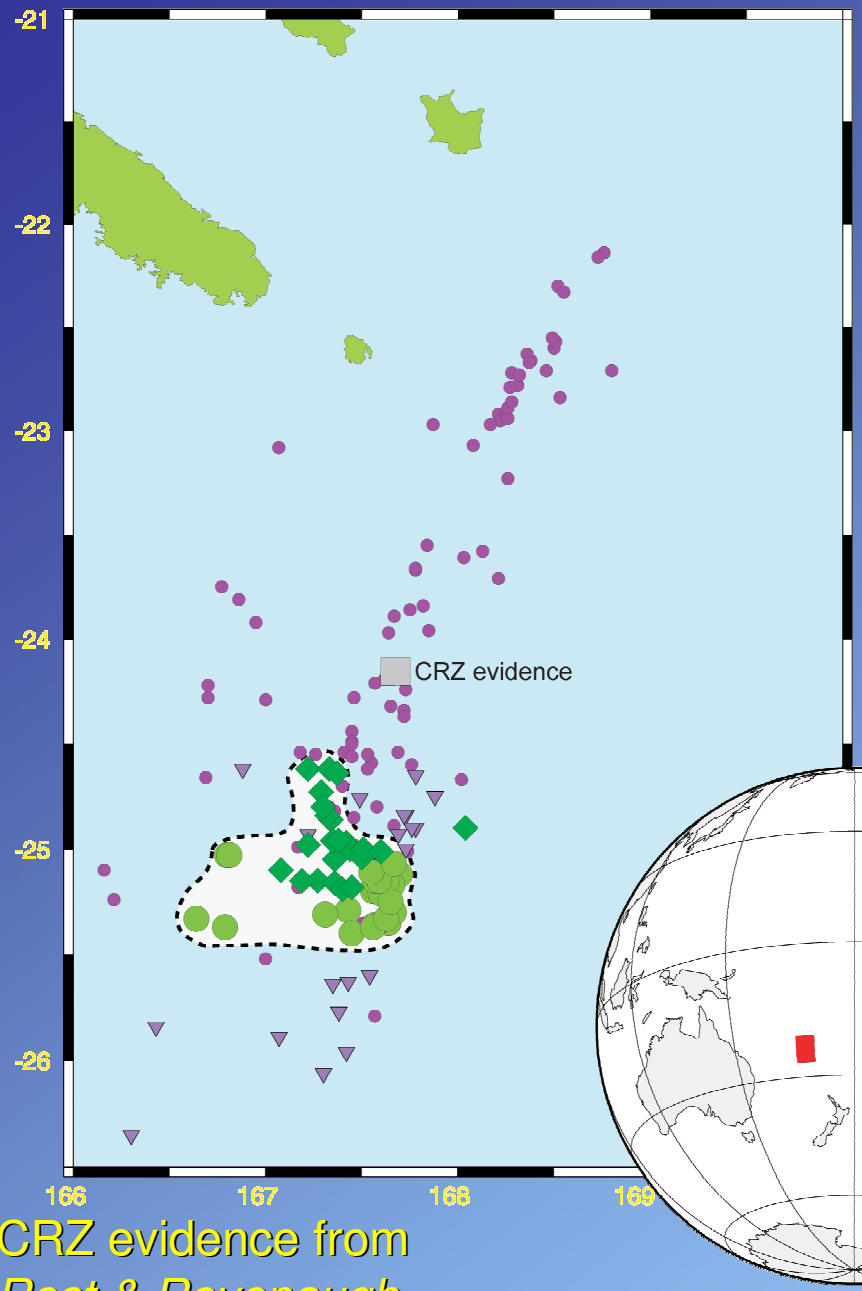
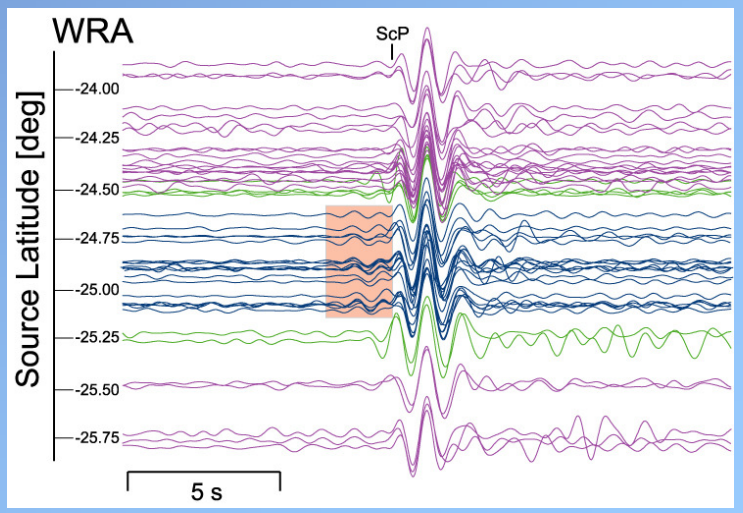


- ~50 by 50 km
- northern boundary –24.5
- southern boundary –25.5
- some boundaries not well resolved



CRZ evidence from *Rost & Revenaugh, Science, 2001*

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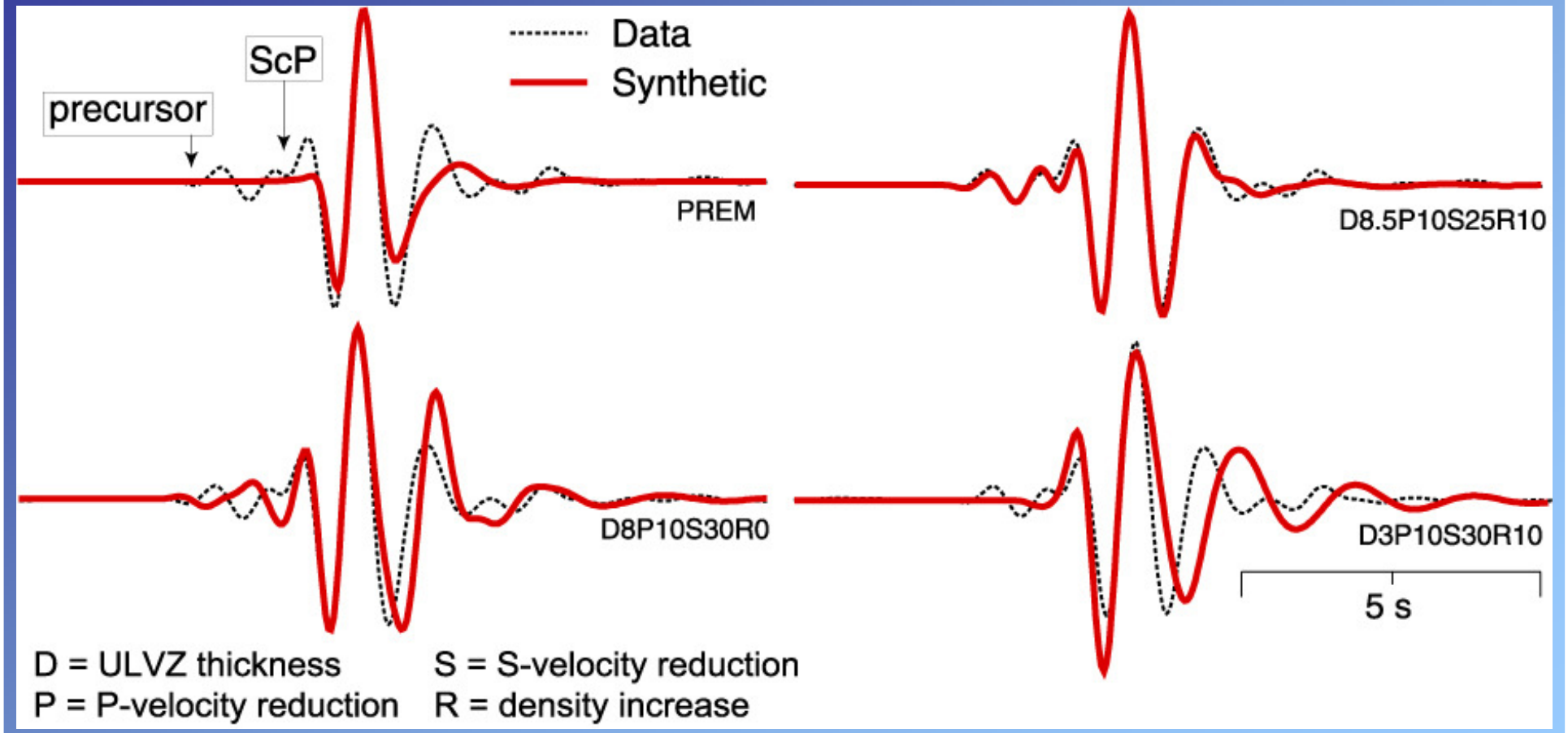
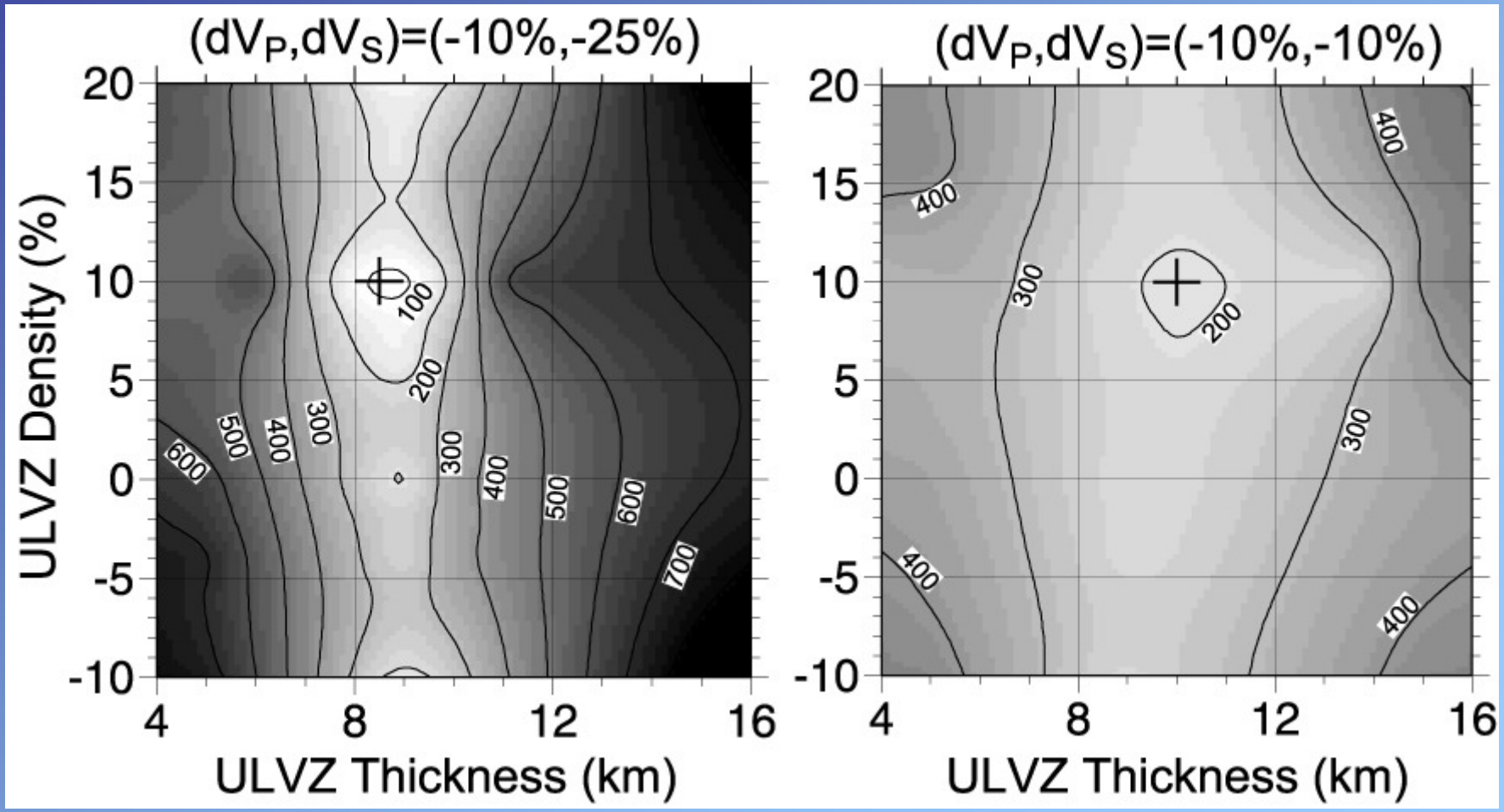
Synthetic waveform forward modeling

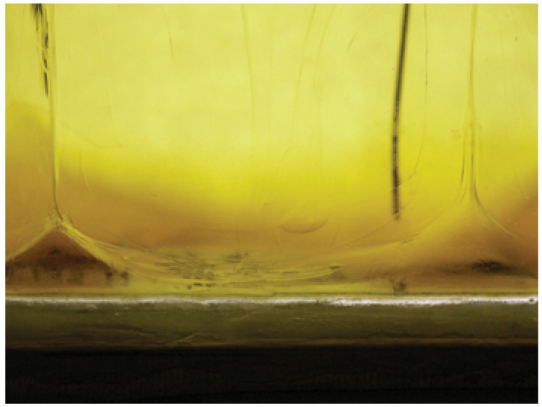


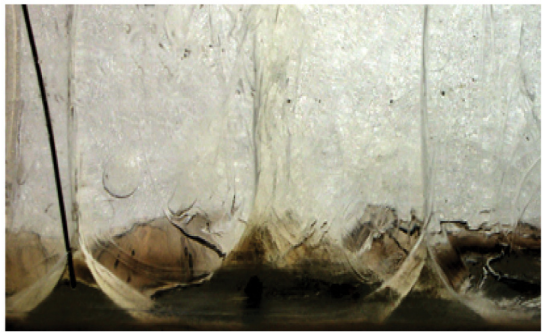
Partial Melt

Chemical Heterogeneity



Small-scale Ultra Low Velocity Zone





[Jellinek & Manga, 2002]

- Best-fit model properties:
  - Thickness: 8.5 (±1) km
  - ΔV_P : -10 (±2.5) %
  - ΔV_S : -25 (±4) %
  - $\Delta \rho$: +10 (±5) %
- $\Delta V_P / \Delta V_S$ indicates partially molten material
- ~50 by 50 km lateral extension
- small lateral extent raises stability questions
- High-frequency data indicate very sharp upper boundary
  - sharpness < 400 m

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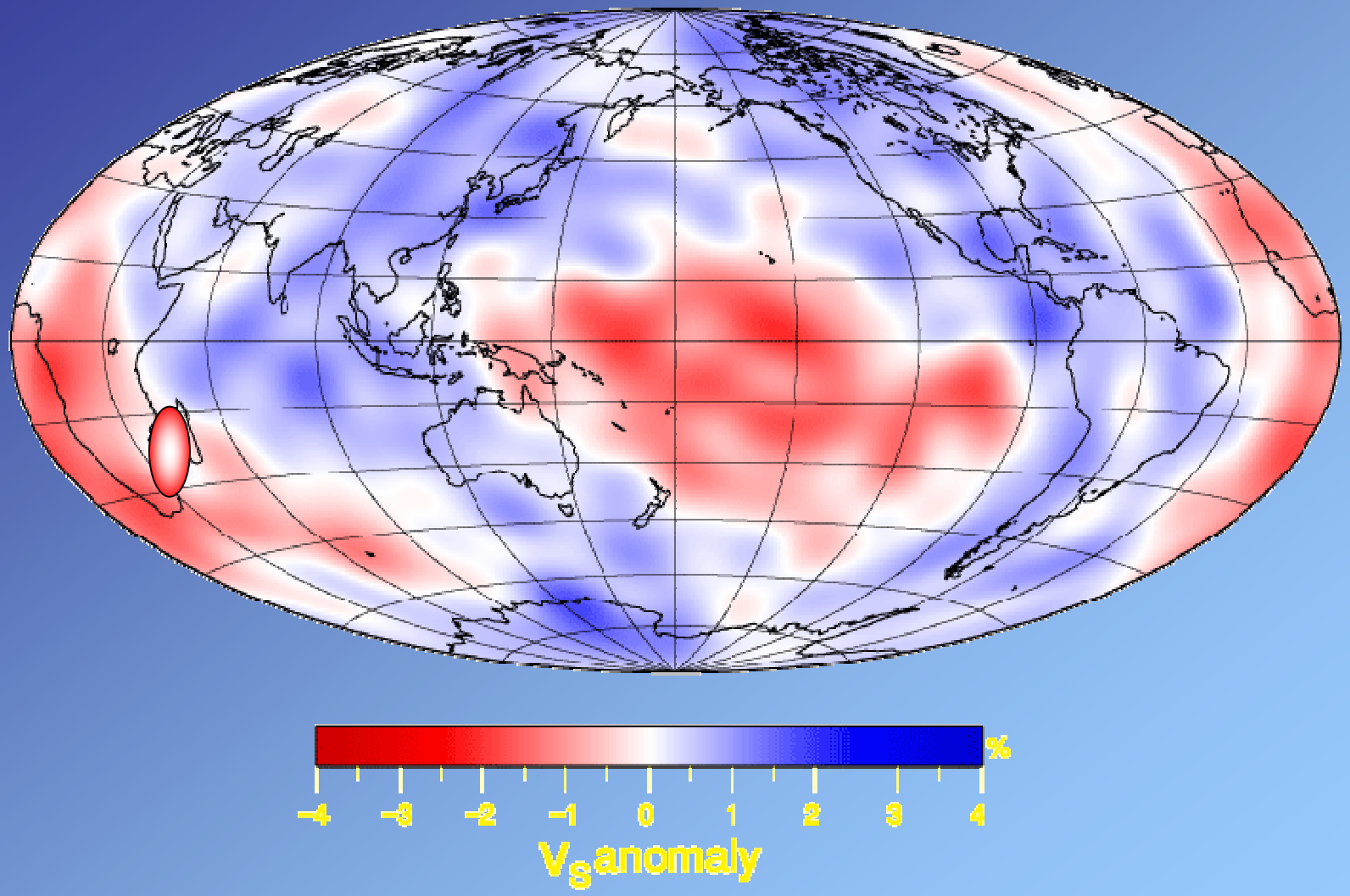
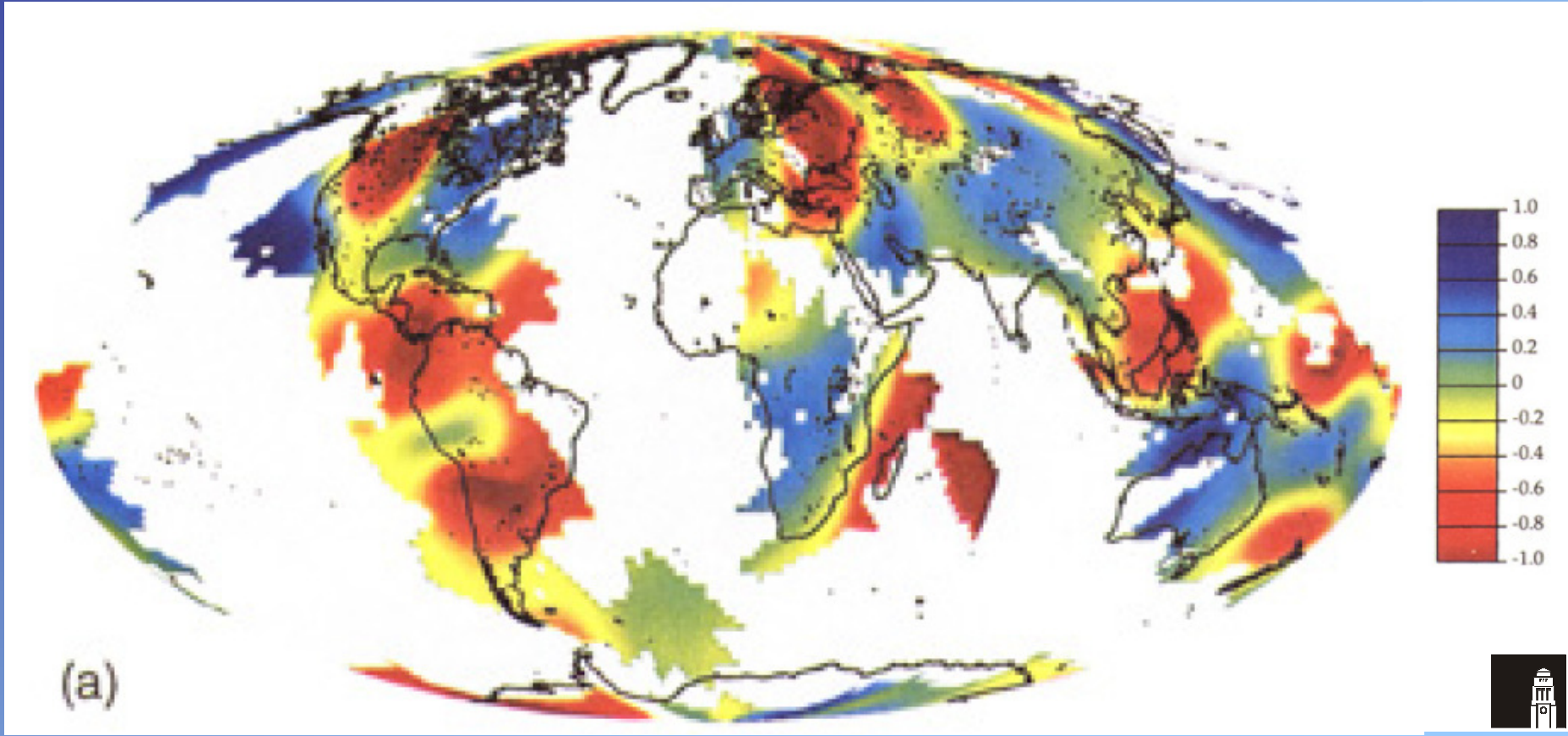
Small-scale scattering



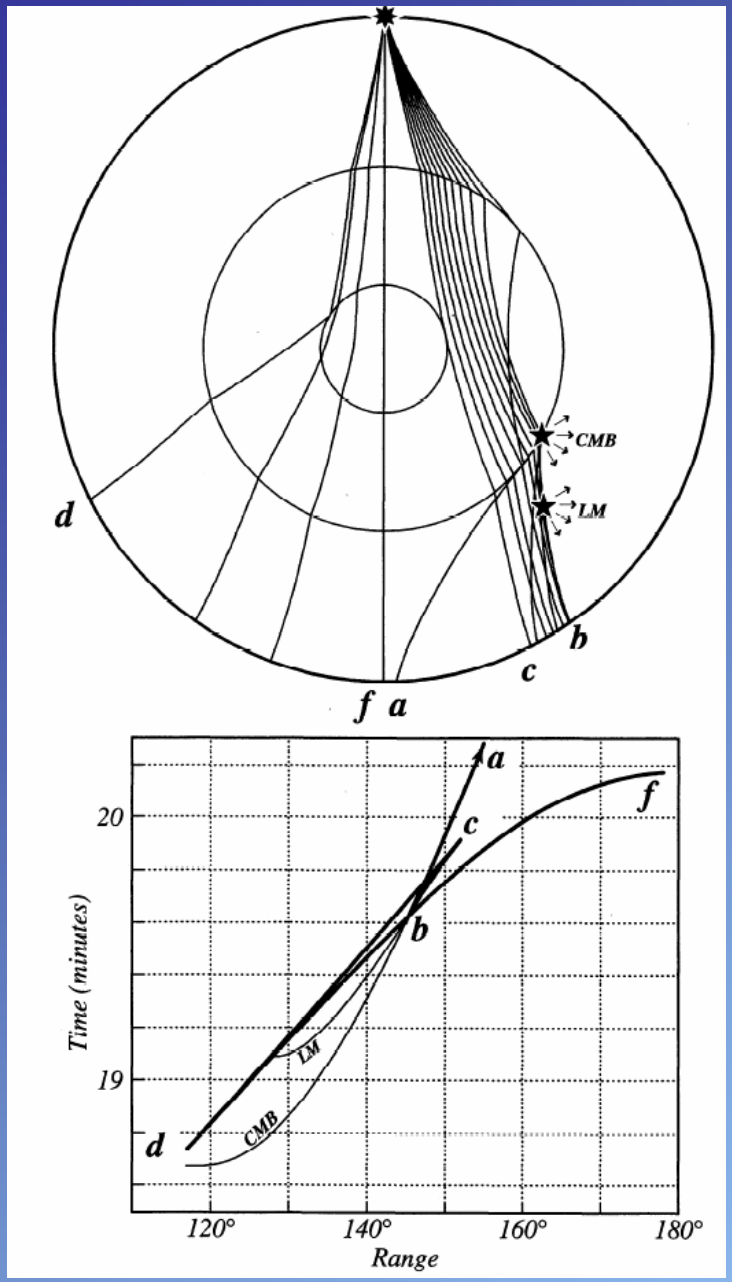
[Ritsema and van Heijst, 2001]

Probing the small-scale structure of the Earth

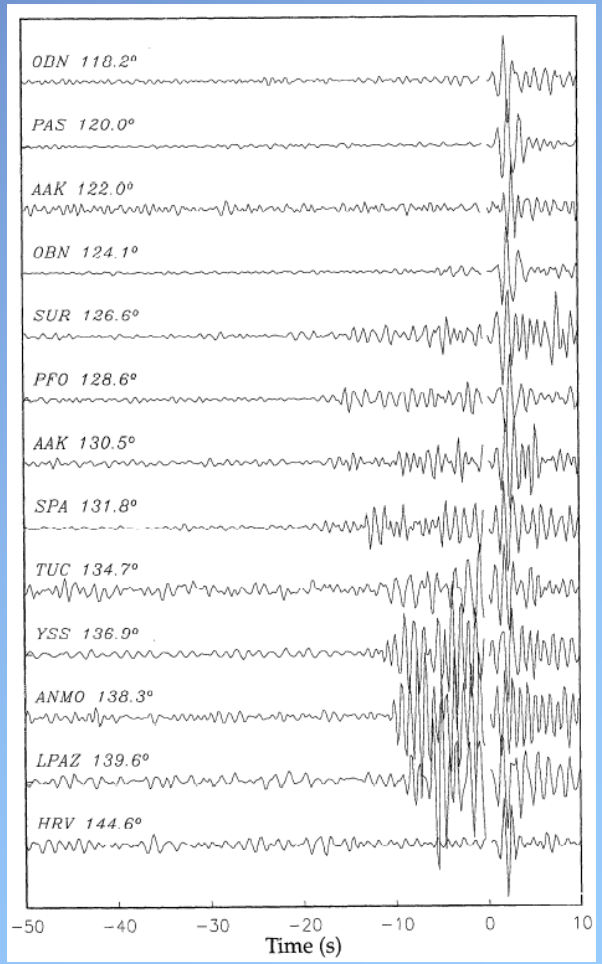
- Sensitive to small-scale heterogeneities of velocity and density
- CMB topography (roughness)
- PKP, PcP, P_{diff}, PKKP



[Hedlin and Shearer, 2000]



- PKP scattering
- Precursors to main PKP arrival
- Statistical material description



[Hedlin and Shearer, 2000]

Array Seismology

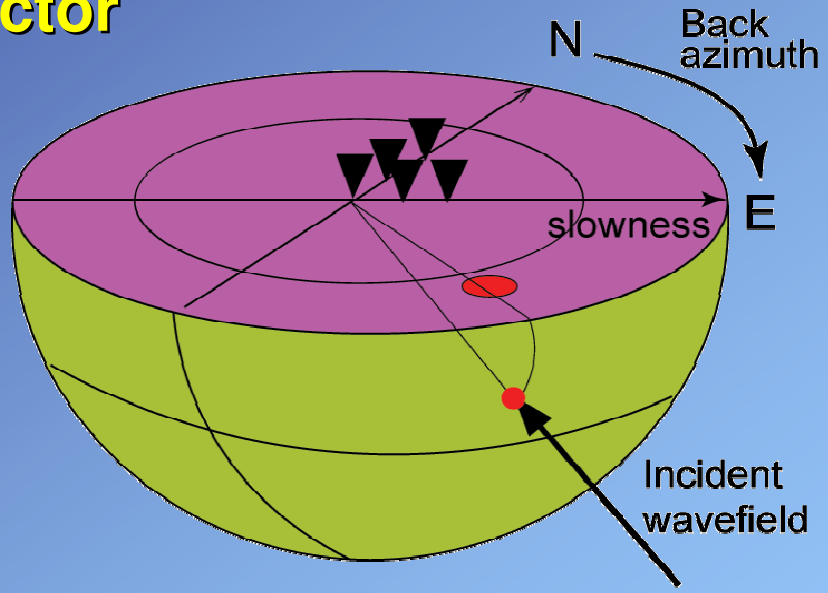
Seismic Array: term used to describe network of seismometers that allow time-series stacking to increase signal-to-noise ratio of coherent energy

Similar to:

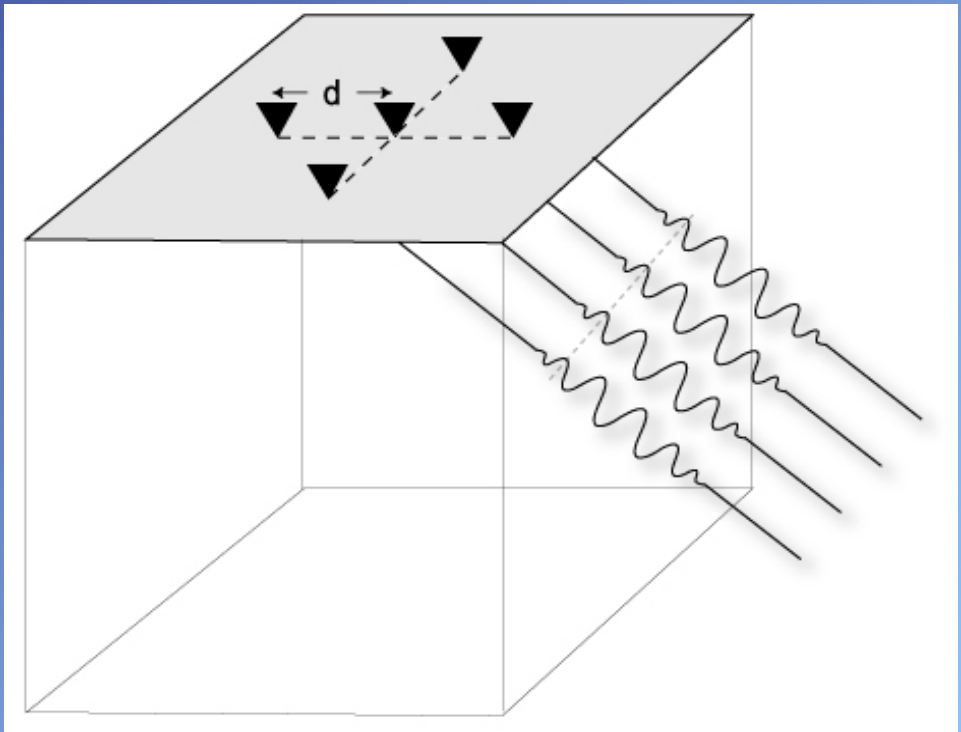
- Chains of geophones
- Antennae
- Radio Telescopes

Very Large Array, New Mexico, USA

- **Measurement of slowness vector**
- **Incidence angle**



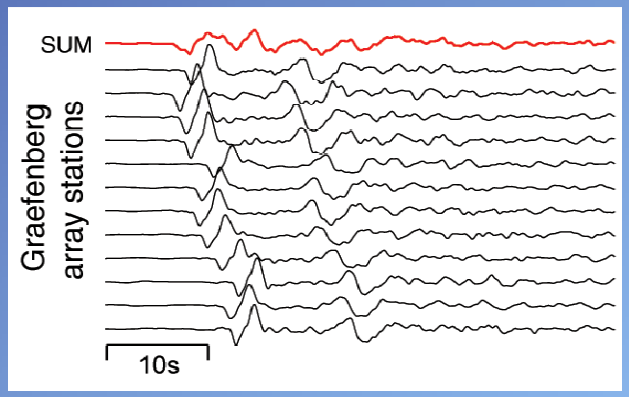
[Jahnke, 1997]

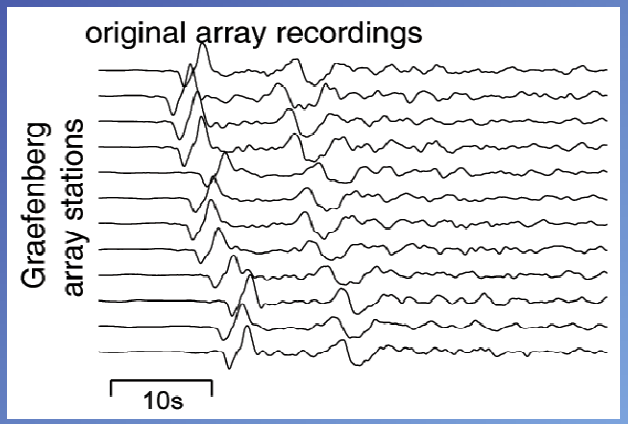


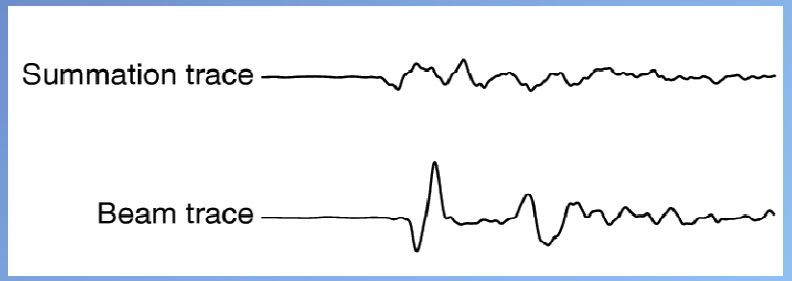
$$u = \frac{1}{v_{app}} = \frac{\sin i}{v_0}$$

Improvement of Signal-to-Noise Ratio

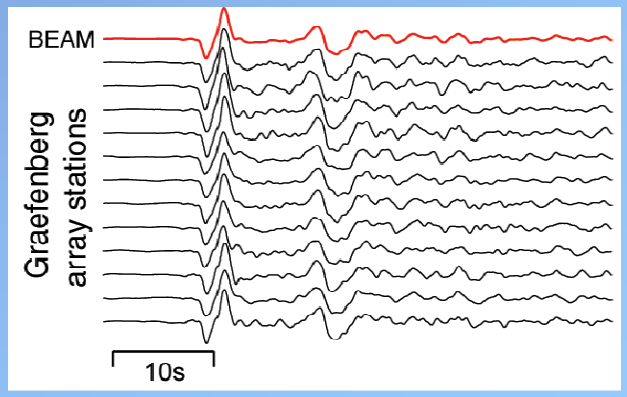
plain sum







Beamforming



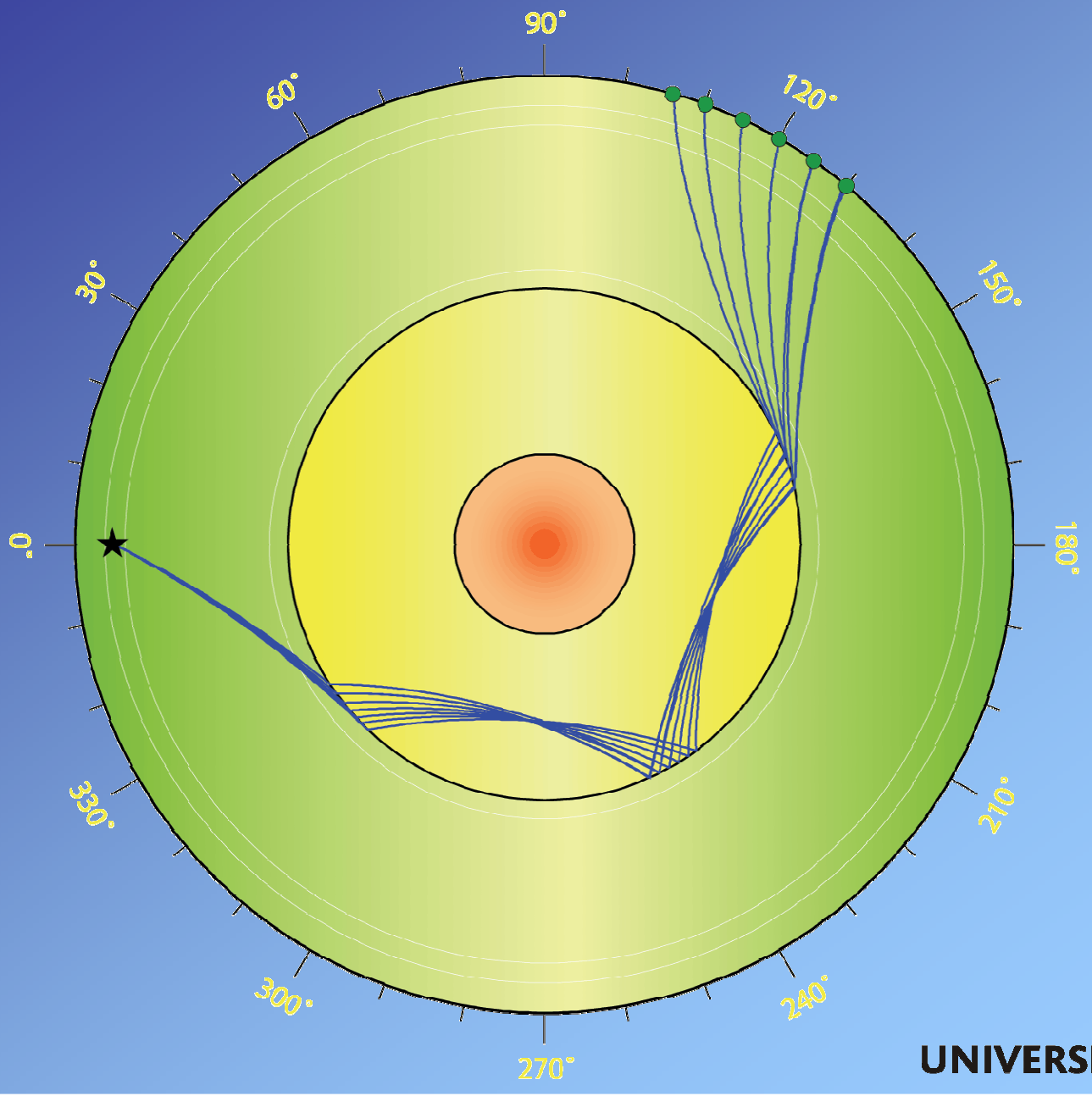
$$x_i(t) = f(t - \vec{r}_i \cdot \vec{u}_{hor}) + n_i(t)$$

$$\overline{x}_i(t) = x_i(t + \vec{r}_i \cdot \vec{u}_{hor})$$

$$b(t) = \frac{1}{M}\sum_{i=1}^{M} \overline{x}_i(t) = f(t) + \frac{1}{M}\sum_{i=1}^{M} n_i(t + \vec{r}_i \cdot \vec{u}_{hor})$$

Rost and Thomas, RoG, 2002

PKKP



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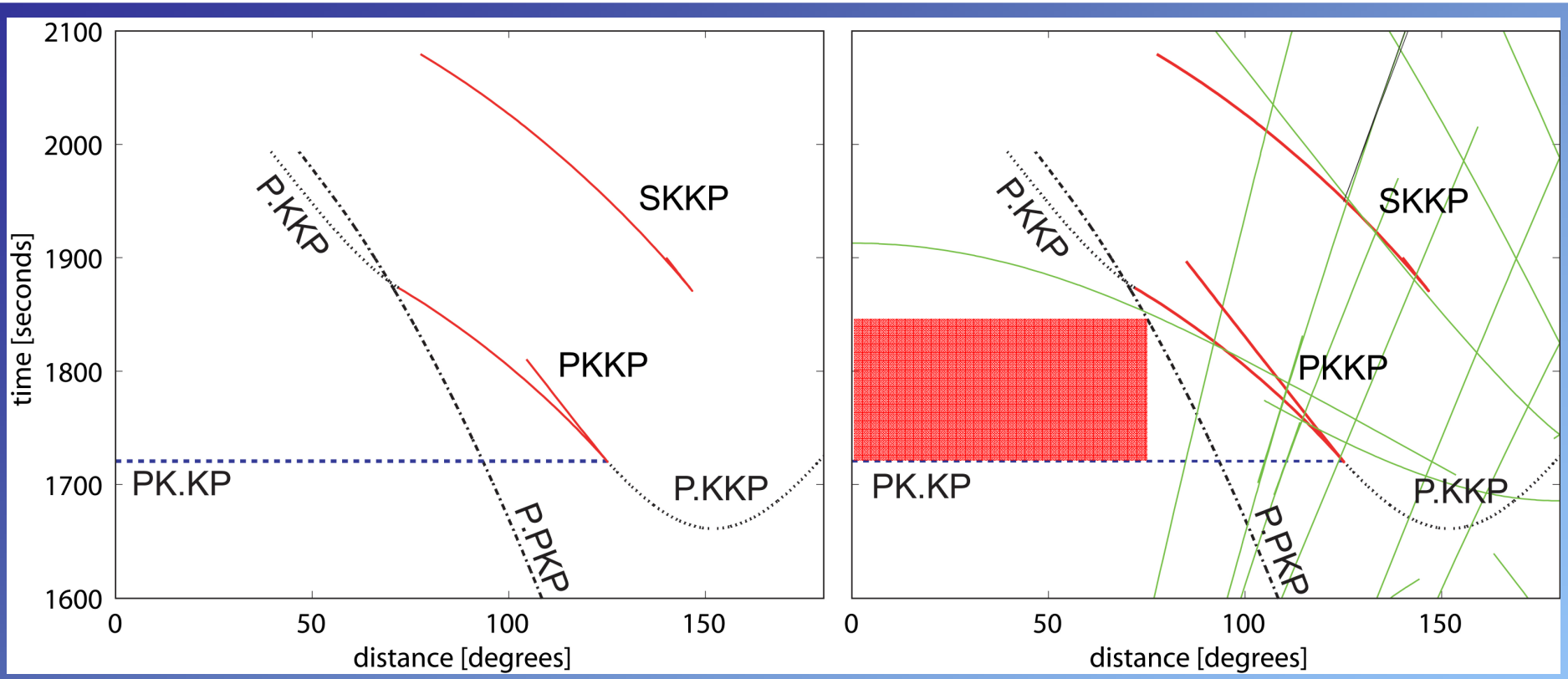
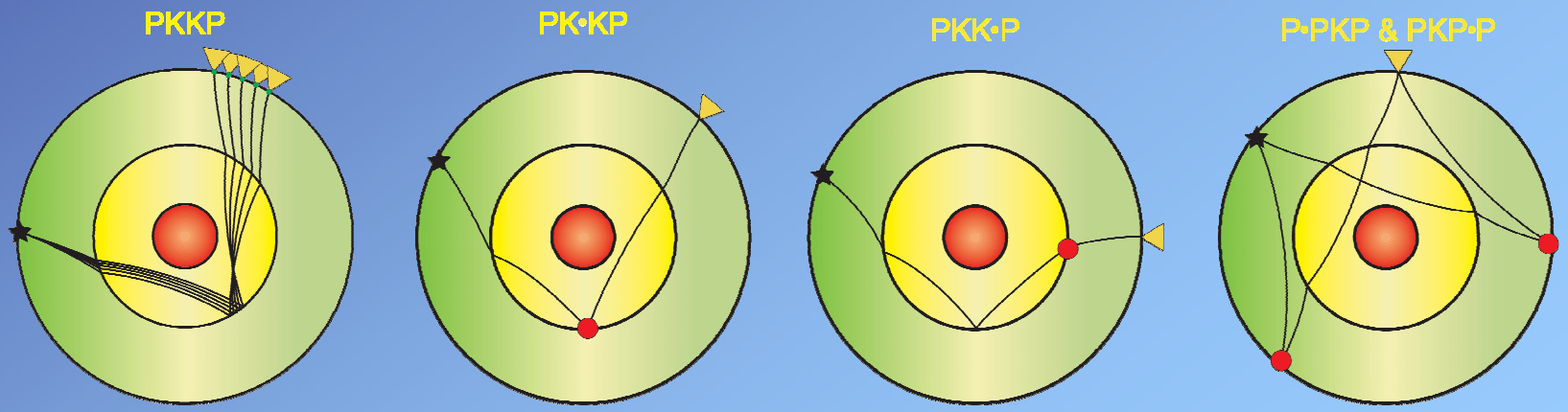


Earle, 2002



[after Earle, 2002]

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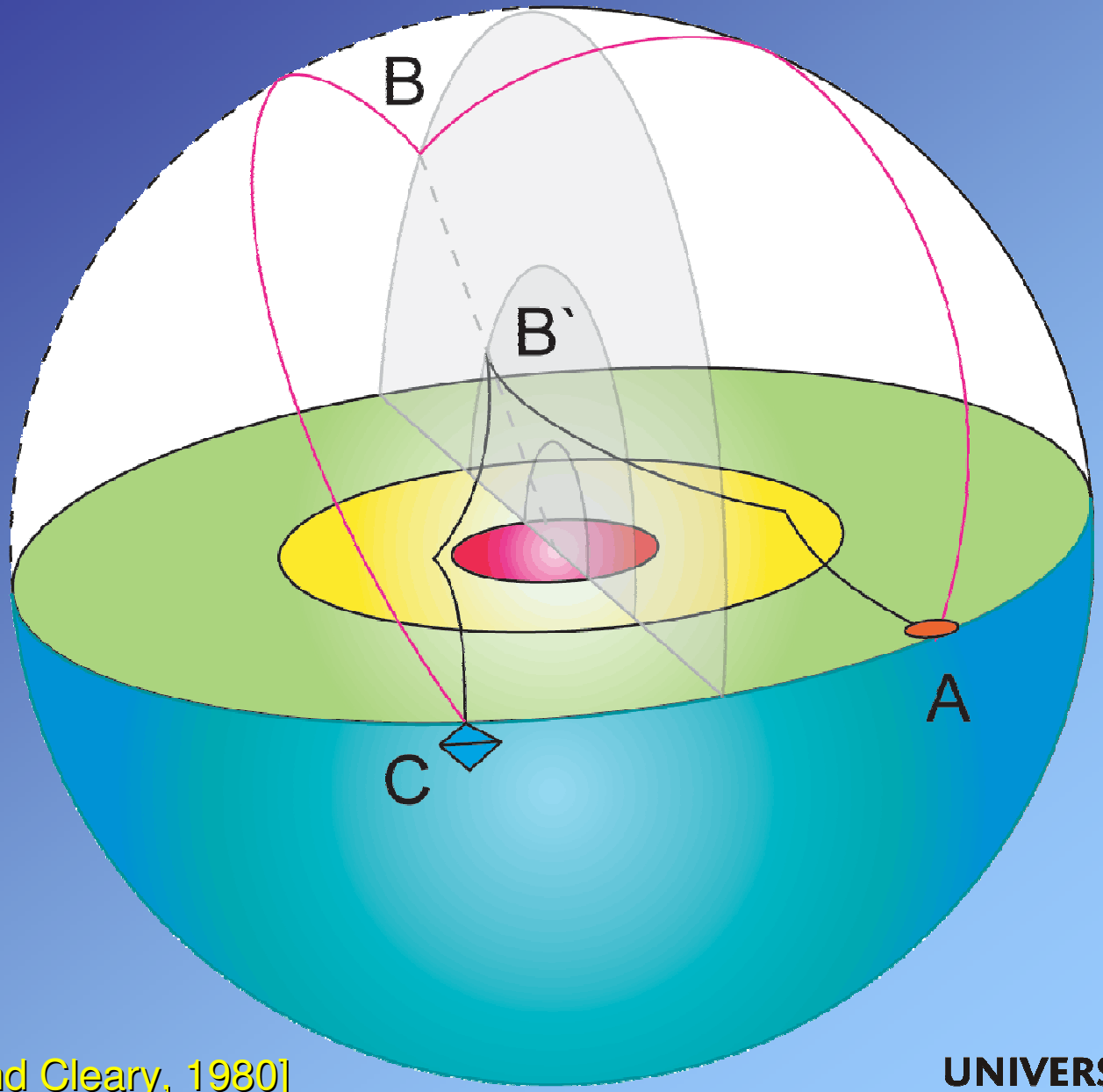
3D - scattering



[after Chang and Cleary, 1980]

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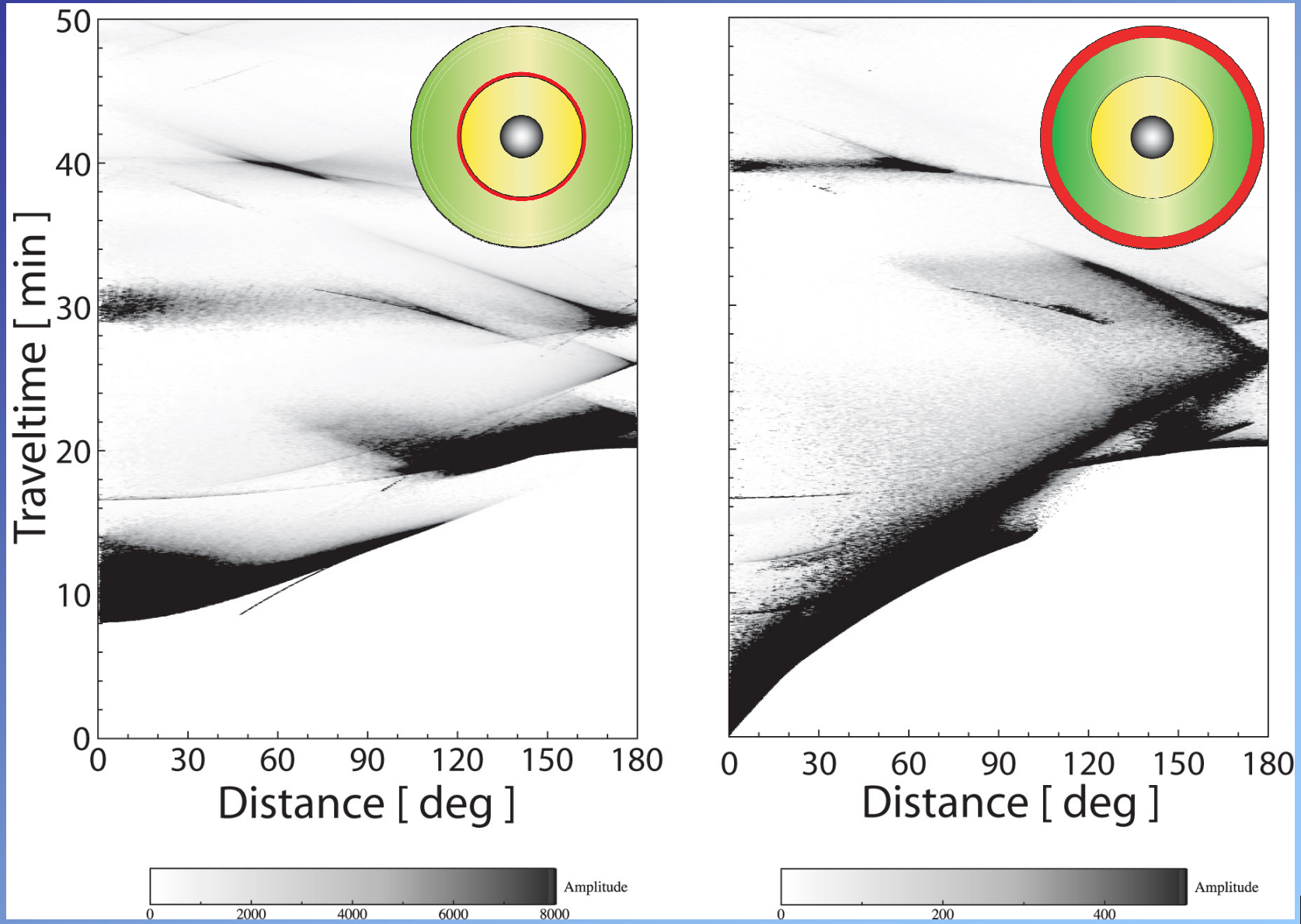
Phonon scattering synthetics



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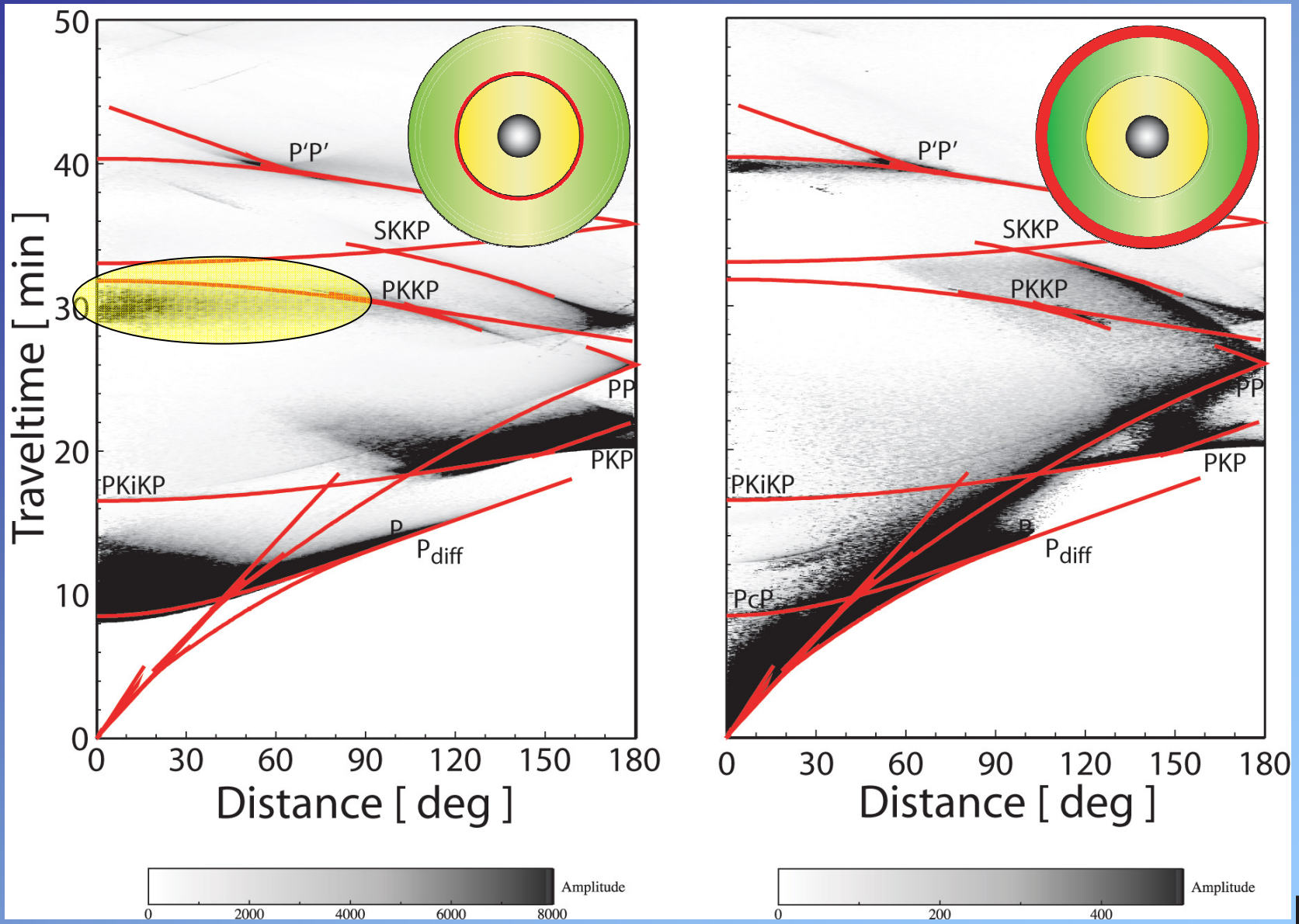

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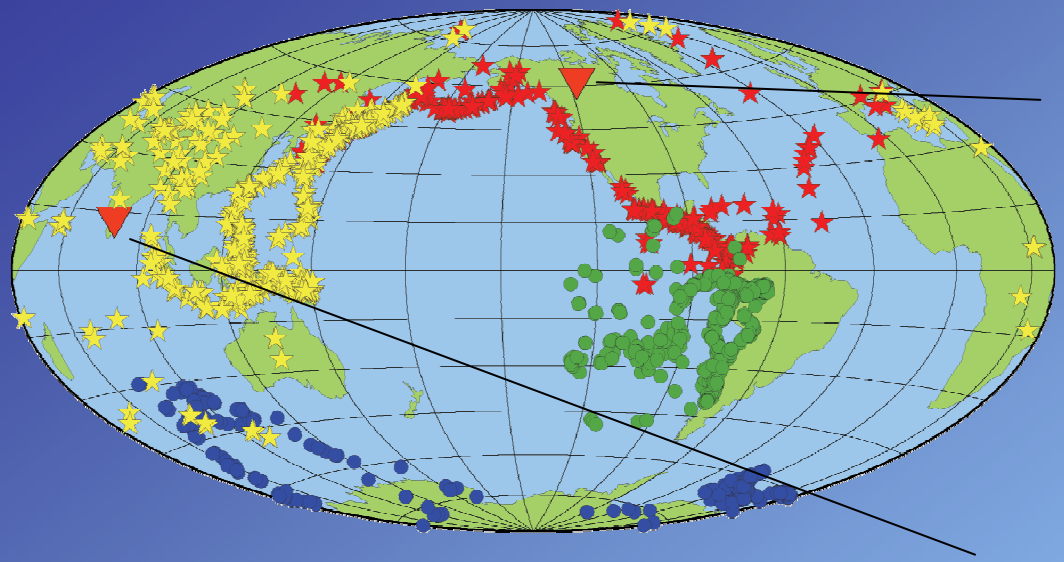
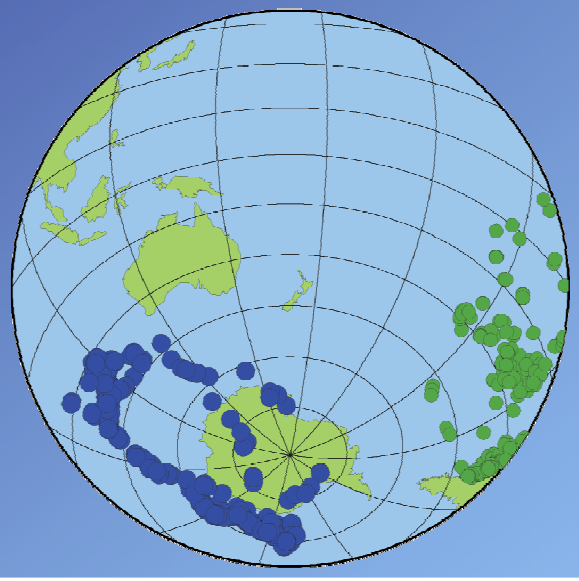
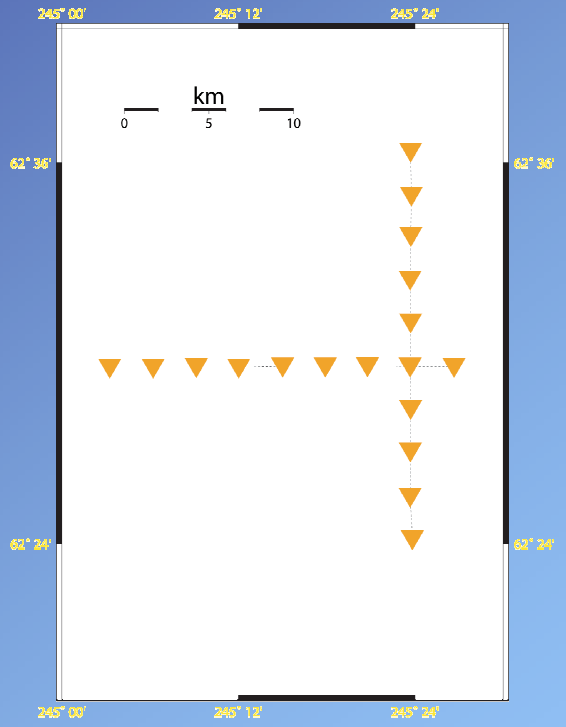
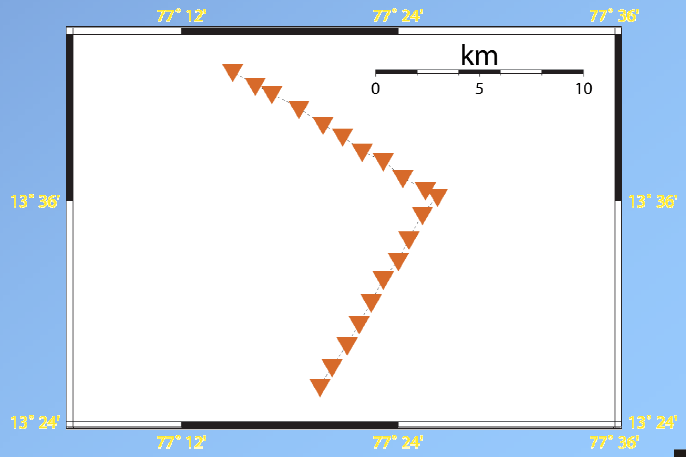
- Distances < 70 deg
- Magnitudes m_b > 6.0









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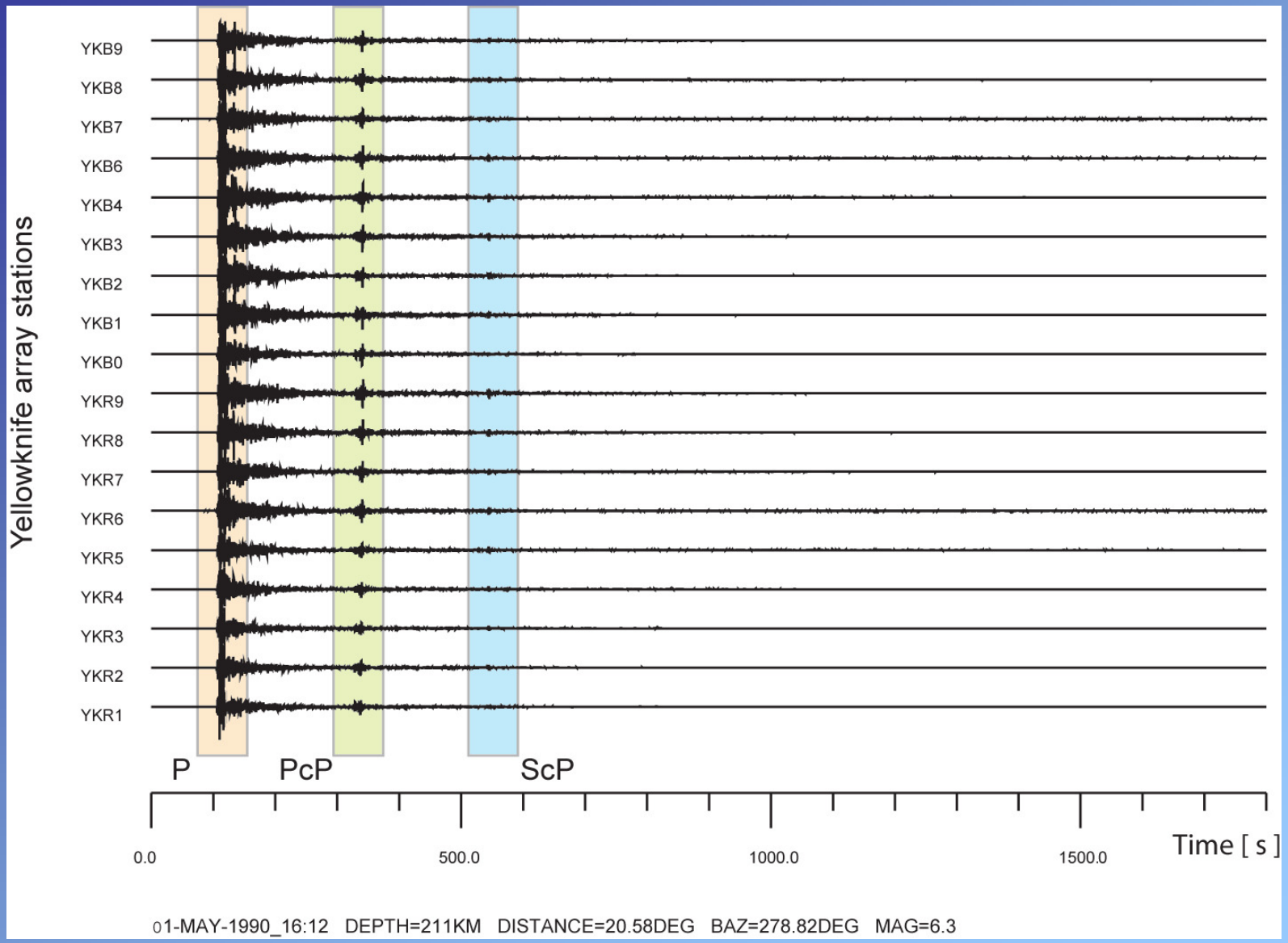

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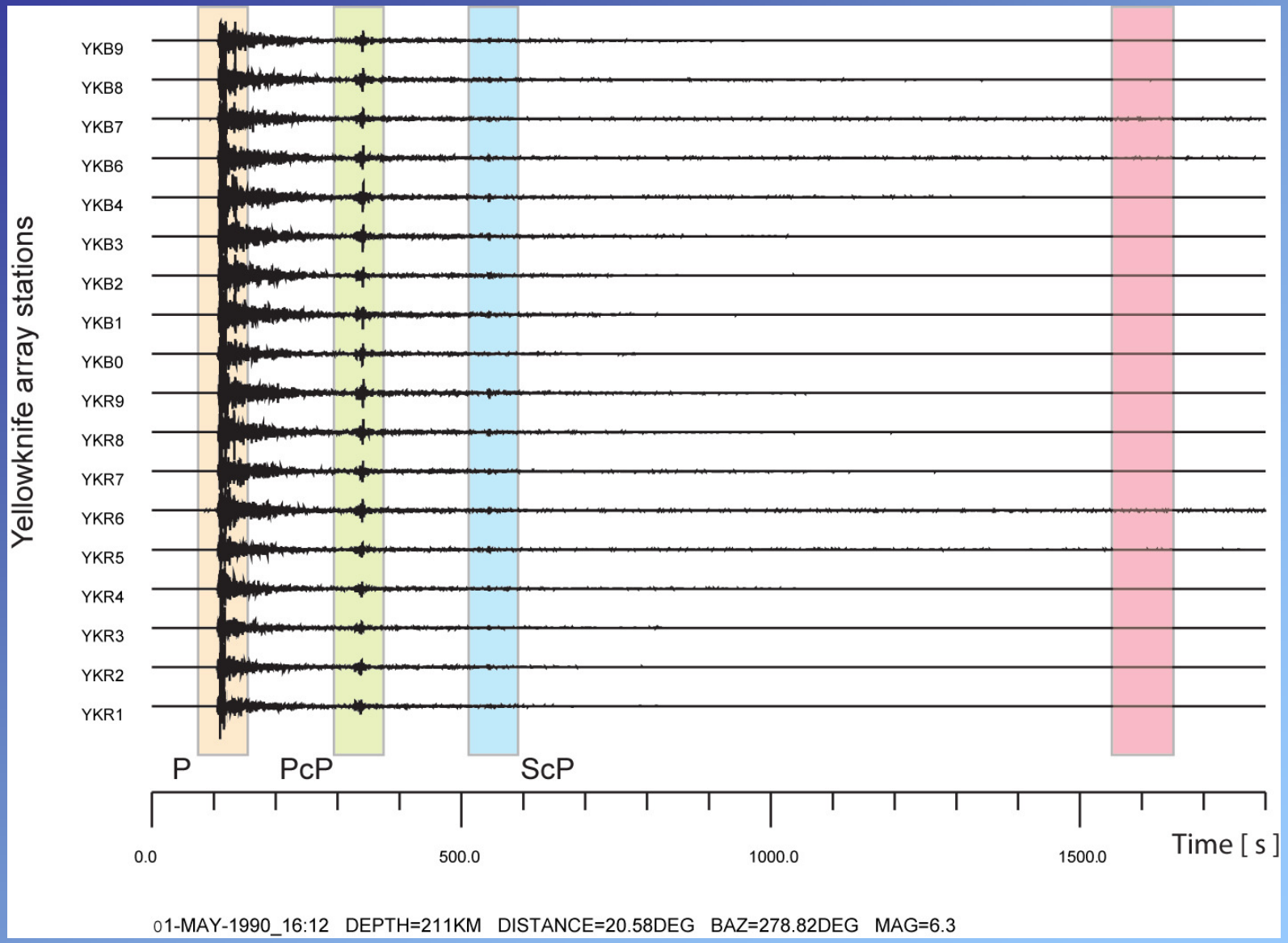

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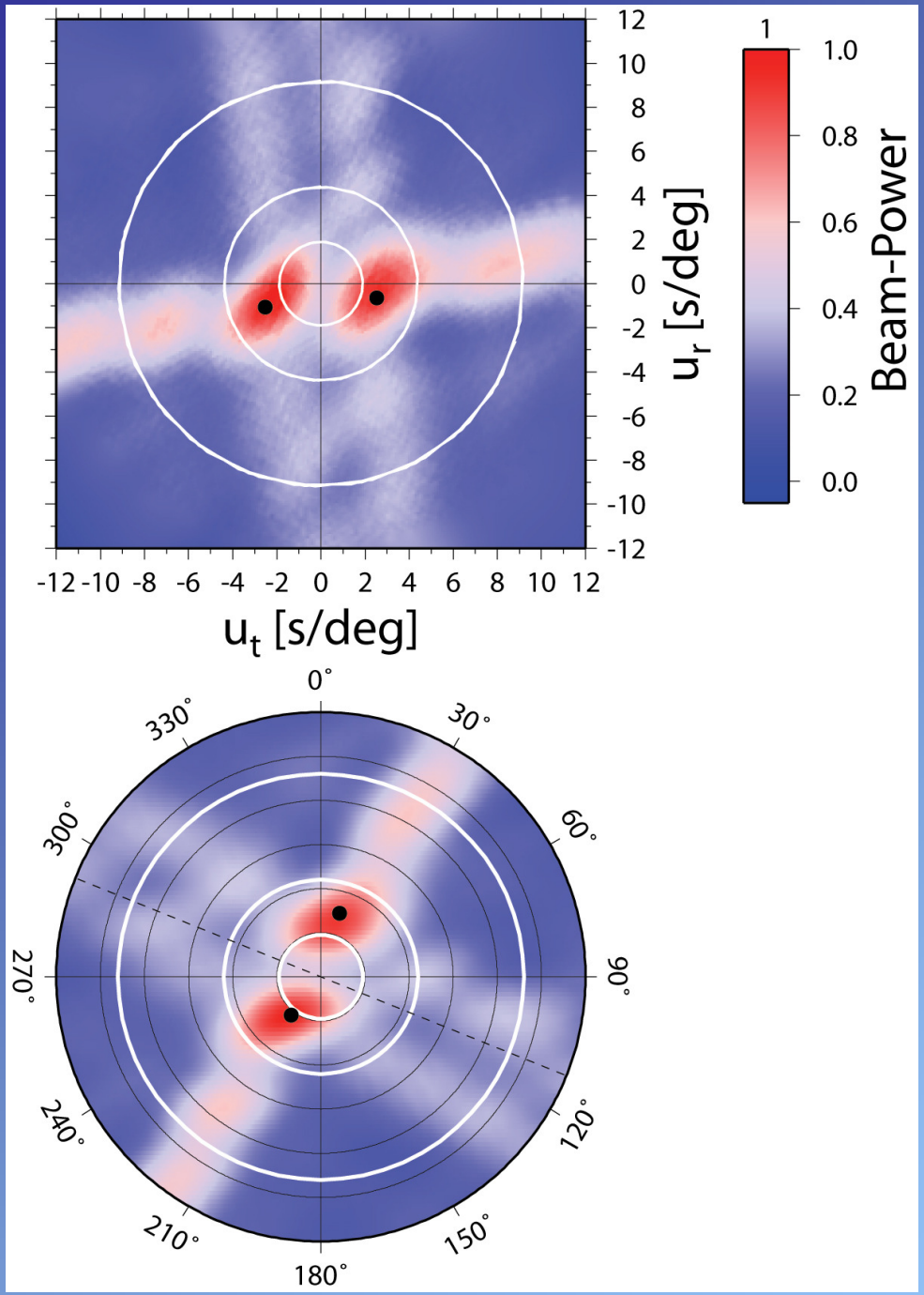

17-JUN-1996_11:22 ⇒ GBA

Lat:	-7.14°
Lon:	122.59°
H:	587 km
M_b:	7.9
Δ:	49.35°
Θ:	111.95°

Energy Maxima

u_{max}= 2.7 s/° and 2.4 s/°

Θ_{max} = 218° and 28°

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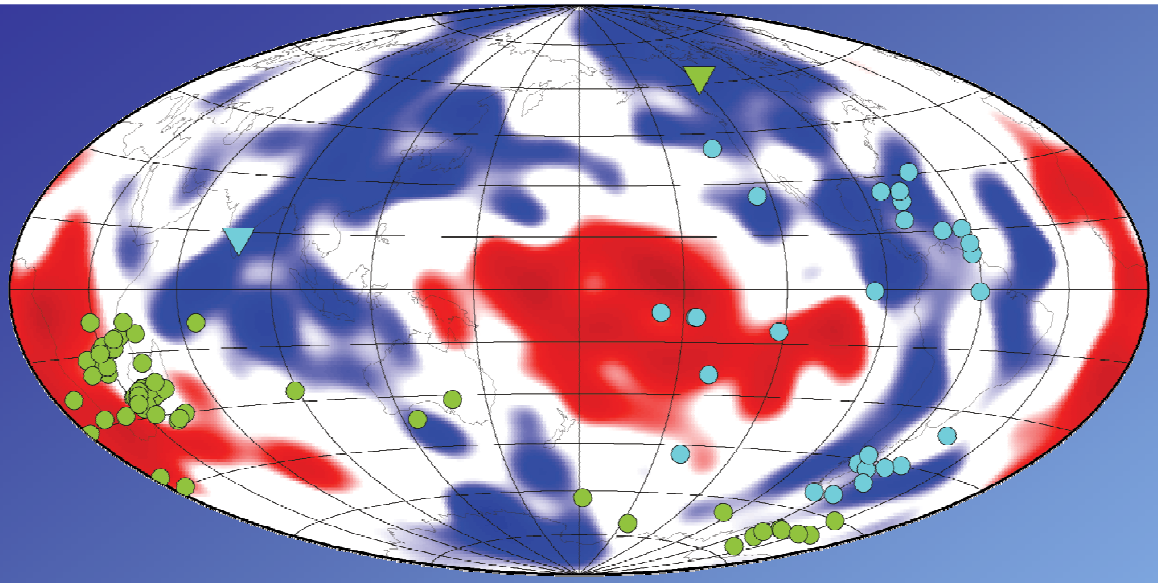
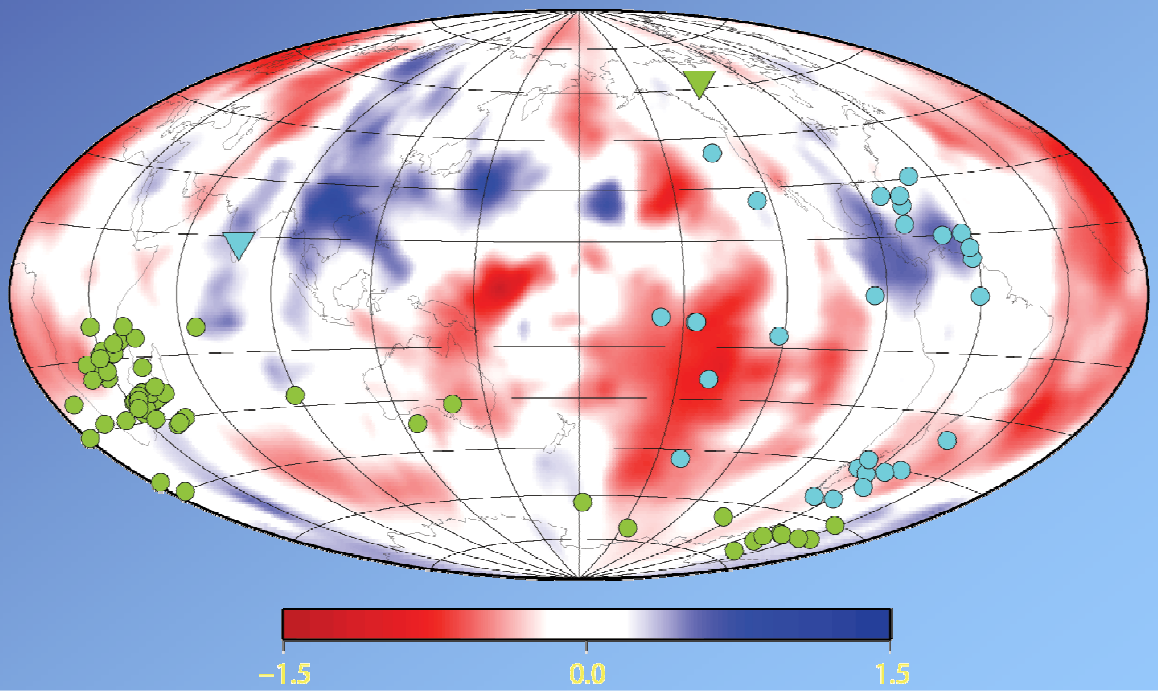


UT S-wave Tomography



MIT P-wave Tomography

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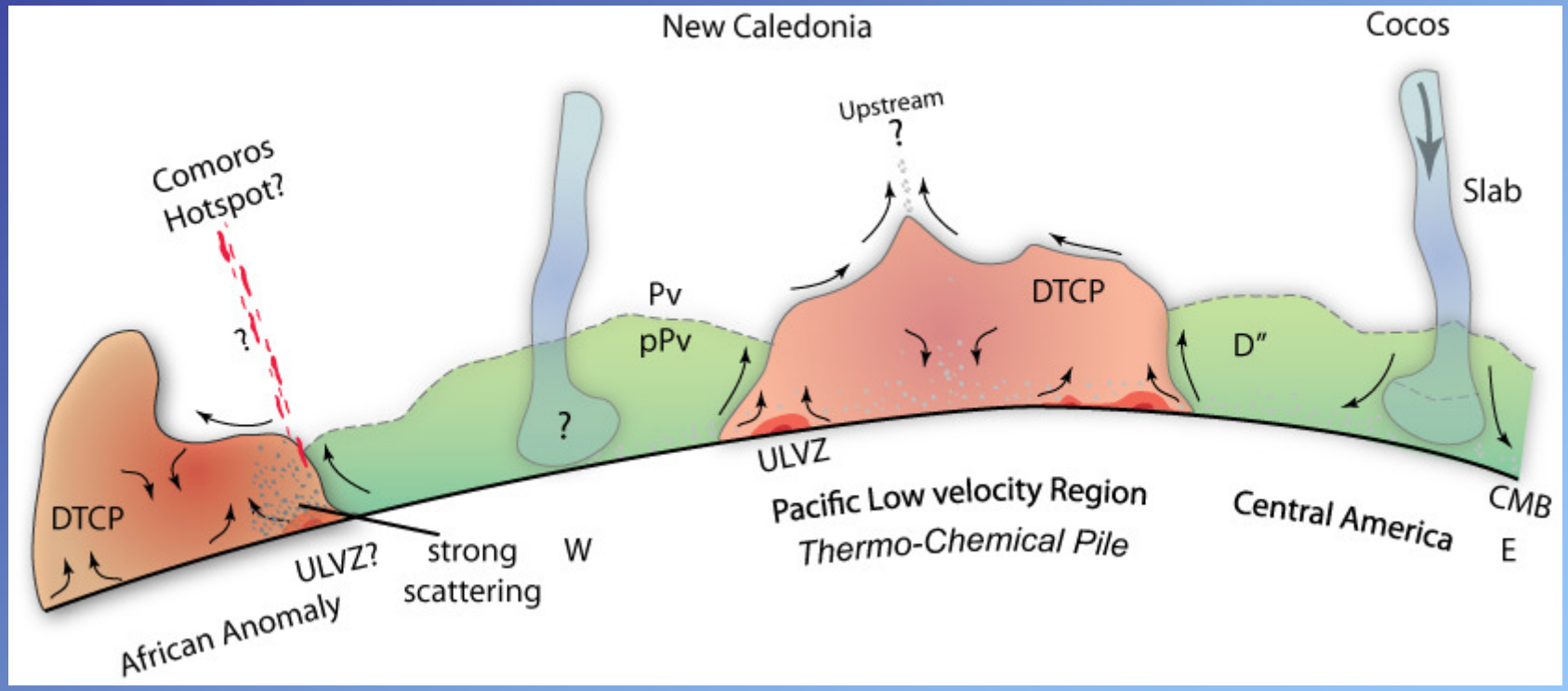
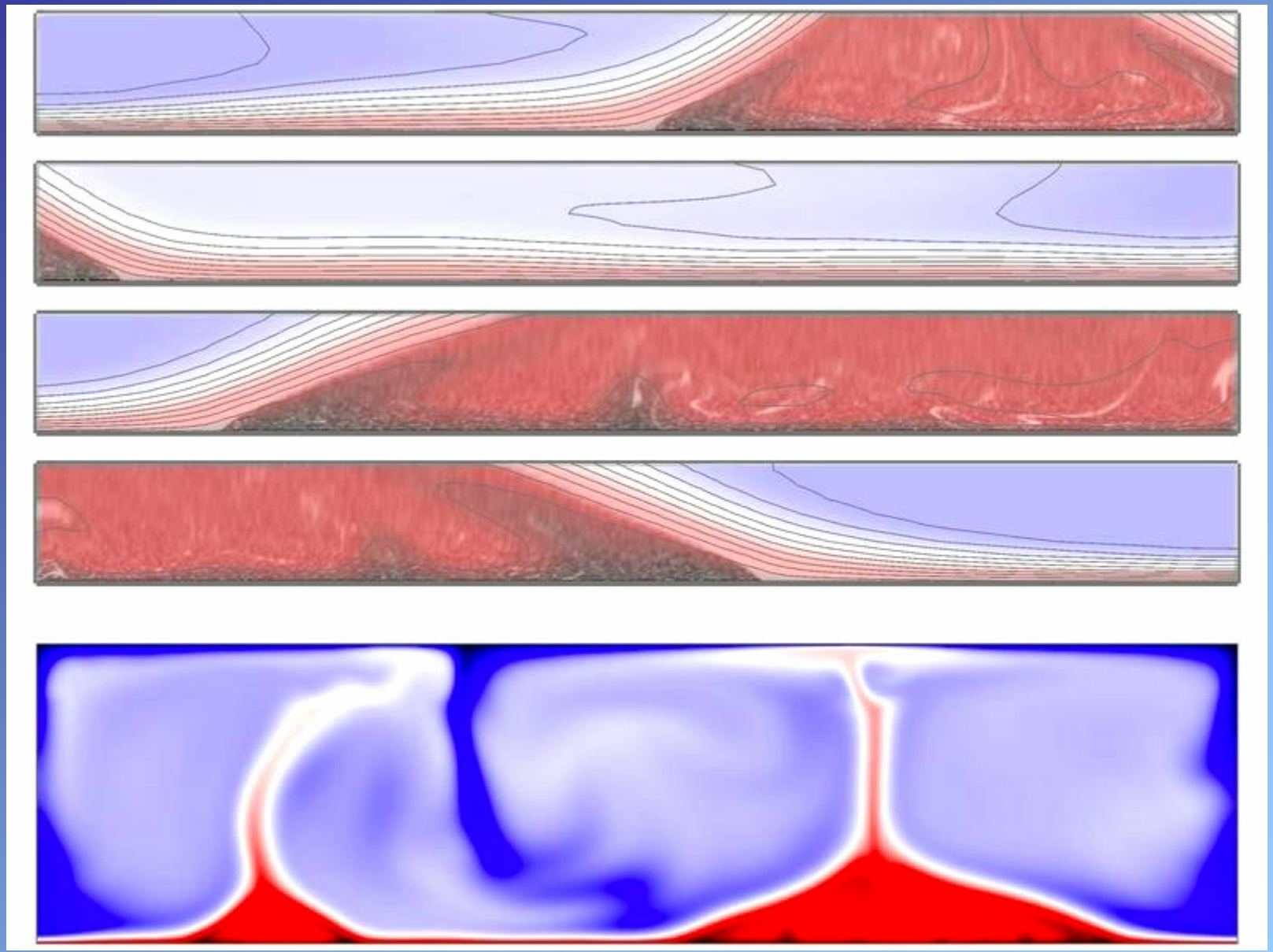
Putting things together





[Courtesy of Allen McNamara]