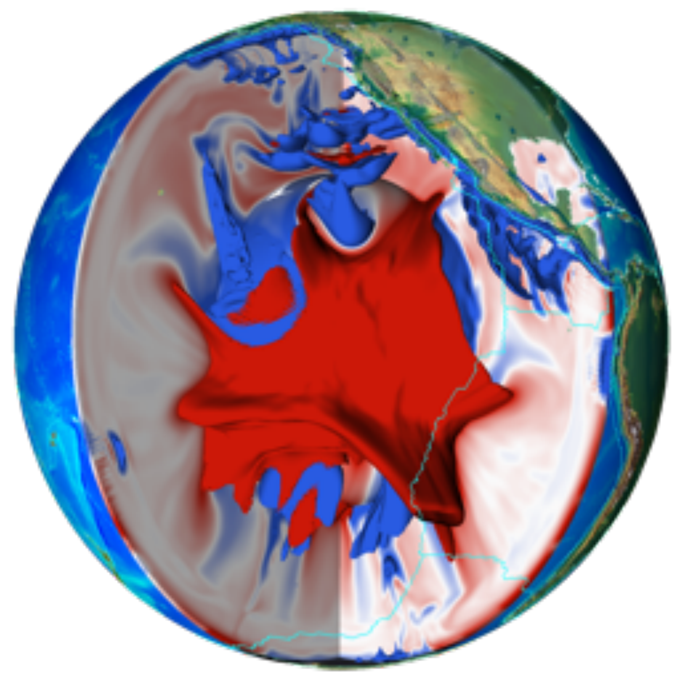
The Importance of Mineral Physics for the Geodynamic Interpretation of Seismic Tomography

1st QUEST Workshop

Capo Caccia

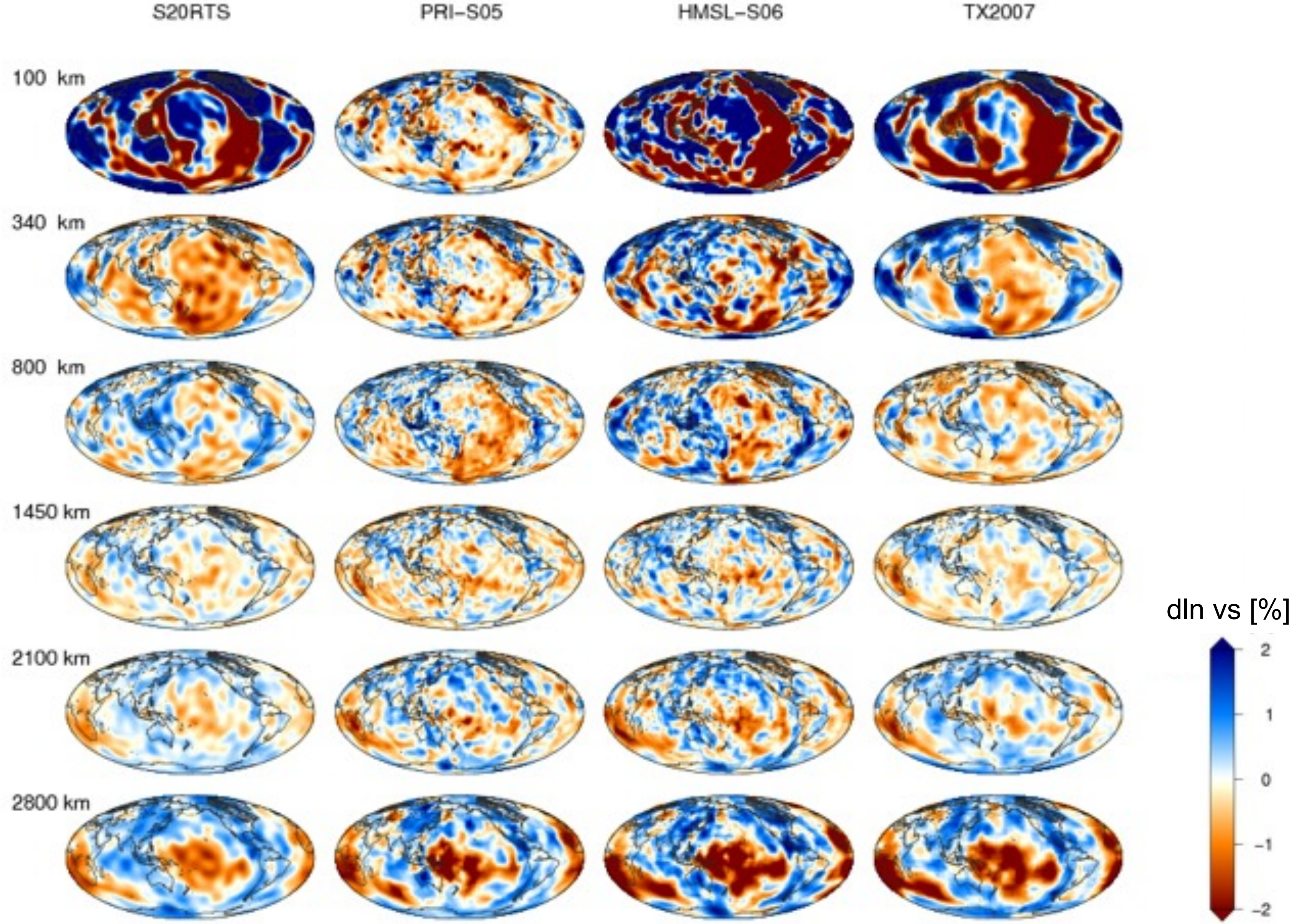


B. Schuberth

UMR GéoAzur, Sophia Antipolis, France

In collaboration with: H.-P. Bunge, G. Nolet, G. Steinle-Neumann, J. Ritsema, L. Stixrude, J. Oeser, C. Moder, K. Schaber, M. Mohr, A. Horbach, A. Piazzoni

Global S-wave Tomography



Schuberth et al., 2009a

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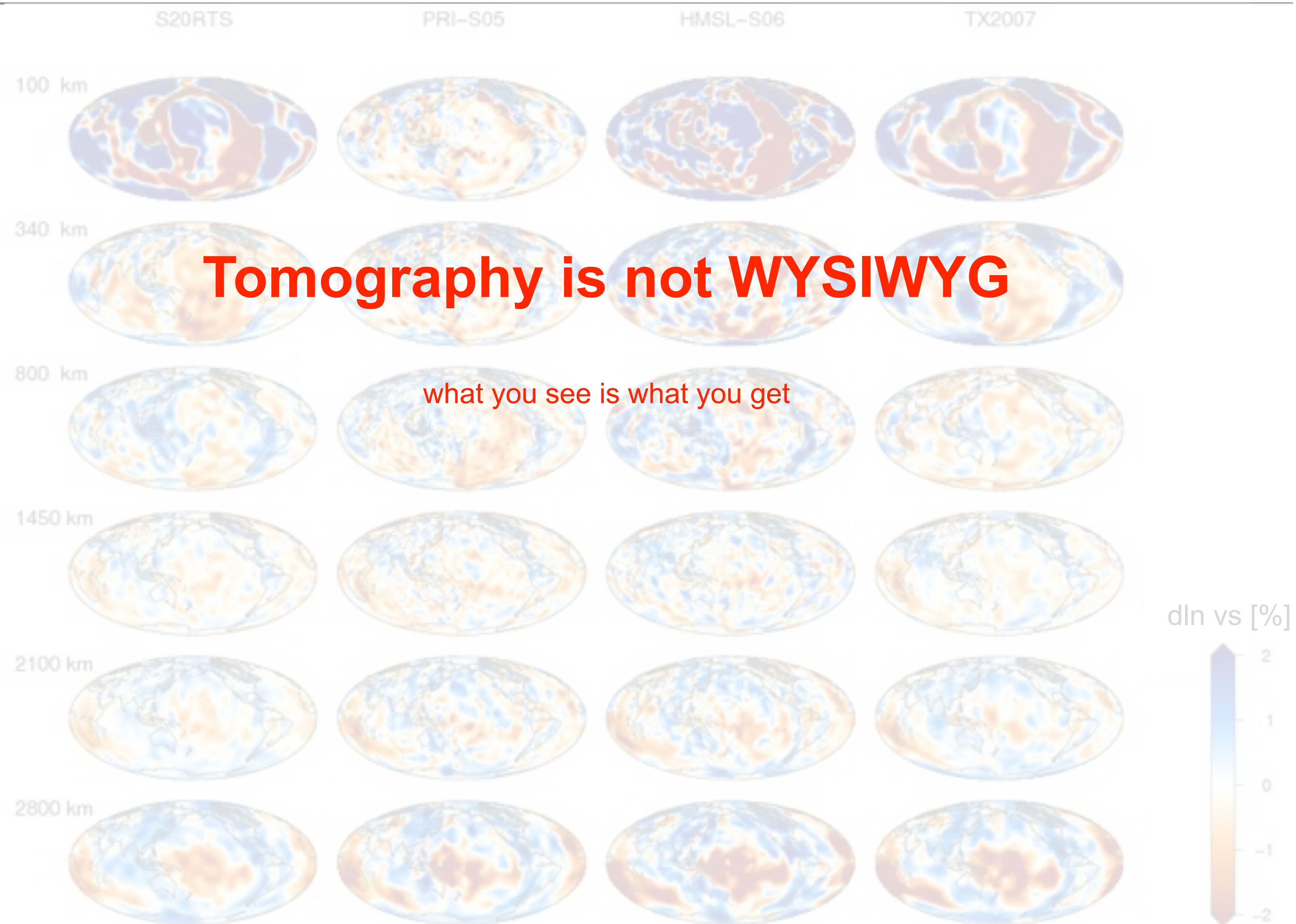


Tomography is not WYSIWYG

what you see is what you get

Schuberth et al., 2009a

Problem: Interpretation of Inversions

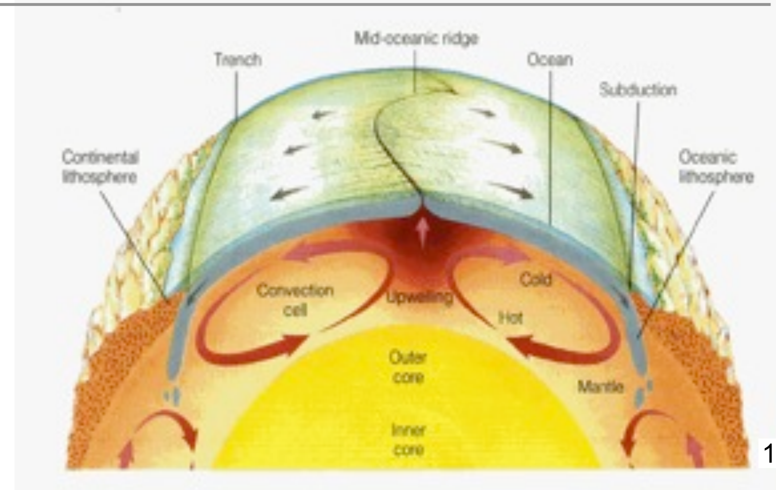
Mantle Dynamics

Interpretation?

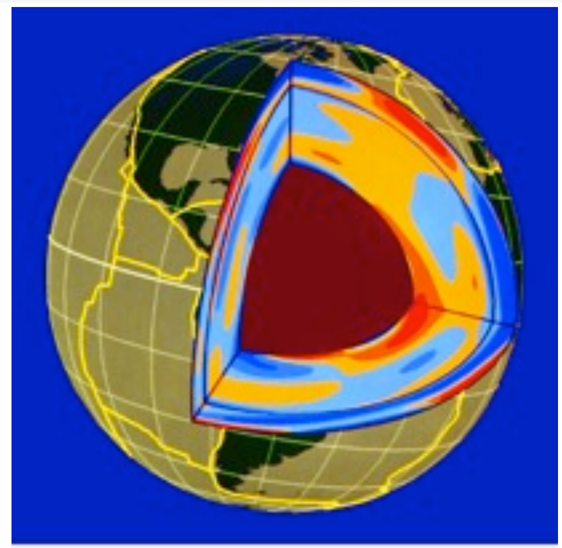
3-D Elastic Structure

Seismic Data

Inverse Problem

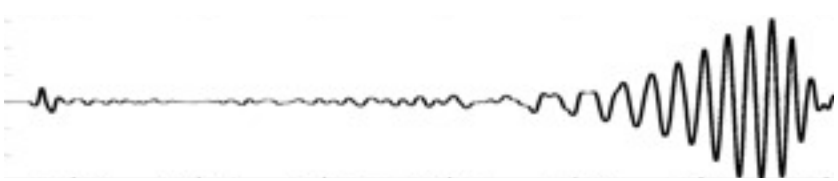


1)



2)

Tomographic Models



1) From Physical Geology Exploring the Earth 4th Edition, James S. Monroe, Reed Wicander, Center Michigan University, brooks/cole
2) http://www.seismology.harvard.edu/~boschi/whole_earth/inner_core_1.gif

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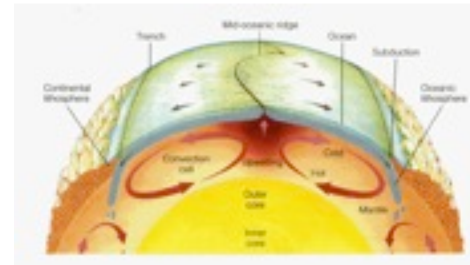


Mantle Dynamics

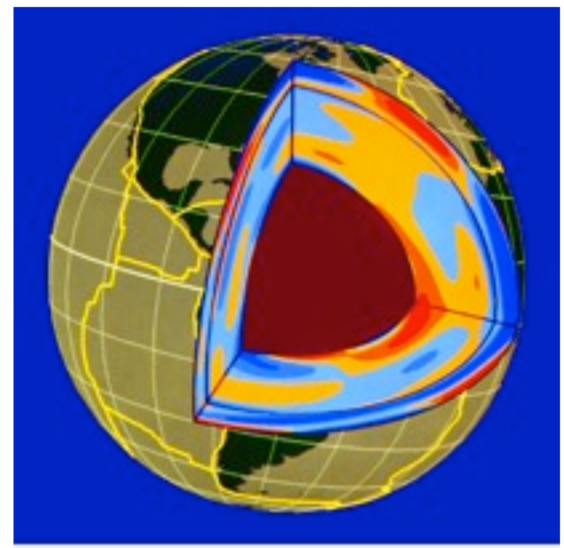
Interpretation?

Mineralogy

Transfer function: temperature ↔ elastic parameters

Inverse Problem

3-D Elastic Structure



Tomographic Models

Seismic Data

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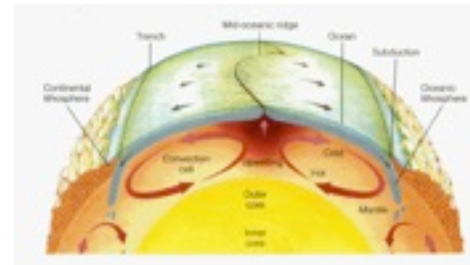

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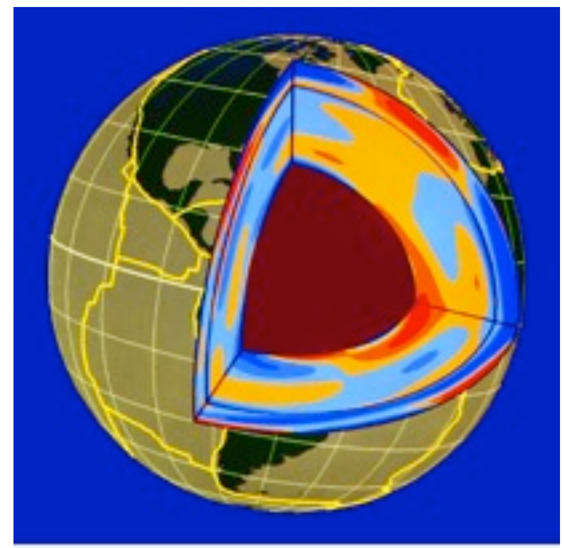
3-D Elastic Structure

Non-Uniqueness



Tomographic Models

Seismic Data

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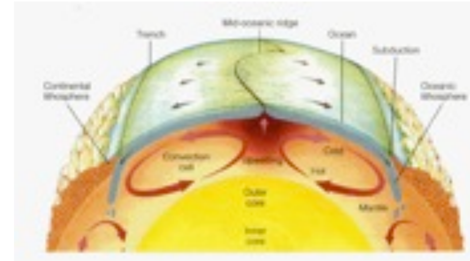

Mantle Dynamics

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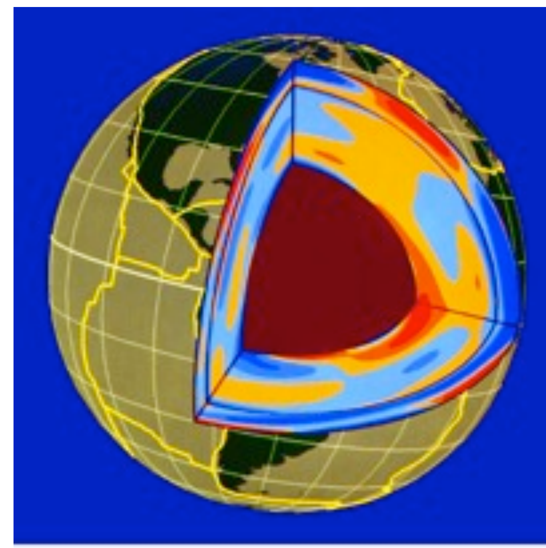
3-D Elastic Structure

Limited Resolution!

Non-Uniqueness



Tomographic Models

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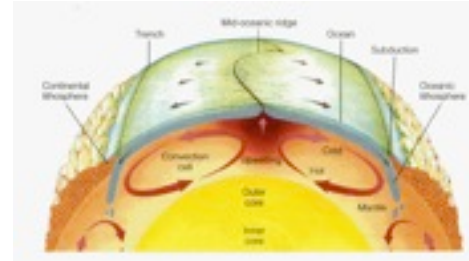


Mantle Dynamics

Interpretation?

Trade-off:
Temperature vs. Chemistry

Mineralogy

Transfer function: temperature ↔ elastic parameters

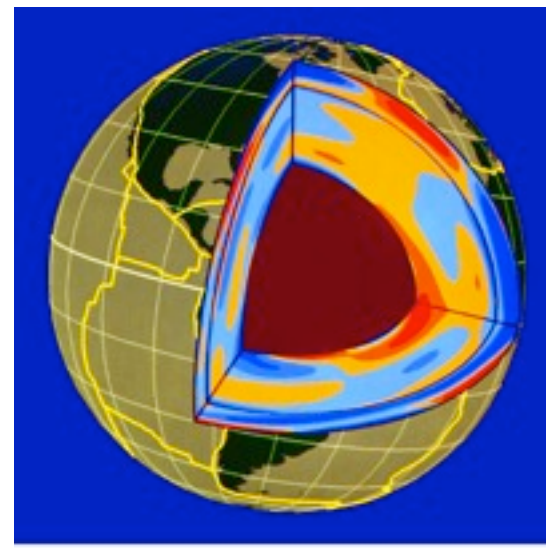
Inverse Problem

3-D Elastic Structure

Limited Resolution!

Non-Uniqueness

Seismic Data



Tomographic Models

Problem: Interpretation of Inversions

Inverse
Problem

3-D Elastic Structure

Prediction of Elastic Structure

Forward Modeling

3-D Elastic Structure

Prediction of Elastic Structure

Forward
Modeling

Mantle Dynamics

3-D Elastic Structure

3-D high-resolution
mantle circulation modeling
Control on thermal fields

Prediction of Elastic Structure

Forward Modeling

Mantle Dynamics	3-D high-resolution mantle circulation modeling Control on thermal fields
↓	
Mineralogy	Transfer function: temperature ↔ elastic parameters Thermodynamic models + composition
↓	
3-D Elastic Structure	

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3-D Elastic Structure

Theoretical Predictions
Study effects of mineralogy on 3-D seismic structure

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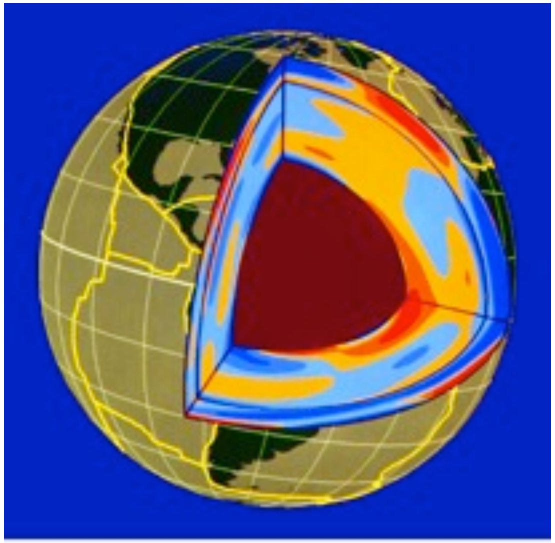
Comparison to Tomography



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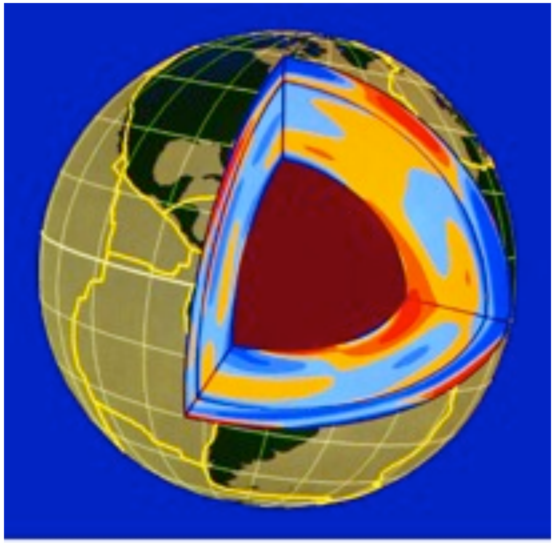

Comparison to Tomography

Quantitative Testing of Hypotheses

Prediction of Elastic Structure

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3-D high-resolution mantle circulation modeling
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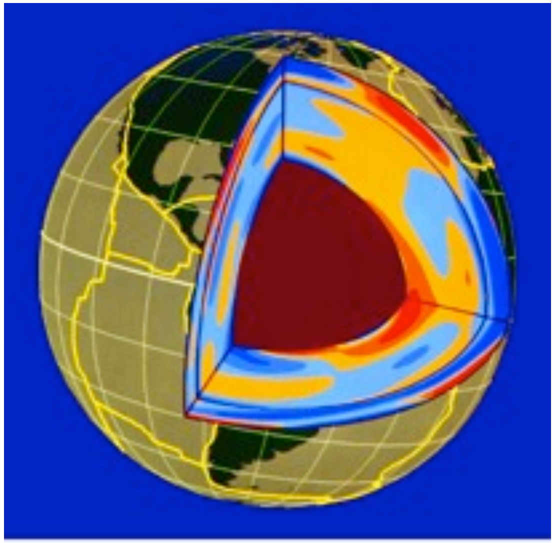

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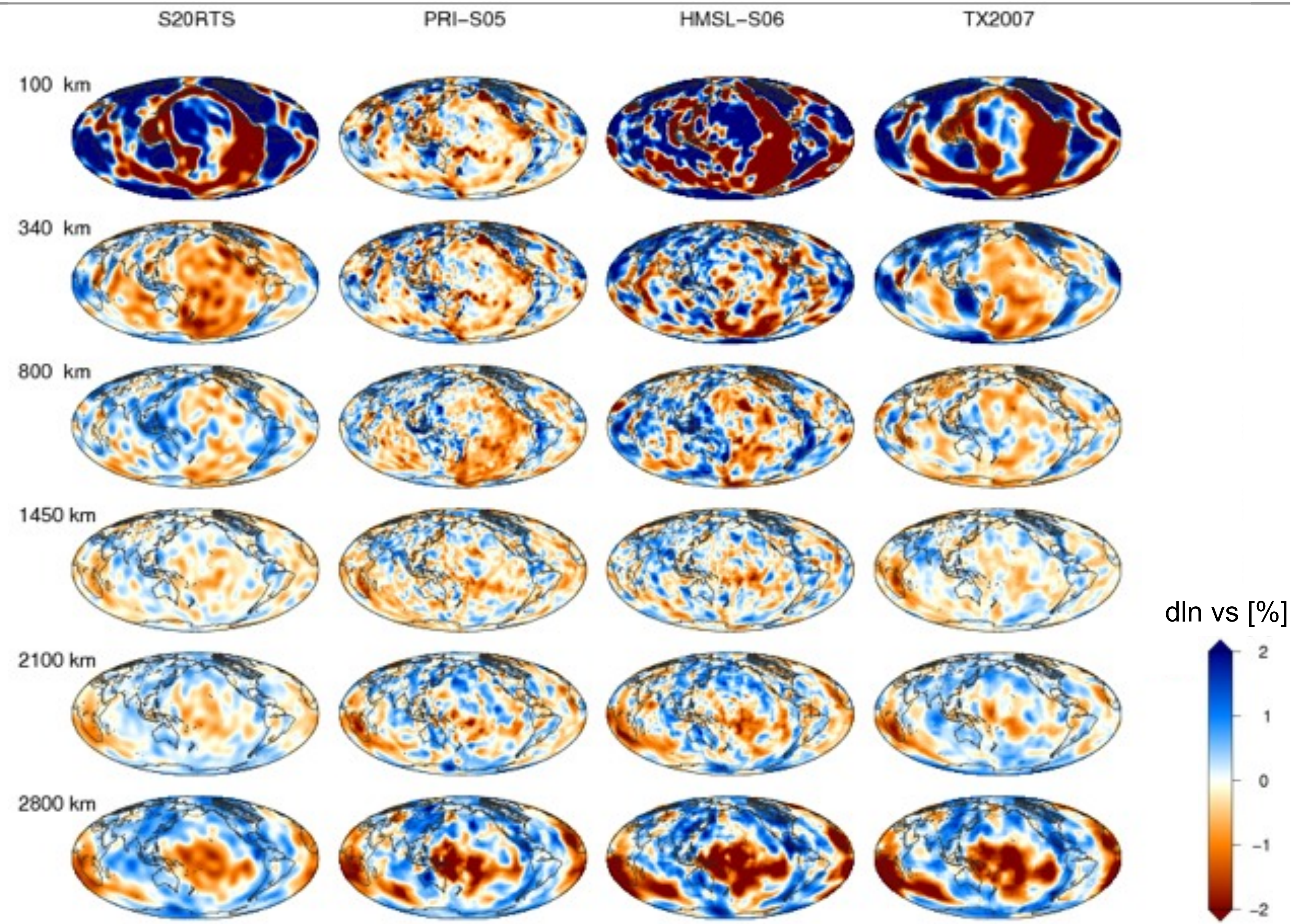
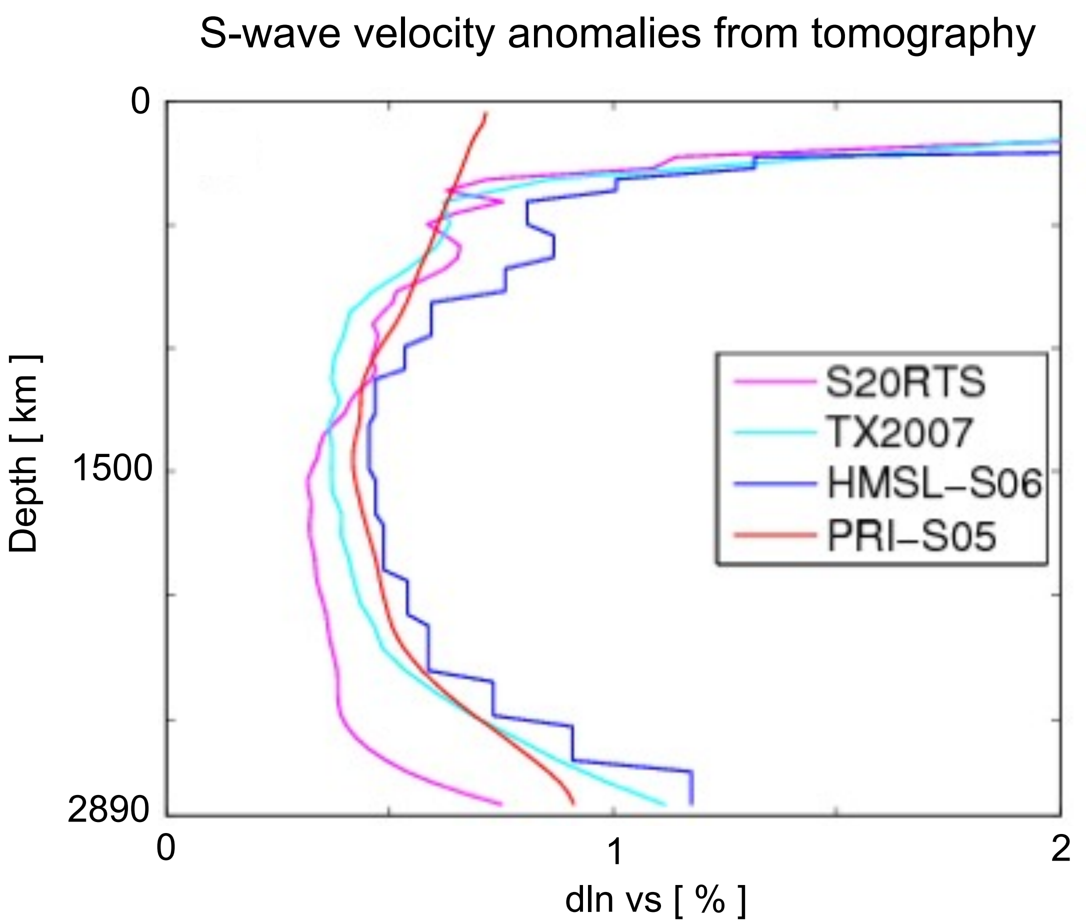


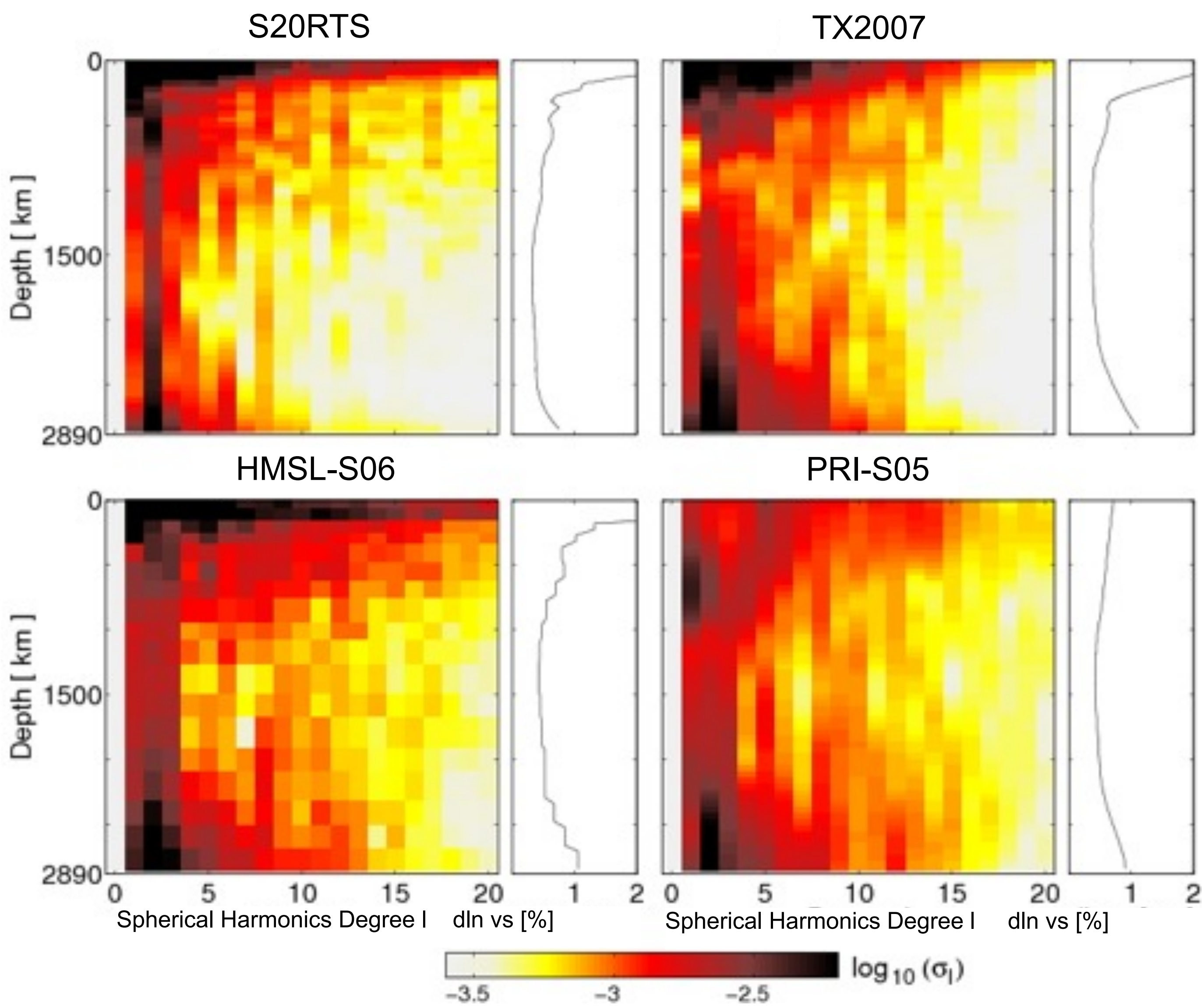
Schuberth et al., 2009a

Root-Mean-Square Profiles of Seismic Heterogeneity



Schuberth et al., 2009a

Statistics for Tomographic Models - Spectral Power



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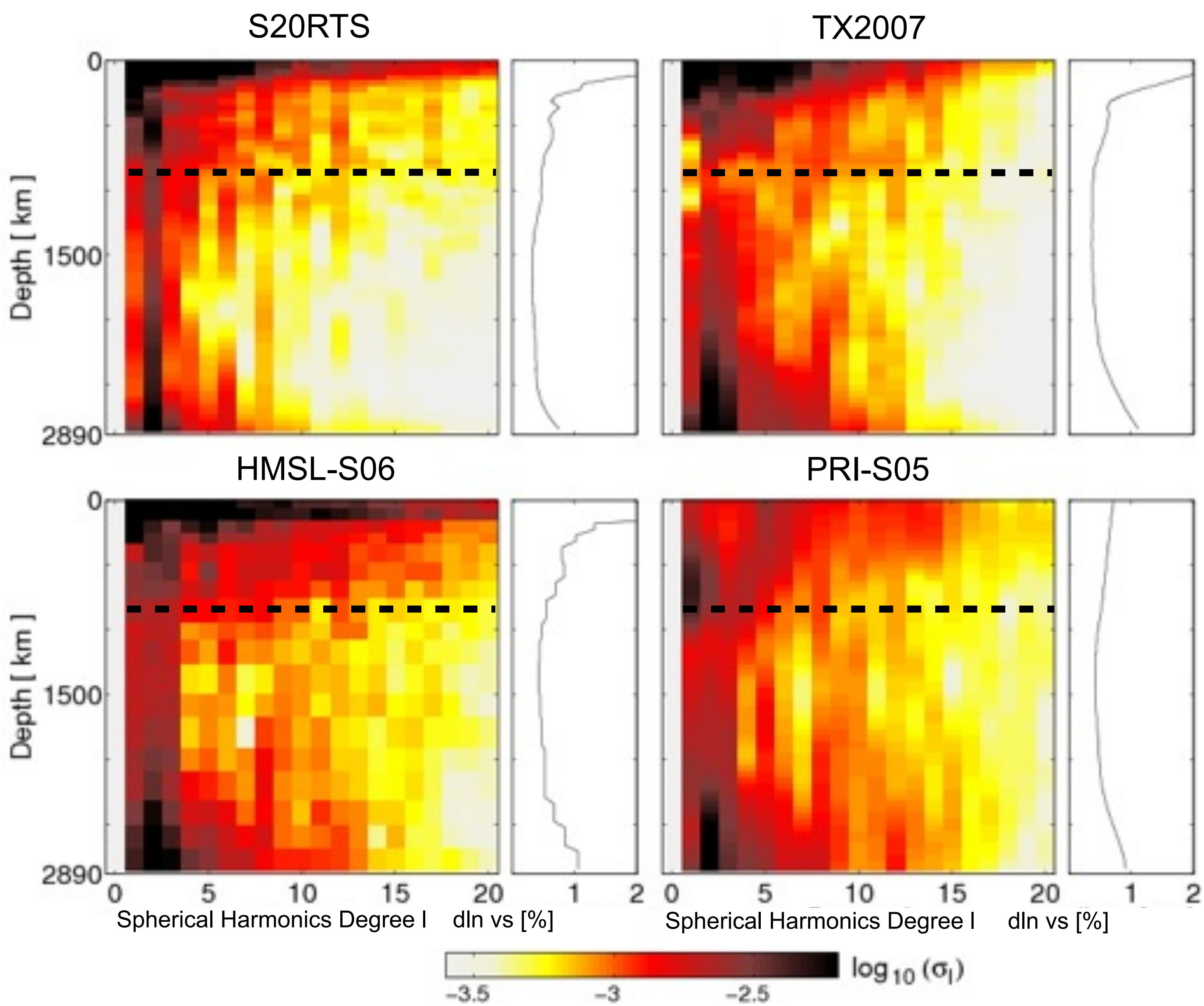

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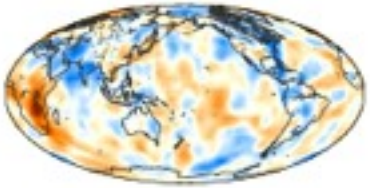
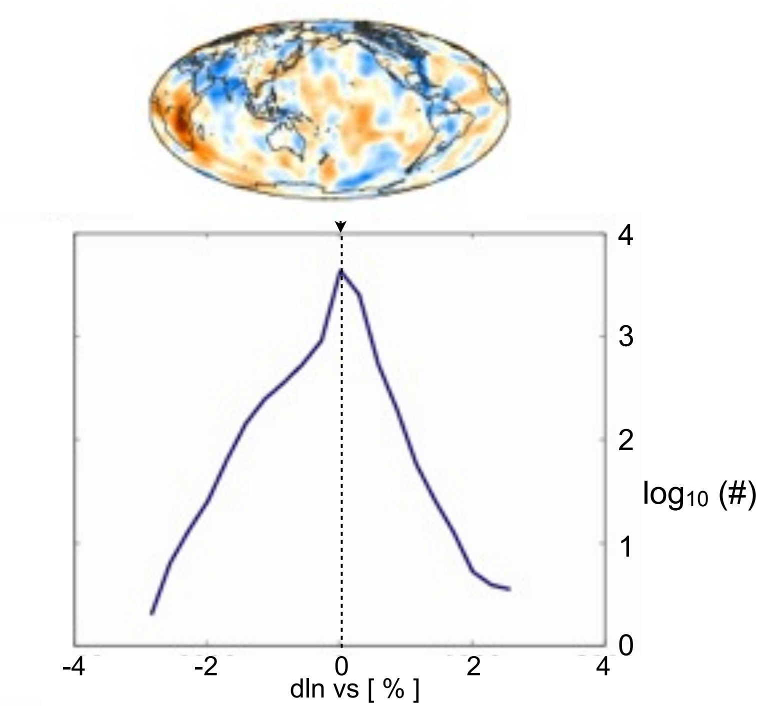
Statistics for Tomographic Models - Histograms



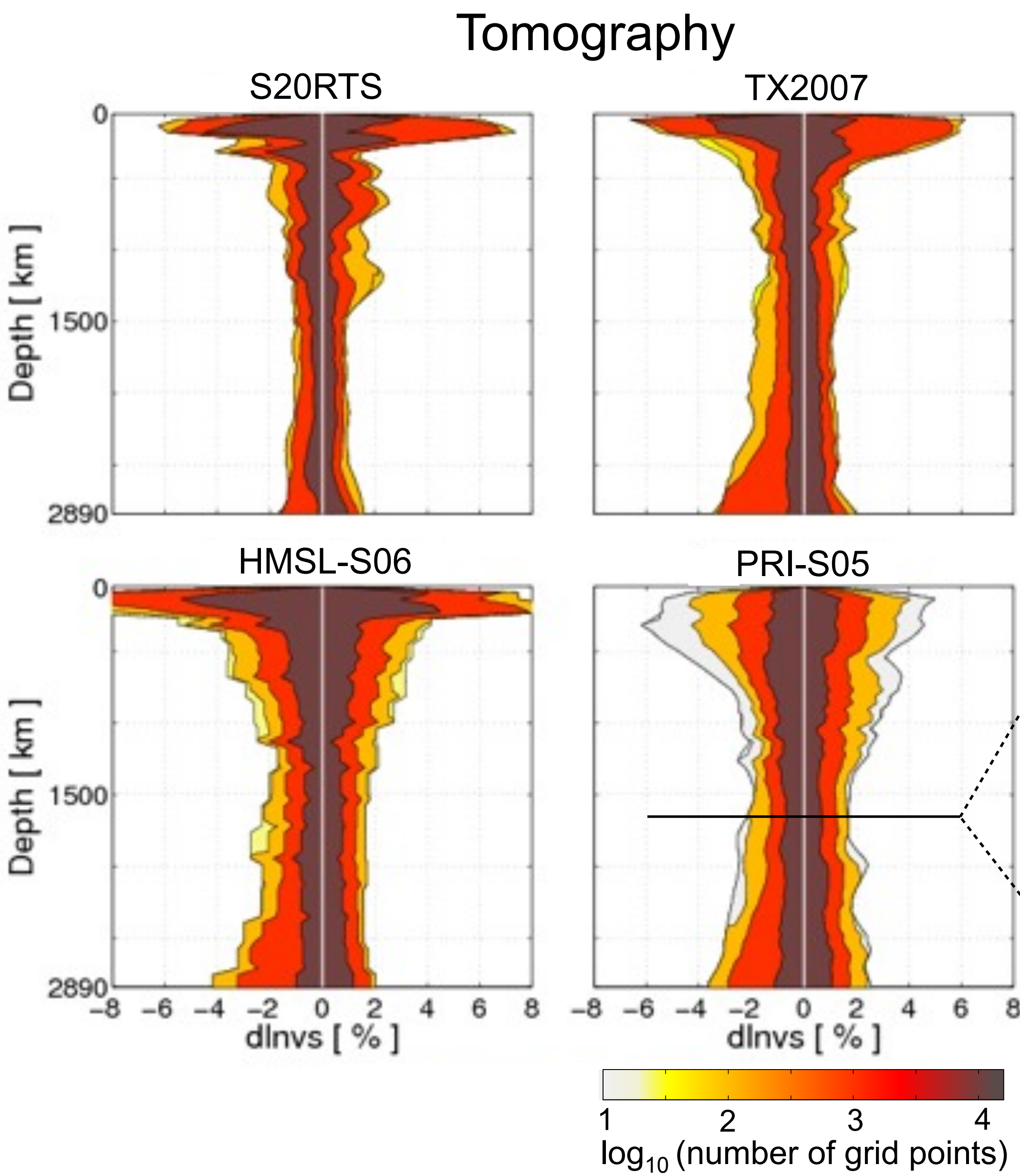
Statistics for Tomographic Models - Histograms

Histograms of heterogeneity

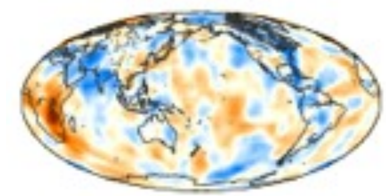


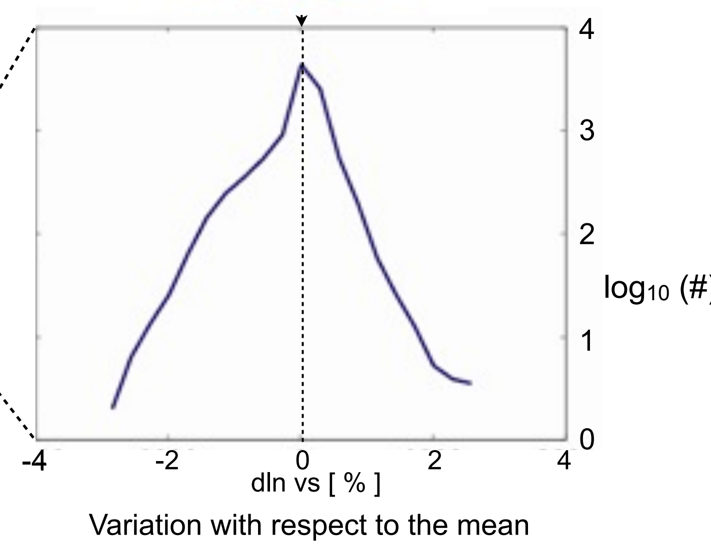
Variation with respect to the mean

Statistics for Tomographic Models - Histograms



Histograms of heterogeneity
as a function of depth





Schuberth et al., 2009a

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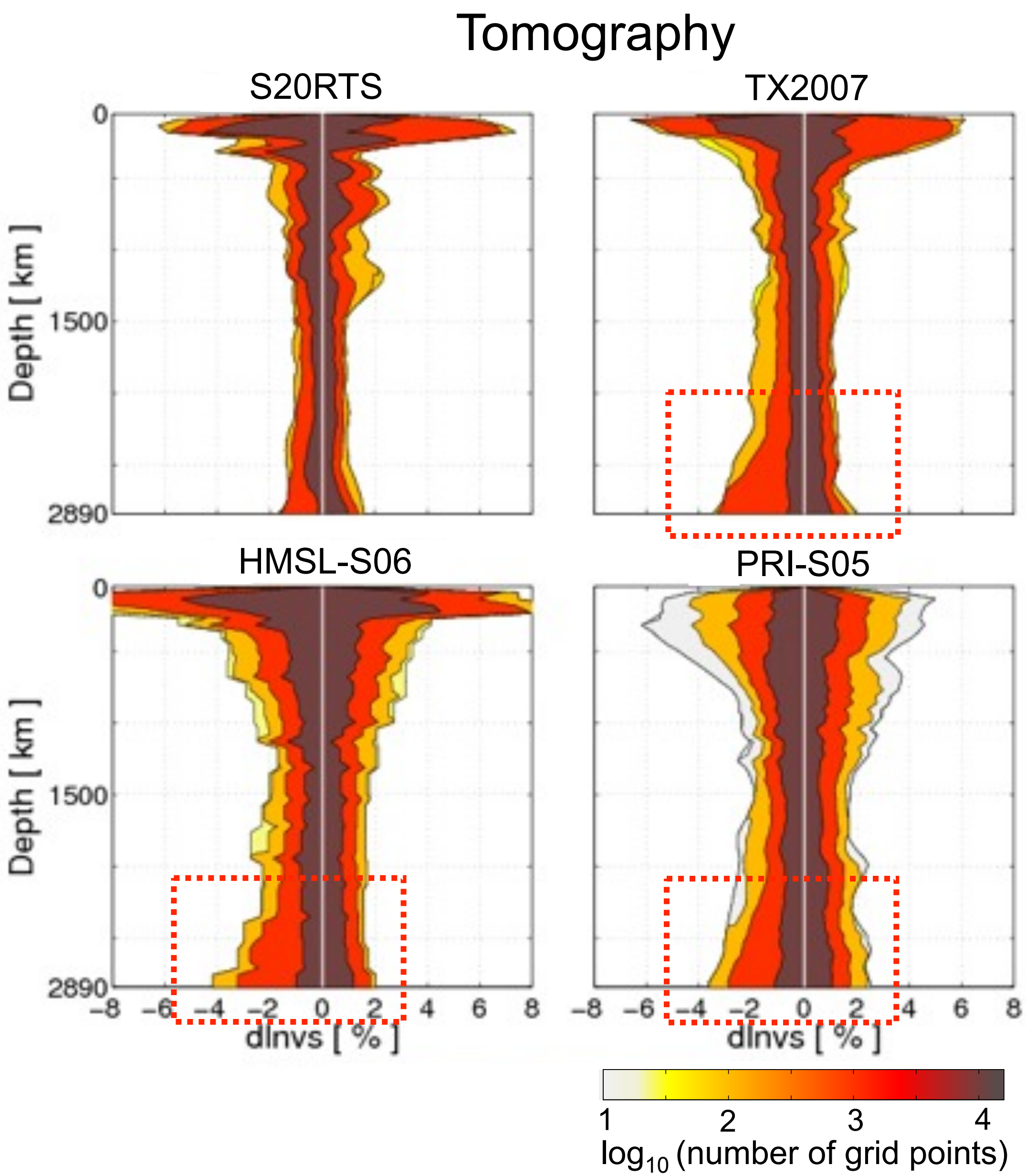


Histograms of heterogeneity

as a function of depth

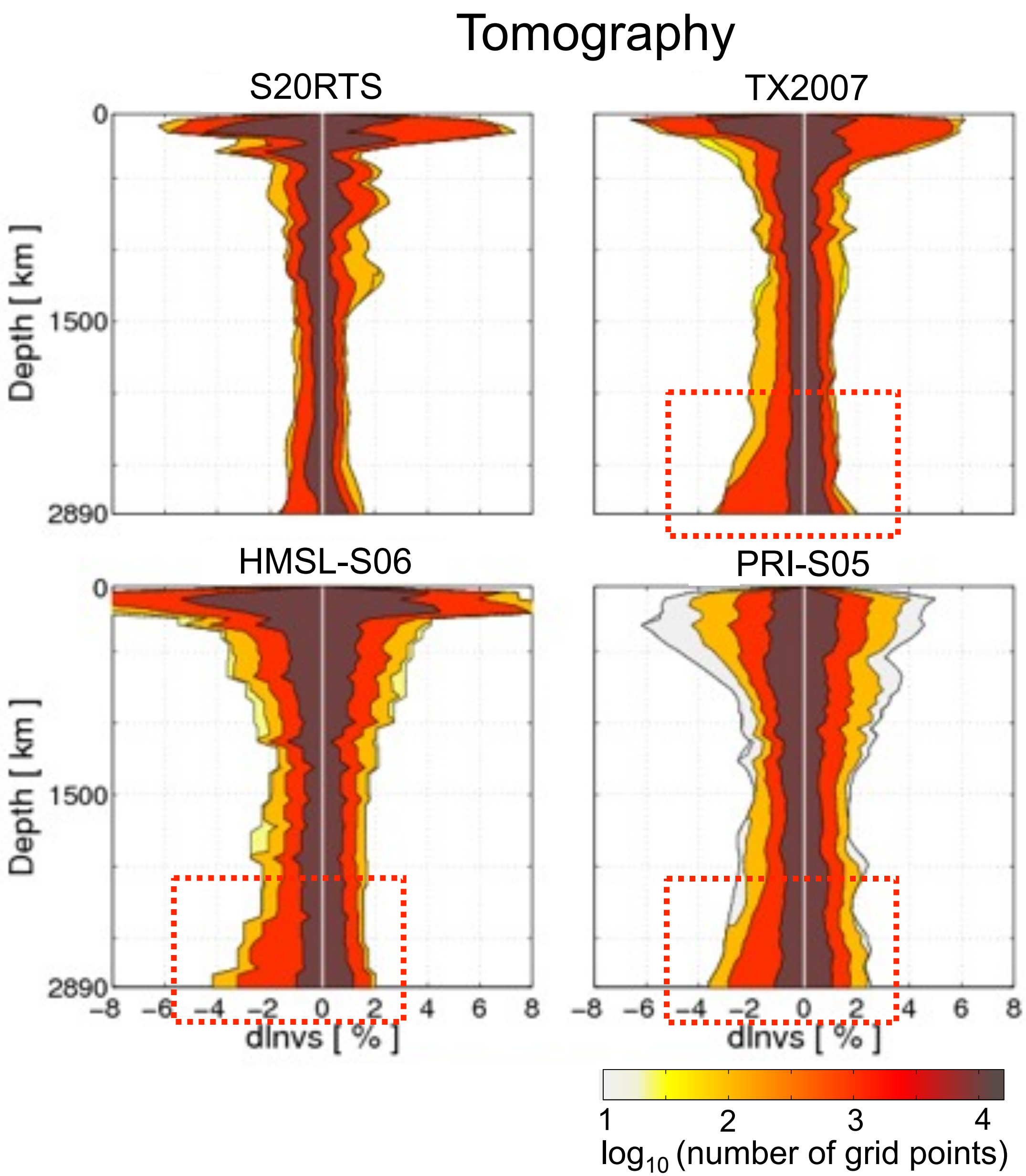
The slow anomalies in the lowermost mantle are revealed by an increased width of the negative side lobe

i.e. histograms have negative skew

see also Yanagisawa & Hamano 1999

Schuberth et al., 2009a

Statistics for Tomographic Models - Histograms



Seismic anomalies

↓

Temperature + Composition

Schuberth et al., 2009a

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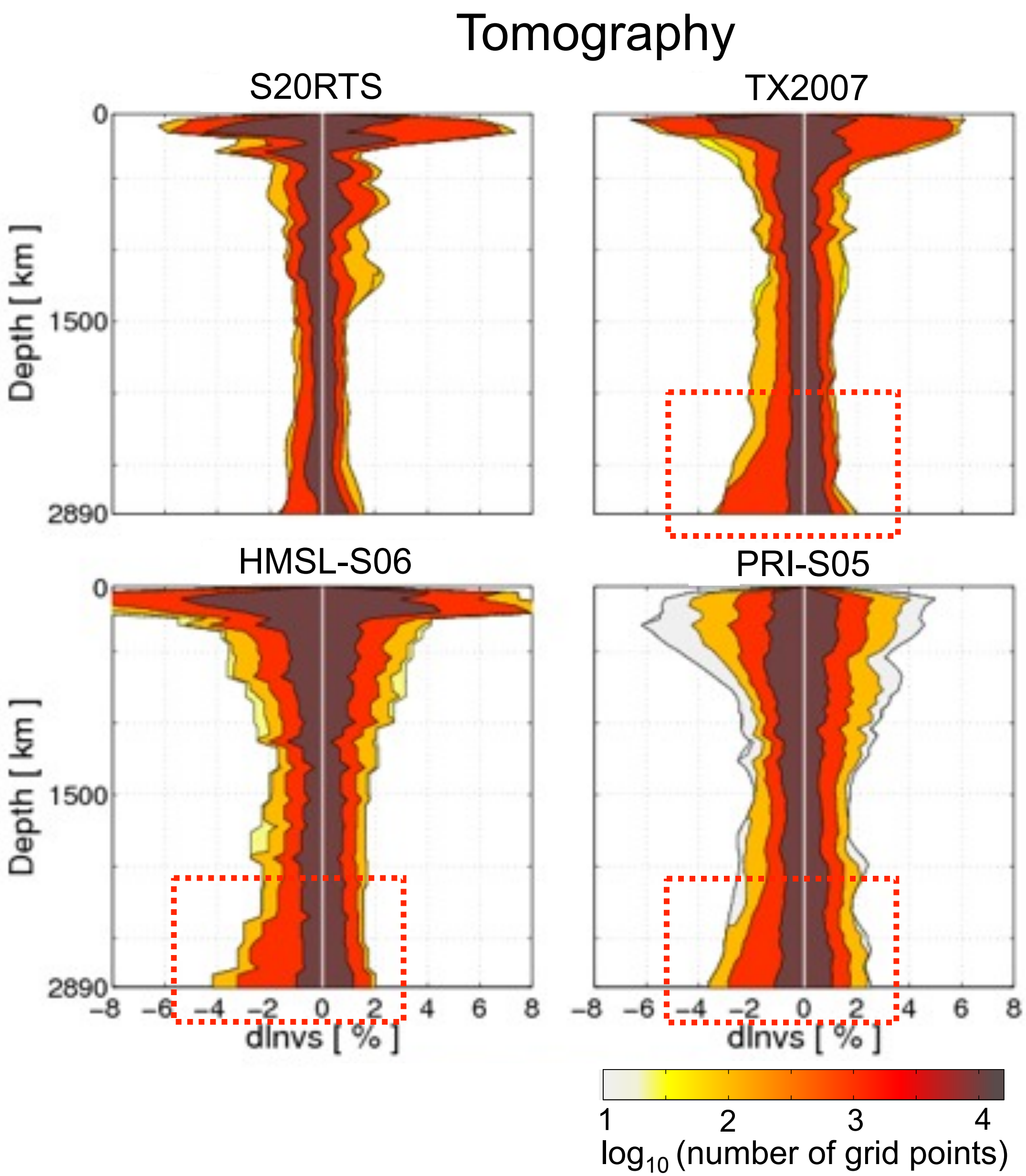

Seismic anomalies

↓

Temperature alone?

Hypothesis

Schuberth et al., 2009a

Large Temperature Variations in the Deep Mantle

High Heat Flux ~ 10 TW

30 % of the total mantle heat budget
(classically 2-3 TW)

High CMB temperature ~ 4000 K

A large thermal gradient in D” > 1000 K

Power requirements of the dynamo

e.g., Glatzmaier & Roberts 1995, Kuang & Bloxham 1997, and many others

Thermal history of the core

e.g., Buffett 2002, Nimmo 2004, Labrosse 2003

Heat conduction along the core adiabat

e.g., Gubbins et al. 2001

High core and CMB temperature from High-P-T exp. and simulations

e.g., Boehler 2000, Steinle-Neumann et al. 2001, Alfé et al. 2002/2007

Seismological Studies of the D” region

e.g., v. d. Hilst et al. 2007

Mantle subadiabaticity and low plume excess temperature in UM

e.g., Bunge et al. 2001, Sleep 2004, Bunge 2005

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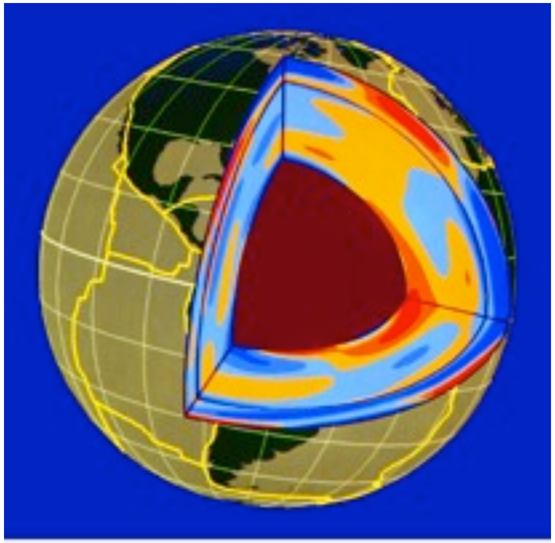
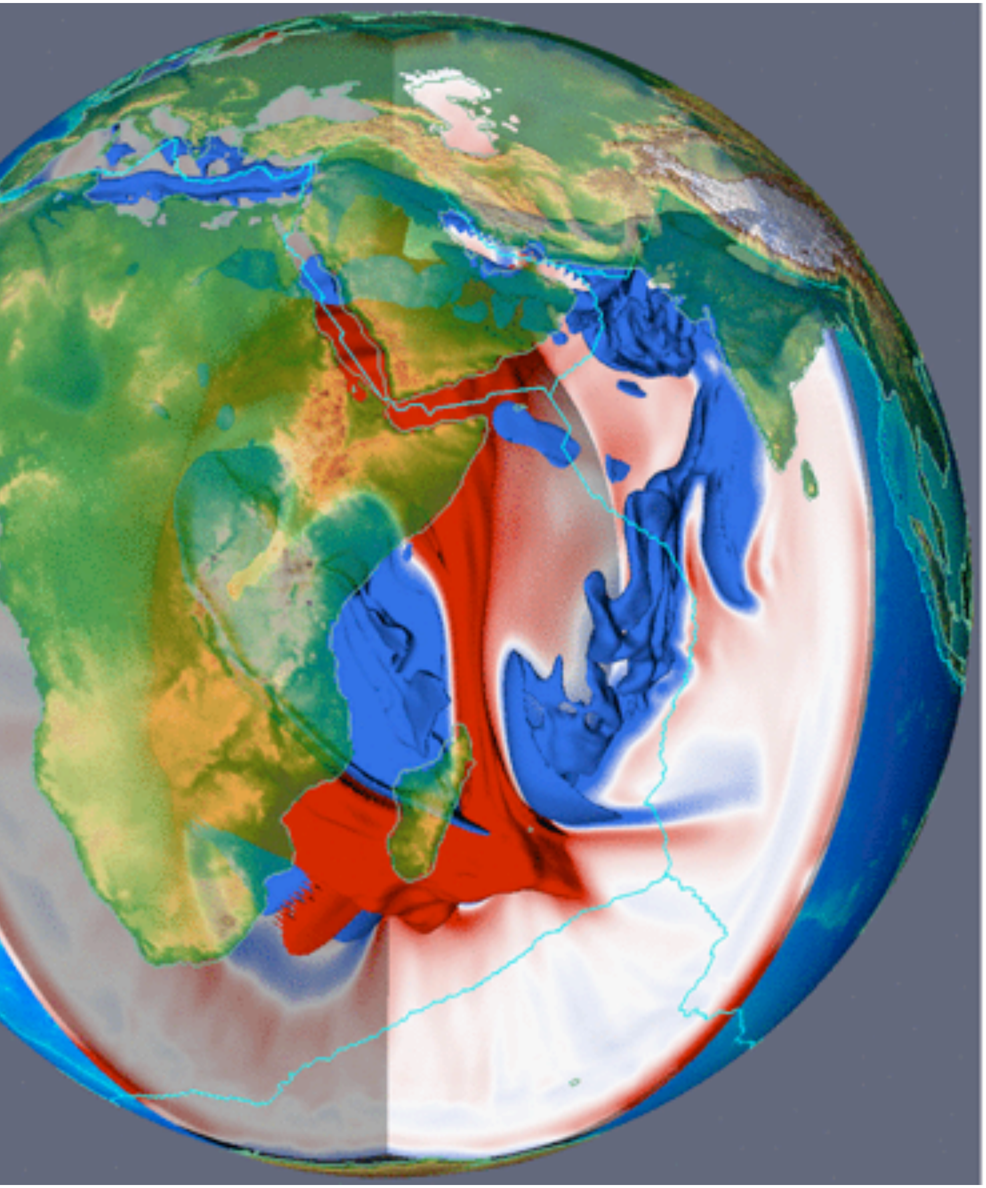


Mantle Circulation Modeling (MCM)



Parallel finite element code
TERRA

Equations of motions in a
3-D spherical shell

Mass, momentum and energy
balance at
infinite Prandtl number

Anelastic liquid approximation
→ compressible

dT Isosurfaces
+400 K (upwellings)
-600 K (downwellings)

Schuberth et al., 2009a

Mantle Circulation Models - Key Parameters

High numerical resolution

80 million grid points**, 25 km** grid spacing throughout the mantle

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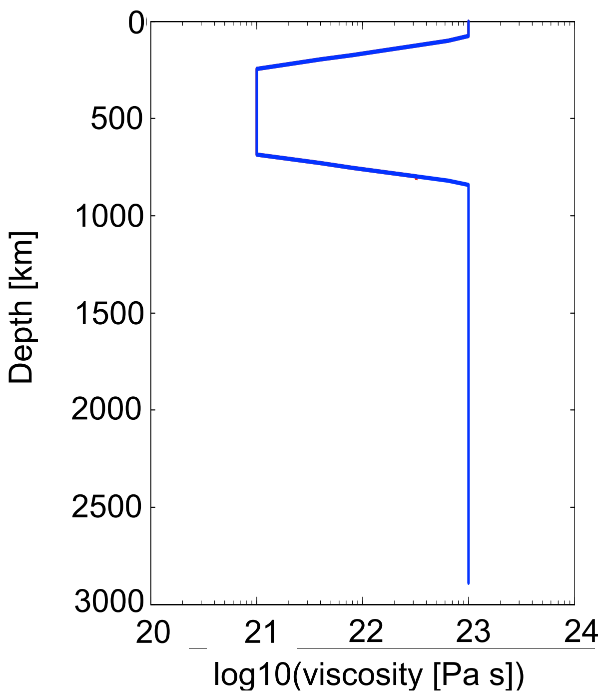
Simple 3-layer viscosity profile

10^{23}, 10^{21}, 10^{23} Pas in the lithosphere, upper & lower mantle, respectively



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Low CMB temperature (standard case) **+ High CMB temperature** (4200 K)

► **large thermal gradient** across CMB

► **high** core heat flux (as high as 12 TW)

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Petrology to link temperature to seismic velocities

Equilibrium phase assemblages by **Gibbs Free Energy minimization**

e.g, Ricard et al. 2005, Stixrude & Lithgow-Bertelloni 2005/2007, Piazzoni et al. 2007

► thermodynamically **self-consistent**

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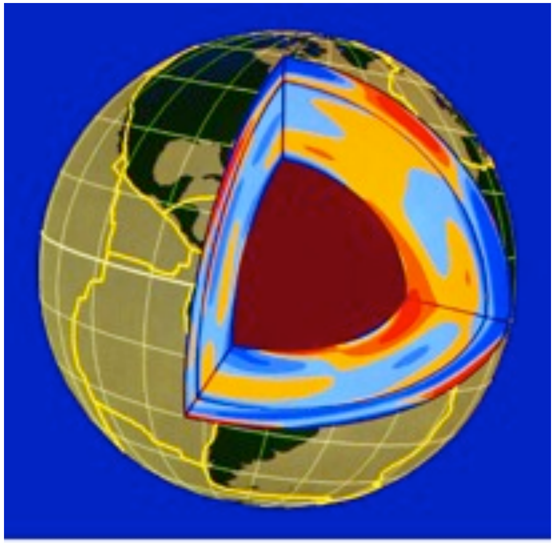
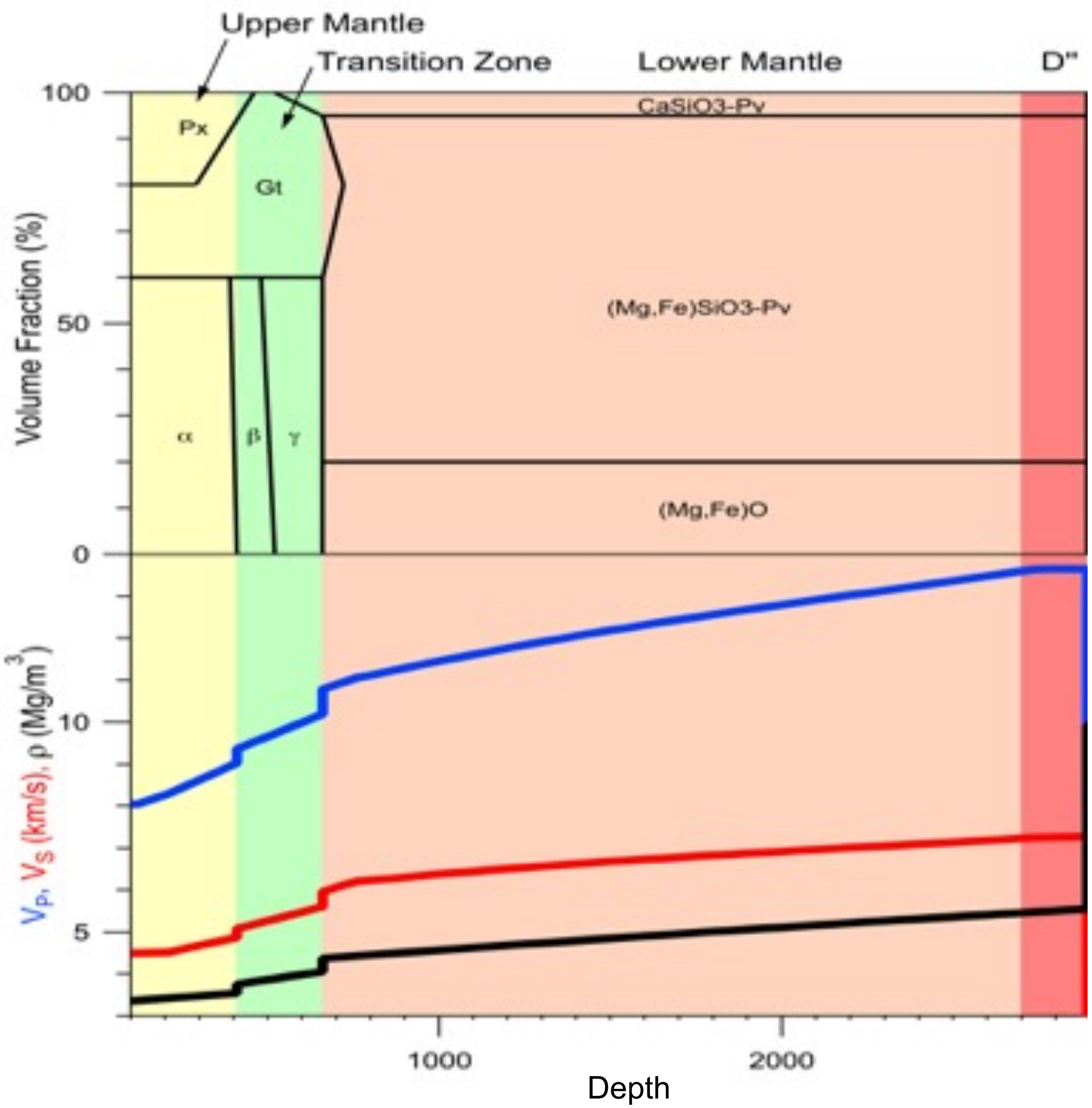


Mantle Mineralogy and 1-D Seismic Profiles



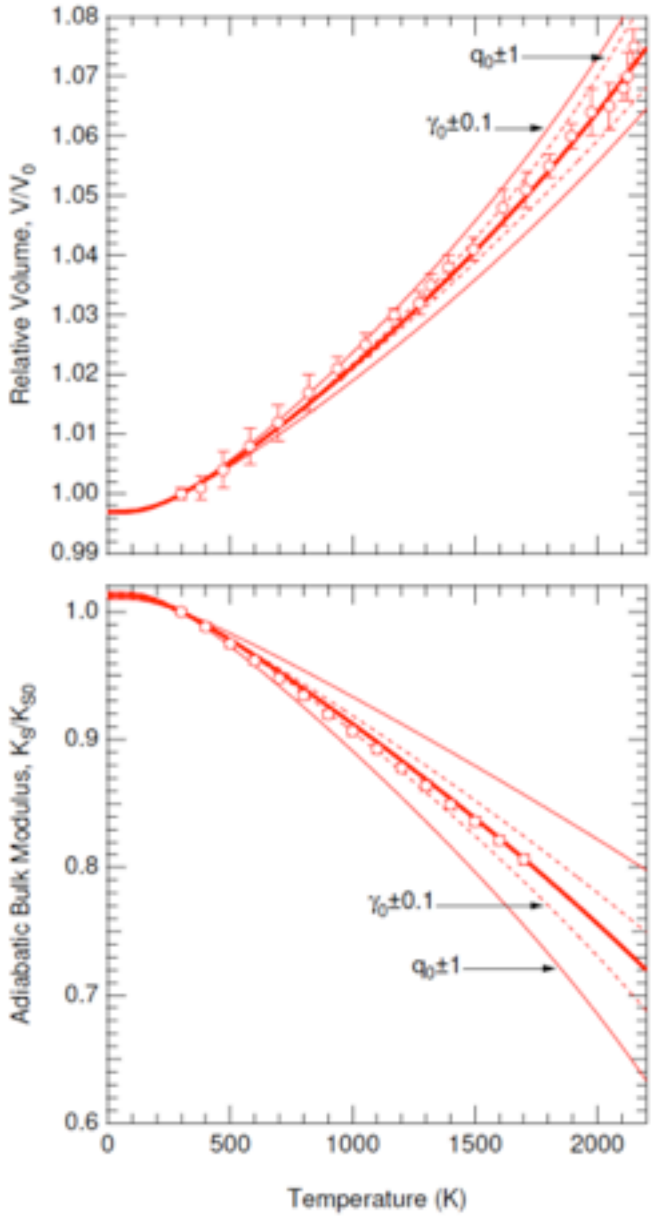
http://eaps.mit.edu/faculty/shim/ImageGallery/images/Shim_Earth_Structure.png

Influence of Temperature on the Physical Properties of Minerals

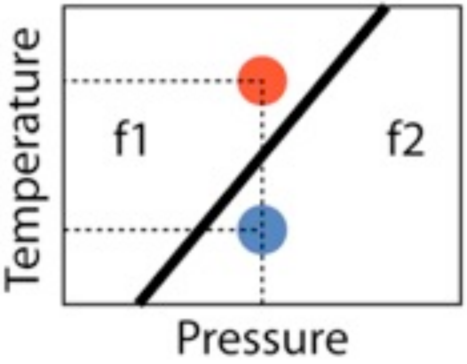
- Most important effect
  Change in volume (density)

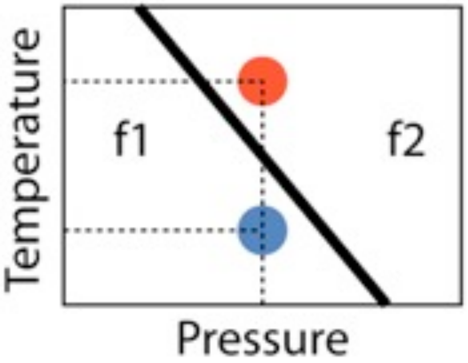
- Moduli co-vary with density
  Dependent on whether density is altered by pressure or temperature

- Microscopic picture
  Lower density means weaker bonds and smaller moduli



Influence of Temperature on Phase Stability

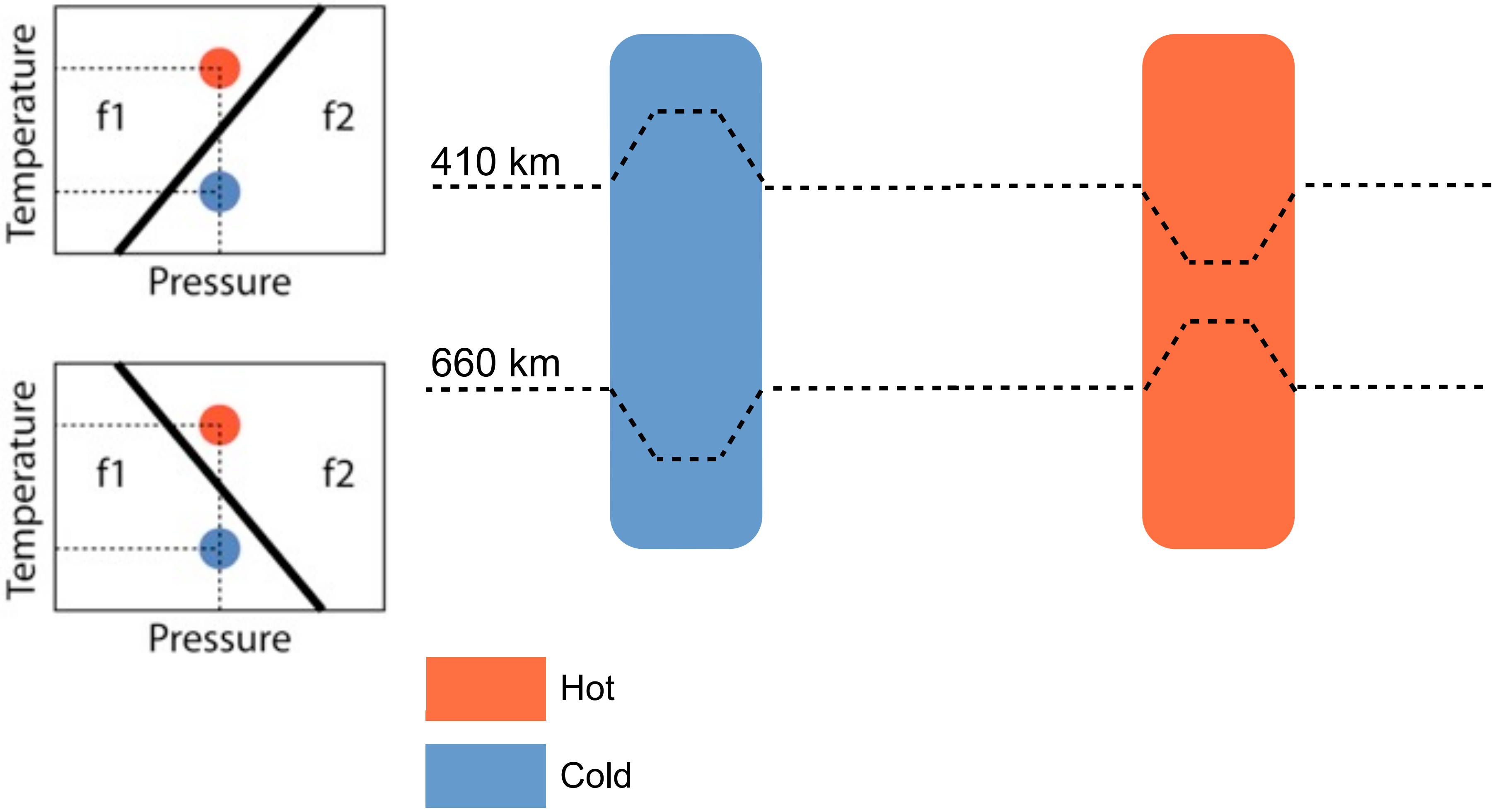




Hot

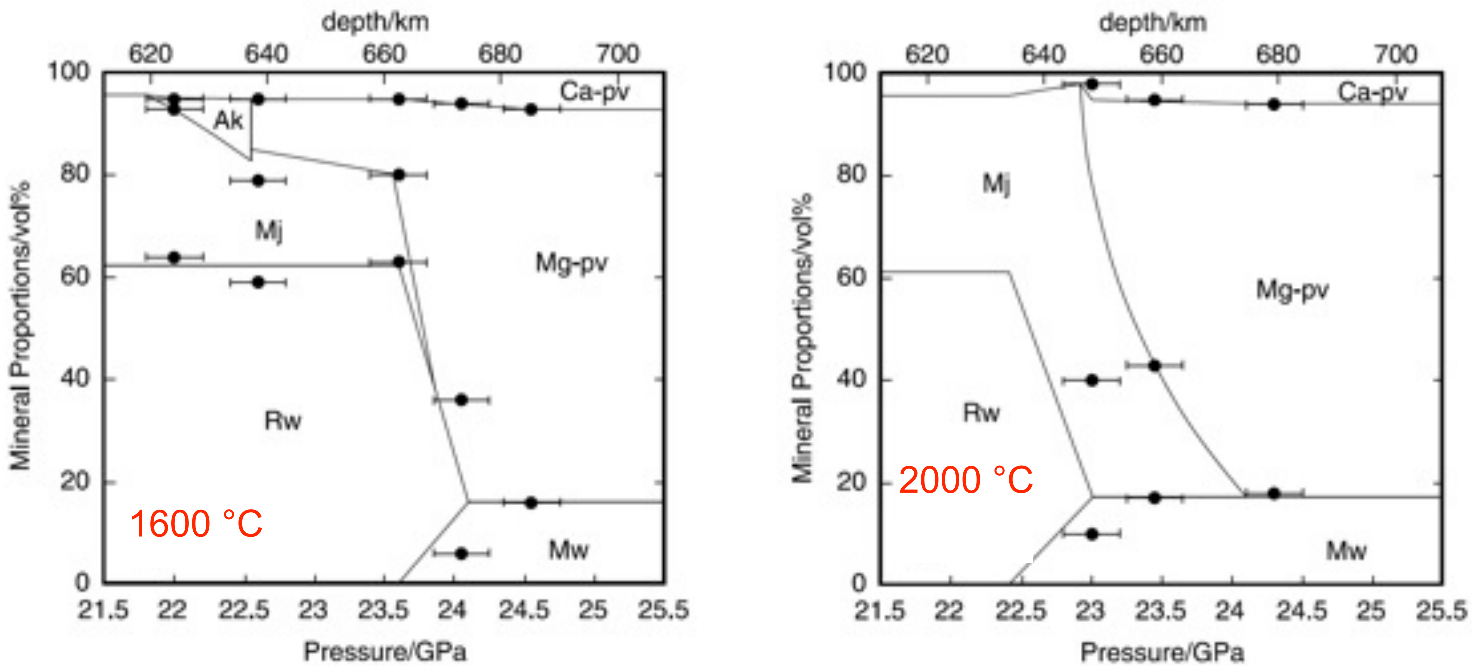
Cold

Influence of Temperature on Mantle Discontinuities



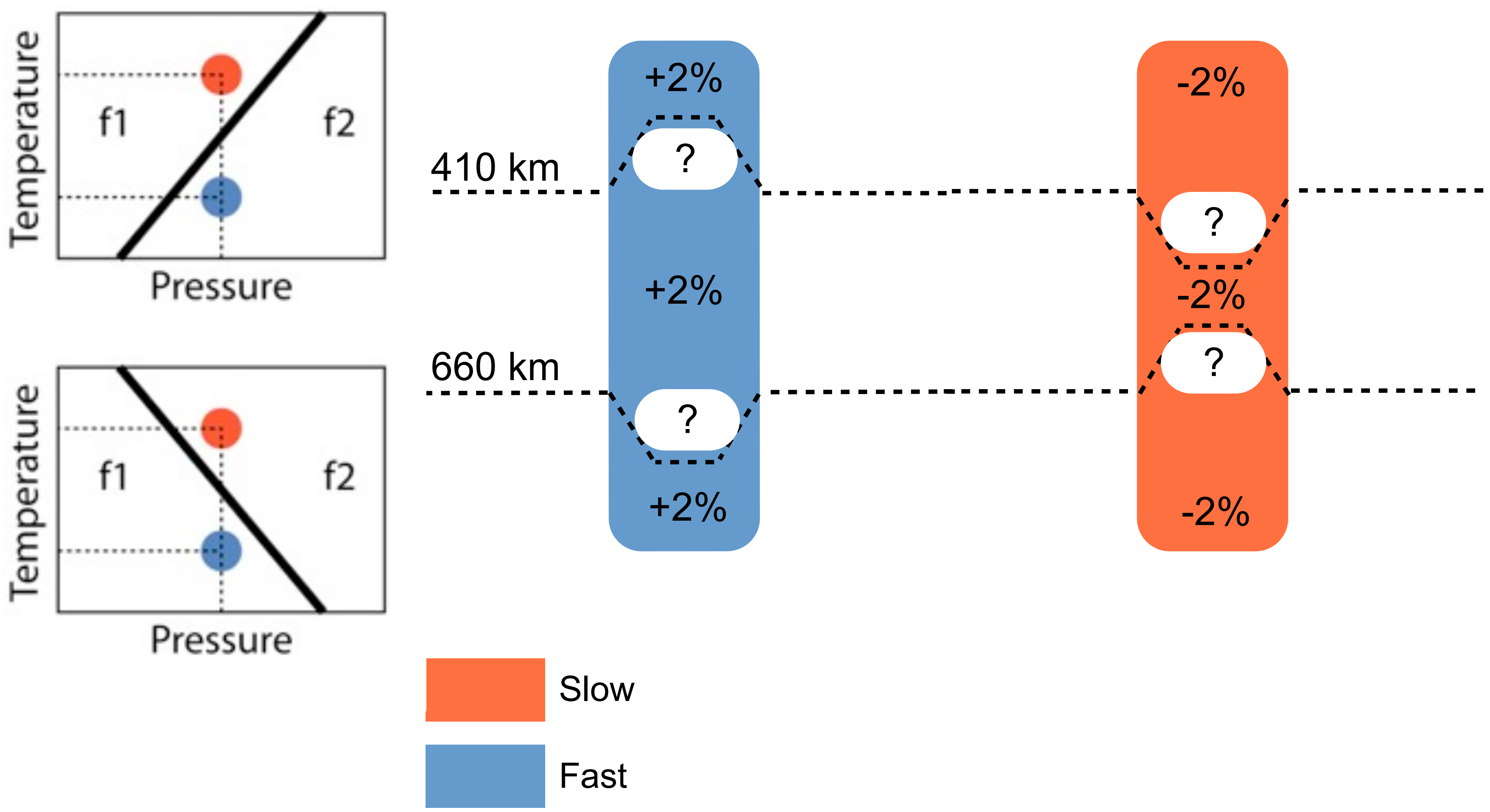
Influence of Temperature on Phase Assemblage

Phase diagram is strongly temperature dependent



Hirose 2002

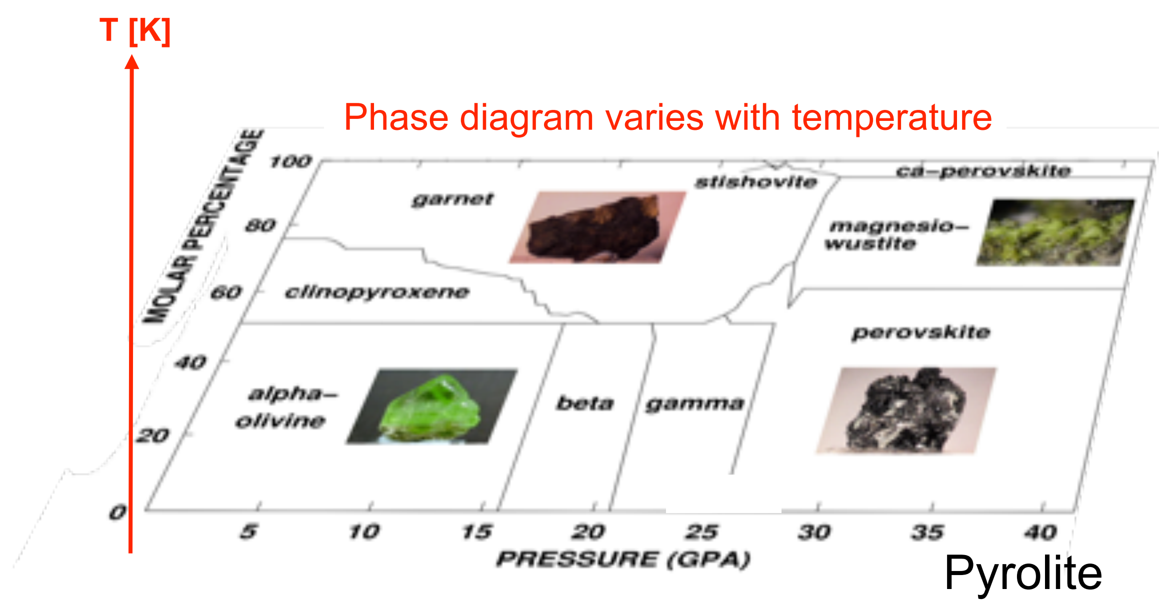
Influence of Phase Transitions on Seismic Heterogeneity



Thermodynamic Mineralogical Models

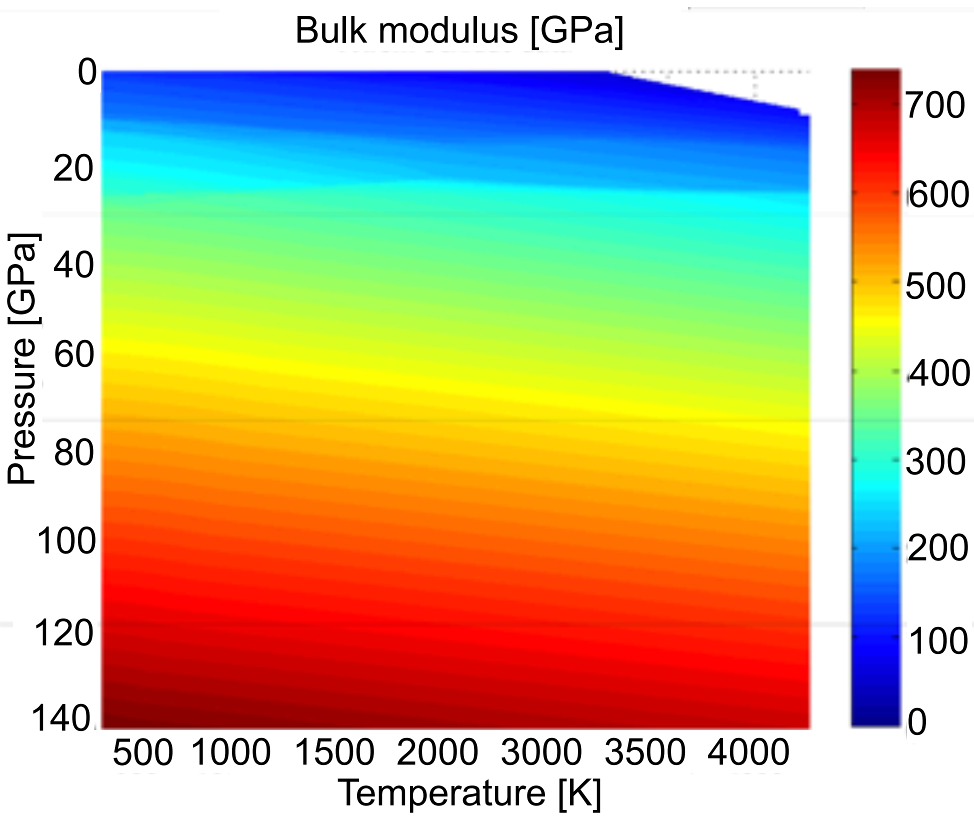
e.g., Stixrude & Lithgow-Bertelloni 2005, Piazzoni et al. 2007

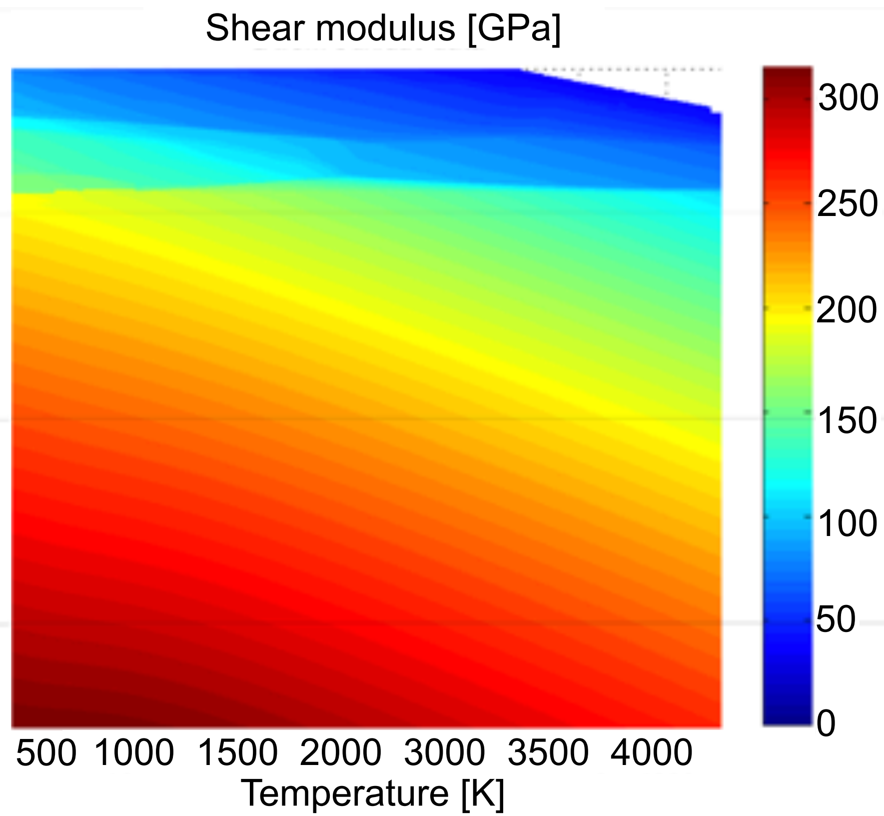
- Equilibrium phase assemblages
  - Gibbs free energy minimization
- Different equations of state (EOS)
  - pressure: 3rd order Birch-Murnaghan
  - temperature: Debye Mie Grüneisen or polynomial
- Database from lab. + num. experiments
  - EOS parameters at various P-V-T conditions
  - Enthalpy and entropy of formation



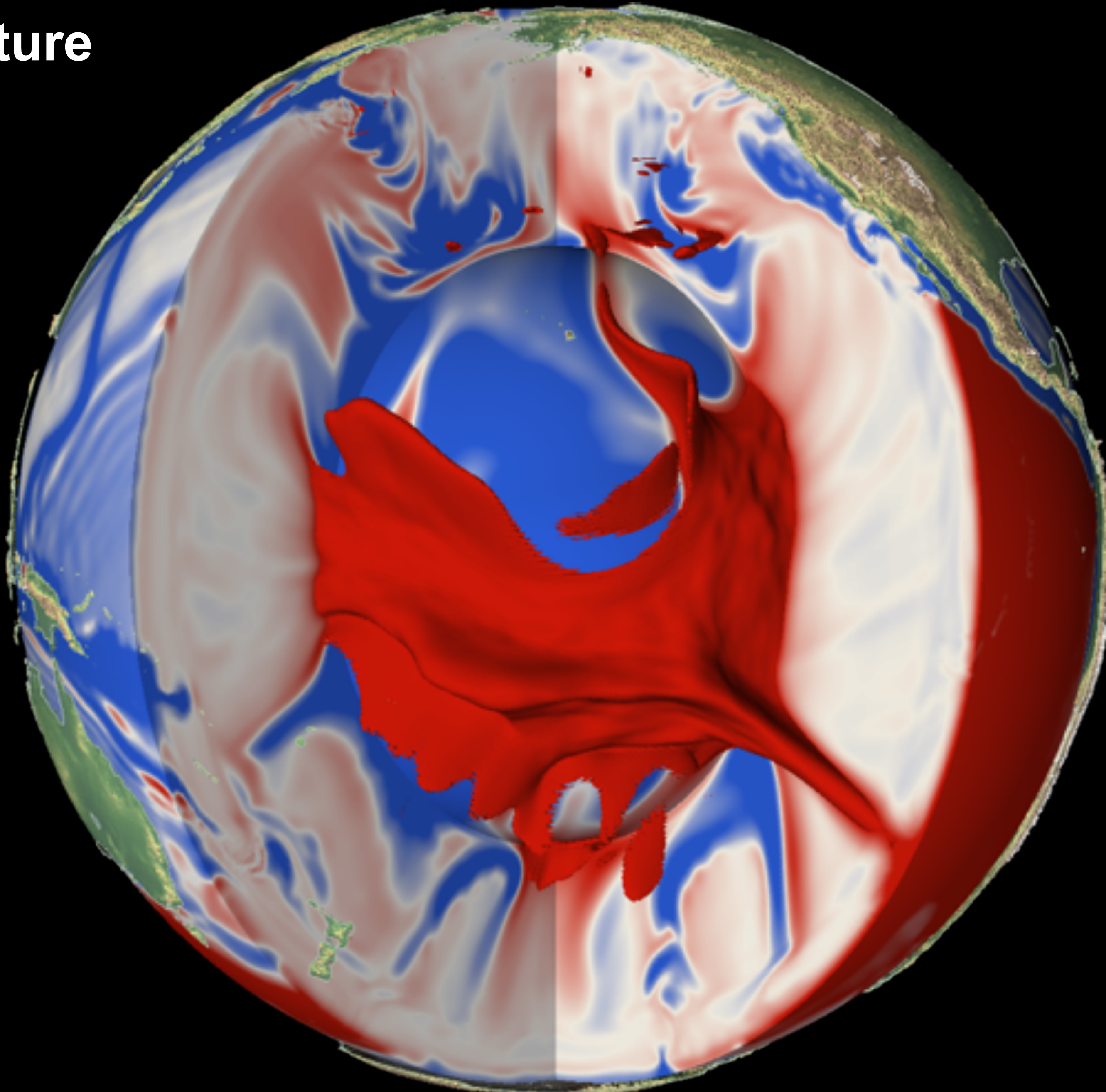
Thermodynamic Mineralogical Models

- Density, bulk and shear moduli for bulk rock at all P-T conditions of the mantle again through EOS



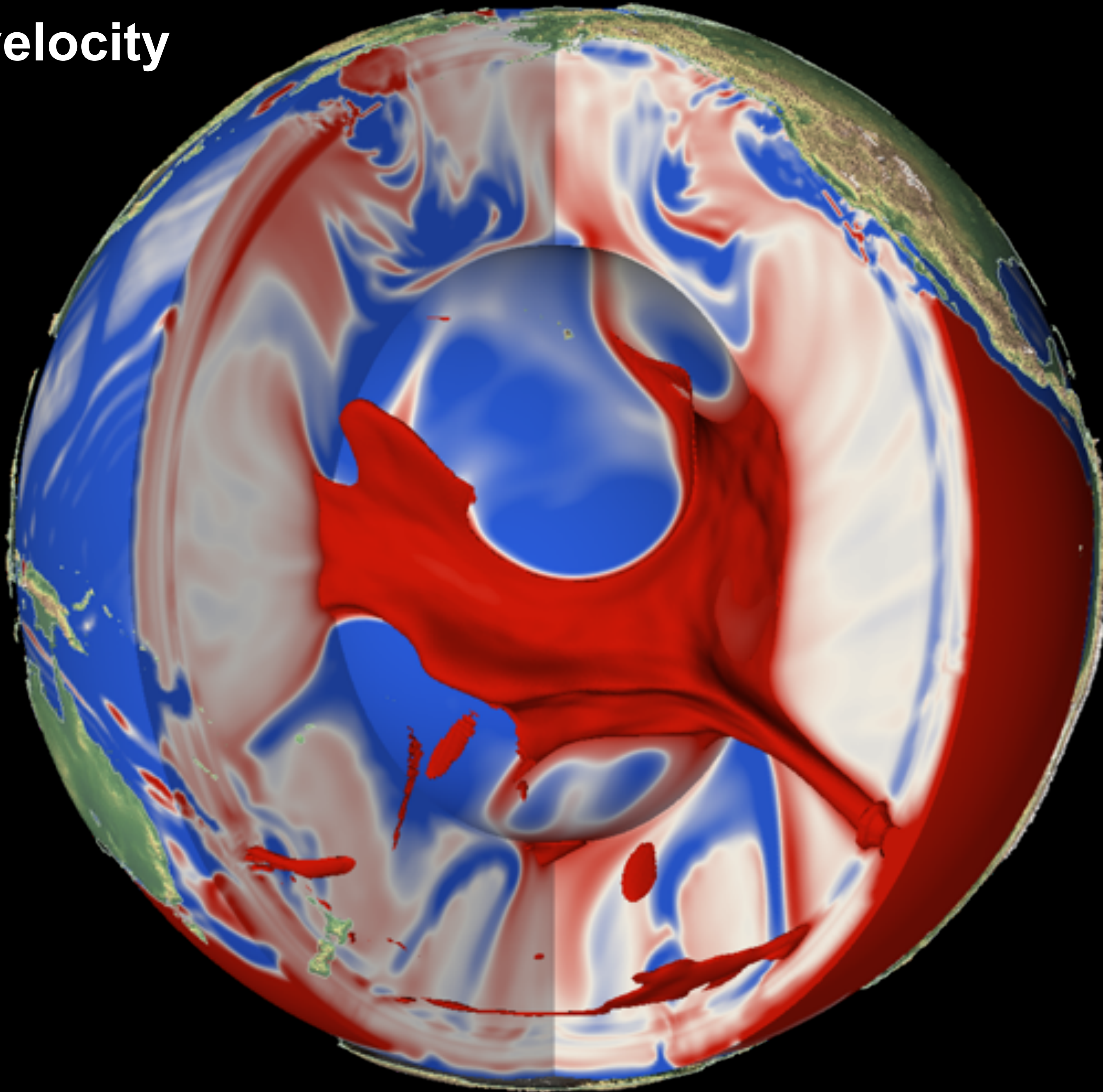


Temperature



Isosurface at +400

S-wave velocity



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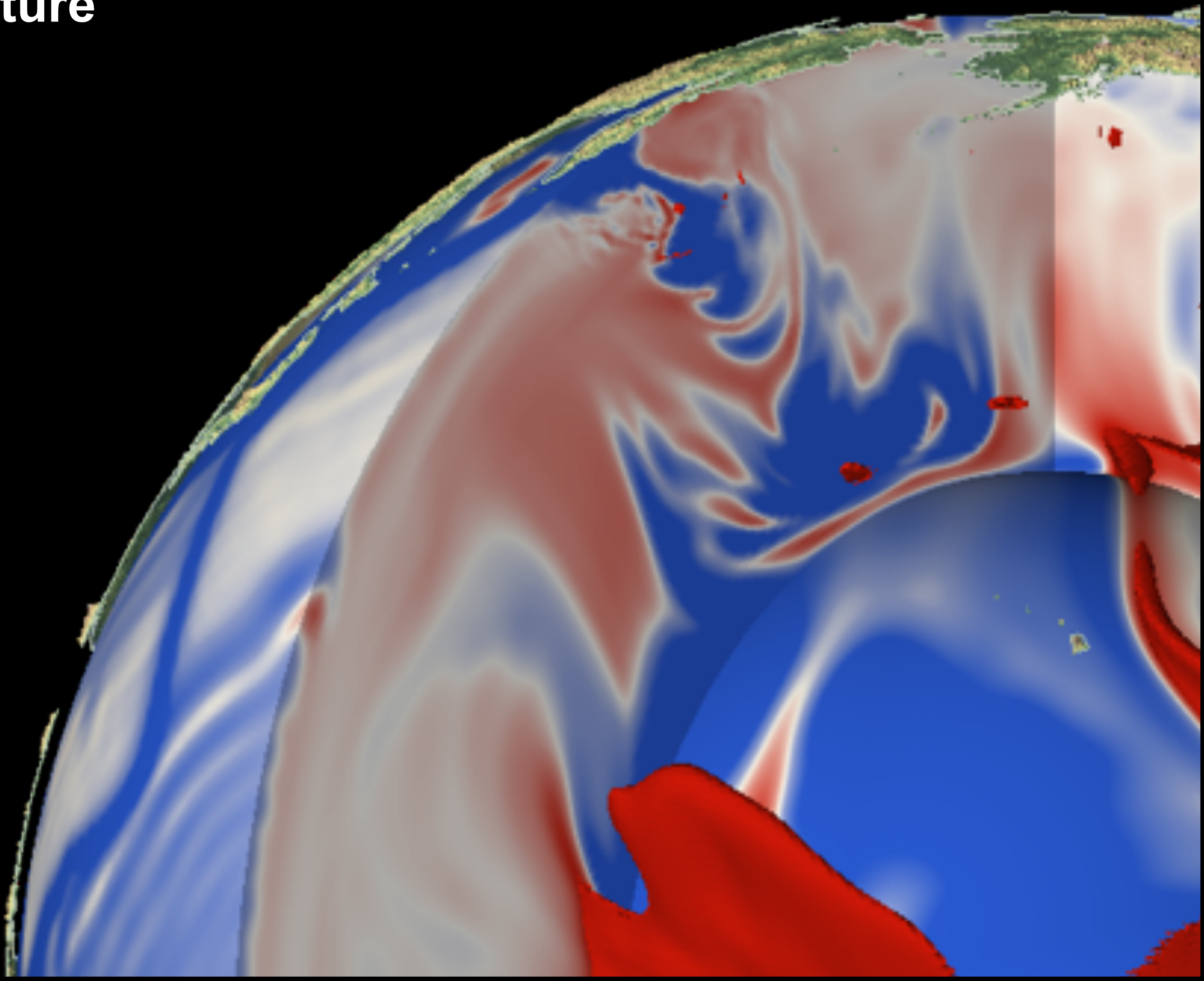

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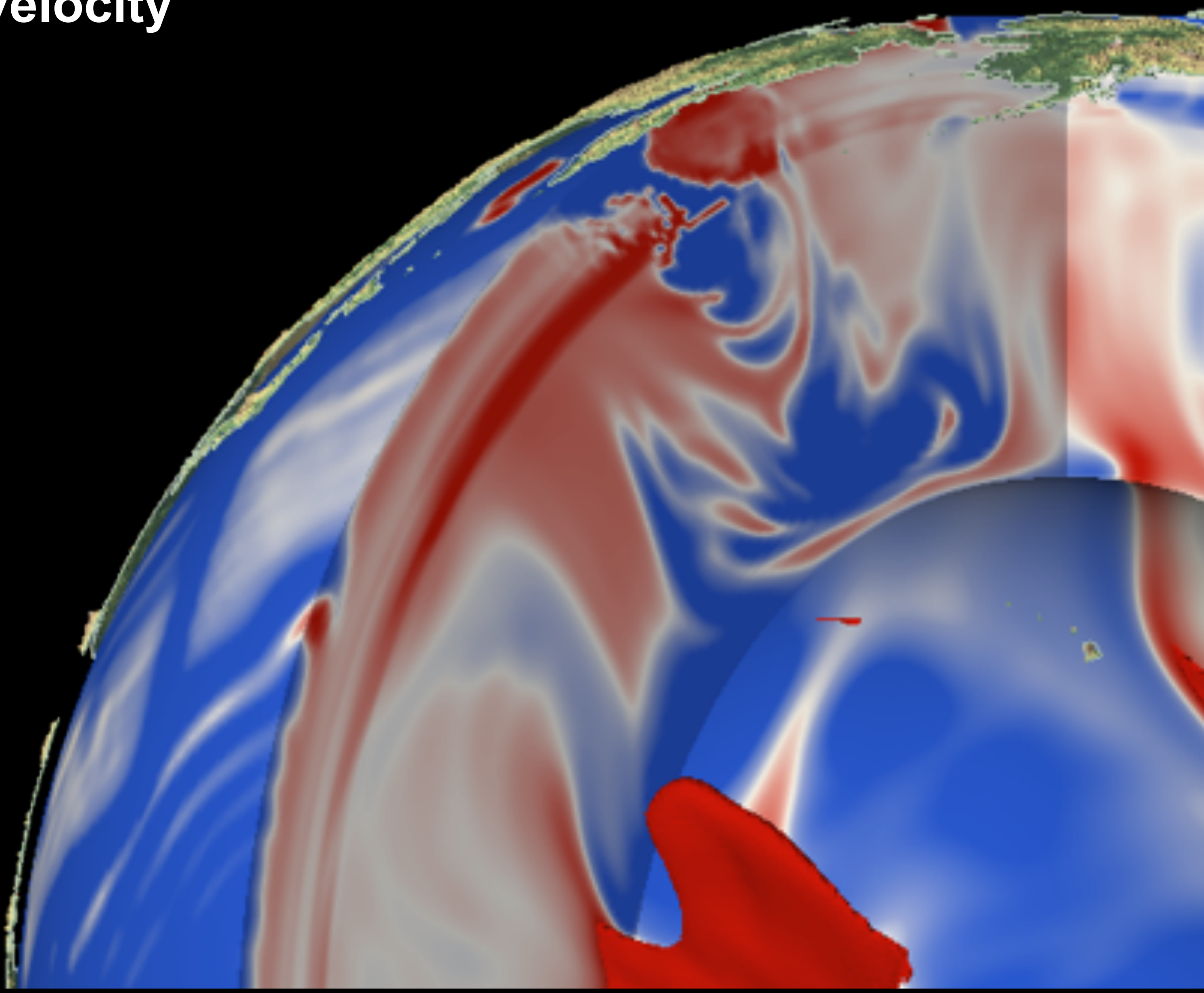
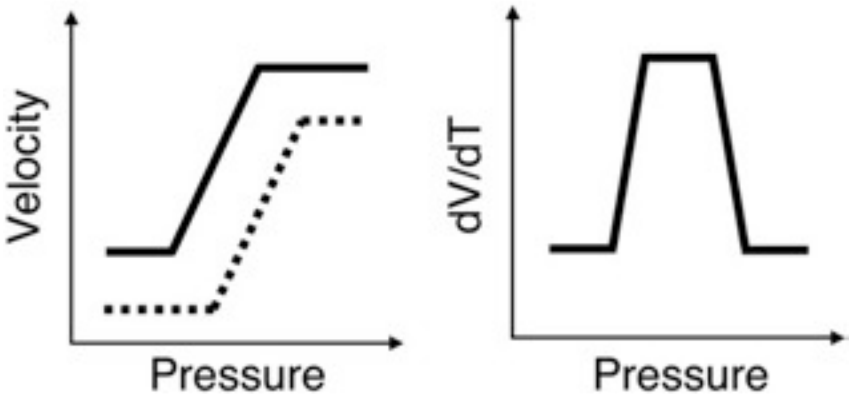
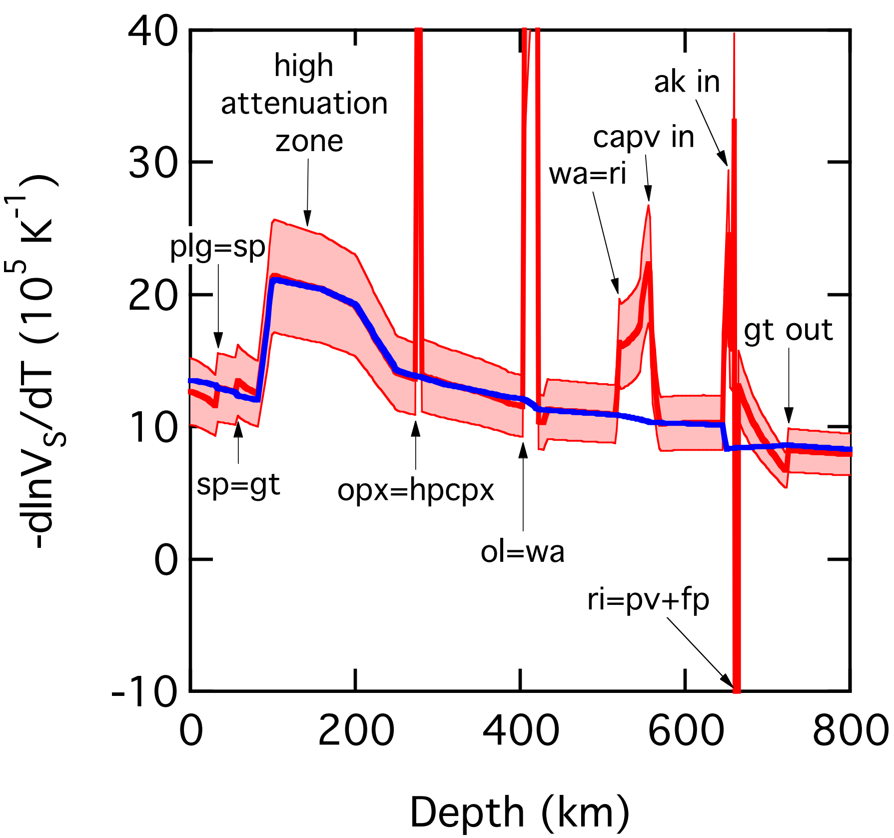


Isosurface at +400

Influence of Phase Transitions on Seismic Heterogeneity

Stixrude et al. (2007) EPSL





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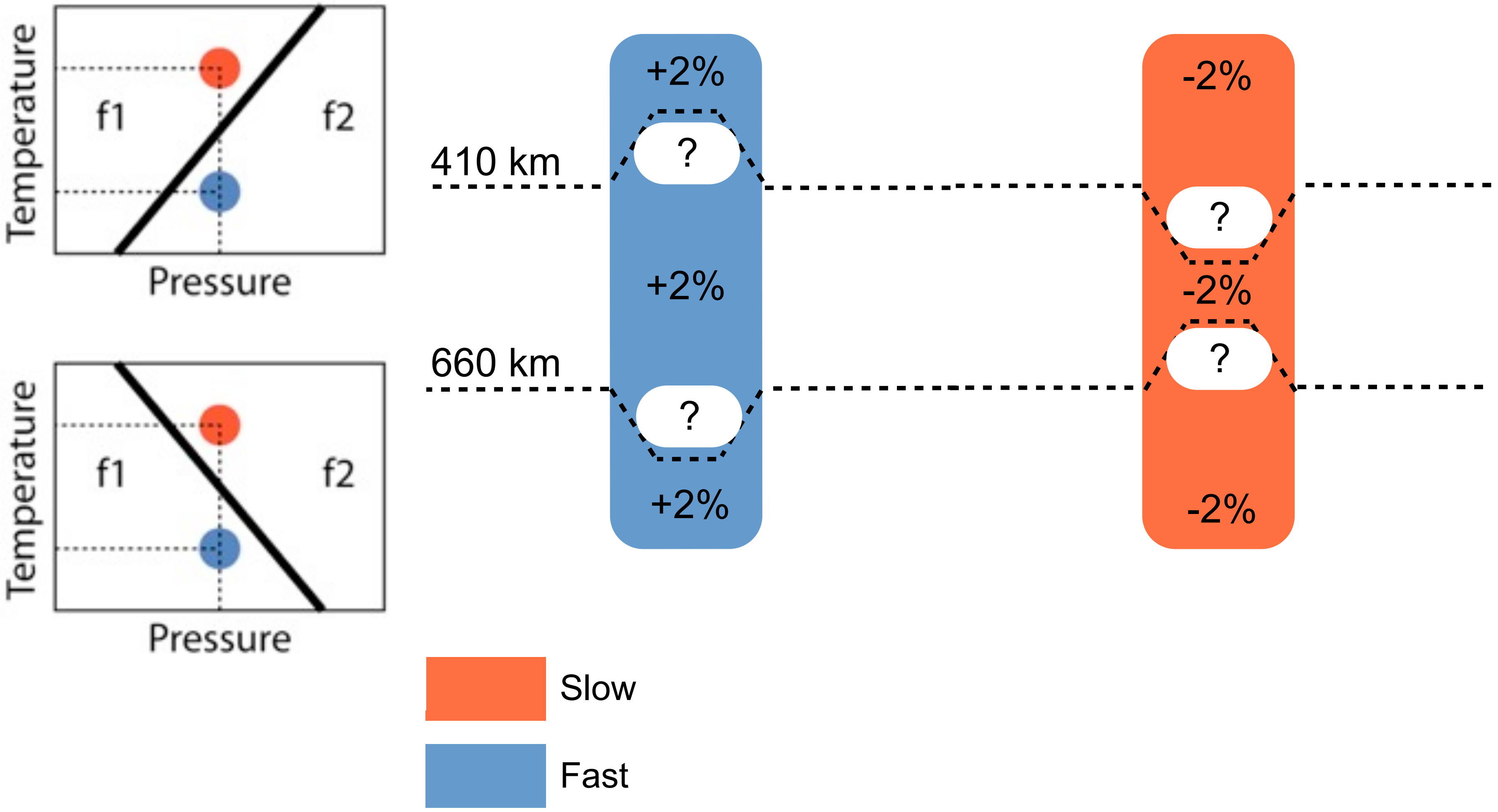

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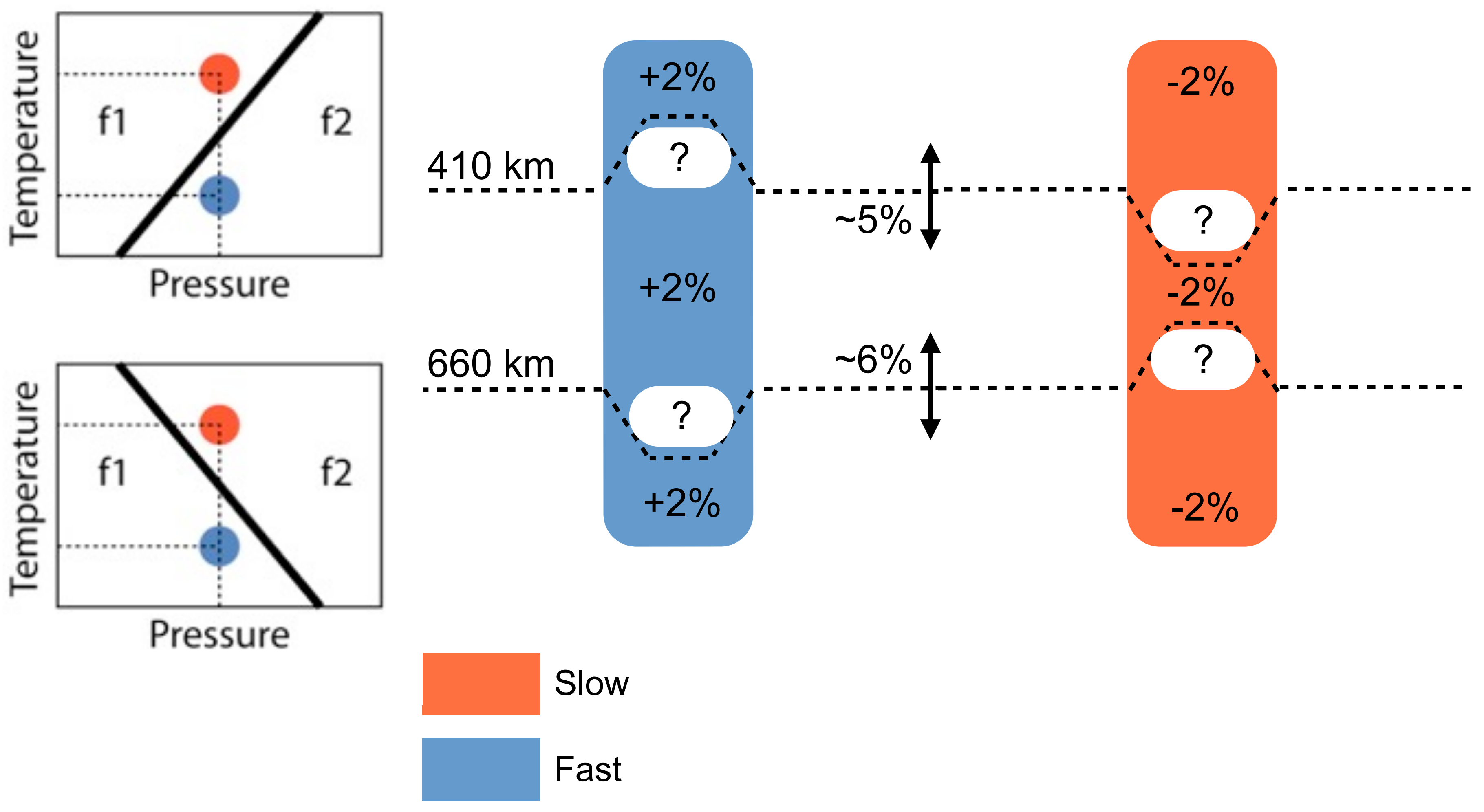
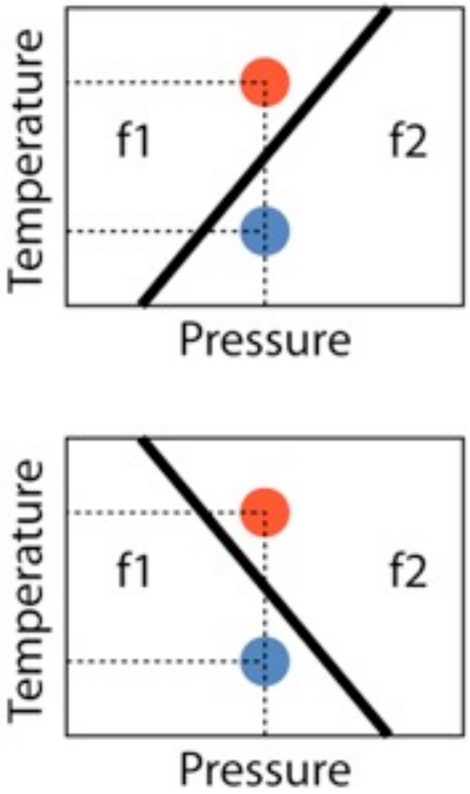
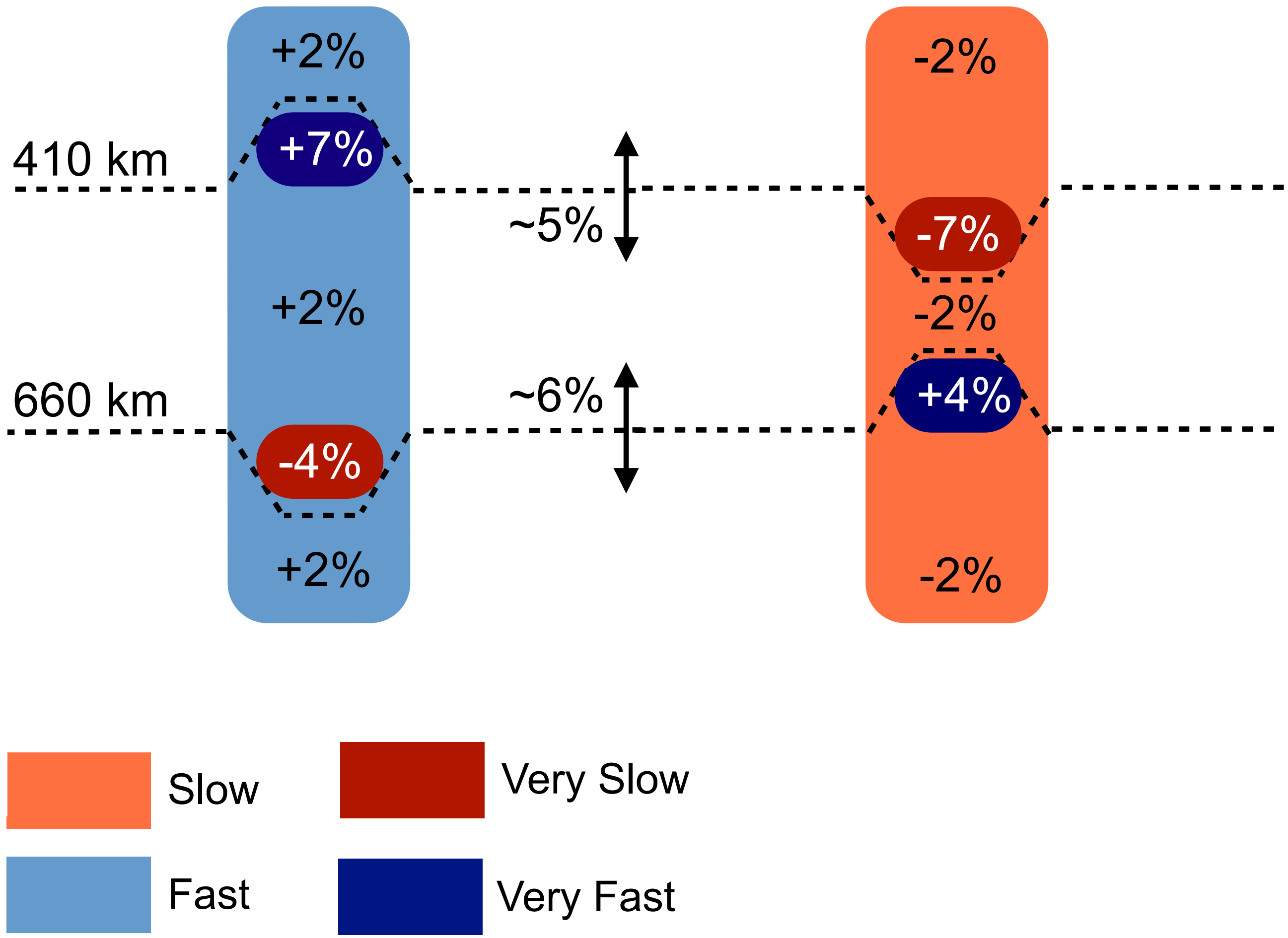


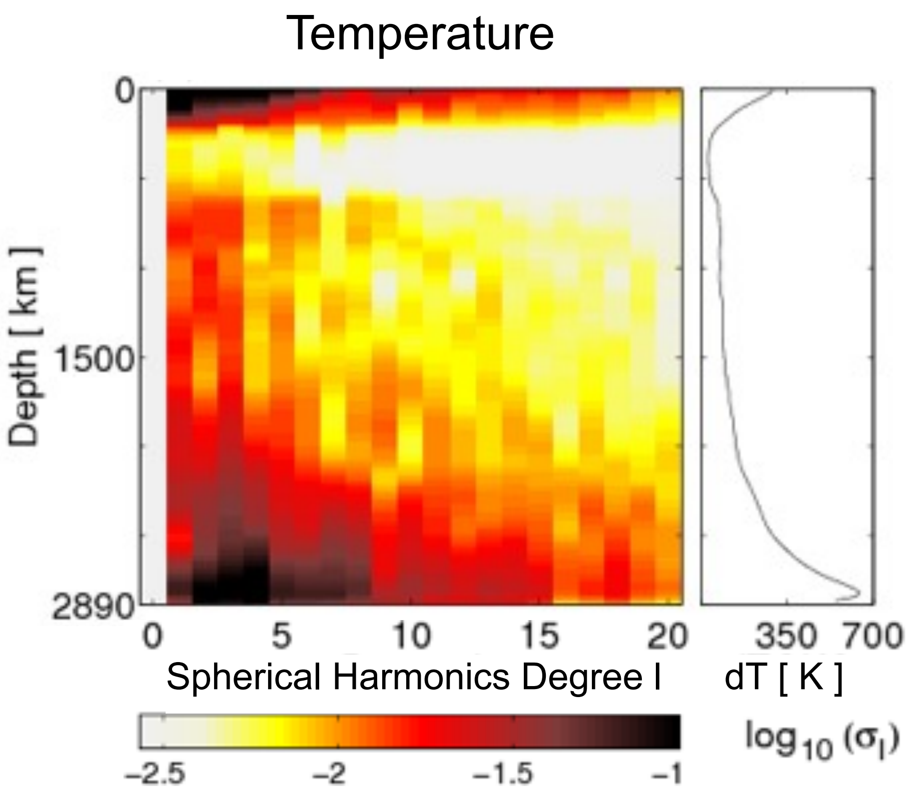
Lateral Variations at the Discontinuities





Spectral Power of Heterogeneity

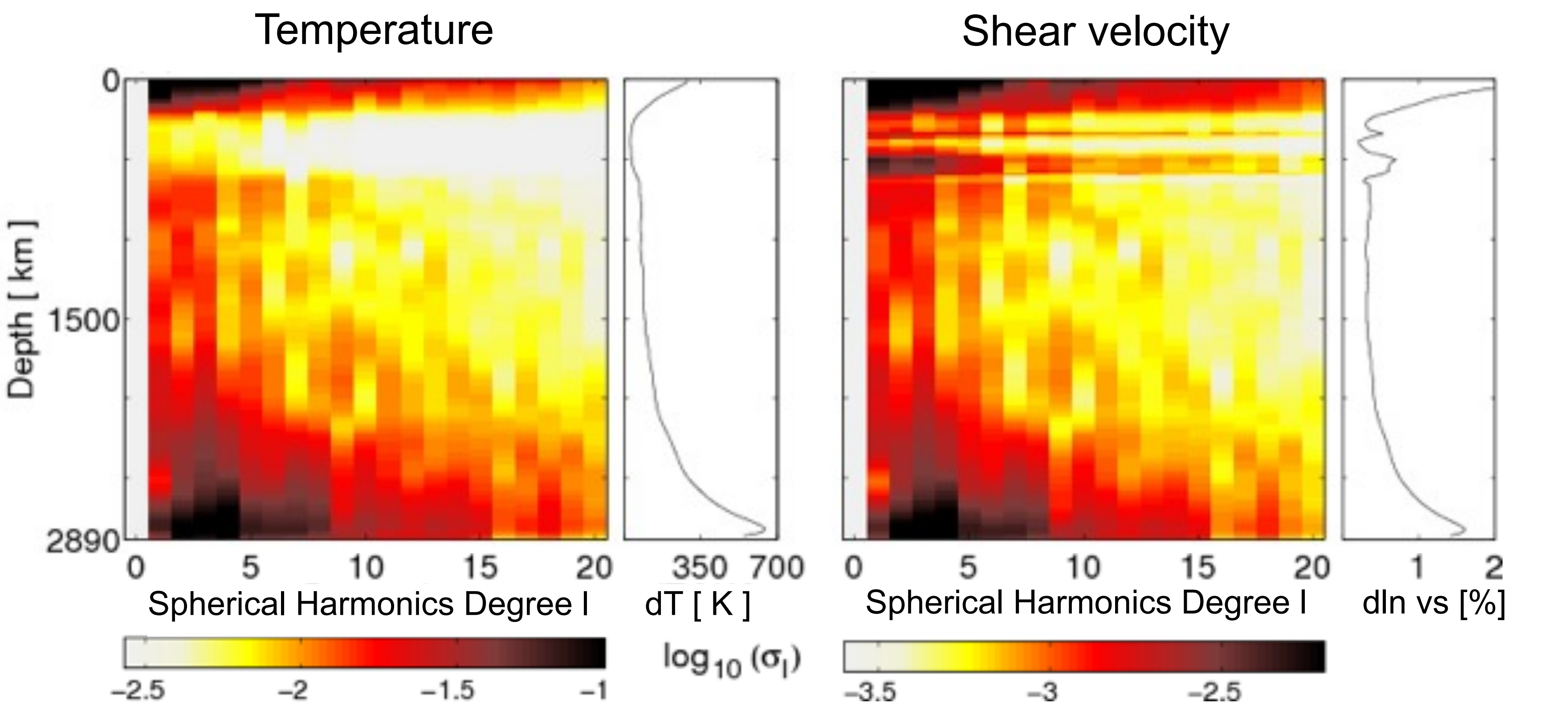
High CMB Temperature — 4200 K



Schuberth et al., 2009a

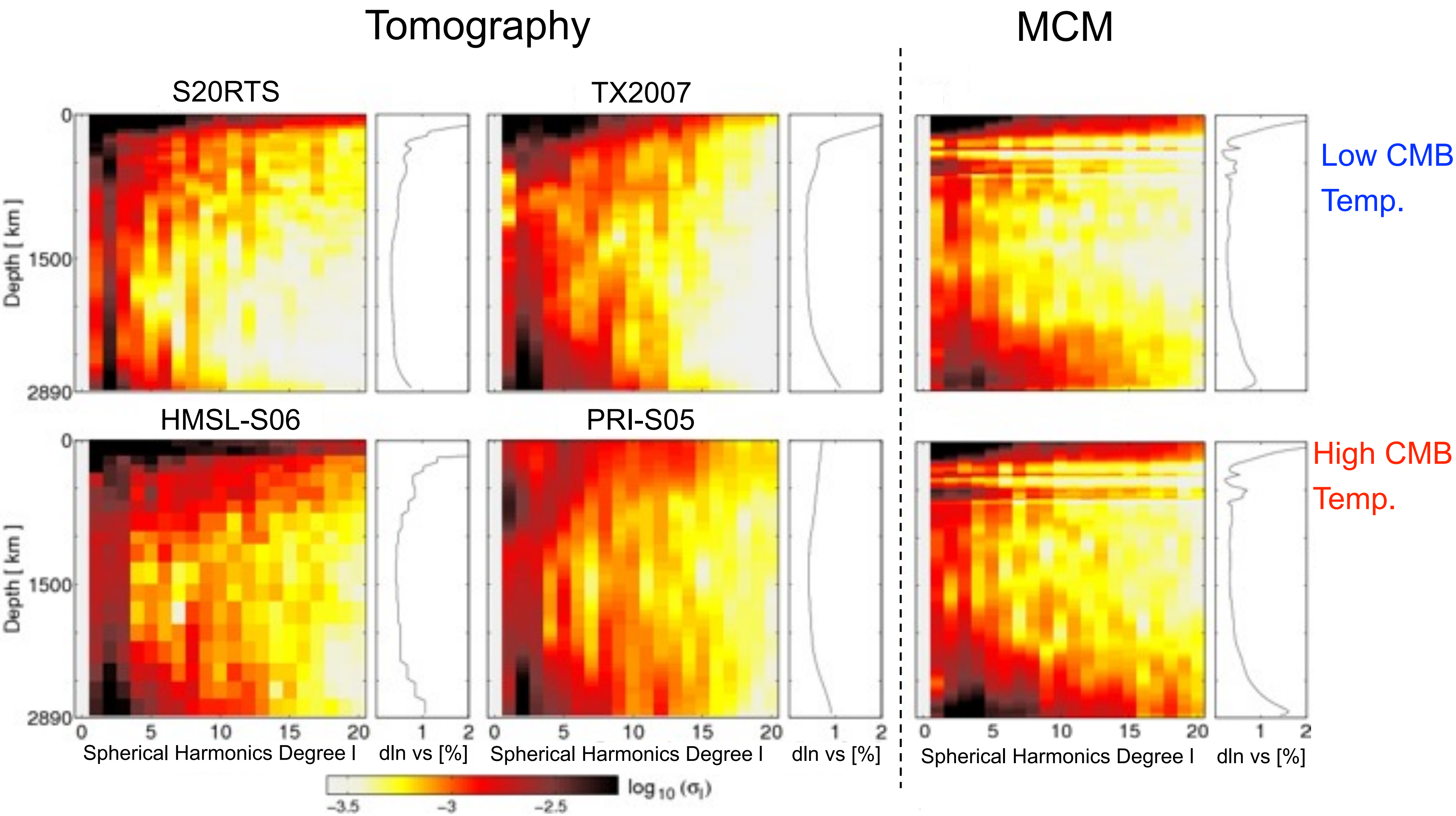
Spectral Power of Heterogeneity

High CMB Temperature — 4200 K



Schuberth et al., 2009a

Statistics for Tomographic Models - Spectral Power

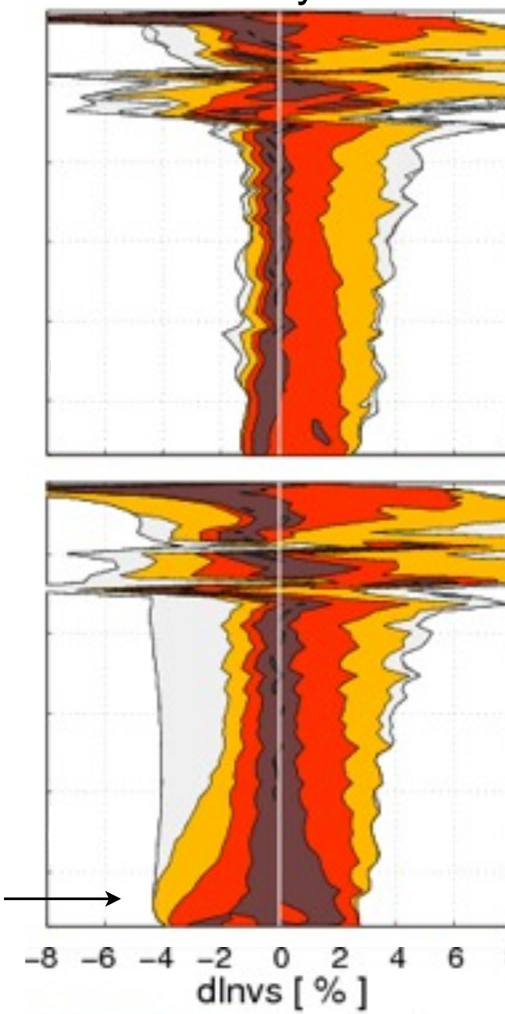


Schuberth et al., 2009a

Magnitudes of Heterogeneity — Histograms

MCM

Shear Velocity Anomalies



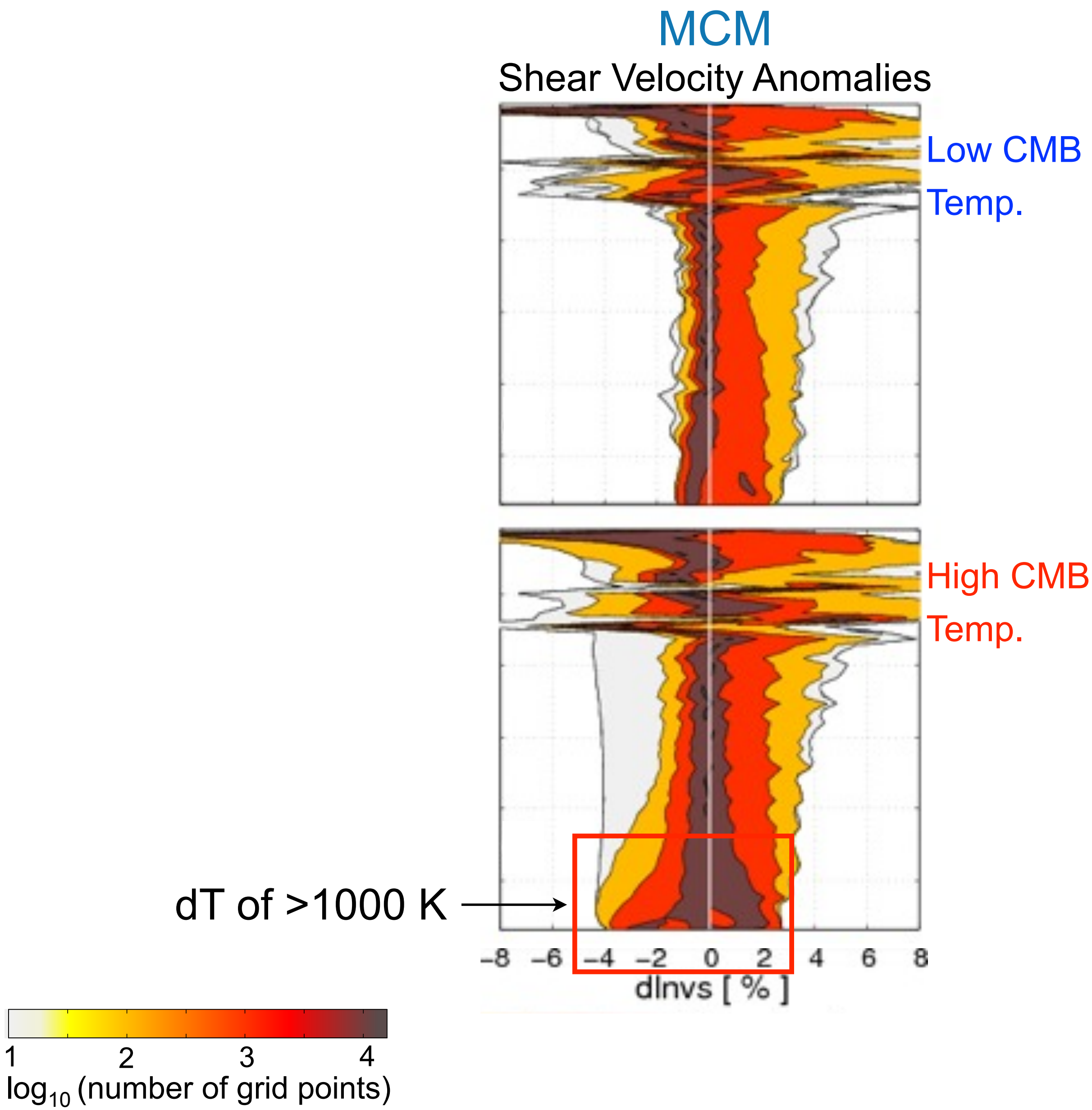
Low CMB Temp.

High CMB Temp.

dT of >1000 K

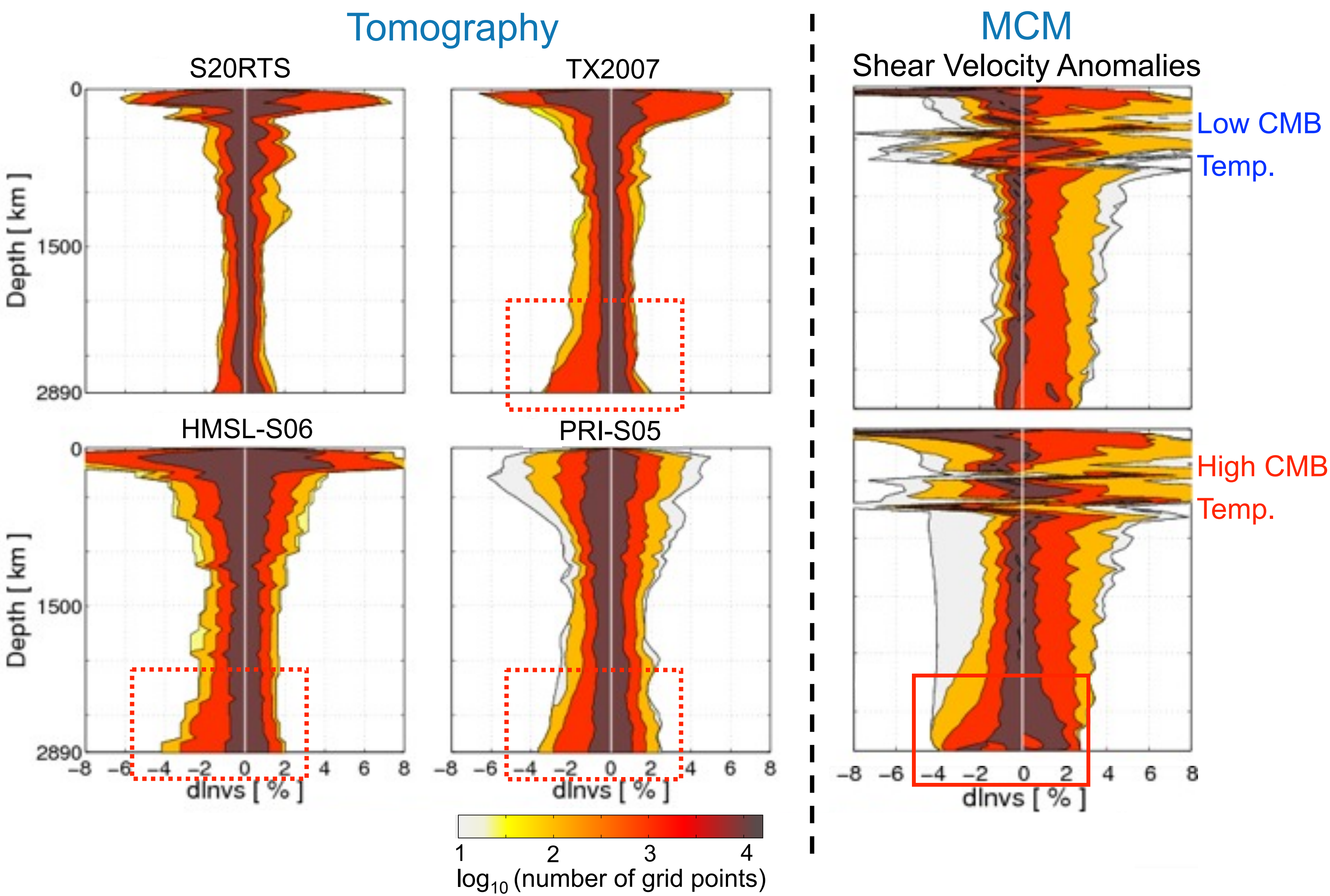
Schuberth et al., 2009a

Magnitudes of Heterogeneity — Histograms



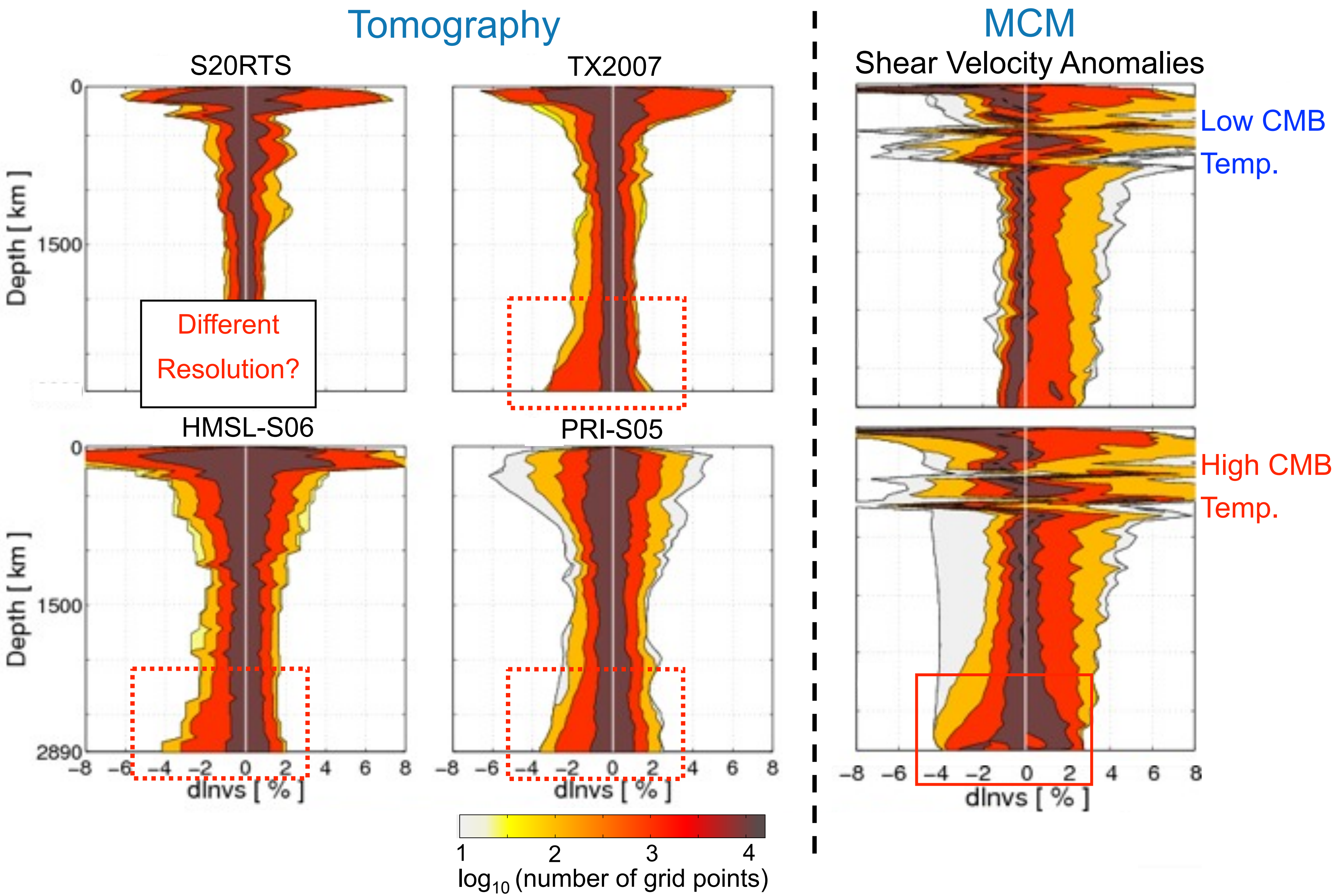
Schuberth et al., 2009a

Histograms — Comparision with Tomography



Schuberth et al., 2009a

Histograms — Comparision with Tomography



Schuberth et al., 2009a

Prediction of Elastic Structure

Forward Modeling

Mantle Dynamics

Mineralogy

3-D Elastic Structure

Limited Resolution

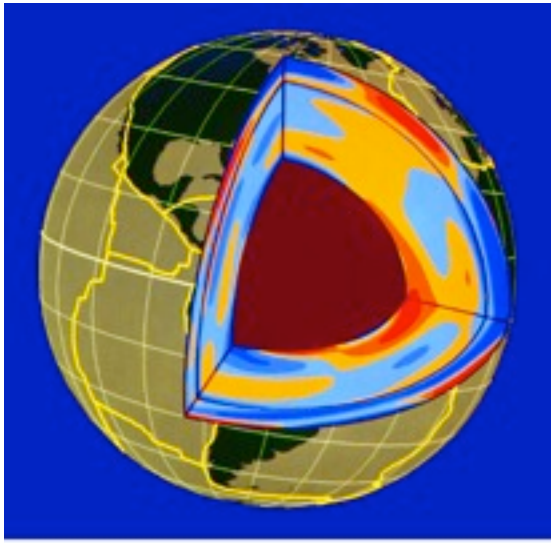
Comparison to Tomography

Quantitative Testing of Hypotheses

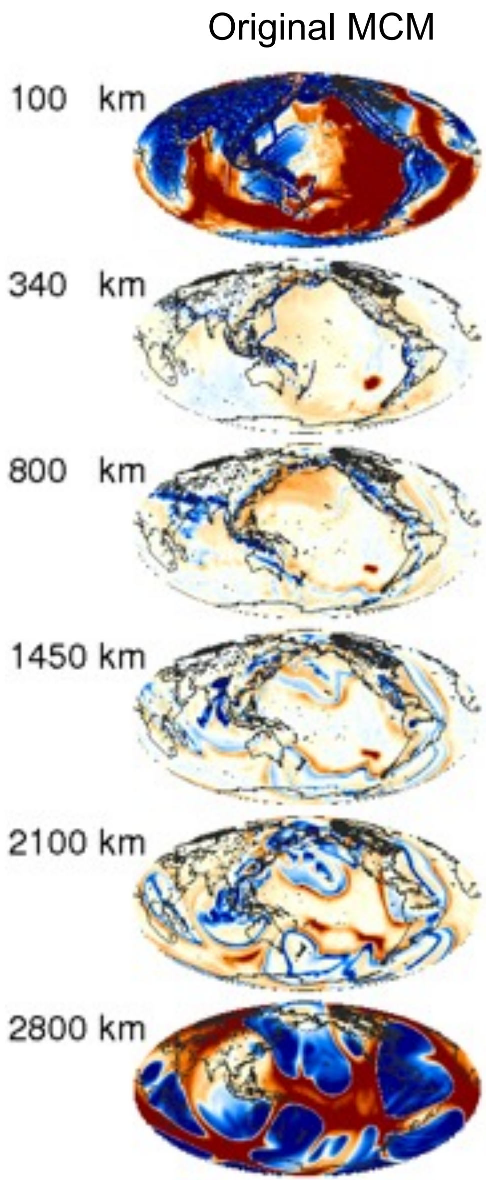
3-D high-resolution mantle circulation modeling
Control on thermal fields

Transfer function: temperature ↔ elastic parameters
Thermodynamic models + composition

Theoretical Predictions
Study effects of mineralogy on 3-D seismic structure



Tomographic Filtering of Flow Models



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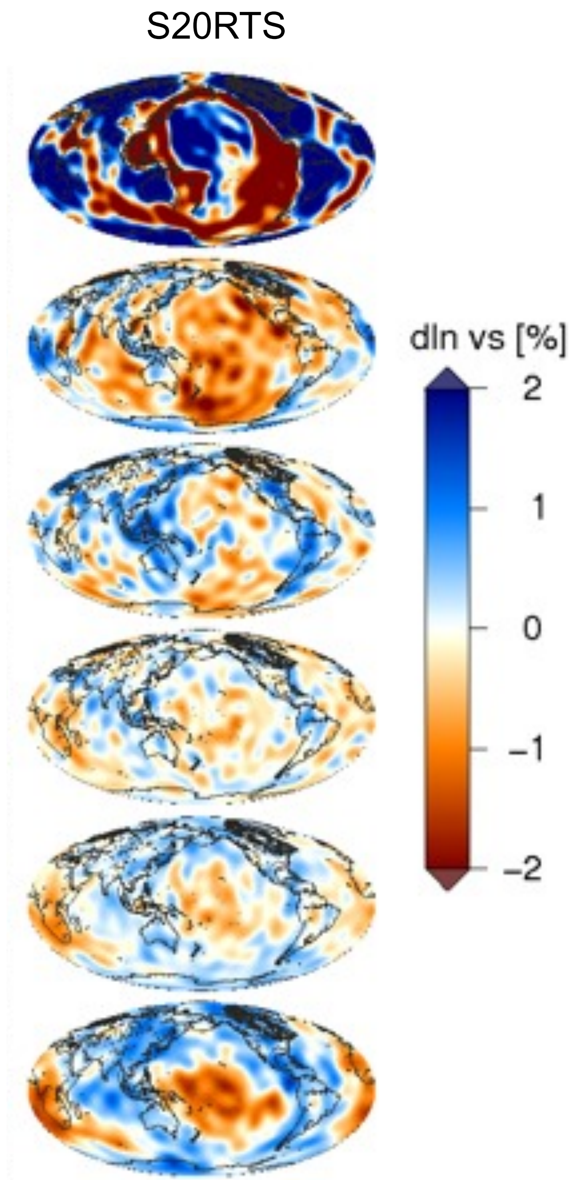
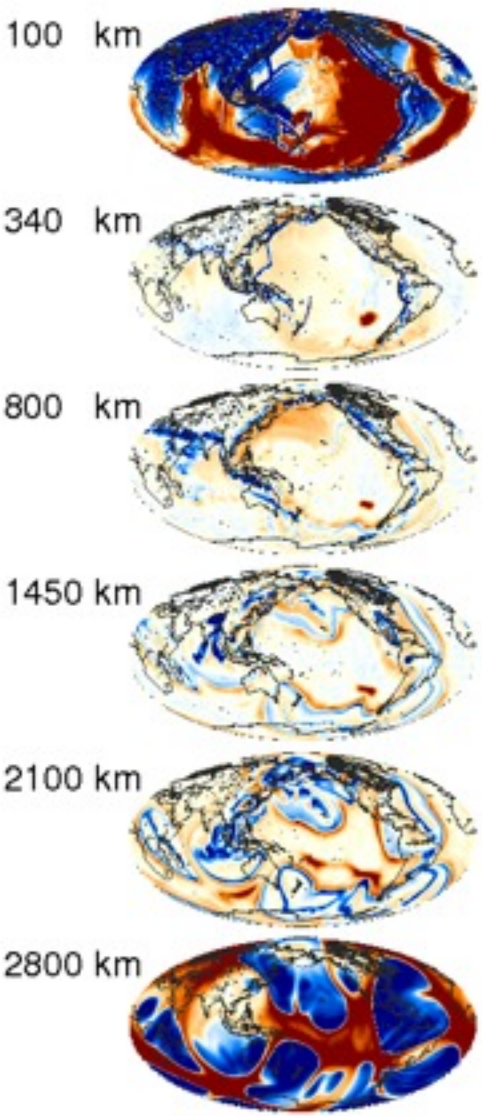


Schuberth et al., 2009b

Tomographic Filtering of Flow Models

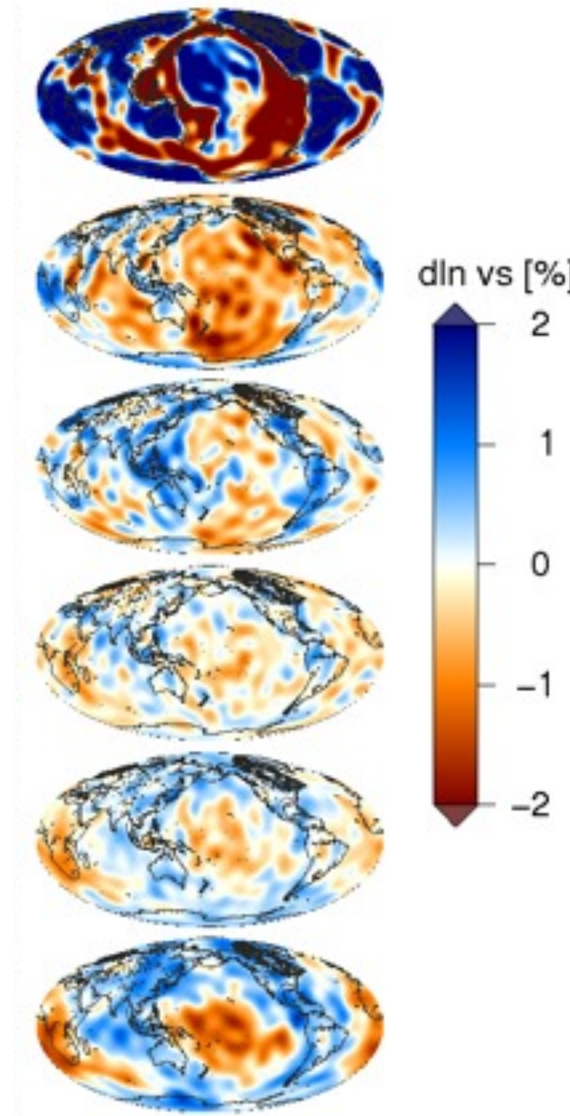
Original MCM



Rm^t

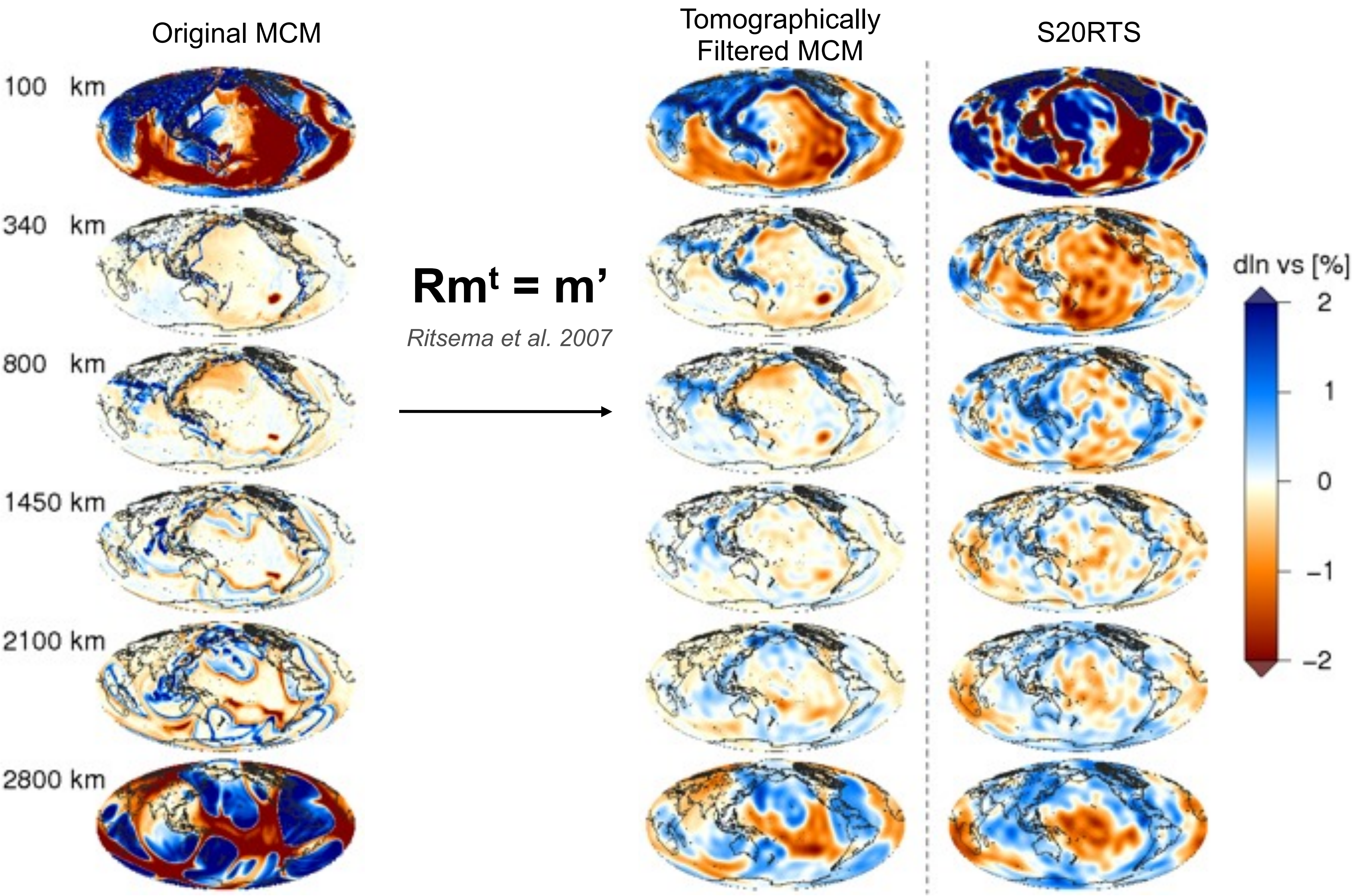
Ritsema et al. 2007

S20RTS



Schuberth et al., 2009b

Tomographic Filtering of Flow Models

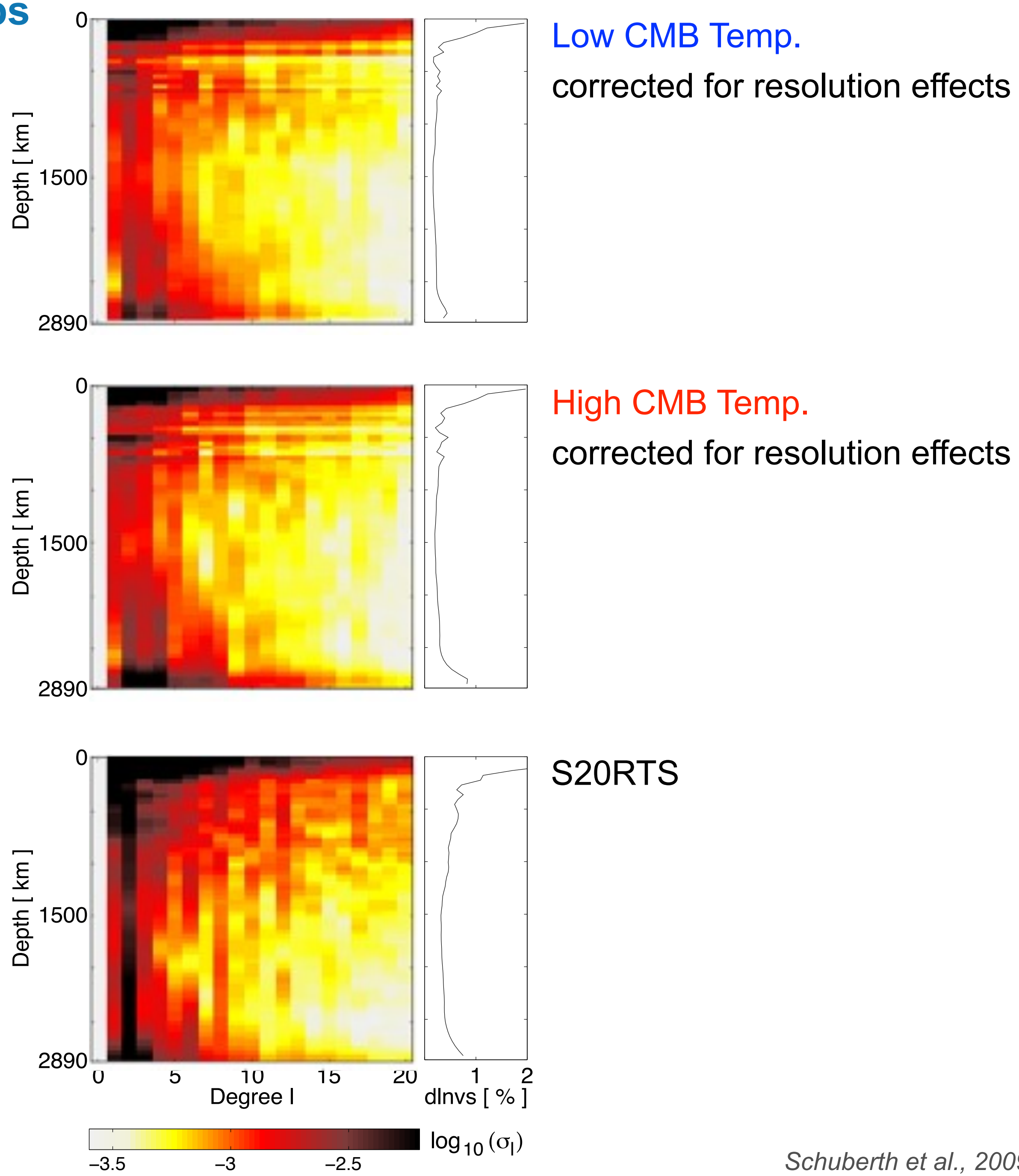


$$Rm^t = m'$$

Ritsema et al. 2007

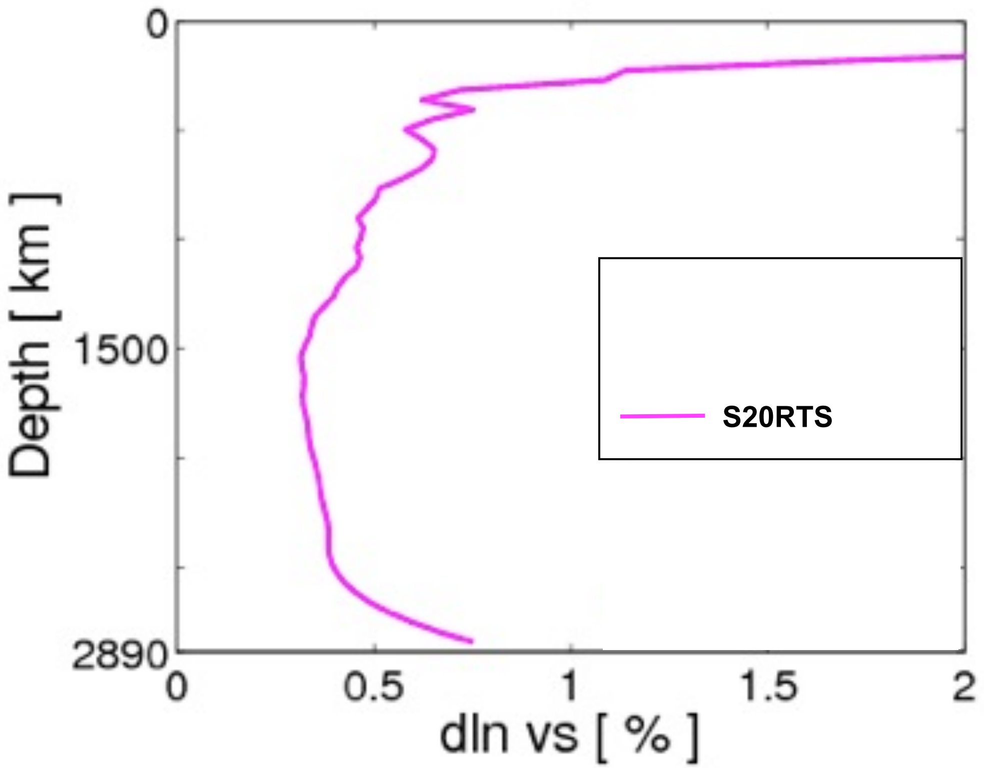
Schuberth et al., 2009b

Spectral heterogeneity maps after tomographic filtering



Schuberth et al., 2009b

Root-Mean-Square Profiles After Tomographic Filtering

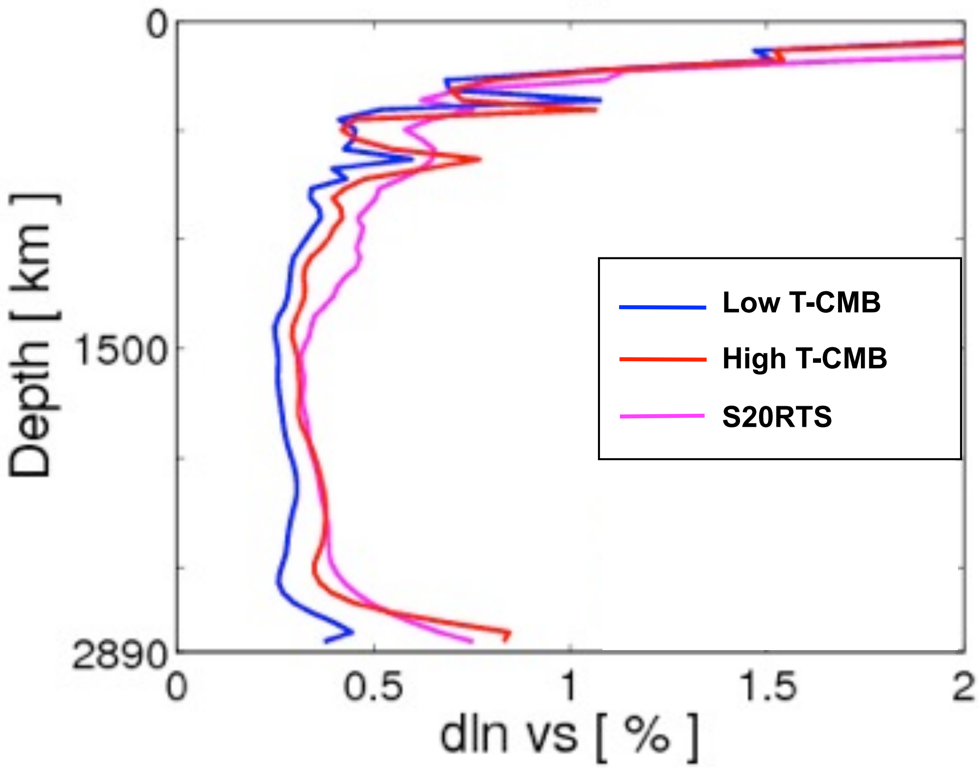


Schuberth et al., 2009b

Root-Mean-Square Profiles After Tomographic Filtering

RMS profiles match well for models with high CMB temperature

especially in the deep mantle



Schuberth et al., 2009b

Conclusions

The characteristics of a model **show large differences between temperature and seismic velocities**, especially in the upper mantle and transition zone

This difference is due to mantle mineralogy which shows **a complex set of phase transformations** in the transition zone

A **large thermal gradient** across the CMB in **isochemical whole mantle flow seems compatible** with the magnitude and lateral gradients of the **elastic structure** as seen by **seismology**

This may have implications for the possible contribution of chemical heterogeneity

Summary

Seismic tomography provides detailed images of **Earth's elastic structure, but we face problems in the interpretation**

High resolution mantle circulation modeling allows for **the prediction** of **temperature variations with realistic magnitudes**

Quantitative testing of geodynamic predictions against tomography
mantle circulation models + thermodynamic models of mantle mineralogy

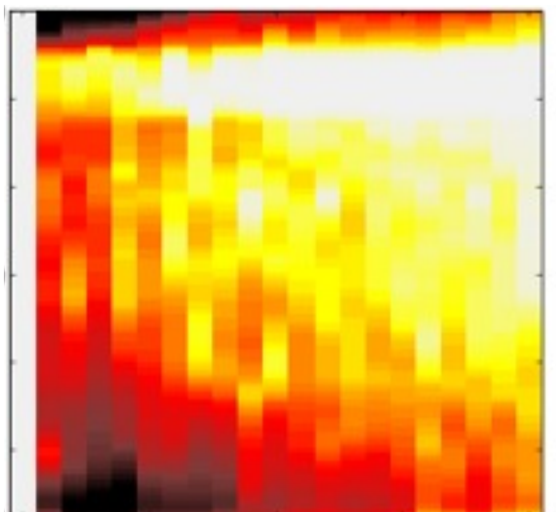
Consistent tests only possible if **limited tomographic resolution** is taken into account

The magnitude of lateral variations in thermal and elastic structure are **a powerful diagnostic** for studying deep earth dynamics

We need reliable information on magnitude of heterogeneity in the Earth from tomography!

Thank You For Your Attention!

Temperature



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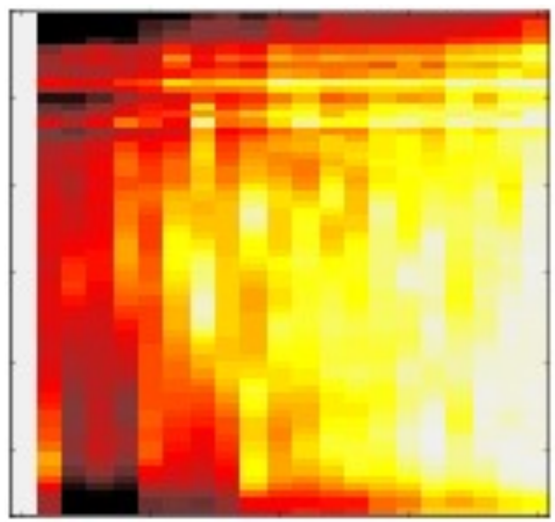
S-wave velocity



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S20RTS