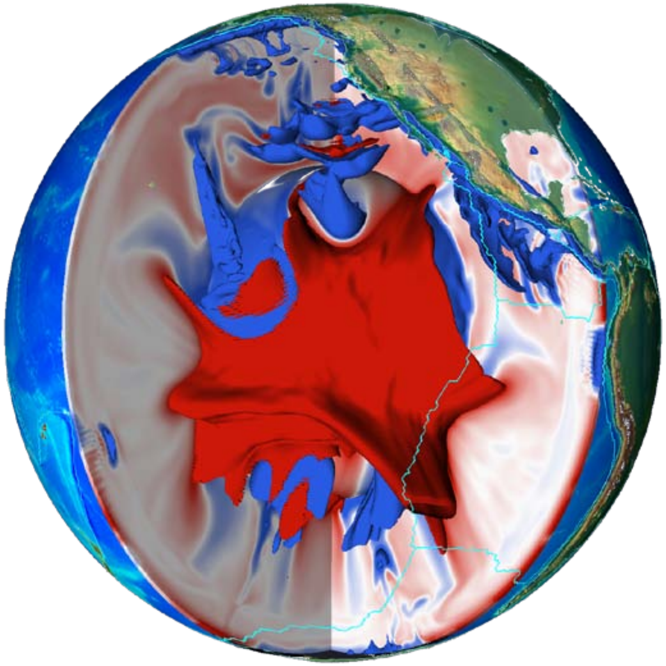
LUDWIG-
MAXIMILIANS-
UNIVERSITÄT
MÜNCHEN

Geophysics
Department of Earth and Environmental Sciences

# Synthetic Seismograms for a Synthetic Earth

## Computing 3-D wavefields in mantle circulation models to test geodynamic hypotheses directly against seismic observations



Collège de France
13 November 2012

Bernhard S.A. Schuberth
Ludwig-Maximilians-University Munich, Germany

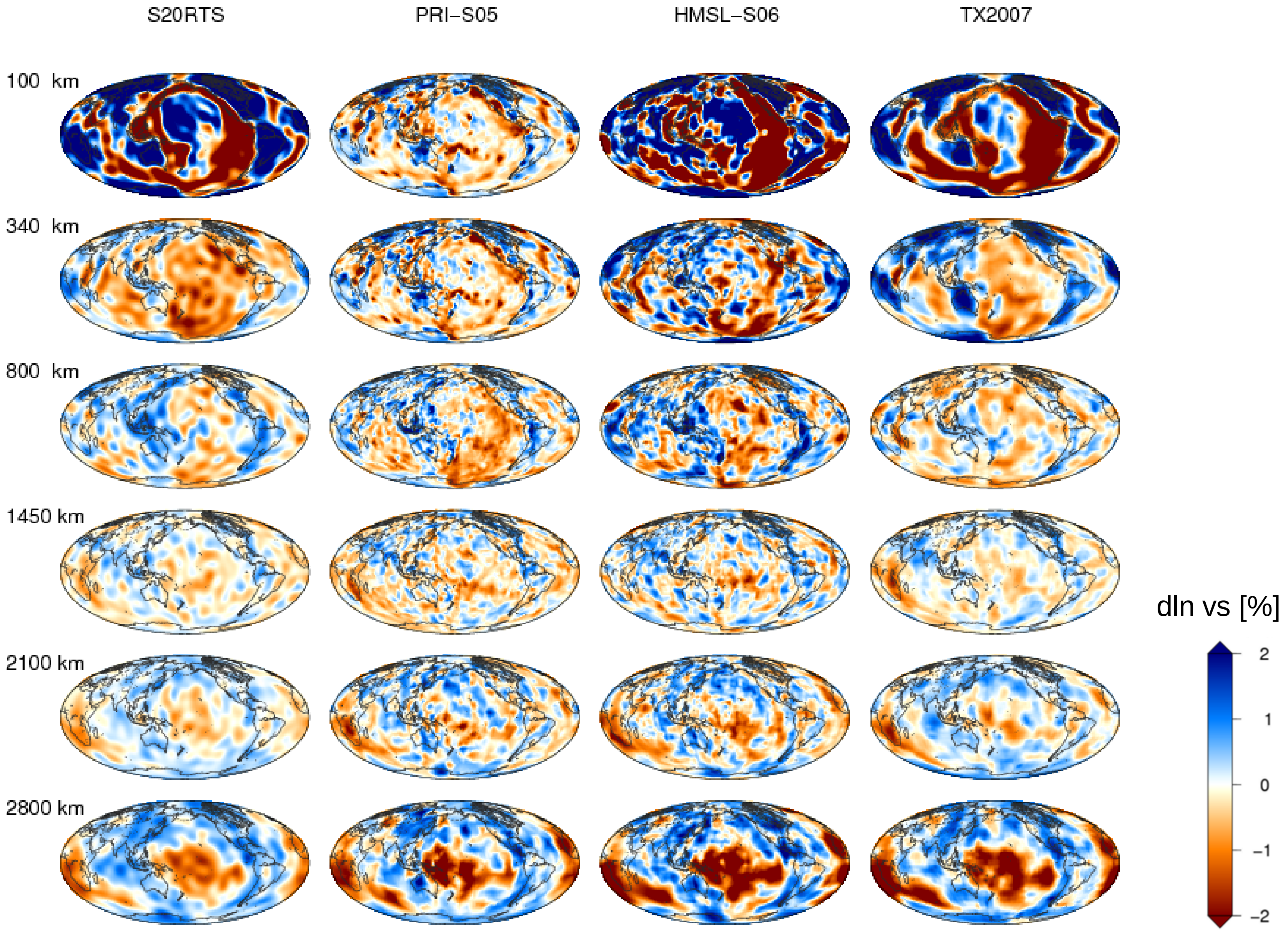
Christophe Zaroli, Guust Nolet, Hans-Peter Bunge,
Heiner Igel, Jeroen Ritsema, Thomas Chust, Gerd Steinle-Neumann, Lars Stixrude, Christoph Moder, Jens Oeser

# Tomographic Models of Seismic Heterogeneity

Surface

- S

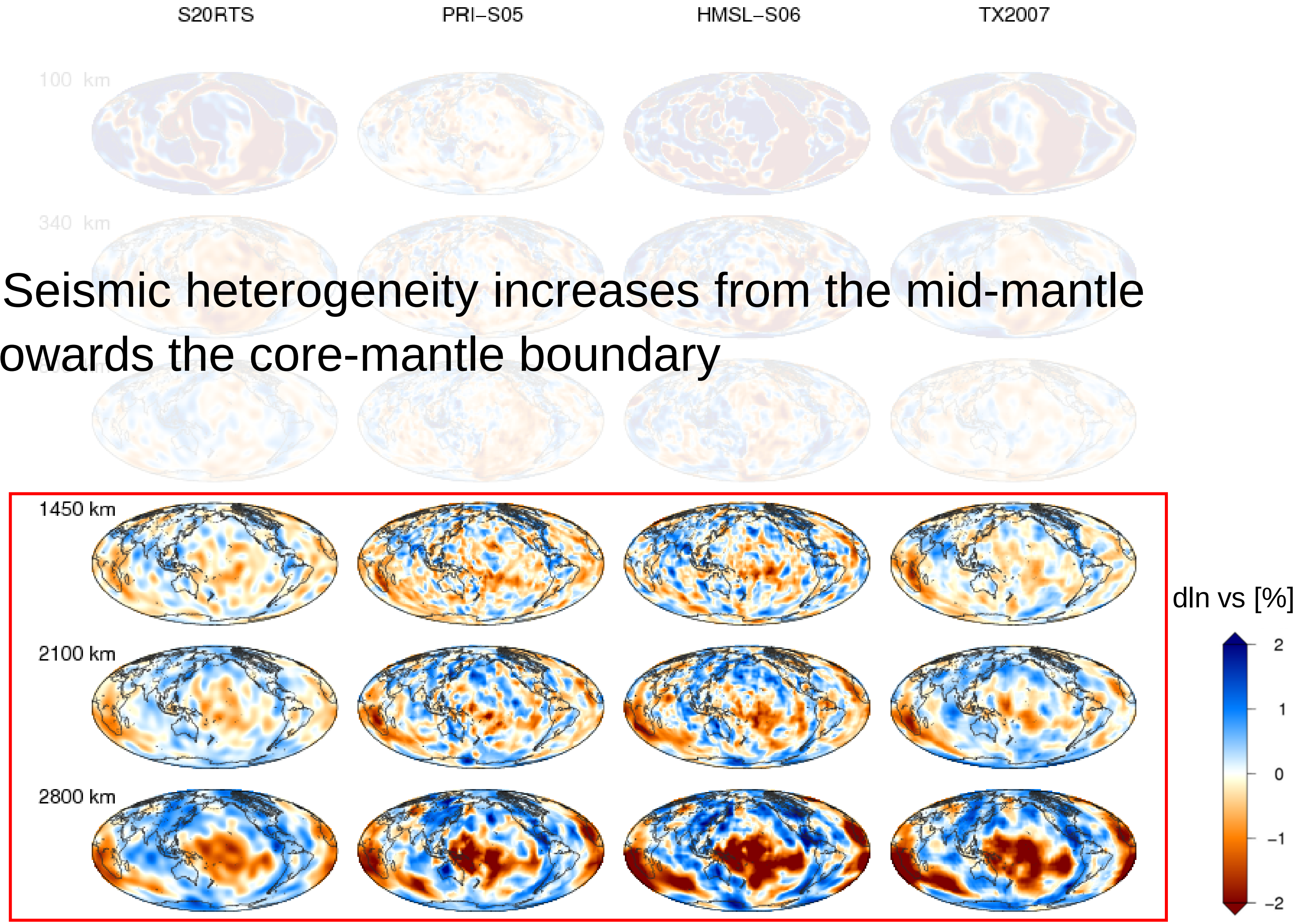
to



Core-Mantle-Boundary (CMB)

Schuberth et al., 2009a

# Origin of Heterogeneity in the Lowermost Mantle?

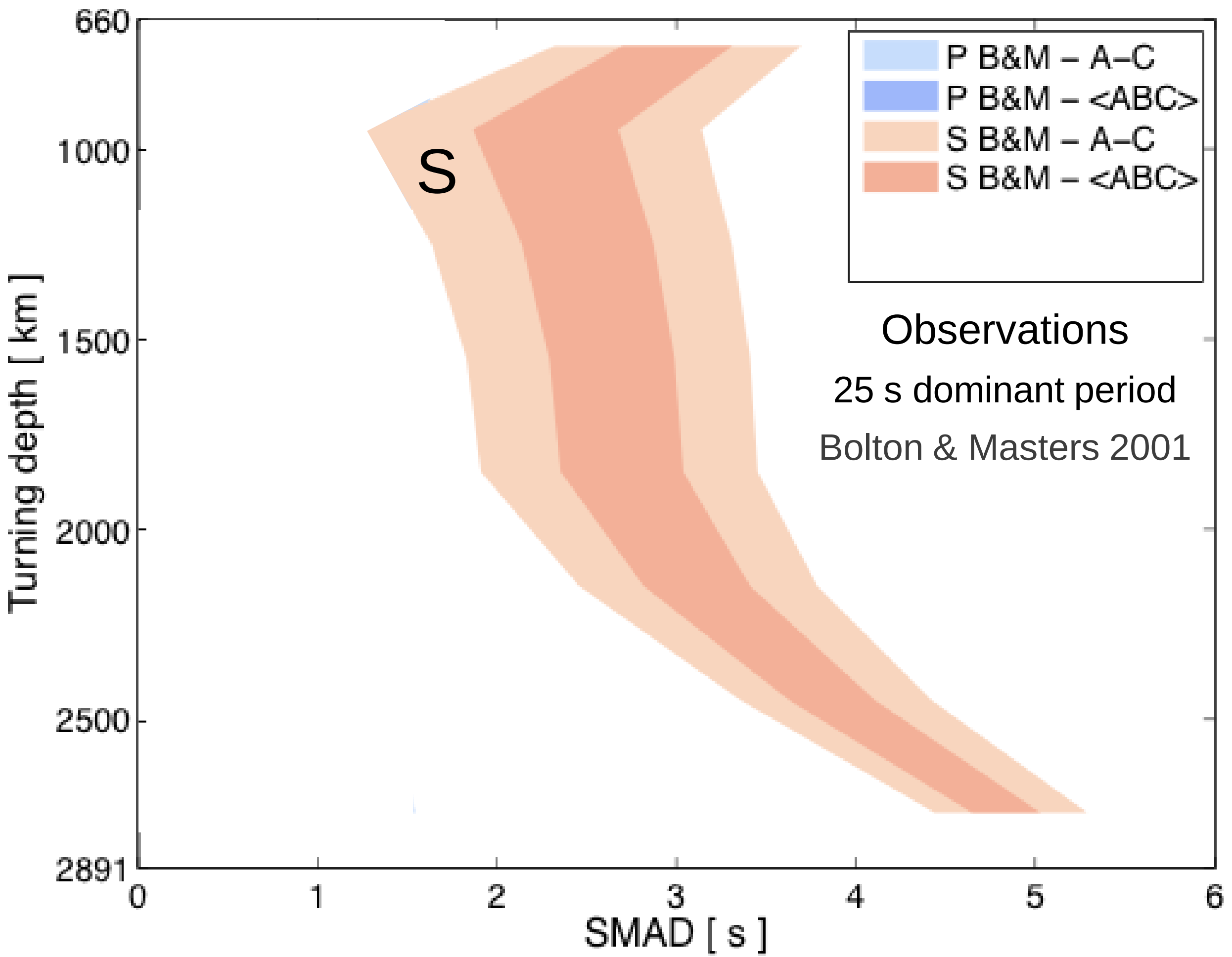


- Seismic heterogeneity increases from the mid-mantle towards the core-mantle boundary

Schuberth et al., 2009a

# Long-Period Body-Wave Observations

Standard deviation of traveltime variations



Observations

25 s dominant period

Bolton & Masters 2001

Scaled Median Average Deviation

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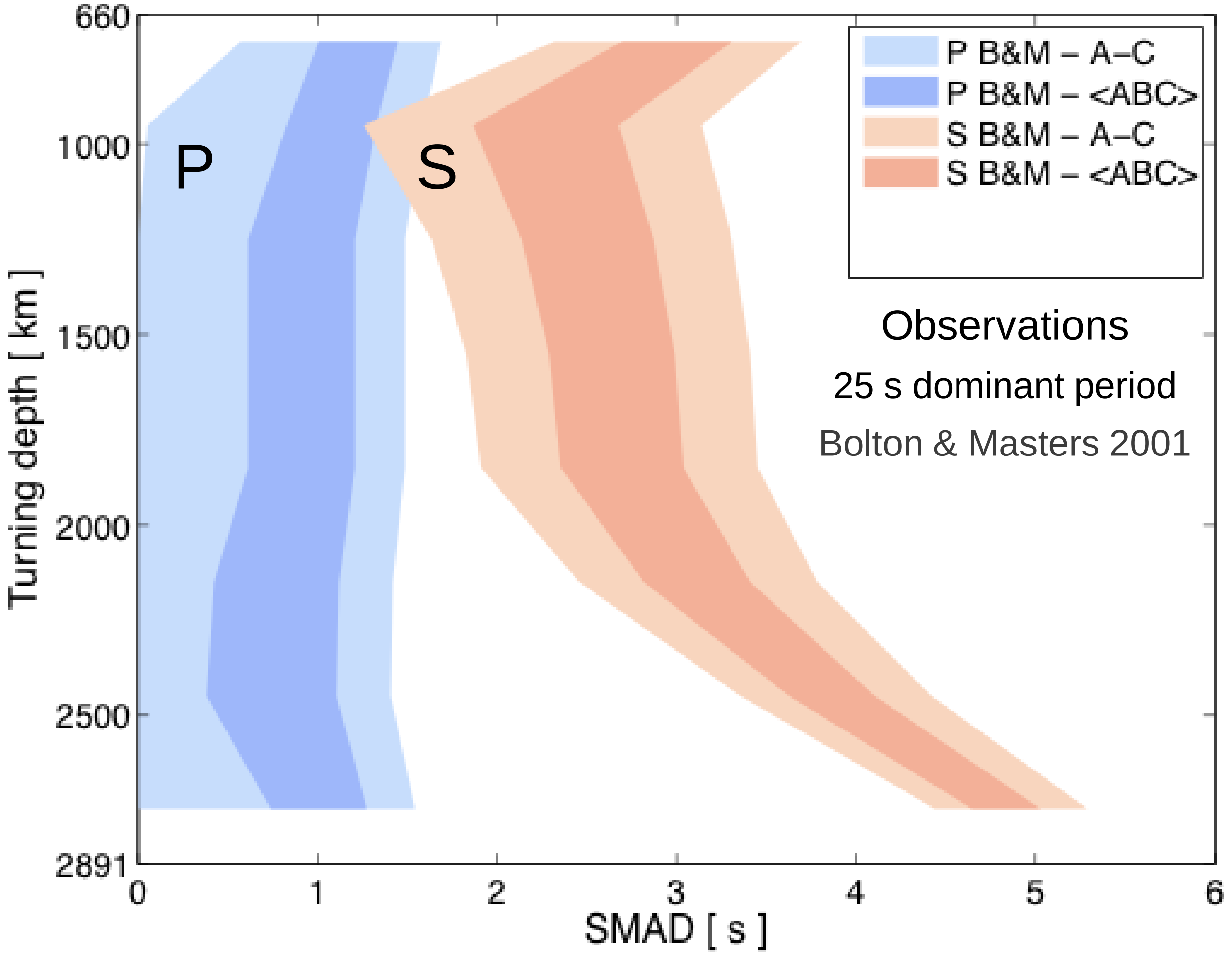

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# Heat Transport as the Dominant Physical Process?

Large lateral temperature variations are expected in the deep mantle, especially in hot upwelling plumes

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

e.g., Glatzmaier & Roberts 1995, Kuang & Bloxham 1997, Buffett 2002, Nimmo 2004,
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But low plume excess temperatures in the asthenosphere (200-300 K)

Schilling 1991, Presnall & Gudfinnson 2008

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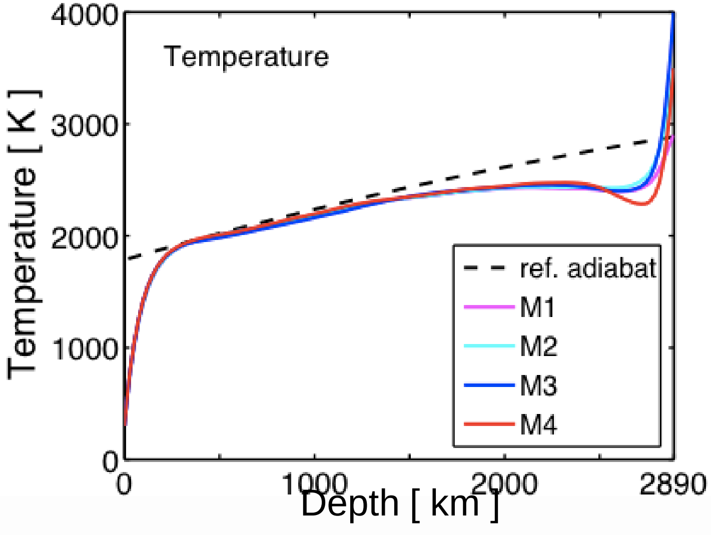

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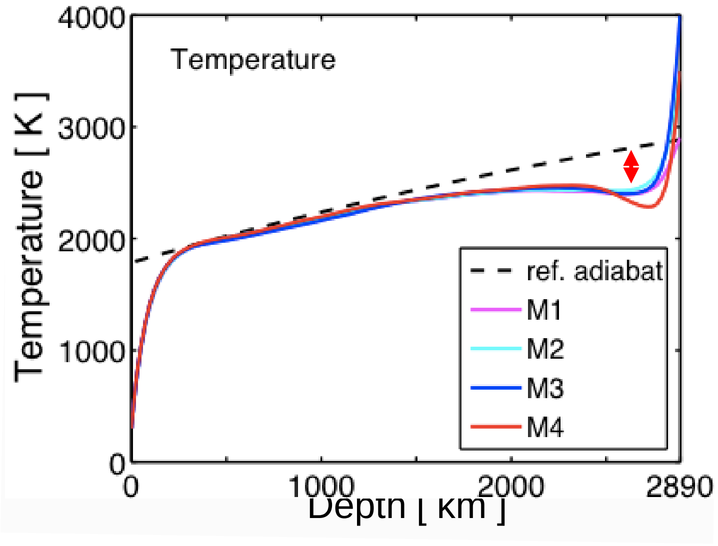

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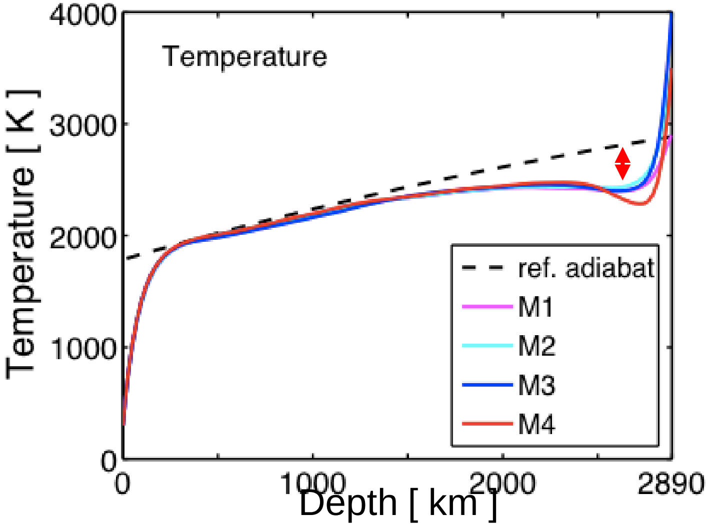

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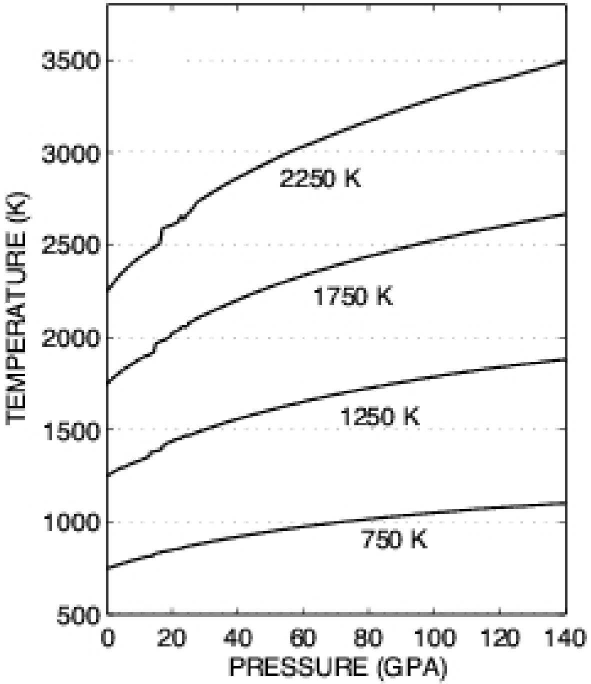
- The adiabat itself depends on temperature



Adiabats for different footing temperatures

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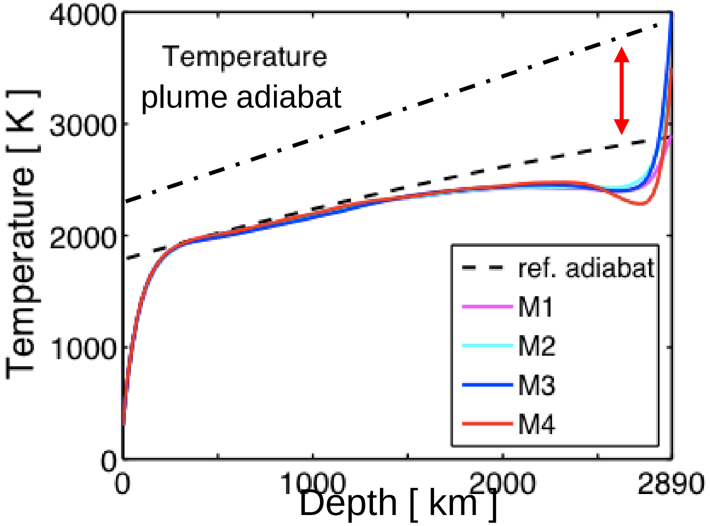

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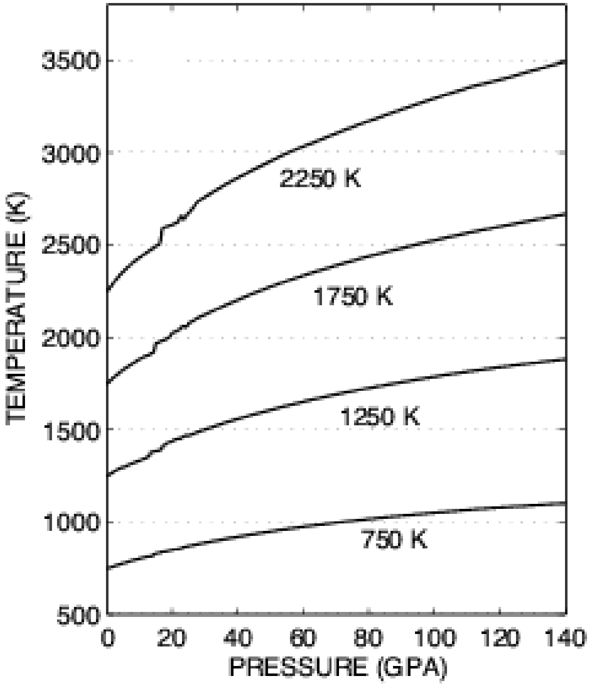

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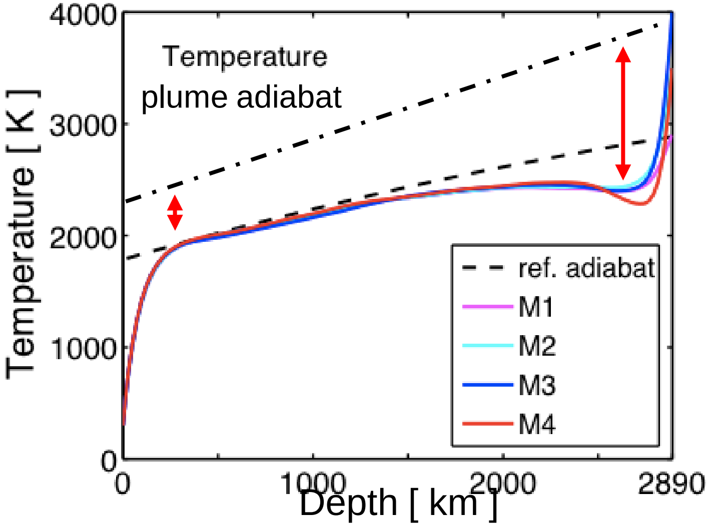

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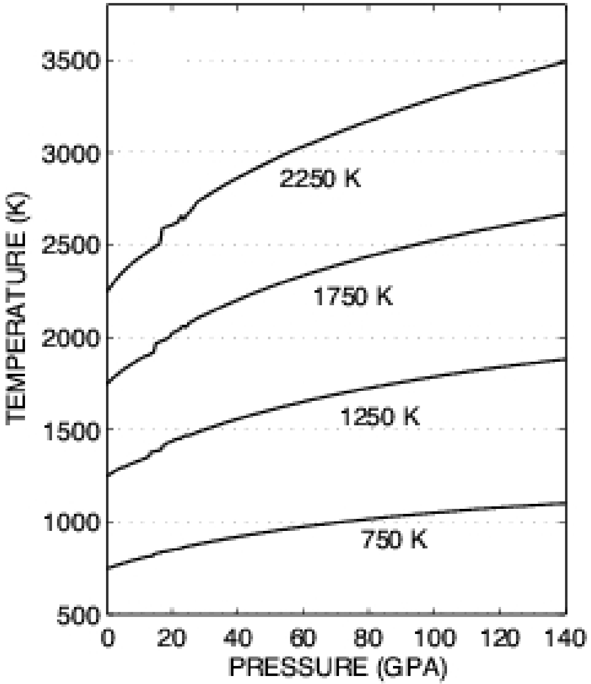
~300 K

- The adiabat itself depends on temperature

\+ ~300 K

~900 K



Adiabats for different footing temperatures

# Key Questions

Large lateral temperature variations are expected in the deep mantle, especially in hot upwelling plumes

- Can they explain the strong shear wave reduction and sharp sides of the low velocity bodies in the deep mantle?

  Especially when accounting for the limited resolving power of seismic tomography?

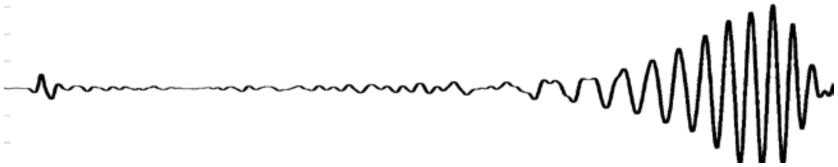
# Classical Approach: Solve Inverse Problem

Inverse
Problem

3-D Elastic Structure

Tomographic inversion

Seismic Data



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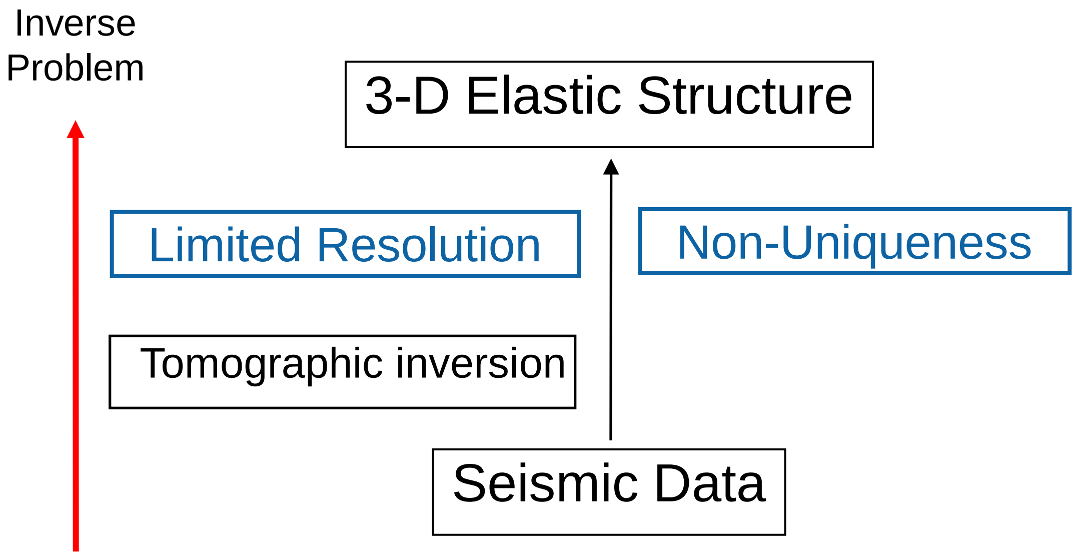


Inverse Problem

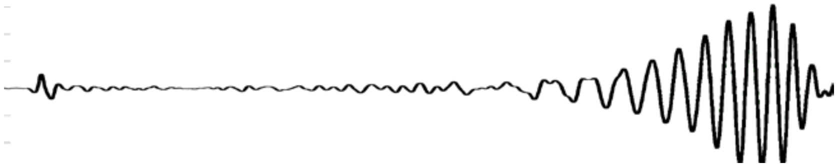
3-D Elastic Structure

Limited Resolution

Non-Uniqueness

Tomographic inversion

Seismic Data



# Joint Modeling Approach

Pure
Forward
Modeling

3-D Elastic Structure

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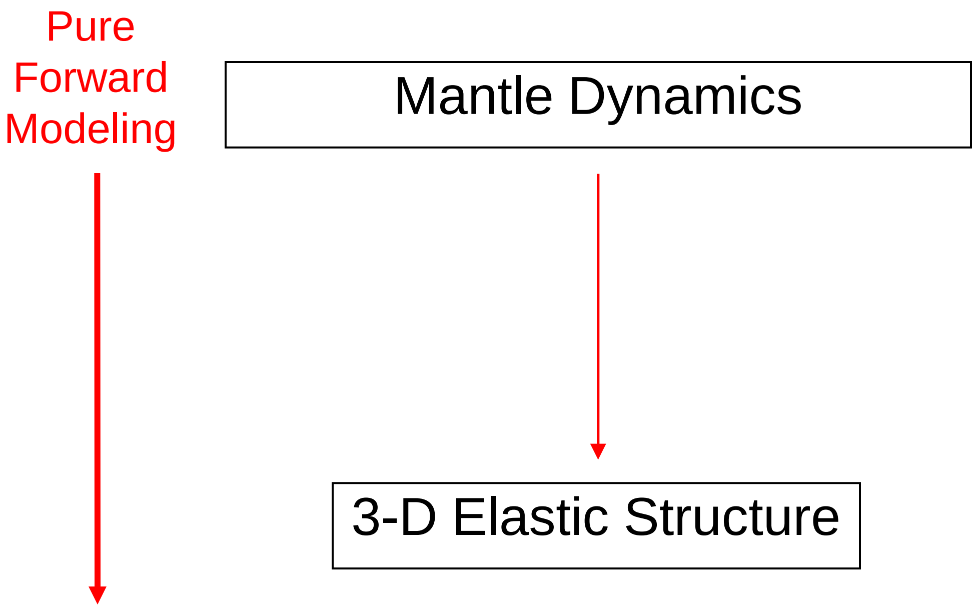


Pure Forward Modeling

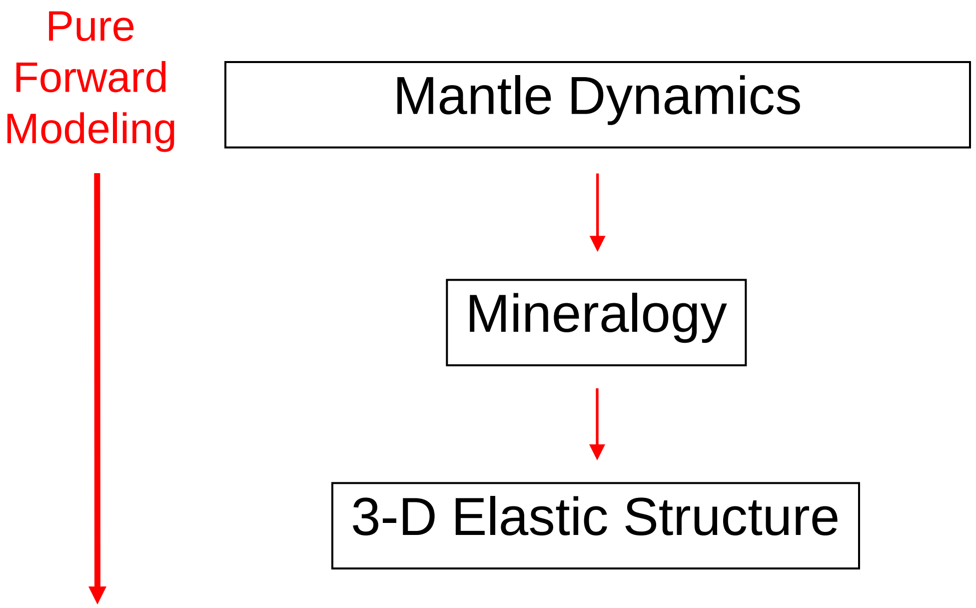
Mantle Dynamics

3-D Elastic Structure

3-D Mantle Circulation Models (MCM)

Temperature

# Joint Modeling Approach



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Thermodynamic Models + Composition

Temperature ↔ Elastic parameters

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Pure Forward Modeling

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3-D Elastic Structure

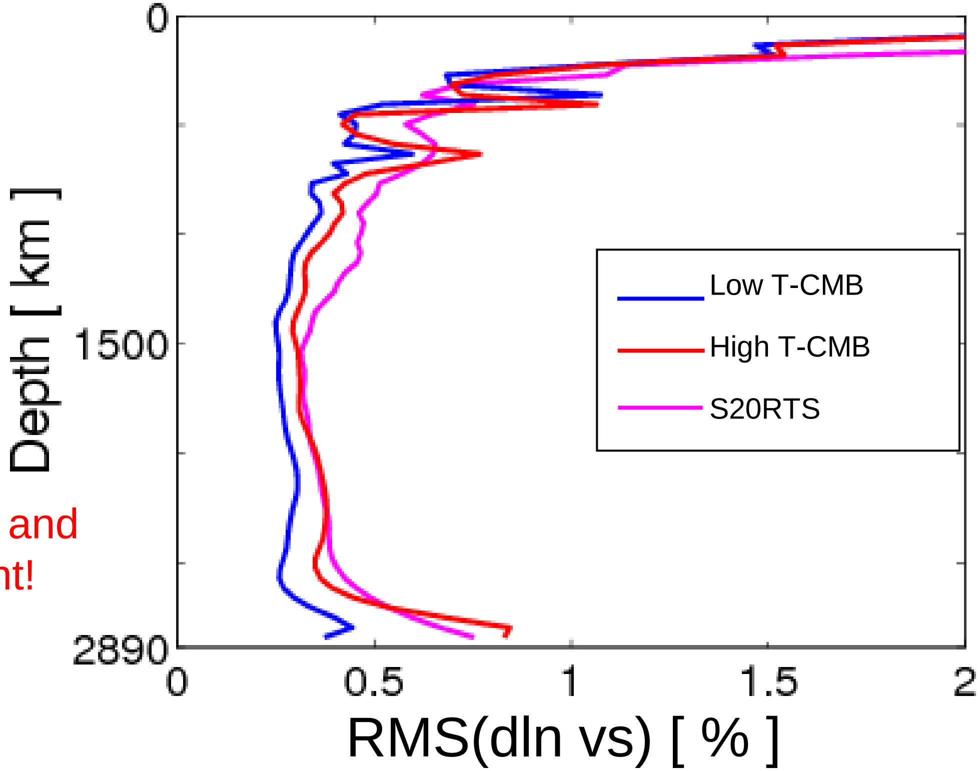
Model Planet
Seismic heterogeneity

# Key Questions

Large lateral temperature variations are expected in the deep mantle, especially in hot upwelling plumes

In case of isochemical whole mantle flow with a pyrolite composition, they can explain the strength of S-wave heterogeneity

Schuberth et al. 2009a,b



Effects of uneven data coverage and damping are taken into account!

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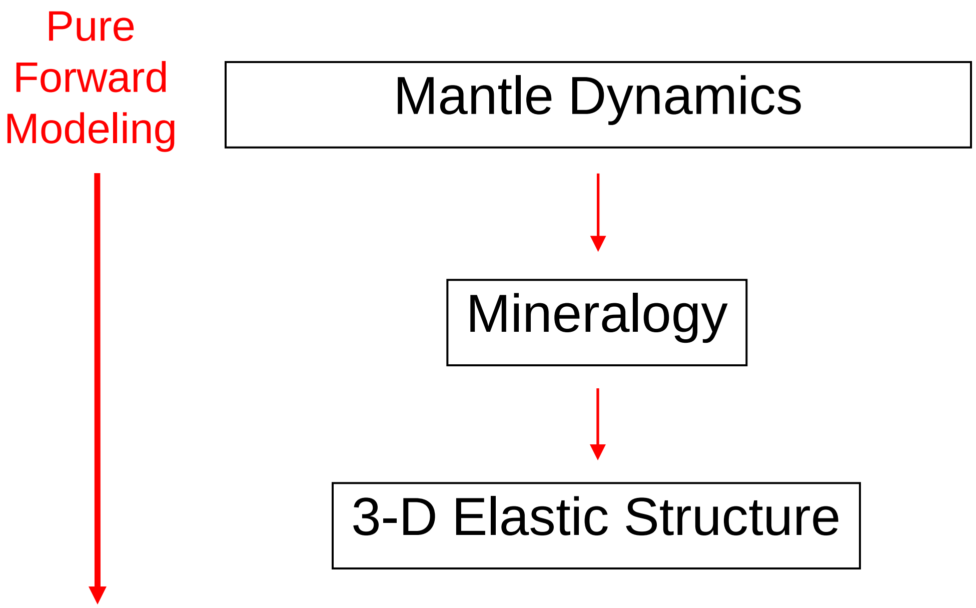
Test geodynamic hypotheses directly against seismic data

# Joint Modeling Approach



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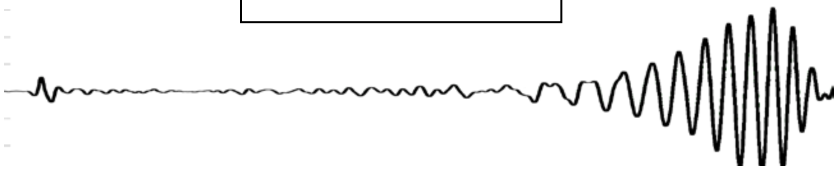

Full Waveforms

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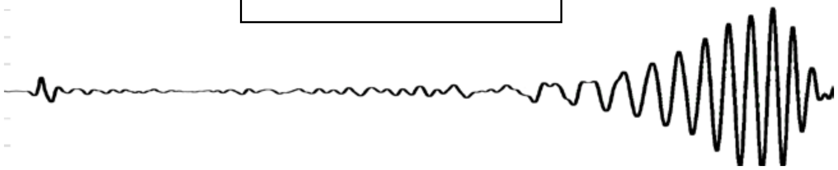
Wave Propagation

Spectral Element Method

Seismic Data

Full Waveforms



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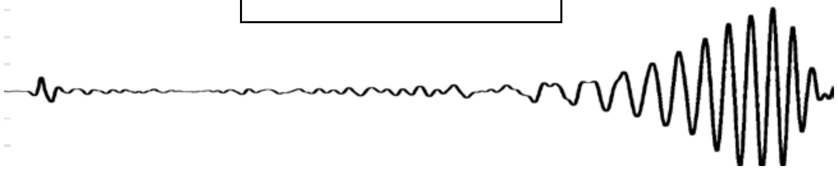


# The Simple-Most Model Planet

QuickTime™ and a
GIF decompressor
are needed to see this picture.

### 3-D Spherical MCM

compressible

### Isochemical

Pyrolite

### Depth-dependent viscosity

3 layers

### High CMB temperature

4200 K

### High resolution

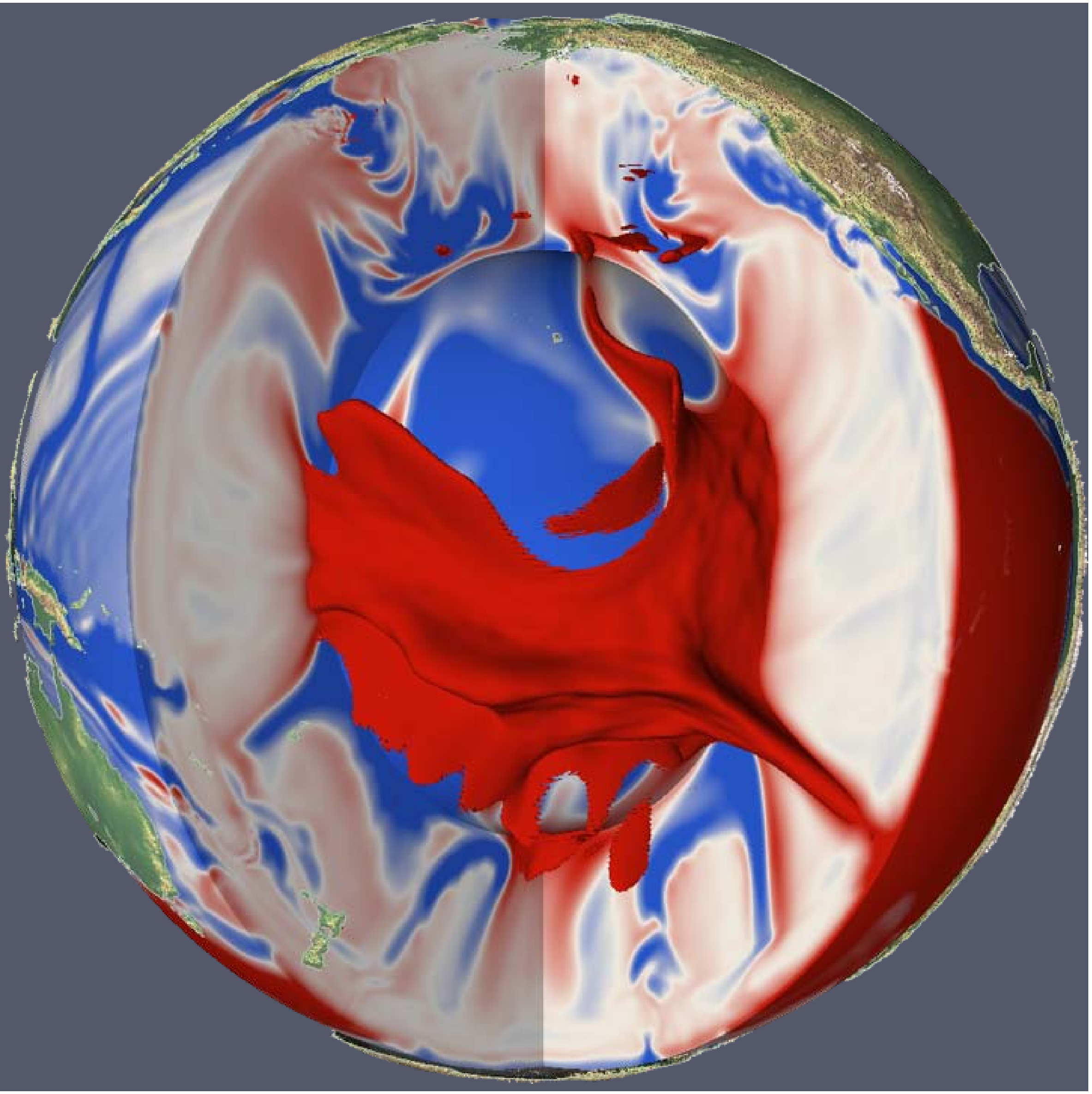
80 million grid points

hot – upwelling plumes

cold – downwellings slabs

Schuberth et al., 2009a

# Linking Temperatures to Seismic Velocities



## Mineralogical model

e.g., Ricard et al. 2005, Stixrude & Lithgow-Bertelloni 2005/2011, Piazzoni et al. 2007

## Gibbs Free Energy minimization

Equilibrium phase assemblages

➡ thermodynamically self-consistent

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Schuberth et al., 2009a

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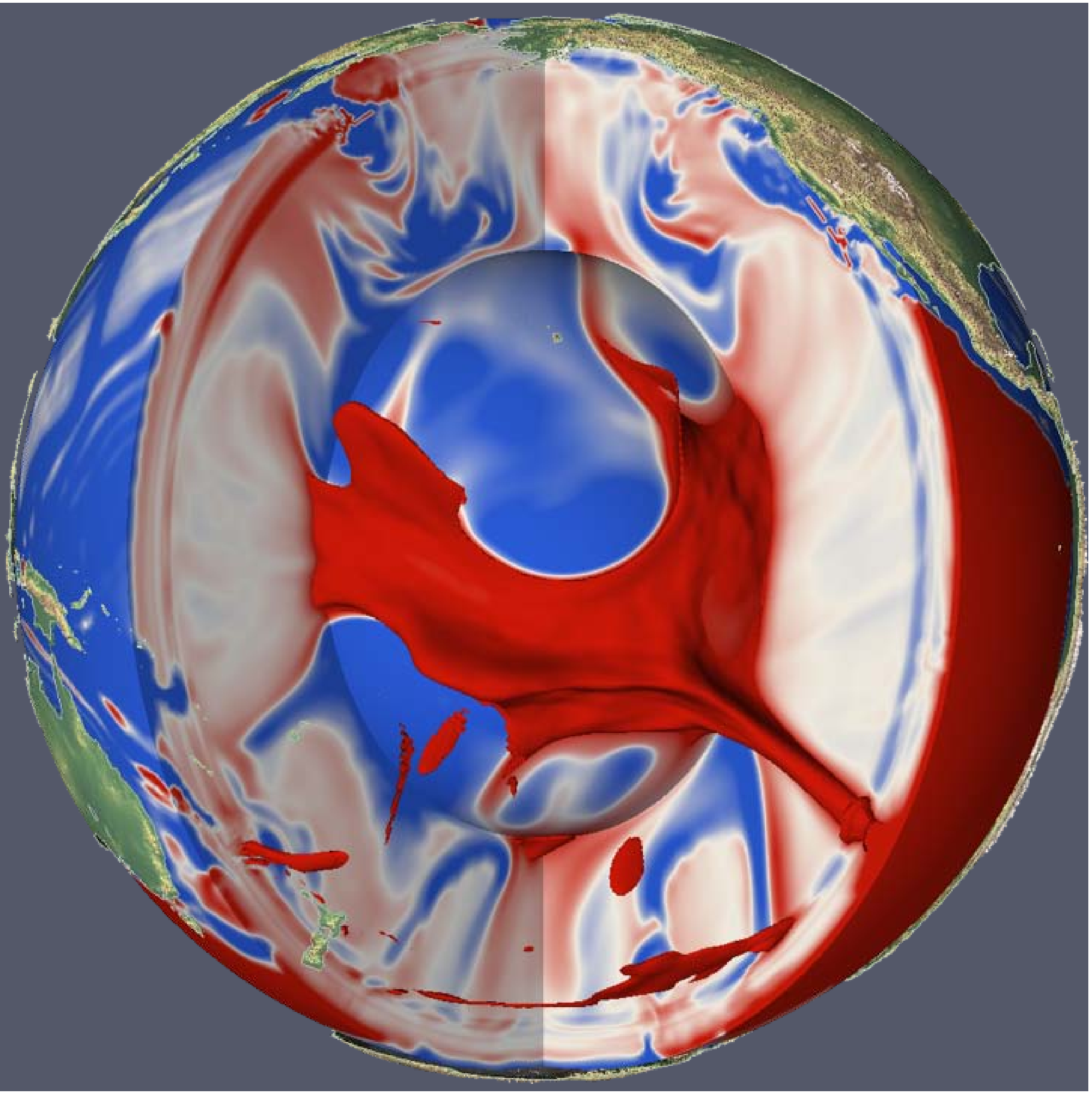

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## S-wave velocity

Schuberth et al., 2009a

# 3-D Wave Propagation in a Synthetic Earth

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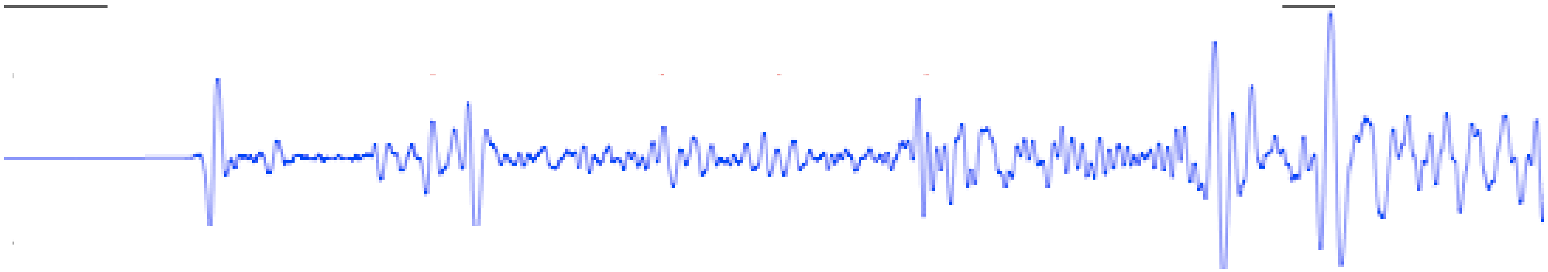
# Setup of Wave Propagation Simulations

## Wavefield with 10 s shortest period

SPECFEM3D_GLOBE



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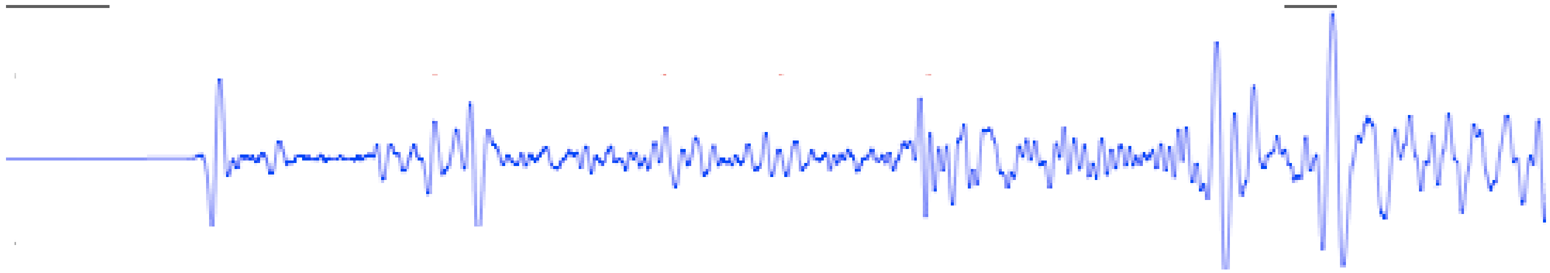
Full waveform cross-correlation at 15 s

➡ Finite-frequency interpretation



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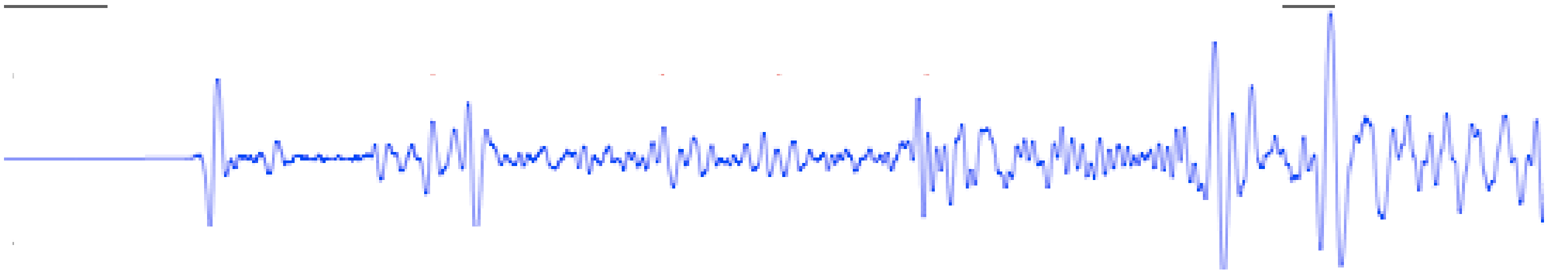
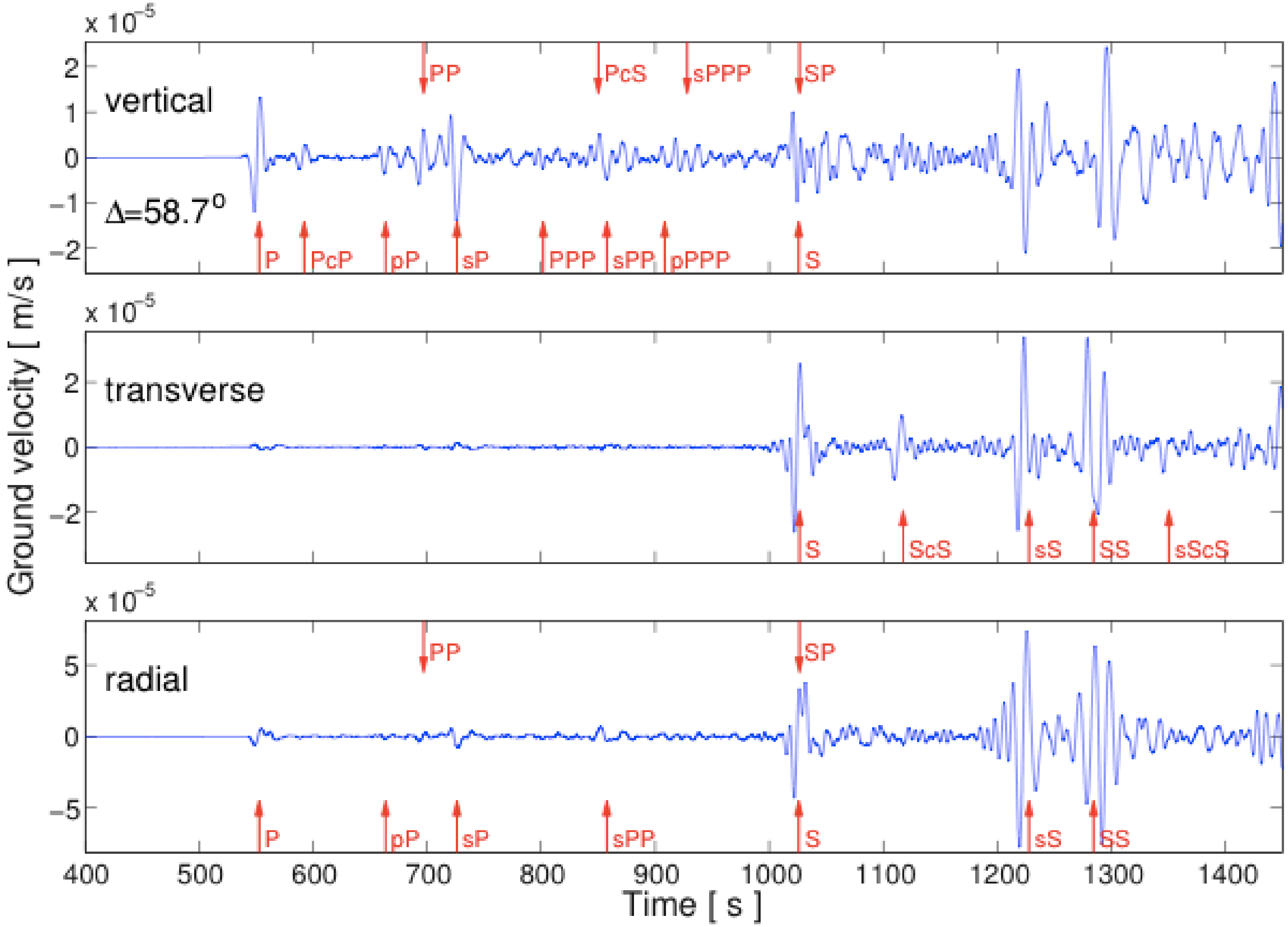
1-D crust
no attenuation, anisotropy, topography, etc.



Schuberth et al. 2012

# Full Waveforms for Model Planets



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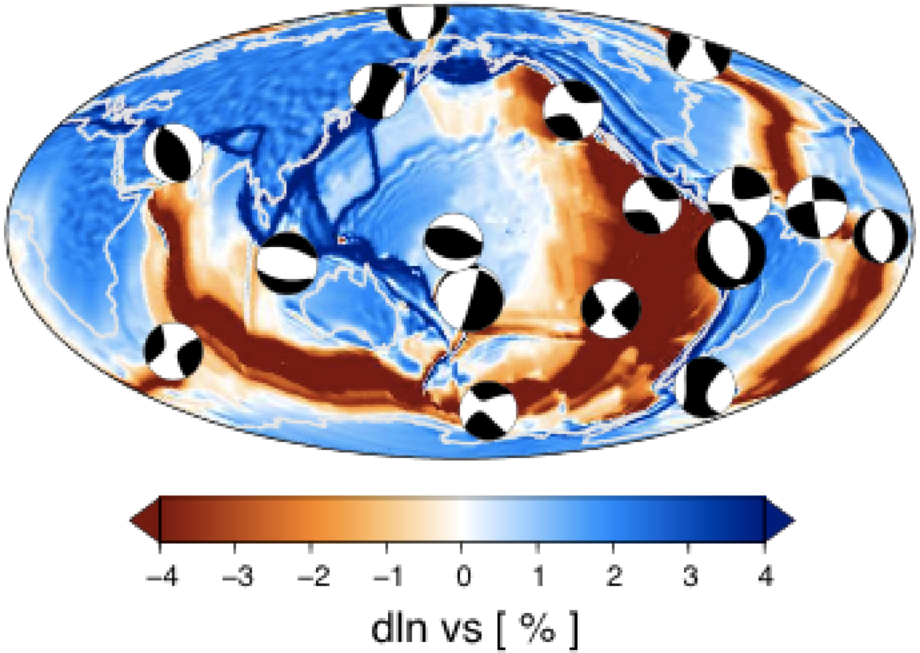
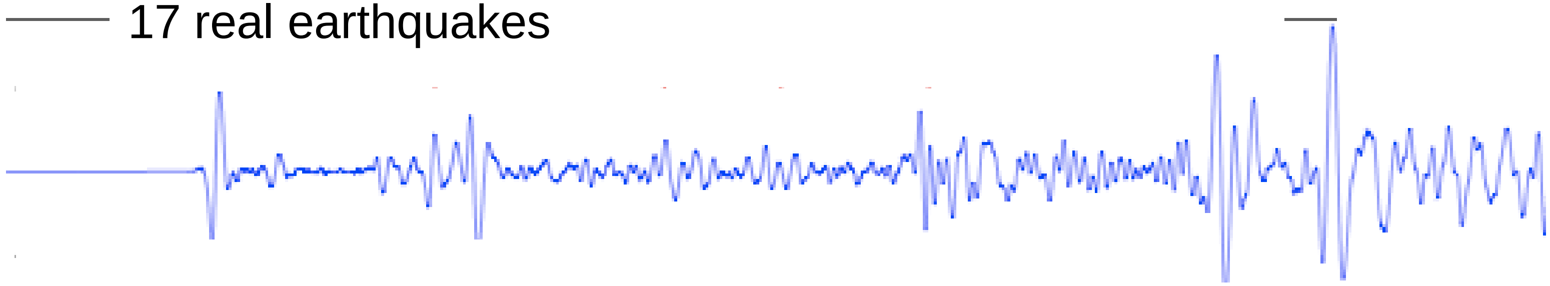


at 50 km depth

## Global Event Distribution

17 real earthquakes



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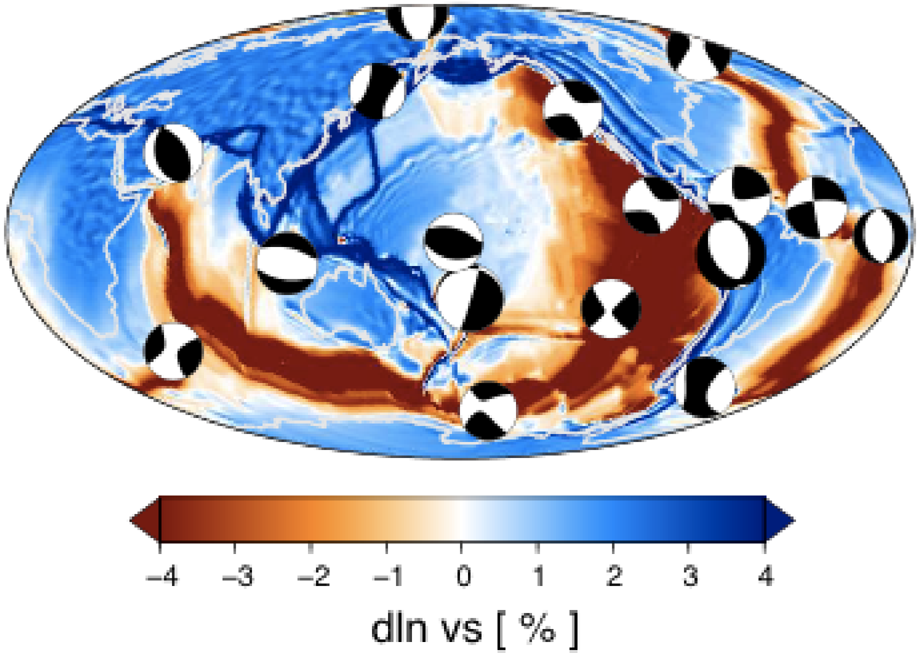
## lobal Event Distribution

7 real earthquakes

## omogeneous data coverage

2250 equidistant virtual stations

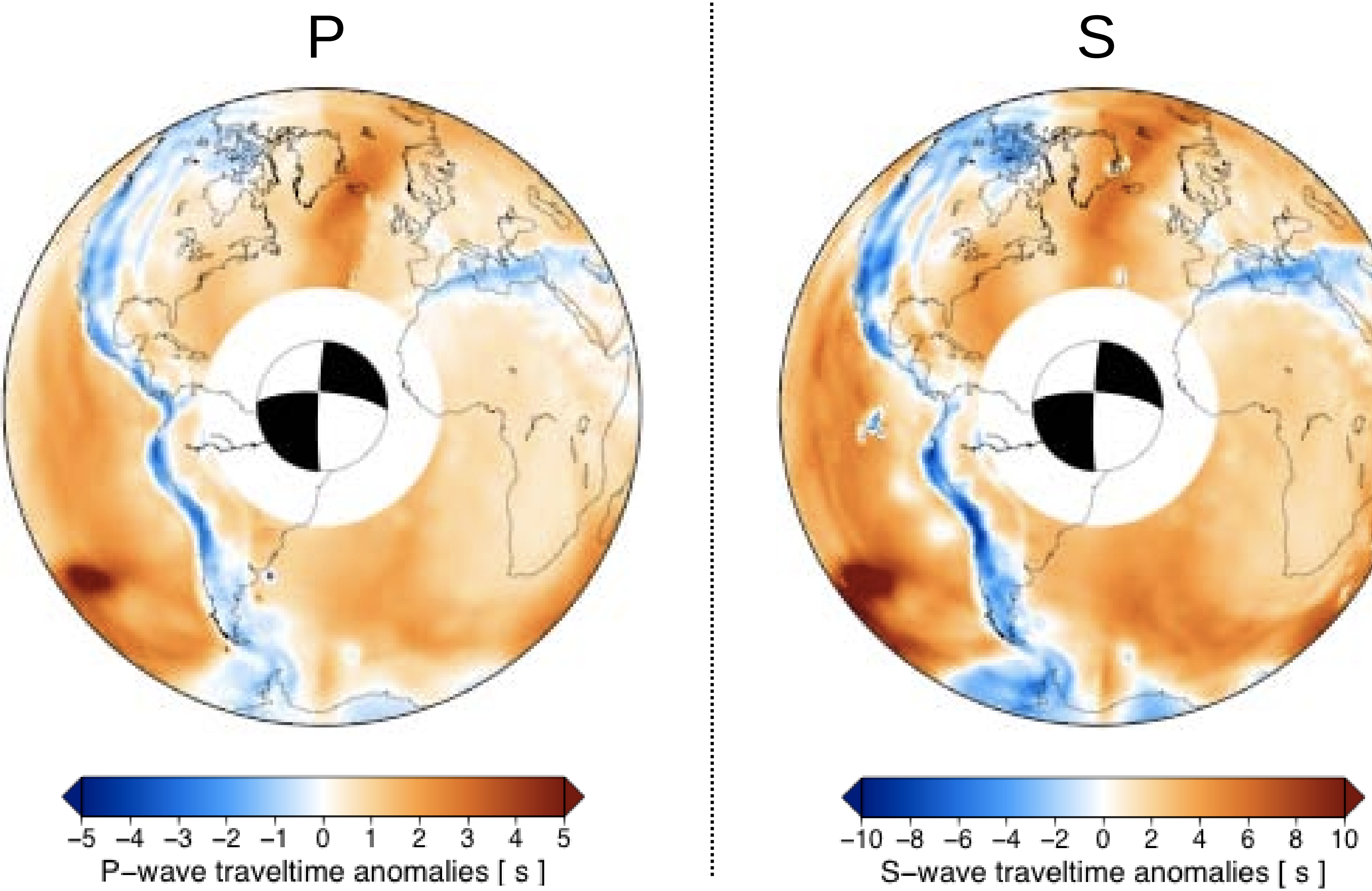


at 50 km depth

~700,000 P- and S-wave measurements

Schuberth et al. 2012

# Traveltime Variations at 15 s Period



Schuberth et al. 2012

# Long-Period Body-Wave Data

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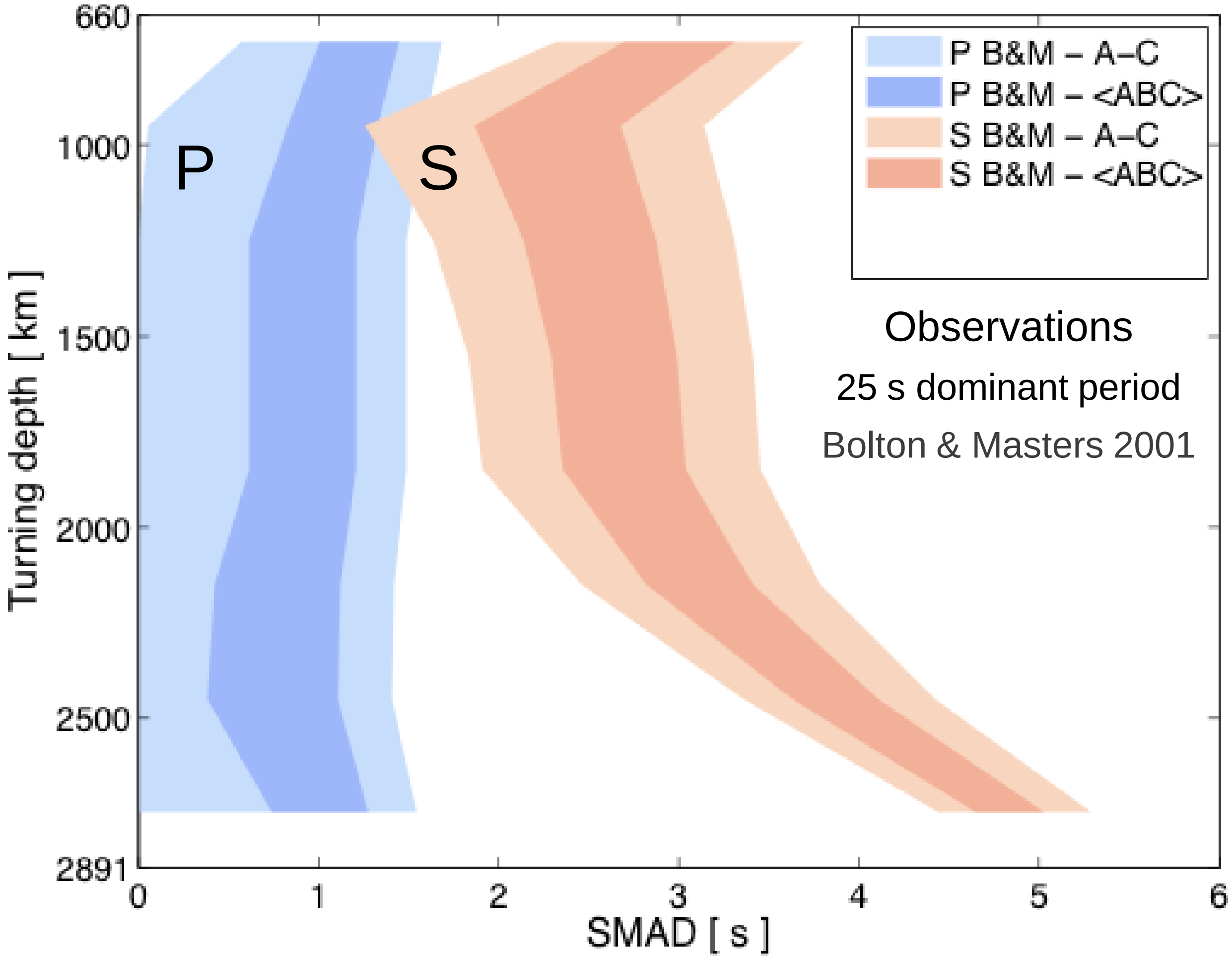

Observations

25 s dominant period

Bolton & Masters 2001

Schuberth et al. 2012

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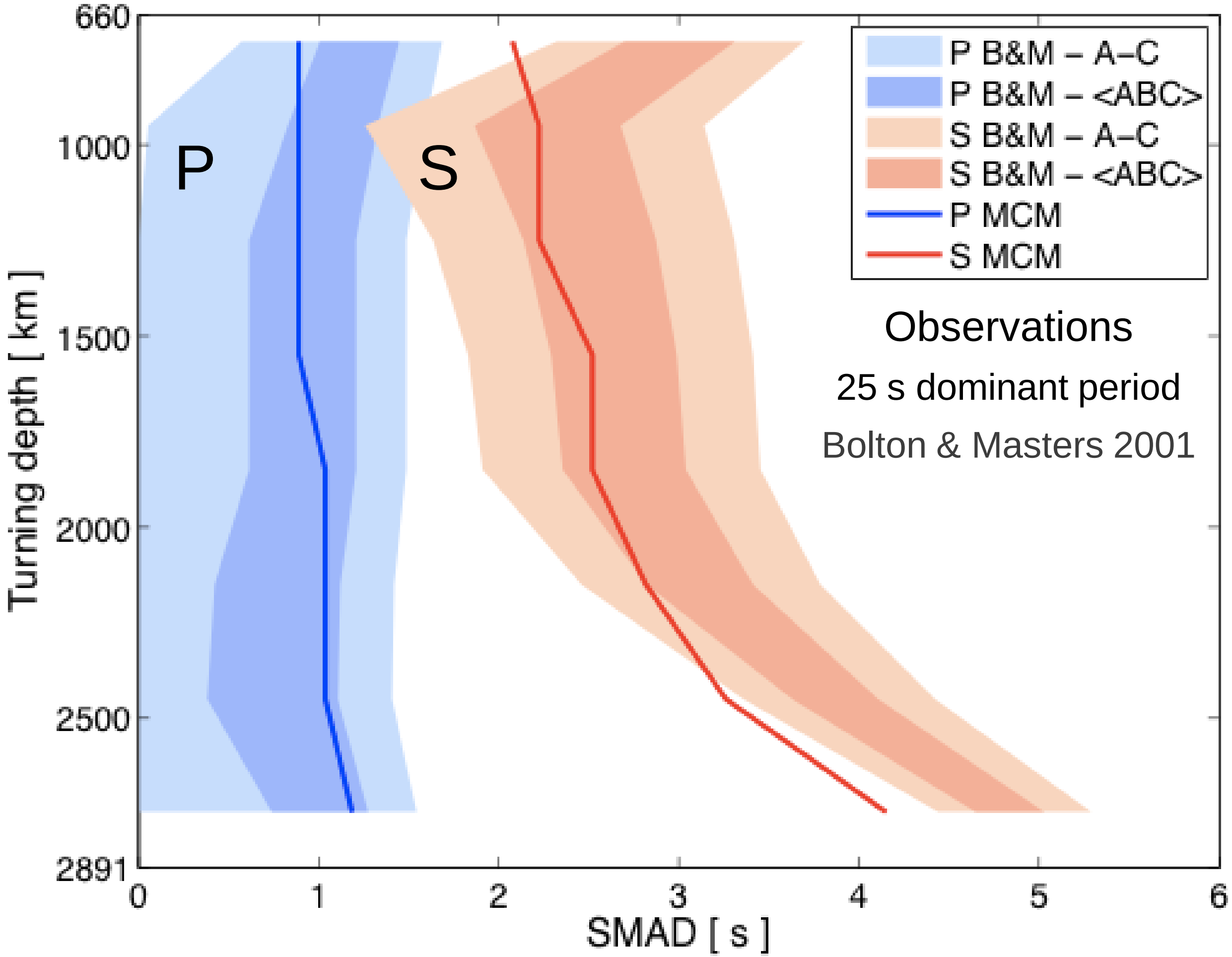

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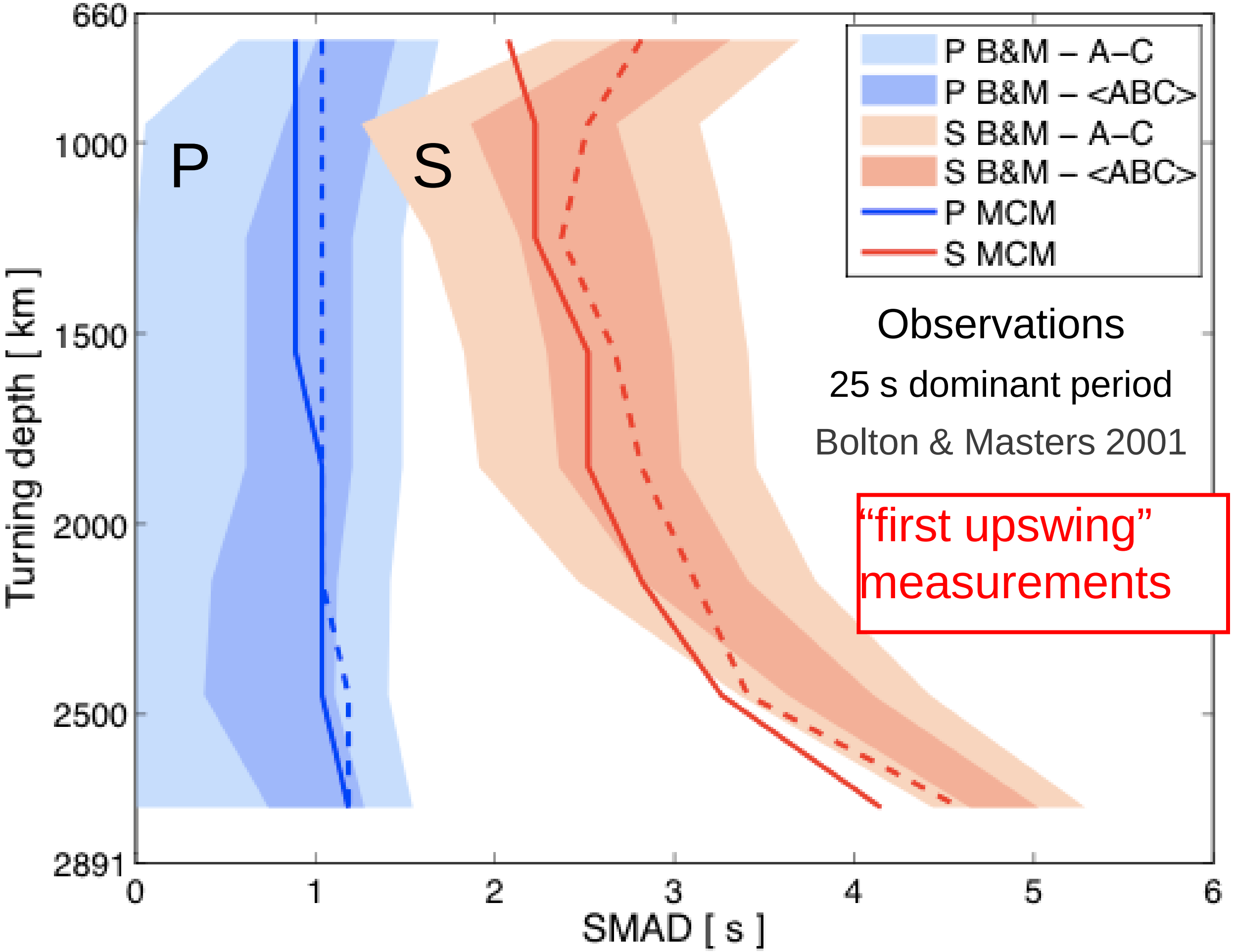

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“first upswing” measurements

Schuberth et al. 2012

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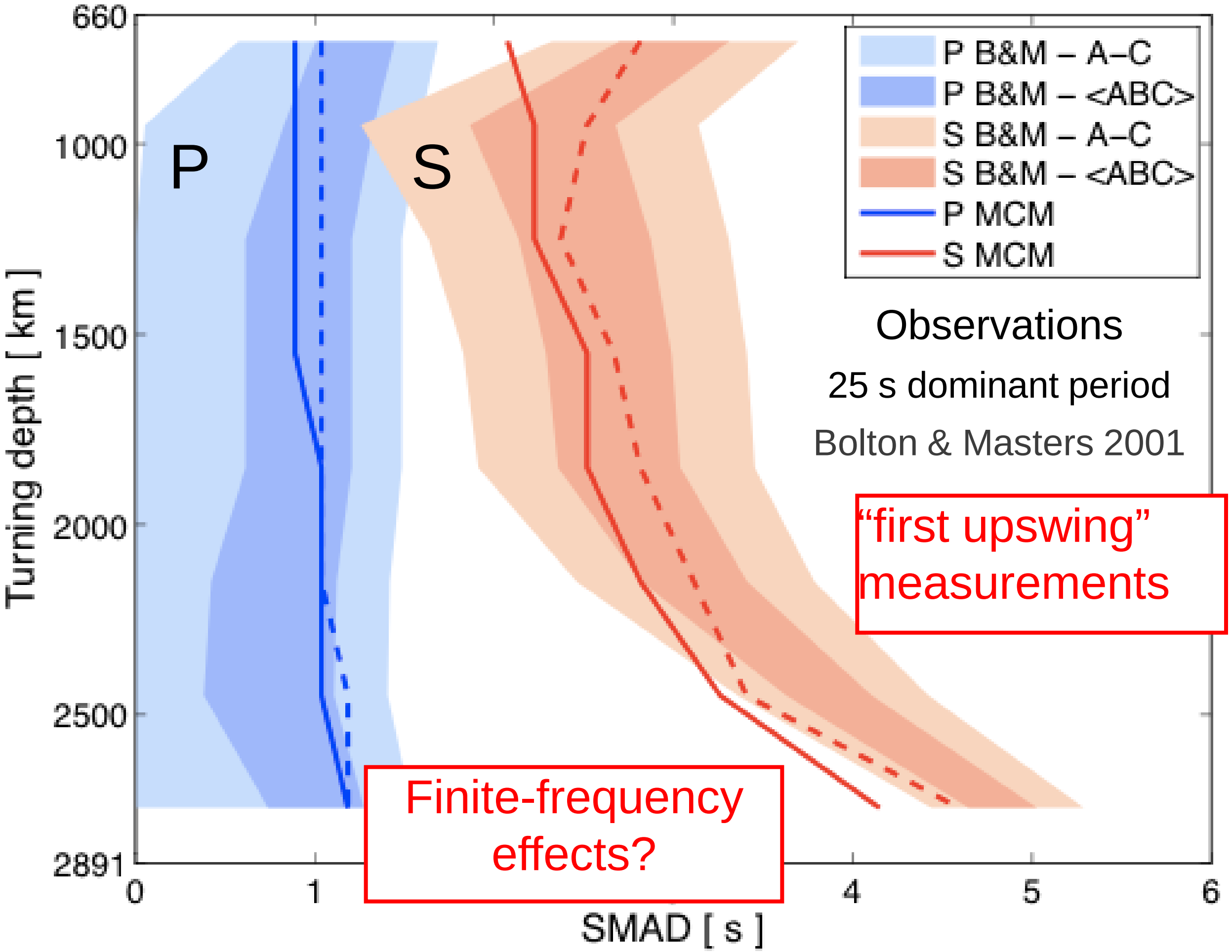

Observations

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Finite-frequency effects?

Schuberth et al. 2012

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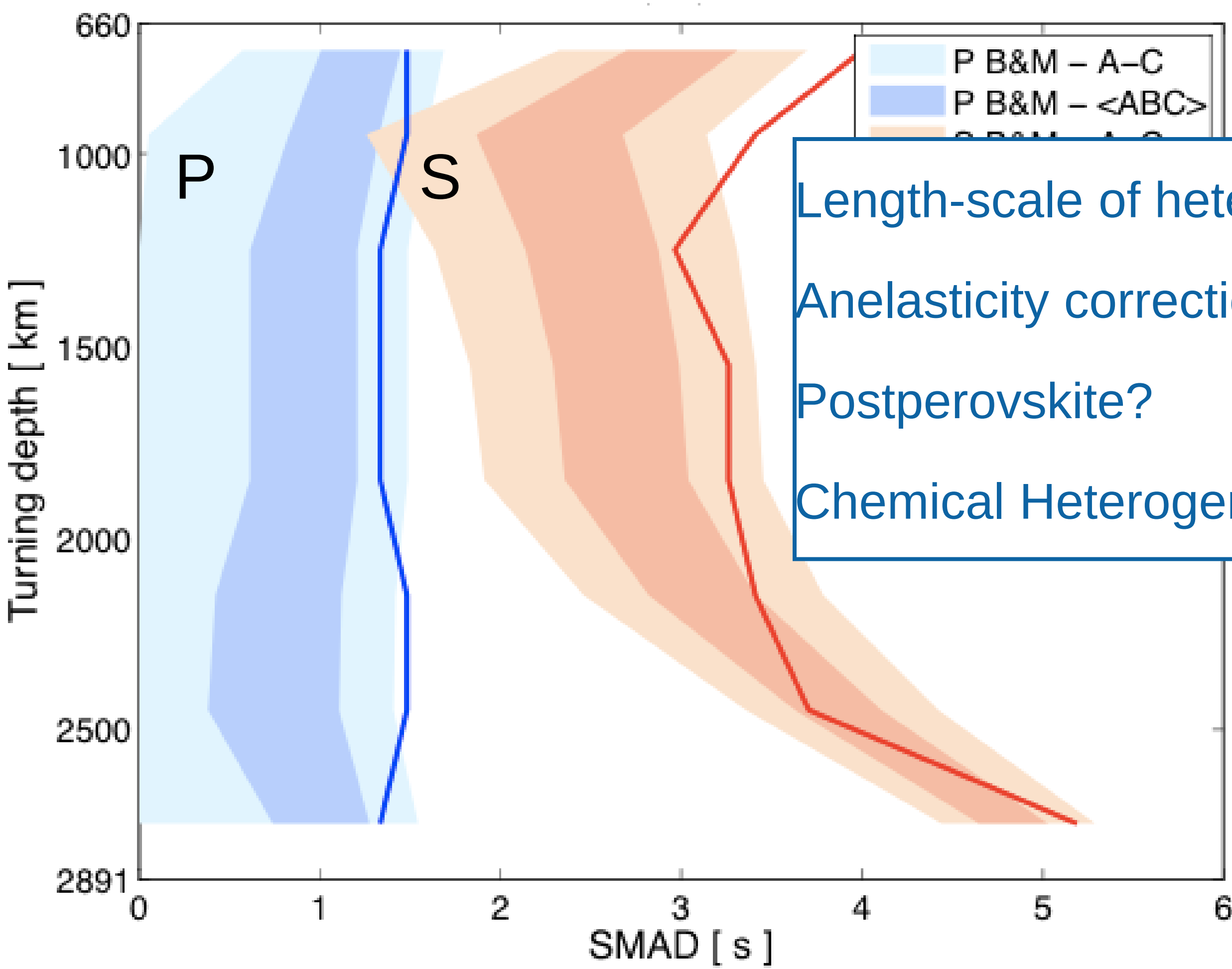

Length-scale of heterogeneity?

Anelasticity correction?

Postperovskite?

Chemical Heterogeneity?

Schuberth et al. 2012

# Summary

- A novel joint modeling approach
- Mantle flow + Mineral physics + 3-D seismic wave propagation

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- Long-period P- and S-wave traveltime variations can be explained by temperature alone

- Chemical heterogeneity is undoubtedly important in the mantle,
- but the seismic body-wave data do not <u>require</u> it on large-scales

# Outlook

- Short-scale versus large-scale heterogeneity?
- Better understanding of wavefield effects

- Study all available data
- Check MCMs against normal mode observations

- Large-Low-Shear-Velocity Provinces
- How robust is the density-Vs anti-correlation
- Morphology and relation to Ultra-Low-Velocity Zones?
- Role of thermal boundary layer?

- Improve tomographic resolution and robustness

- Use the joint forward-modeling approach as a complementary tool to test geodynamic hypotheses