Origin and dynamical consequences of heterogeneity in Earth's mantle

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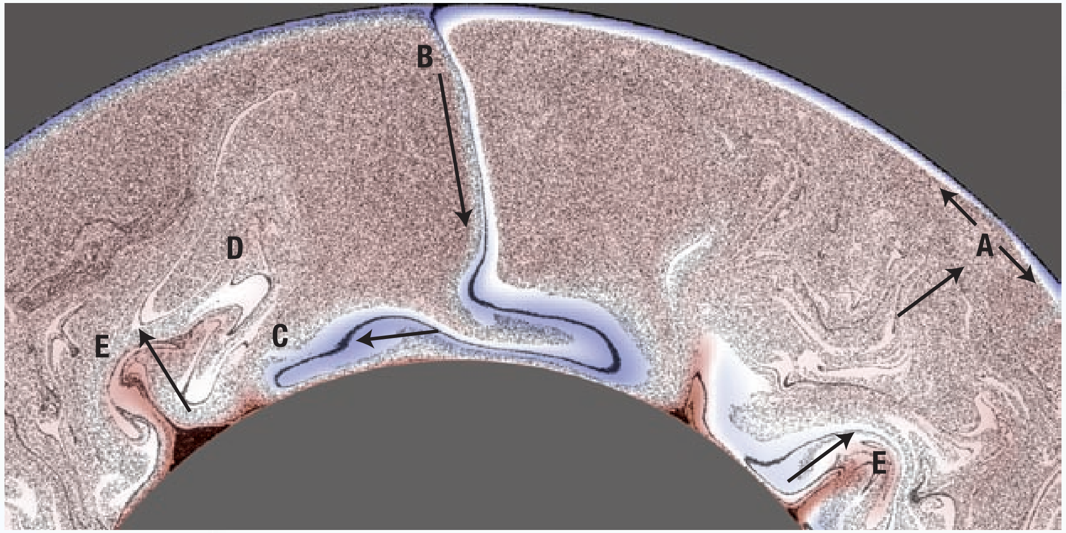
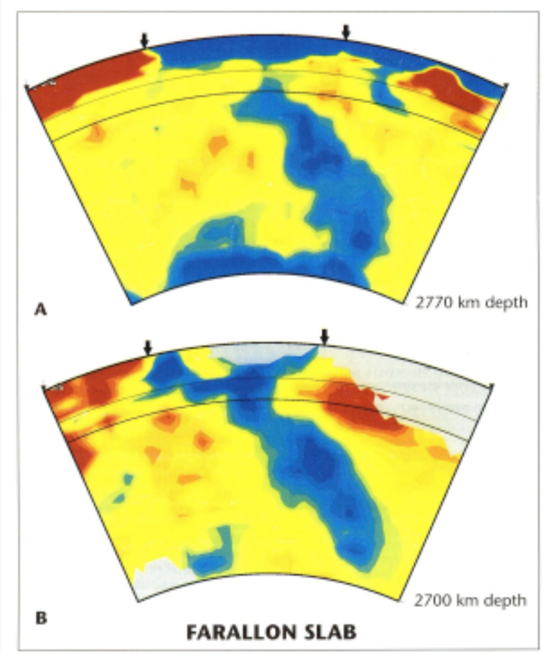
How to relate these two pictures?



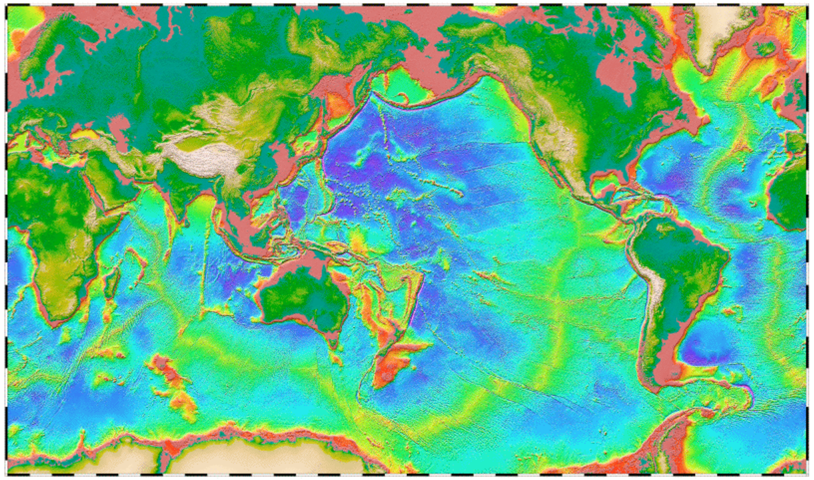
Brandenburg and van Keken, 2007



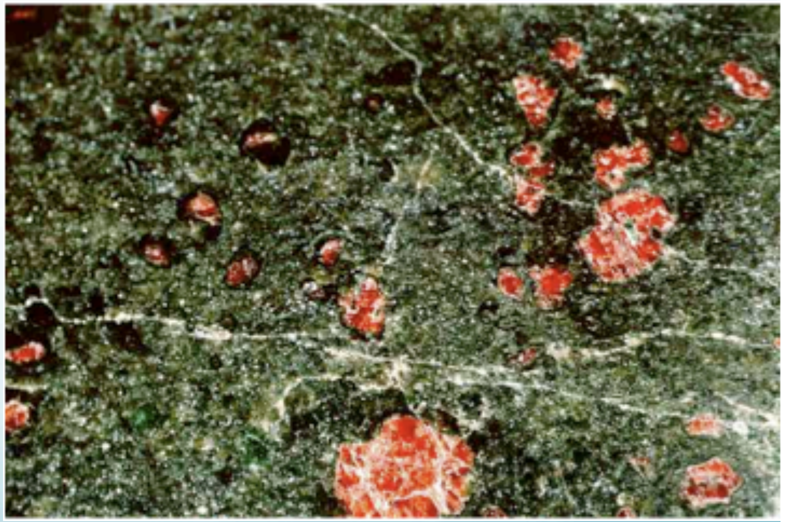
Grand et al., 1997

- Understand two separate but **interrelated** questions:
  - What is the origin of heterogeneity?
  - What do seismic anomalies mean?

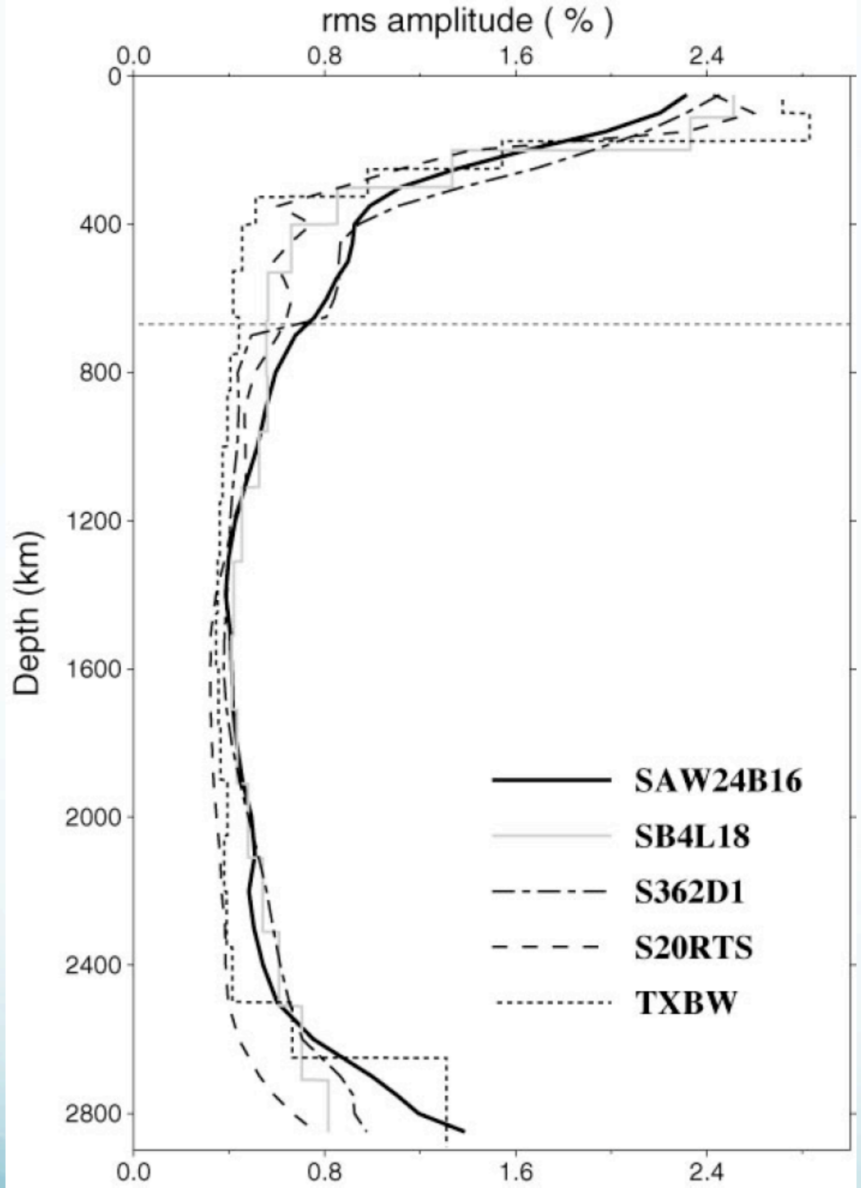
Heterogeneity on many scales

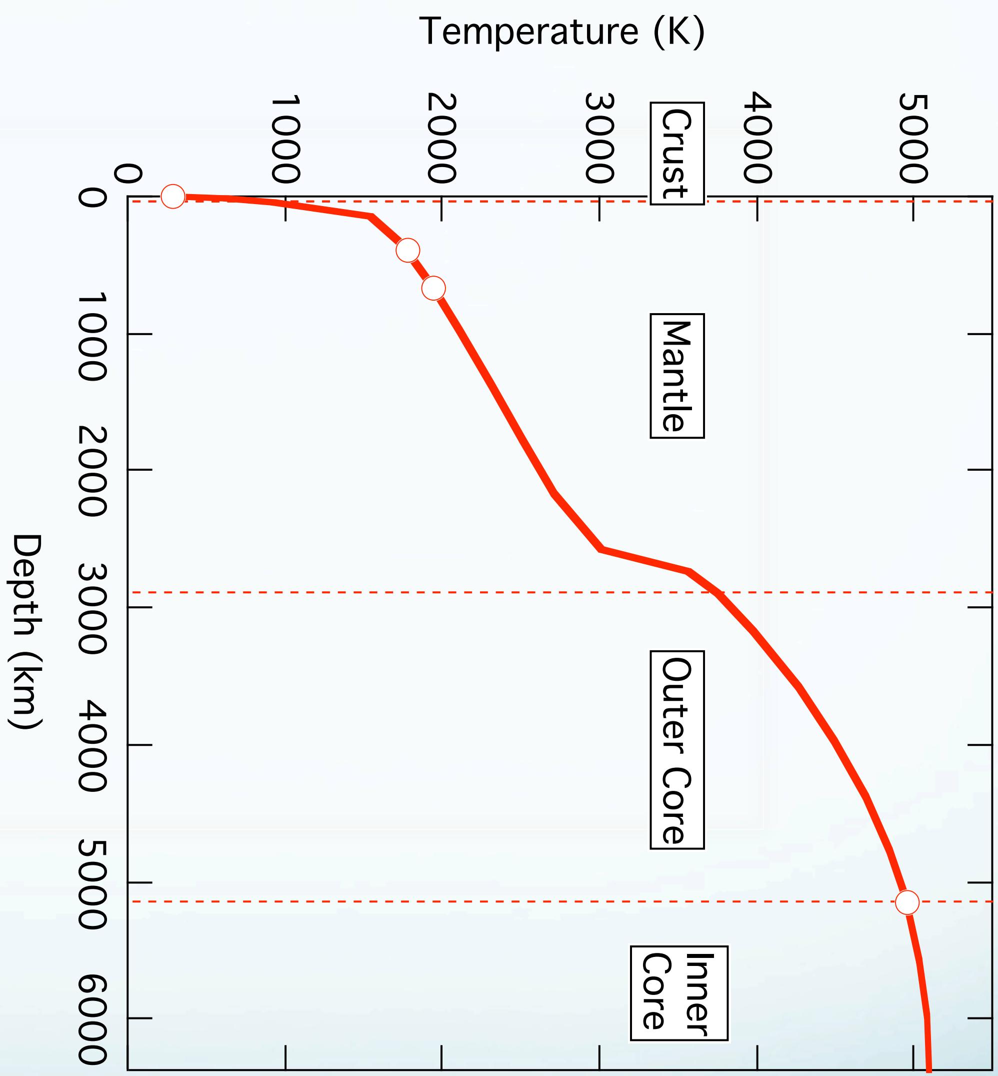


- Equilibrium thermodynamics of multi-component systems
- Differentiation
- Affects physical properties



What might we expect dynamically?



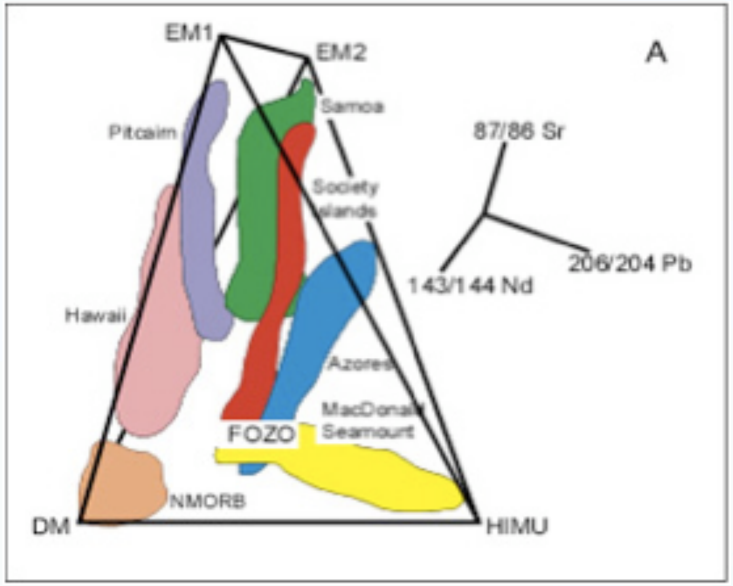


Romanowicz, 2003, Ann. Rev. EPS

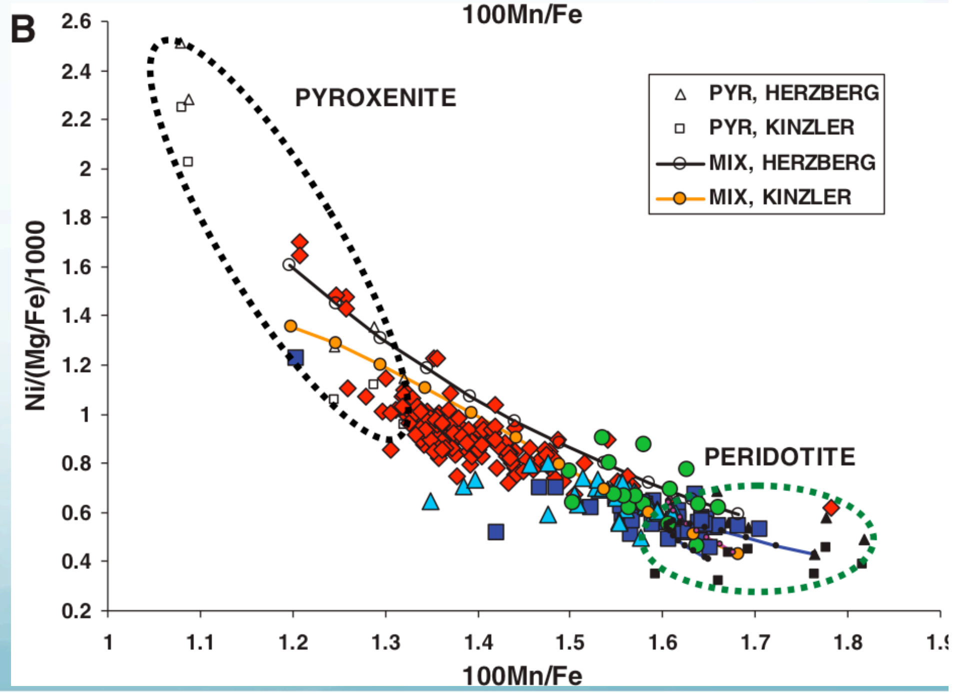
Geochemical Signatures

- Mantle geochemical reservoirs
- Trace elements
- Isotopic abundances
- Information on geometry of reservoirs is limited
- Major elements?
  - pyroxenite signature from subducted crust
  - 2-20% recycled crust involved in melting

Hart et al. (1992) Science

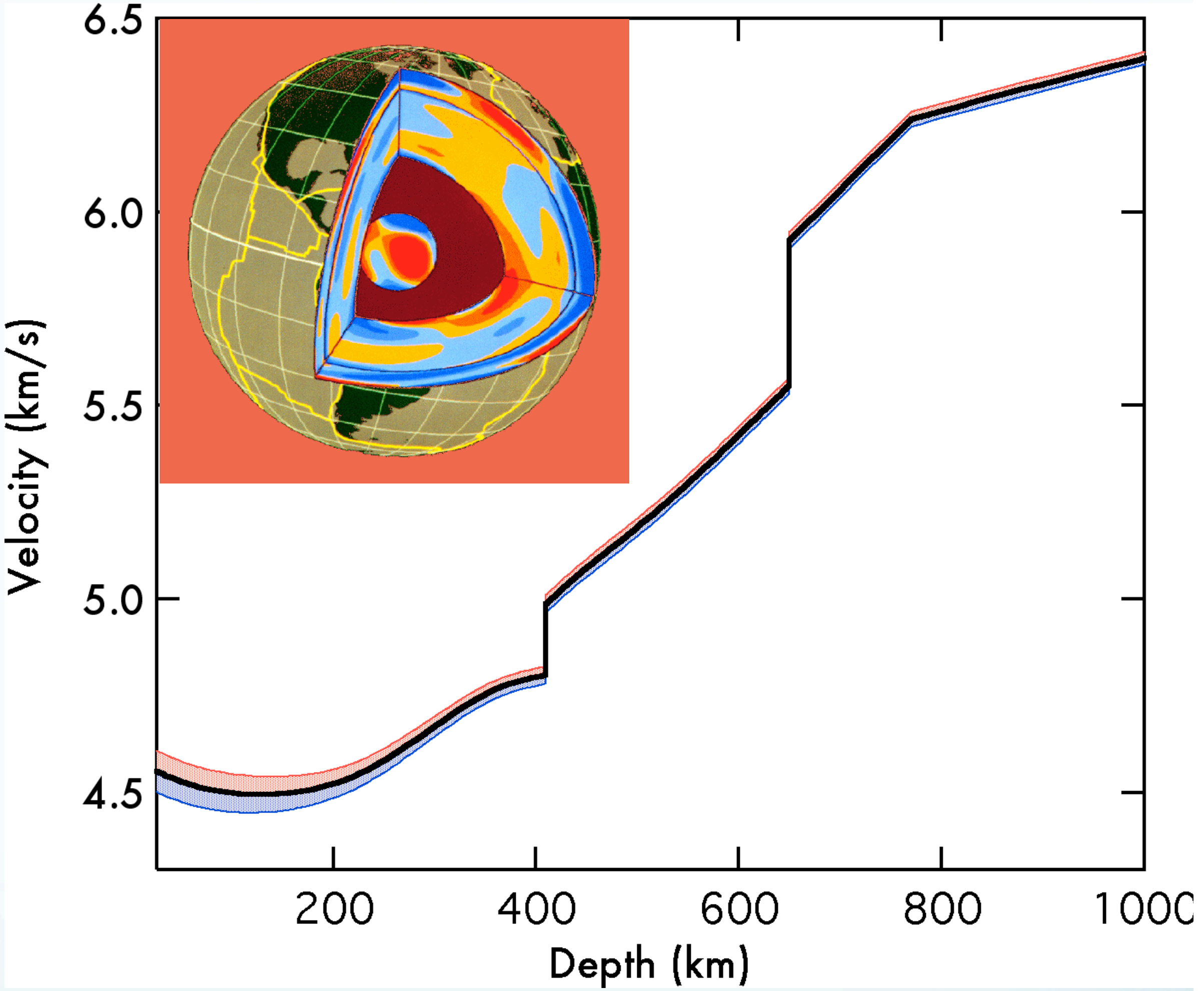


Sobolev et al. (2007) Science



Seismic Signatures

- Radial and lateral variations in seismic wave velocity and density require:
- Radial and lateral inhomogeneities in entropy, bulk composition, phase
- Link through mineralogical models

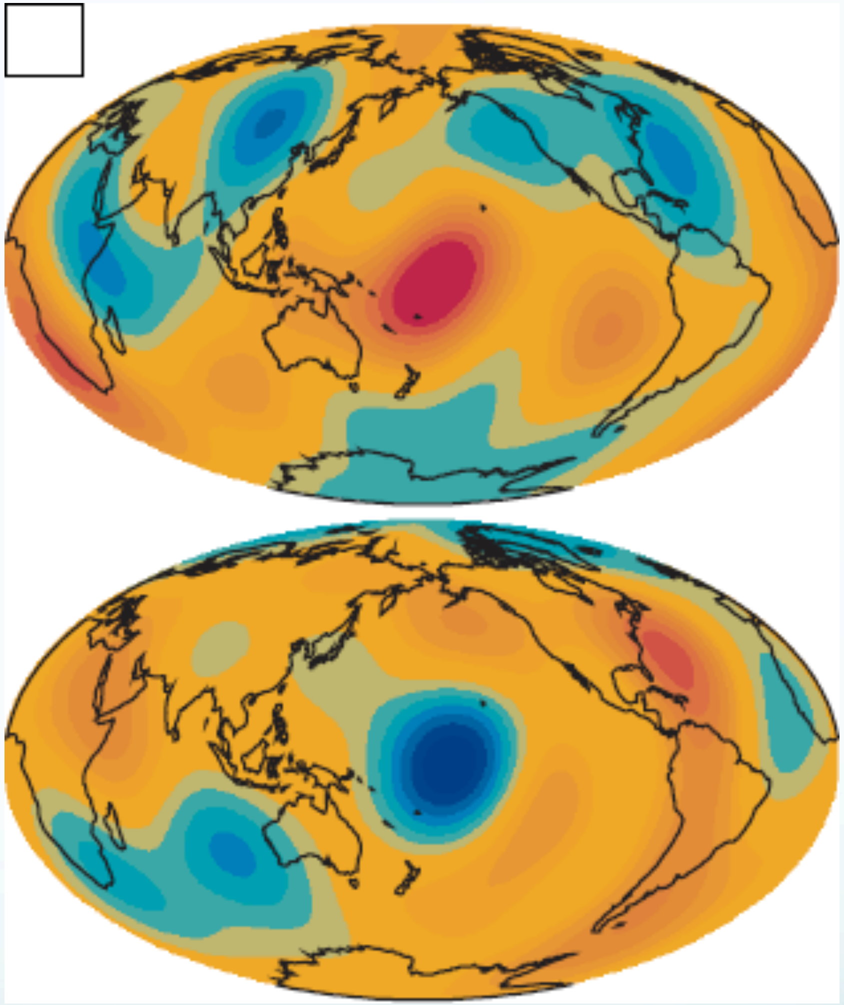


Dziewonski (1986); Kustowski et al. (2008); Romanowicz (2003)

Compositional Heterogeneity

Ishii & Tromp, 1999

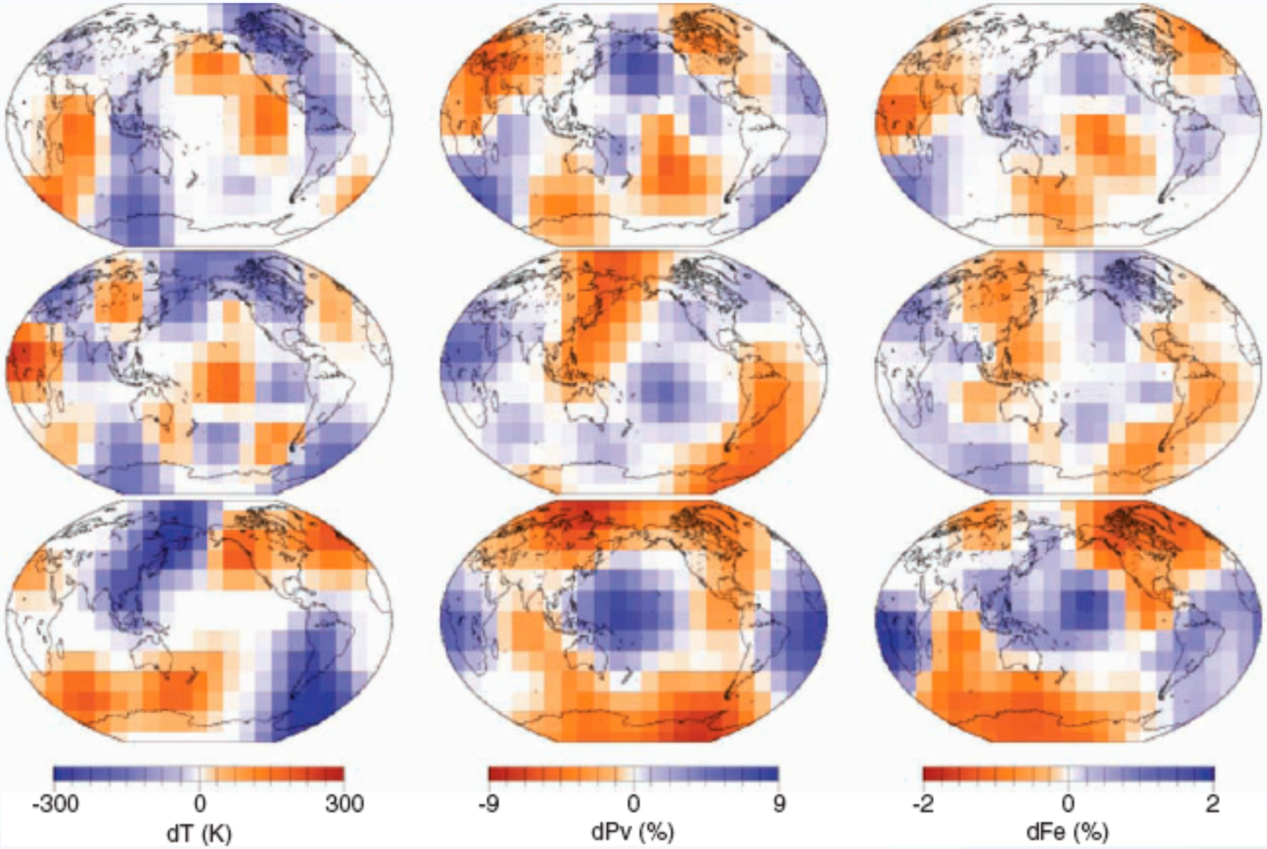
- Lateral variations in shear and bulk sound velocity may be anti-correlated in the lowermost mantle
- This cannot be caused by lateral variations in temperature alone
- Observational probes of the deep Earth are limited
- Geophysics: limited information of temperature or composition
- Geochemistry: limited spatial information



Compositional Heterogeneity

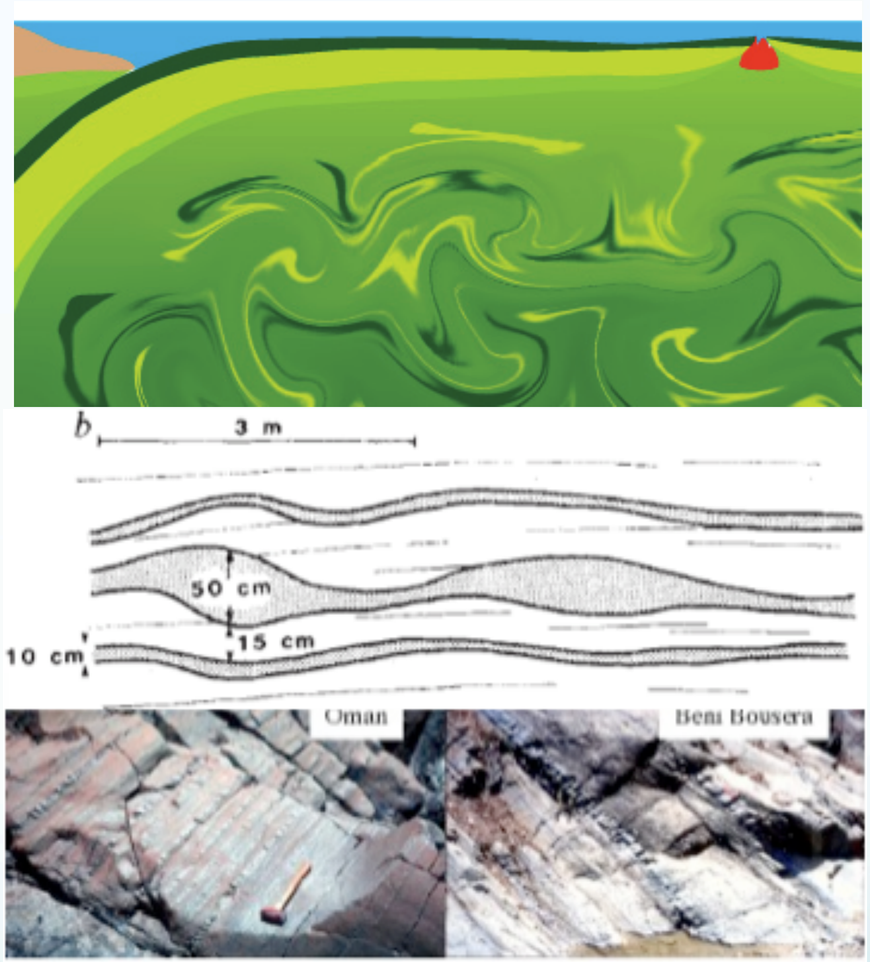
- Studies as lateral variations in major elements independent of each other Si/Mg; Fe/Fe+Mg ratios
- No clear connection to genetic process

Trampert et al. (2004)



Production of Heterogeneity

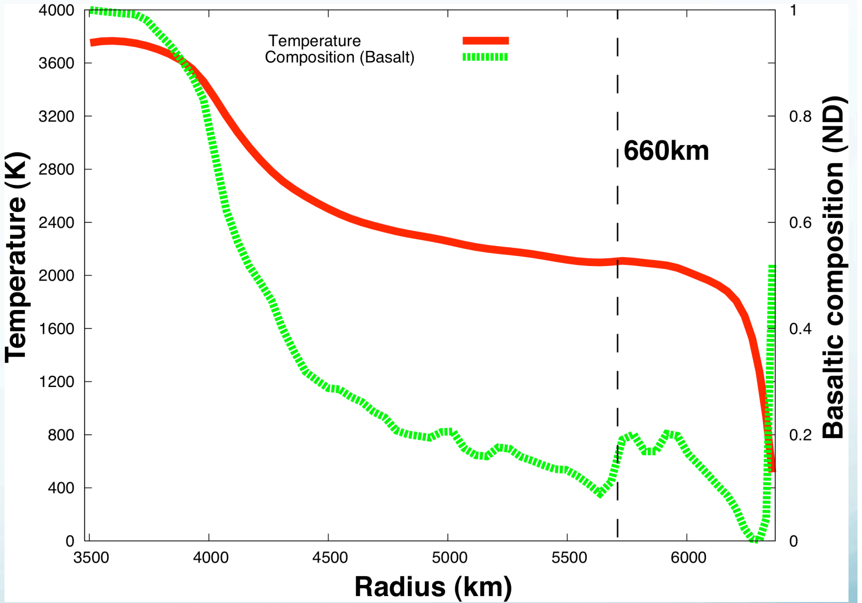
- Melting...
  - Dominant source of surface heterogeneity over Earth's history
  - Mass equal to that of the mantle processed through ridge at least once
  - Heterogeneity likely survives for long periods
  - Subduction returns differentiated products continuously to the mantle
- Other sources of heterogeneity
  - Continents?
  - Deep melting?
  - Accretion?



Xu et al. (2008) EPSL; Allegre & Turcotte (1986); Nature, Stolper

Major Element Chemical Geodynamics

- Notion of subducted heterogeneity originally motivated by trace element and isotopic geochemistry
- Notion has important implications for structure
- Major elements are seismically visible
- Potential to map geochemical reservoirs

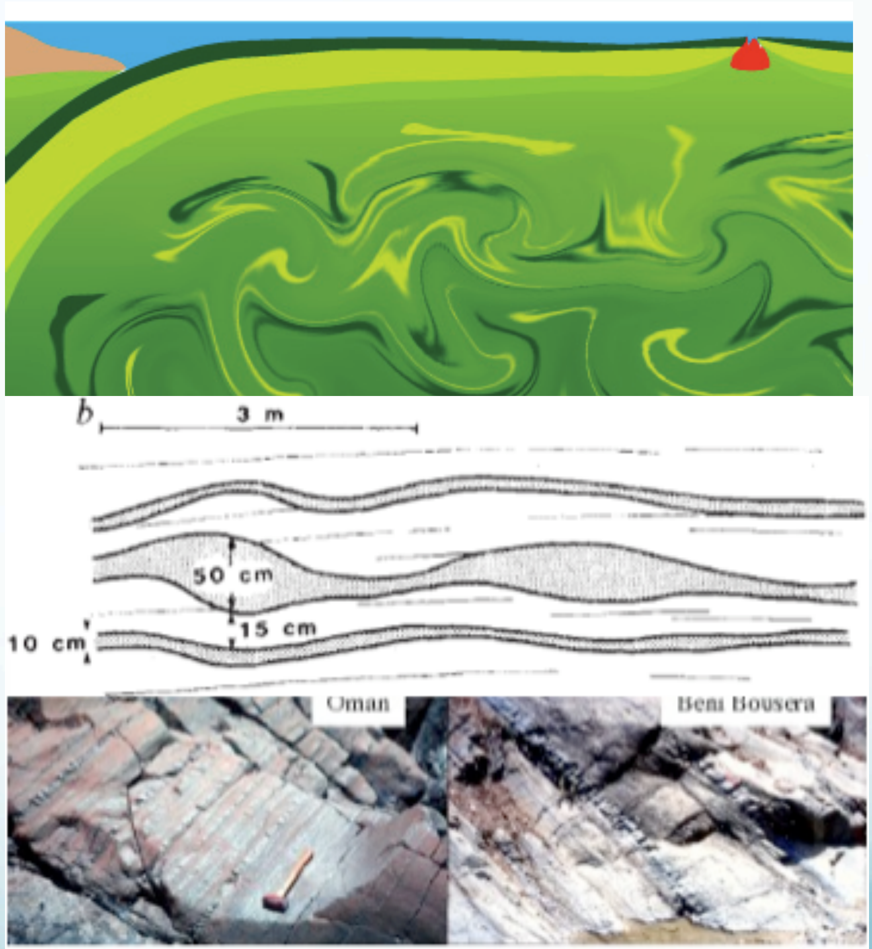


Christensen & Hofmann (1994) JGR
Nakagawa & Buffett (2005) EPSL

Models of Mantle Lithology

- Basalt depletion is a natural compositional metric
- Components co-vary along the harzburgite-basalt join
- Scale length of heterogeneity

- Equilibrium Assemblage (EA)
  - Complete re-equilibration between basalt and harzburgite
- Mechanical mixture (MM)
  - Perfect dis-equilibrium between basalt and harzburgite
- Compare at same bulk composition f_{basalt}=18 %
  - reasonable f~12-20% compared to subducted flux (Xu et al. 2006, Morgan and Morgan, 1999)



Xu et al. (2008) EPSL; Allegre & Turcotte, (1986); Nature; Stolper

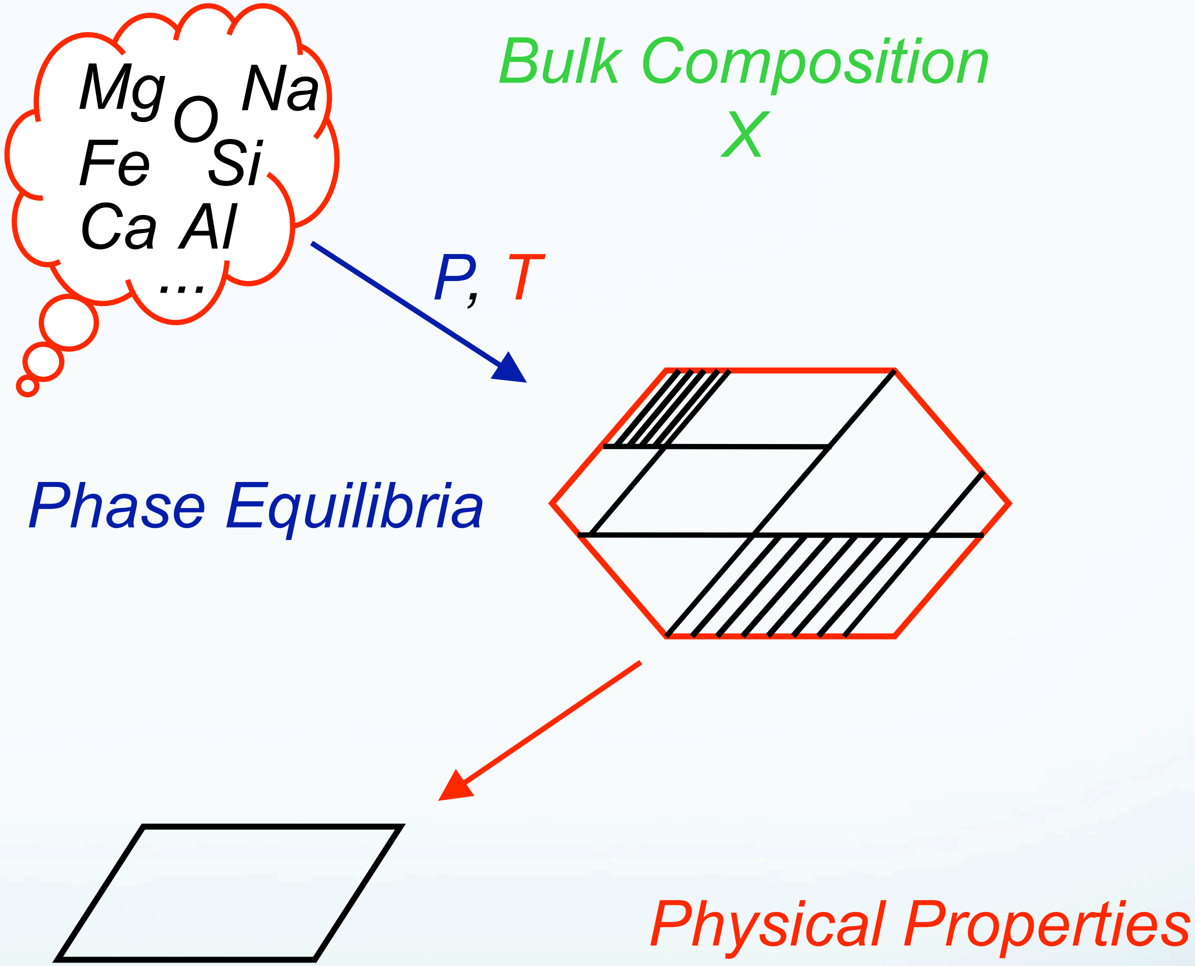
Thermodynamic Model

Stixrude and Lithgow-Bertelloni (2005) GJI

- Bulk composition
- Pressure
- Temperature

⇩

- Phase Equilibria
- Physical Properties
- Self consistent



$\rho, \alpha, C_P, V_P, V_S, \ldots \quad (X, P, T)$

HeFESTo

- Based on Fundamental Thermodynamic Relations
- Minimize Gibbs free energy over the amounts of all species n_i

$$G(P,T,n_i) = \sum_{i=1}^{species} n_i\left[\mu_{0i}(P,T) + RT\ln a_i\right]$$

- Subject to constraint of fixed bulk composition

$$s_{ij}n_j = b_i$$

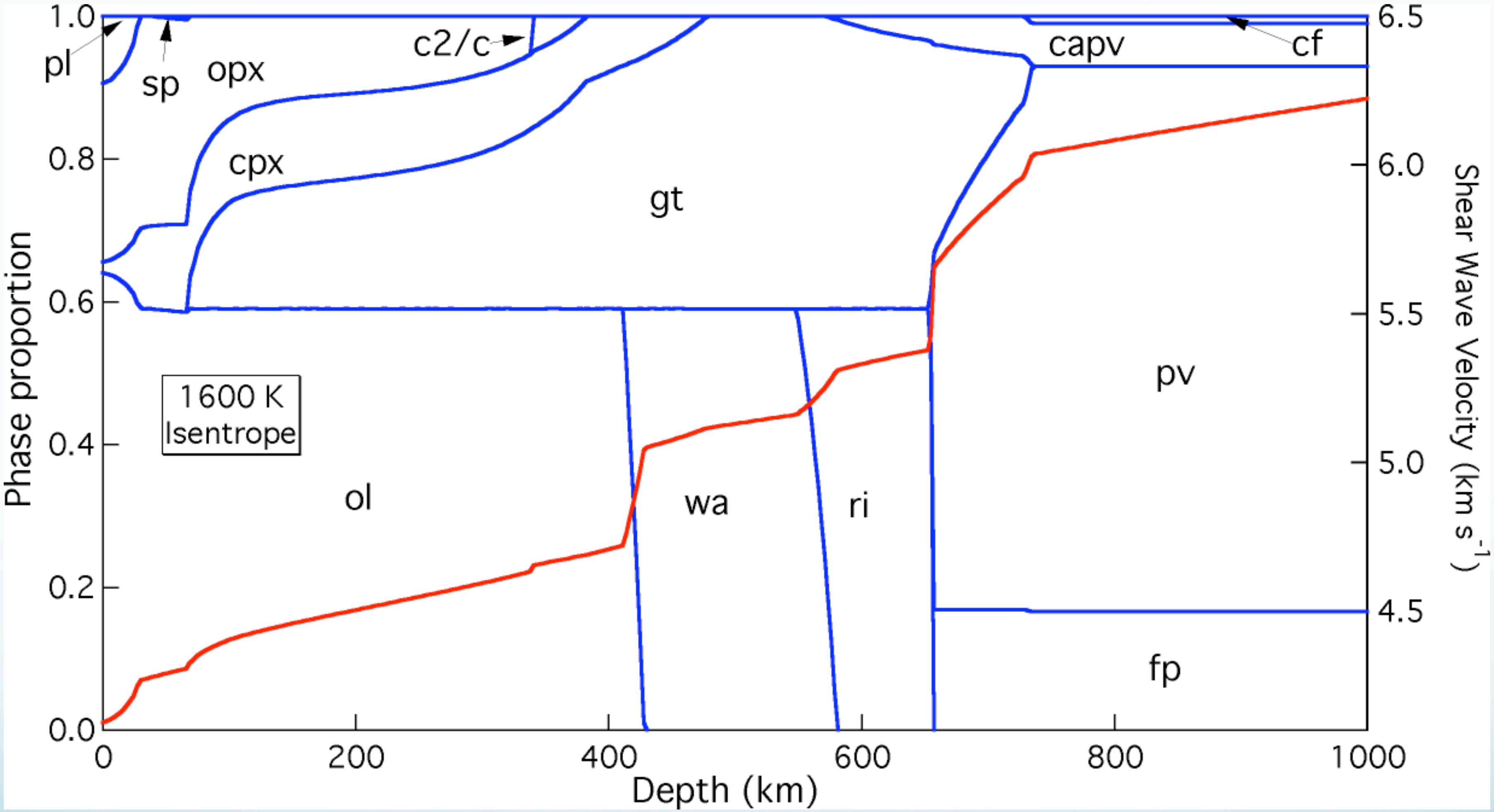
- Full Anisotropic Generalization

$$c_{ijkl} = \frac{1}{V}\left(\frac{\partial^2 F}{\partial E_{ij}\partial E_{kl}}\right)_{S'_{ij},T} + P\left(\delta_{ij}\delta_{kl} + \delta_{il}\delta_{jk} + \delta_{jl}\delta_{ik}\right)$$

- Many previous efforts, however
  - Full self-consistency between phase equilibria and physical properties (not only one or the other)
  - Anisotropic generalization and robust thermal extrapolation for shear properties

Mantle Phases and Velocity

6 components: SiO_2, MgO, FeO, CaO, Al_2O_3, Na_2O, 46 species, 20 phases

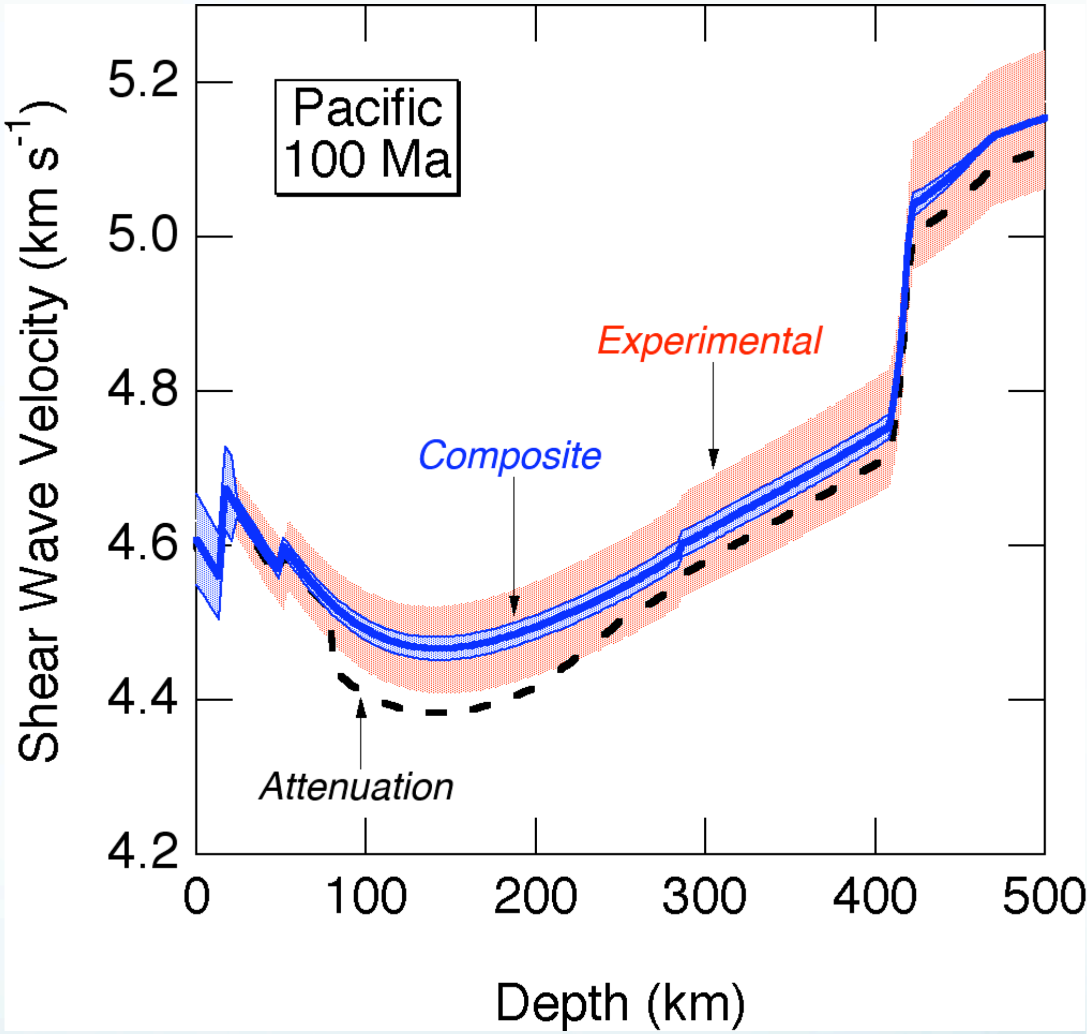


plagioclase (plg); spinel (sp); olivine (ol); orthopyroxene (opx); clinopyroxene (cpx); garnet (gt); wadsleyite (wa); ringwoodite (ri); akimotoite (ak); Mg-perovskite (mgpv); Ca-perovskite (capv); ferropericlase (fp); Calcium-Ferrite str. (cf)

Xu et al. (2008) EPSL

Scaling in Space and Time

- Space
  - Wavelength of seismic wave greater than scale length of heterogeneity
  - Velocity bounded by assumption of uniform stress/strain (Reuss/Voigt)
- Time
  - Attenuation: $Q^{-1}(P,T,\omega)$
  - Velocity depends on frequency (dispersion)
  - Use seismological Q models
  - Assume passage of seismic wave sufficiently rapid that it induces no phase transformation



$$M_R^* = \left(\sum_\alpha \frac{\phi^\alpha}{M^\alpha}\right)^{-1} < M^* < \sum_\alpha \phi^\alpha M^\alpha = M_V^*$$

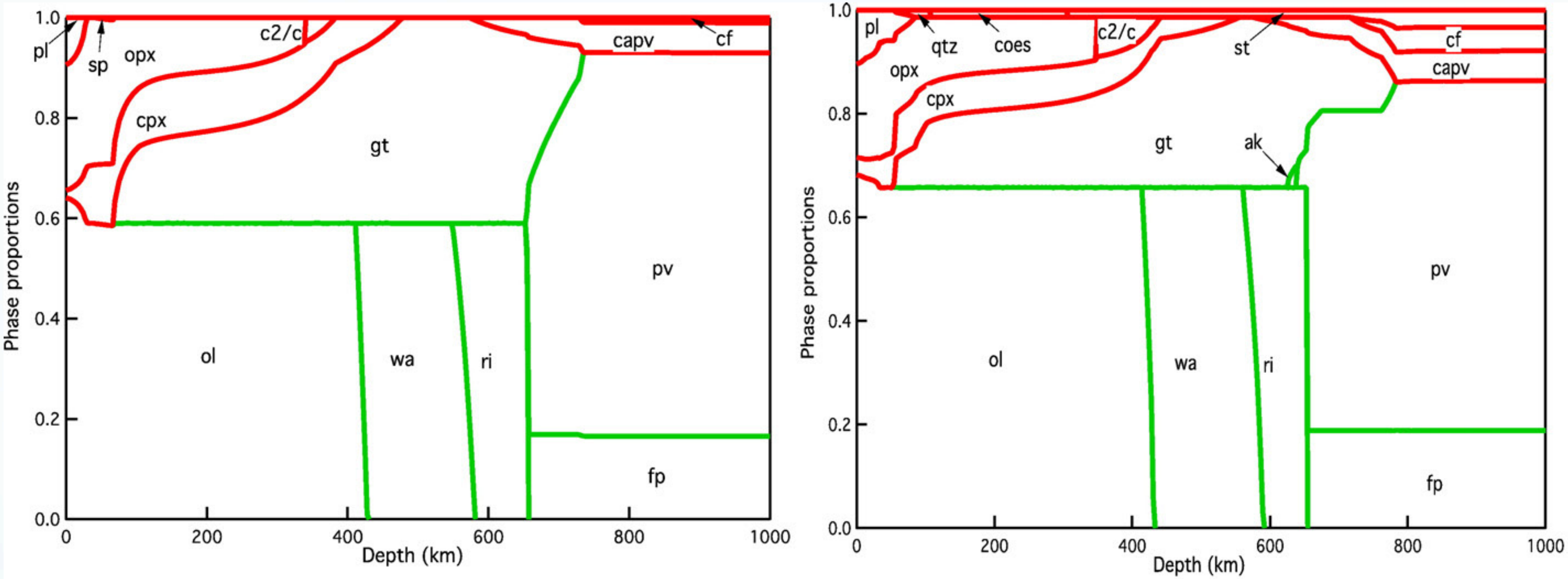
$$\frac{V_S(P,T,X,\omega)}{V_S(P,T,X,\infty)} = 1 - \frac{1}{2}\cot\left(\frac{\pi\alpha}{2}\right)Q^{-1}(P,T,X,\omega)$$

Stixrude & Lithgow-Bertelloni (2005) JGR
Stixrude & Jeanloz (2007) ToG

Phase Diagrams

W. Xu et al. / Earth and Planetary Science Letters 275 (2008) 70–79

Xu et al. (2008)



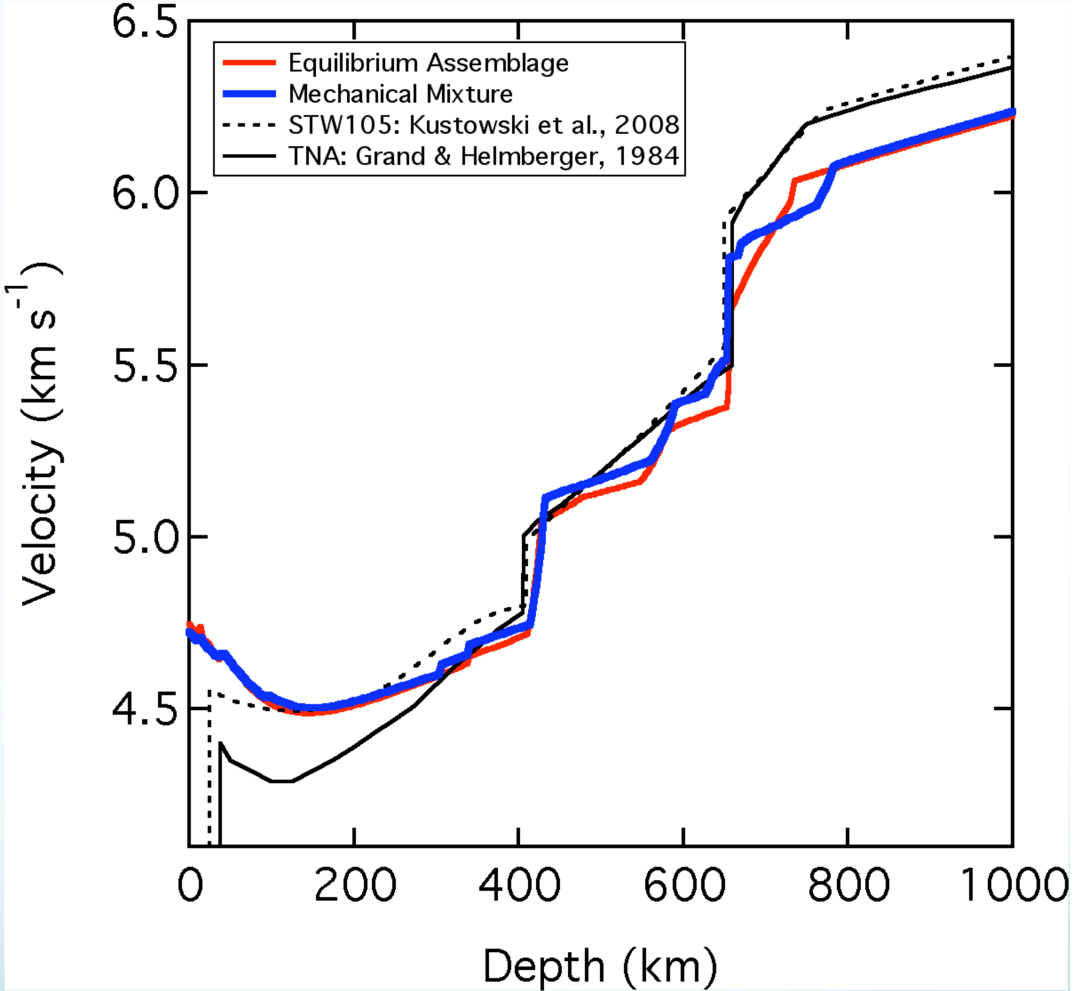
- Bulk Composition (DMM; MORB-Workman and Hart (2005); Harzburgite (modified);
- Larger amount of olivine

Mechanical Mixture

- Velocity differs from EA
  - MM faster
  - MM has higher velocity gradient
  - MM agrees better with seismological models in T-zone
- Why?
- Olivine and silica both faster than pyroxene and garnet

$2MgSiO_3 = Mg_2SiO_4 + SiO_2$

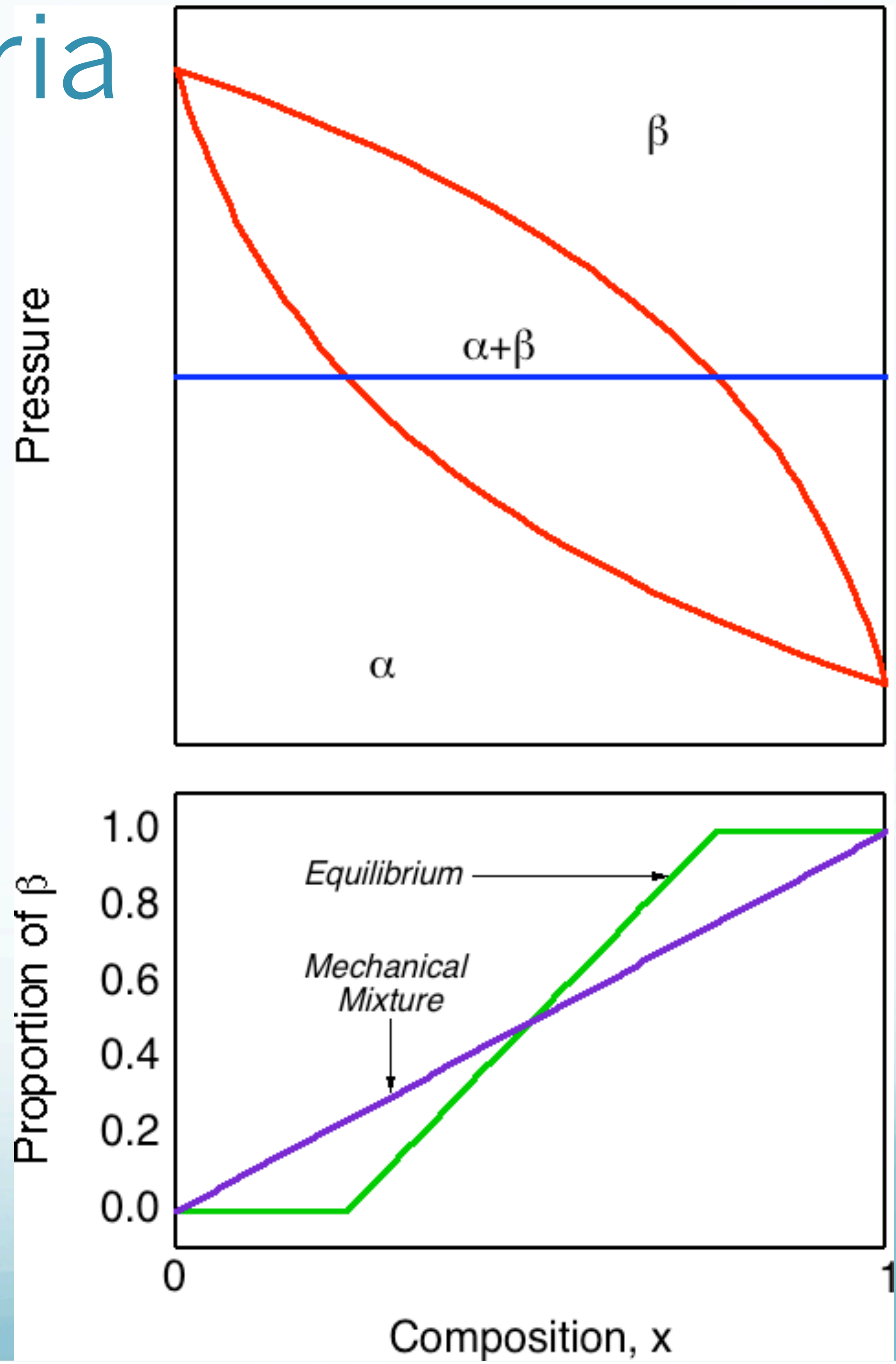
EA Harzburgite Basalt



Xu et al. (2008) EPSL

Phase Equilibria

- Phase equilibria of mechanical mixture differs from that of equilibrium assemblage of the same bulk composition
  - Lever rule
  - Configurational entropy favors solid solution
- Consequences
  - Velocity differs for the same bulk composition
  - Velocity-composition scaling differ

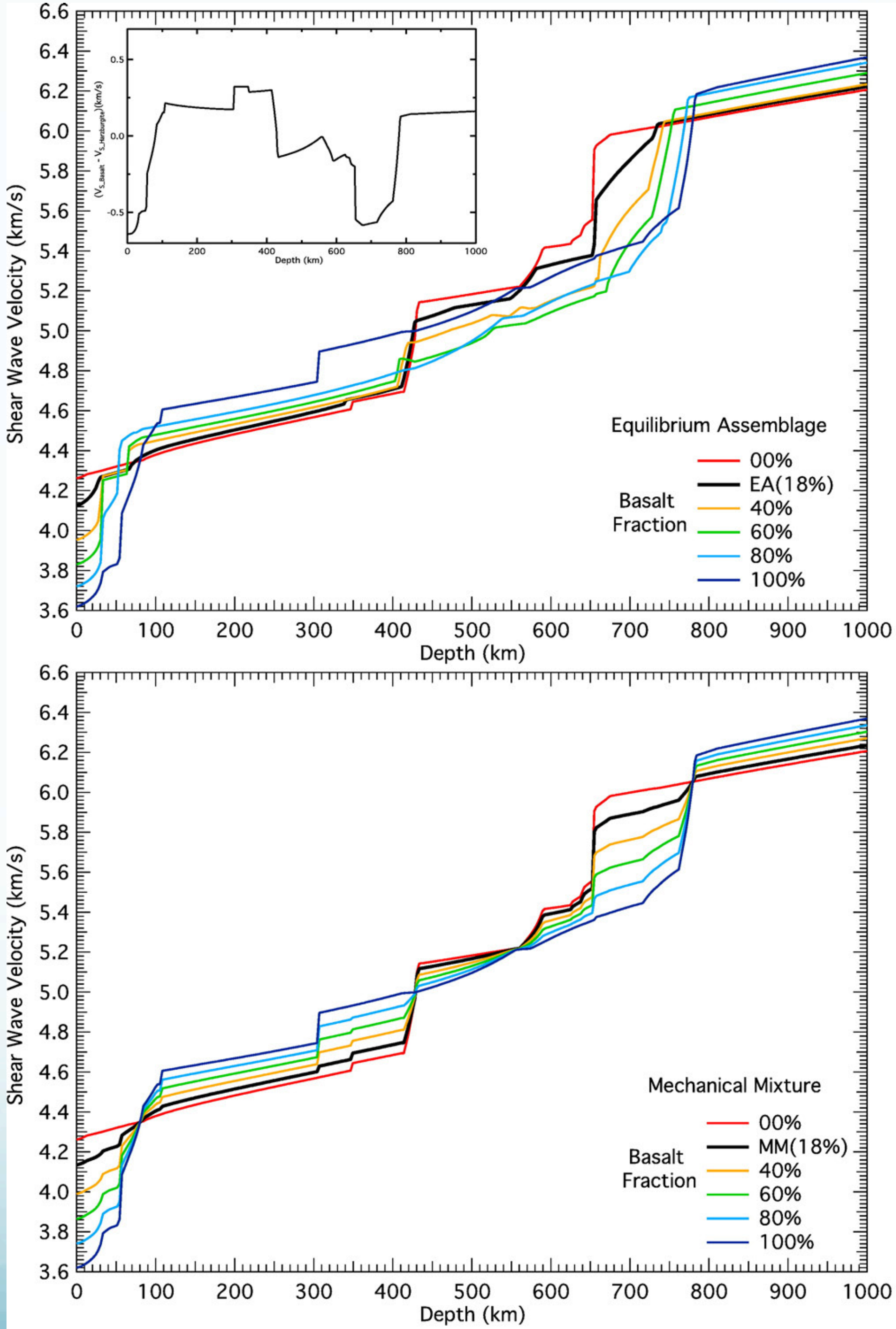


Effects of Composition

- Upper mantle and Lower mantle
  - Velocity depends strongly on basalt fraction
  - Eclogite
  - Ca-perovskite, silica in basalt, no ferropericlase
- Transition zone
  - Little compositional dependence
  - Garnet, wadsleyite, ringwoodite have similar velocities

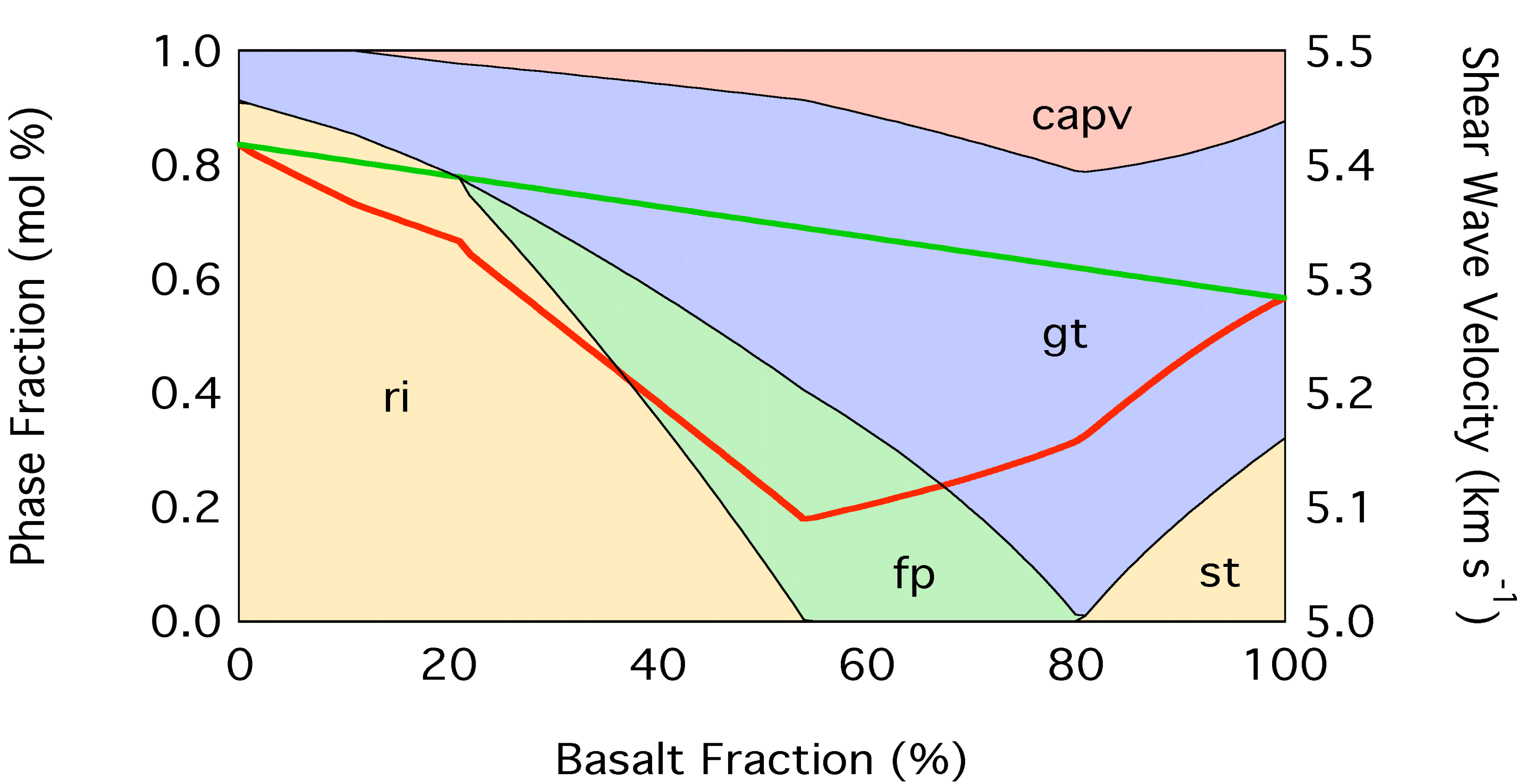
Xu et al. (2008) EPSL

W. Xu et al. / Earth and Planetary Science Letters 275 (2008) 70–79



Mechanical Mixture

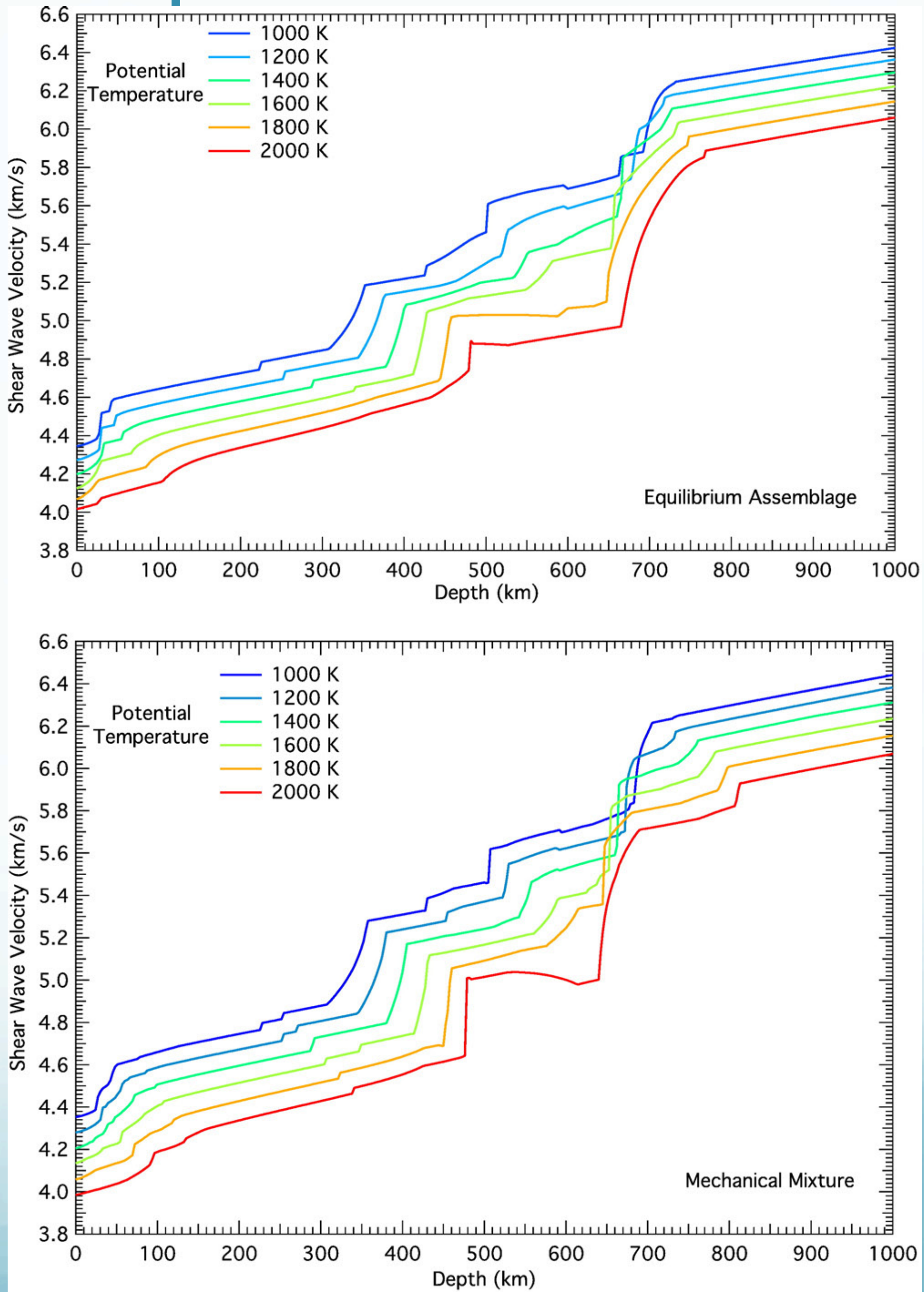
- In MM, transition zone velocity, discontinuity structure depend weakly on basalt fraction



Xu et al. (2008) EPSL

Effects of Temperature

- Transition zone
  - Depth of discontinuities
  - Complex 660 and 520 (disappearance)

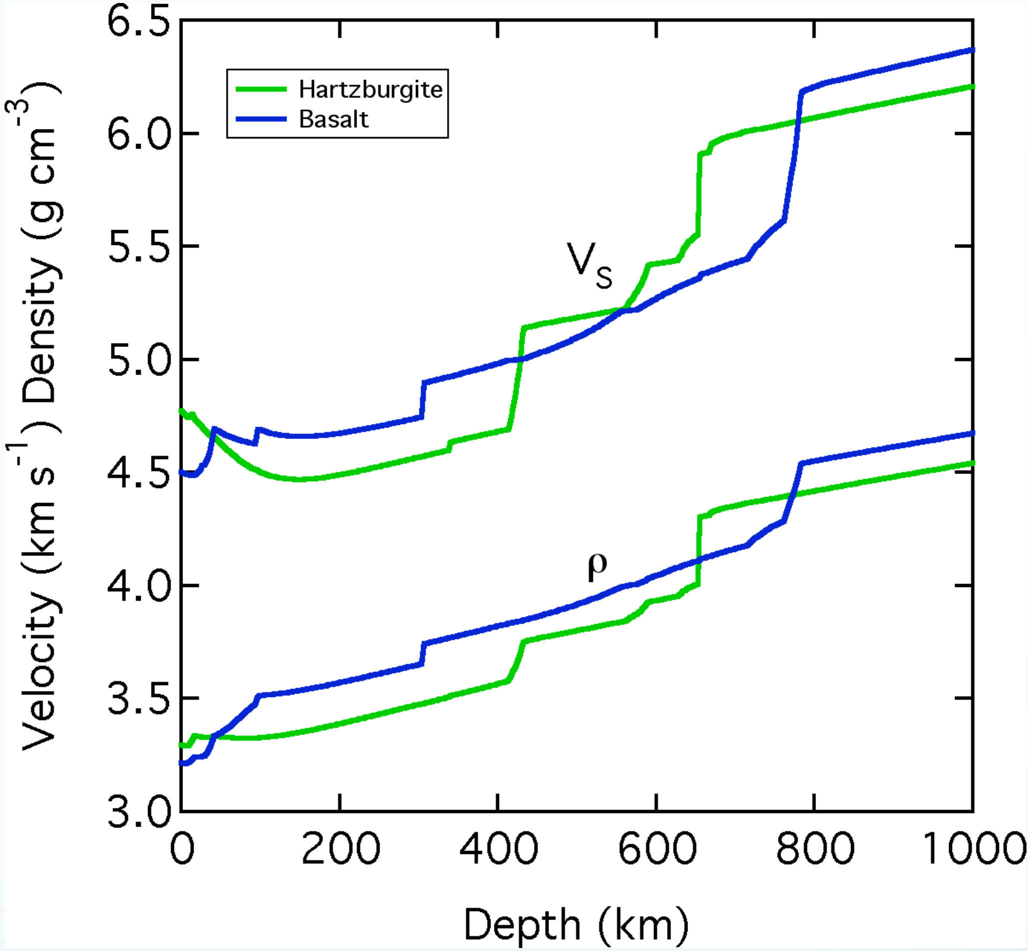


Xu et al. (2008) EPSL

Mechanical Mixture

- Two lithologic components (basalt and harzburgite) have different physical properties
- Density
  - Buoyancy
  - Drives segregation
  - Radial and lateral compositional heterogeneity
- Seismic wave velocity
  - Altered by segregation
  - Scattering
- Lower mantle enriched in basalt?

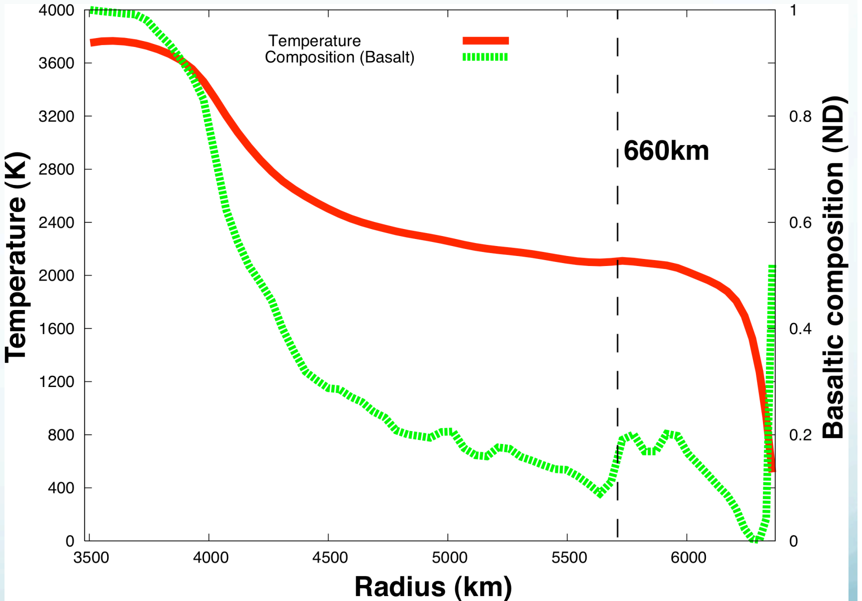
Helffrich (2002)



Xu et al. (2008) EPSL

Major Element Chemical Geodynamics

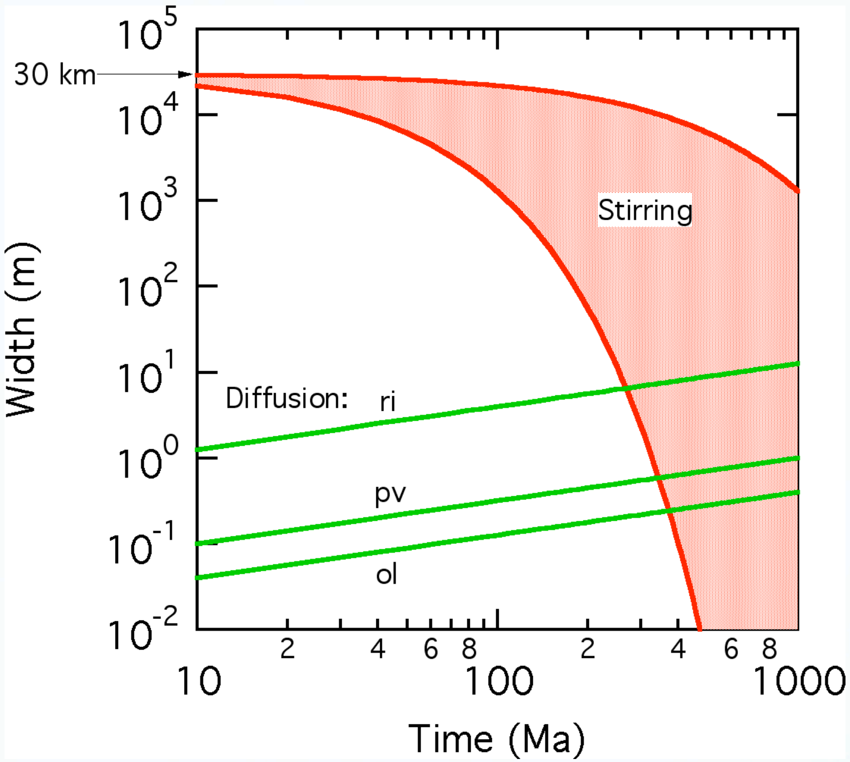
- Compositional heterogeneity at many length scales as seen dynamically
- Basalt pile-ups increase wavelength of heterogeneity
- Seismic signal in 1-D structure
- Physically averaged basalt fraction varies a lot with depth
- Seismic signal in 3-D structure?
- Scatterers?



Christensen & Hofmann (1994) JGR
Nakagawa & Buffett (2005) EPSL

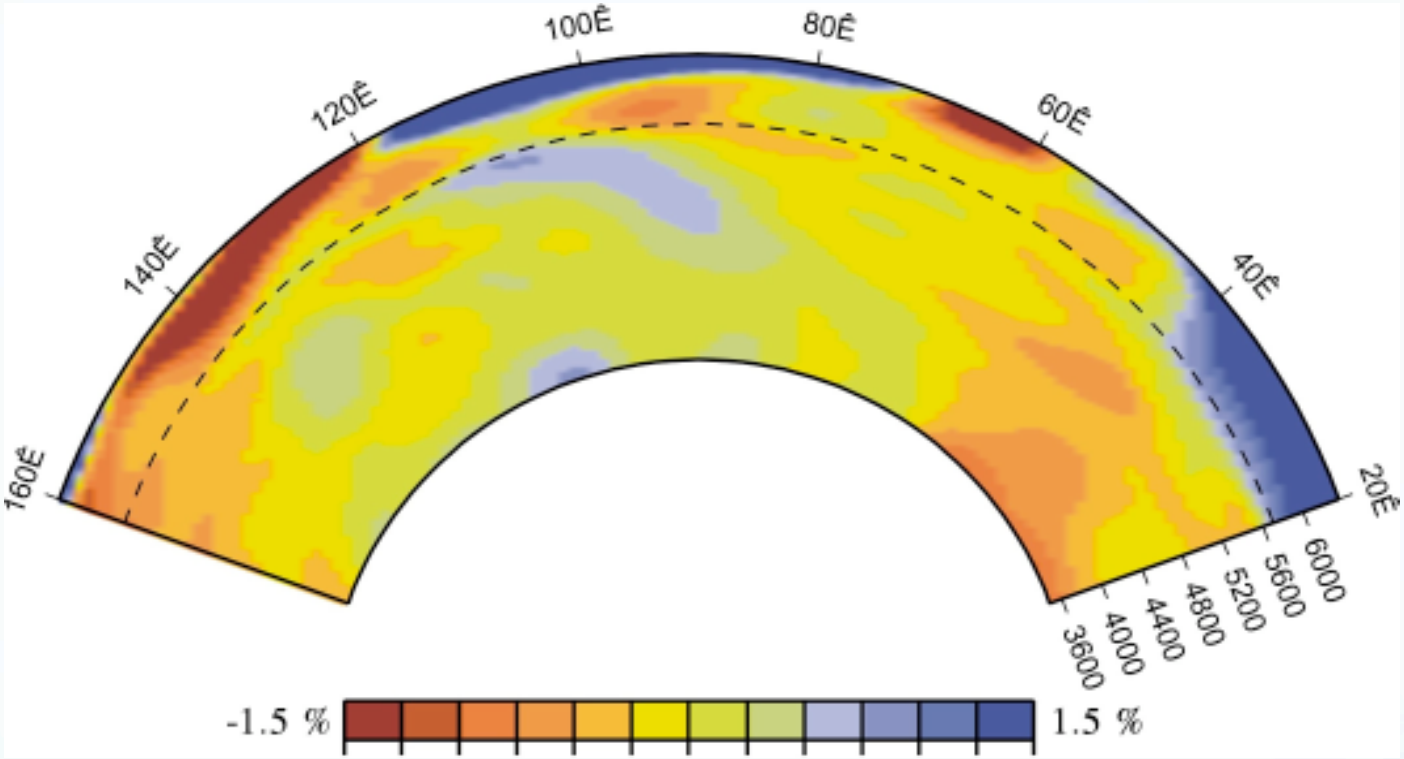
Duration of heterogeneity

- Long…
- *Hofmann & Hart, 1978, EPSL; Allegré & Turcotte, 1986, Nature*
- Uncertainties
  - Role of fluids?
  - Role of deep melting processes?
- Re-homogenization cannot be rapid (crustal signatures in OIB)
- *Hofmann and White, 1982, EPSL*



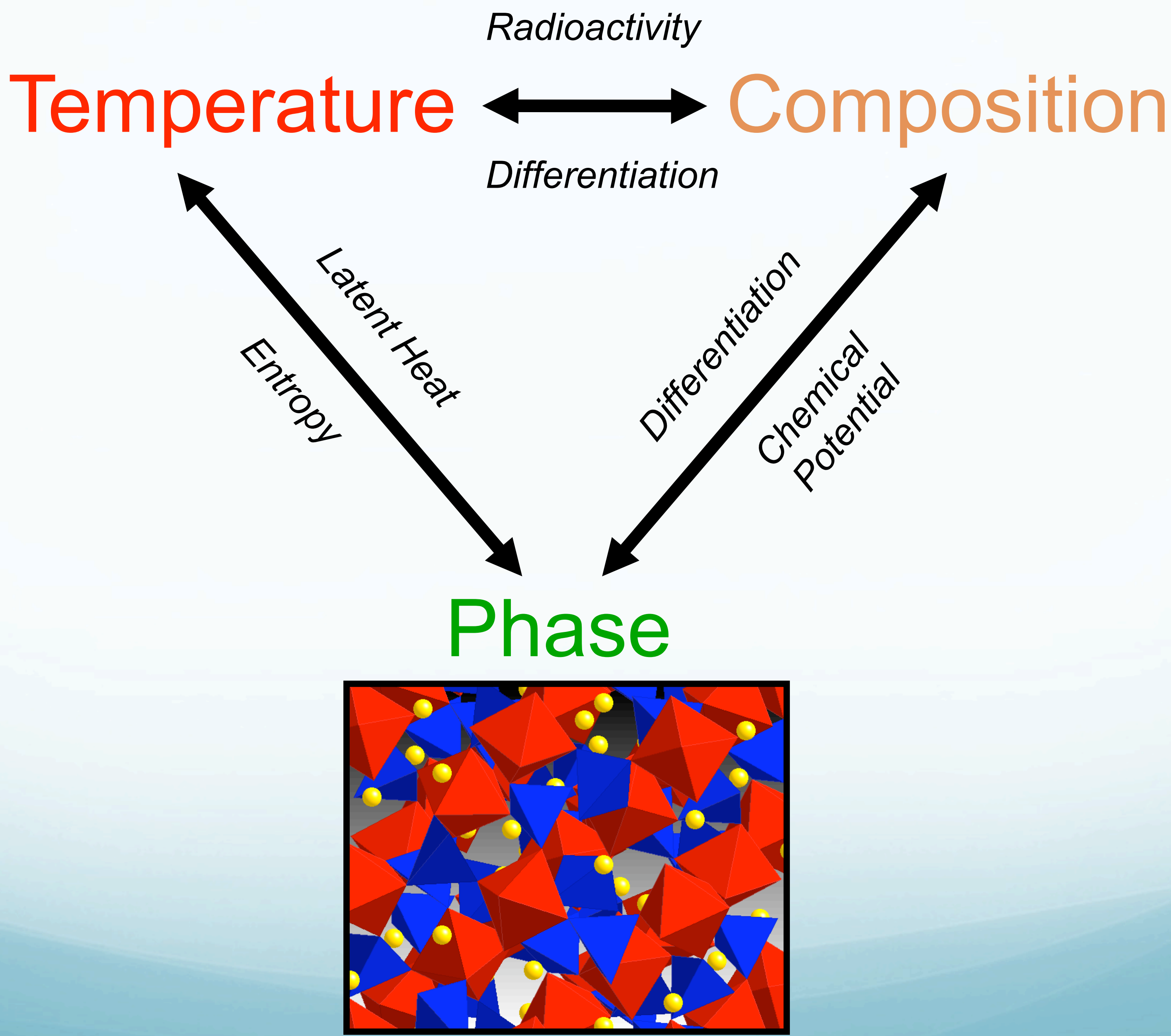
ol: *Farber et al. (1994) Nature;* ri: *Farber et al. (1994) Nature;* pv: *Yamazaki et al. (2000) PEPI; Kellogg and Turcotte (1985);*

What do anomalies mean?



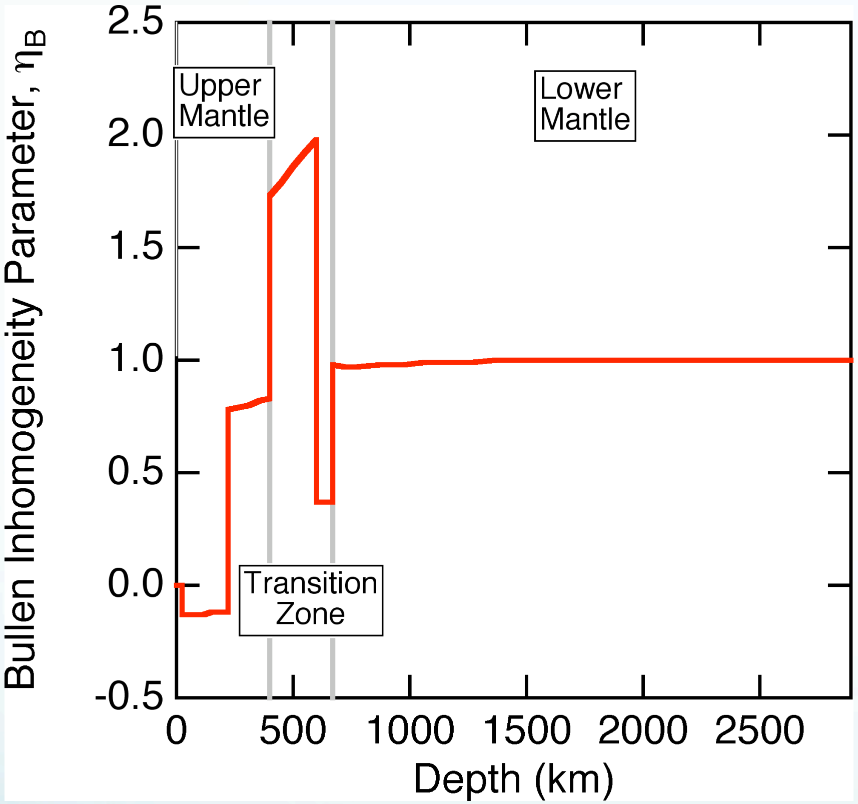
Ritsema et al. (1999)

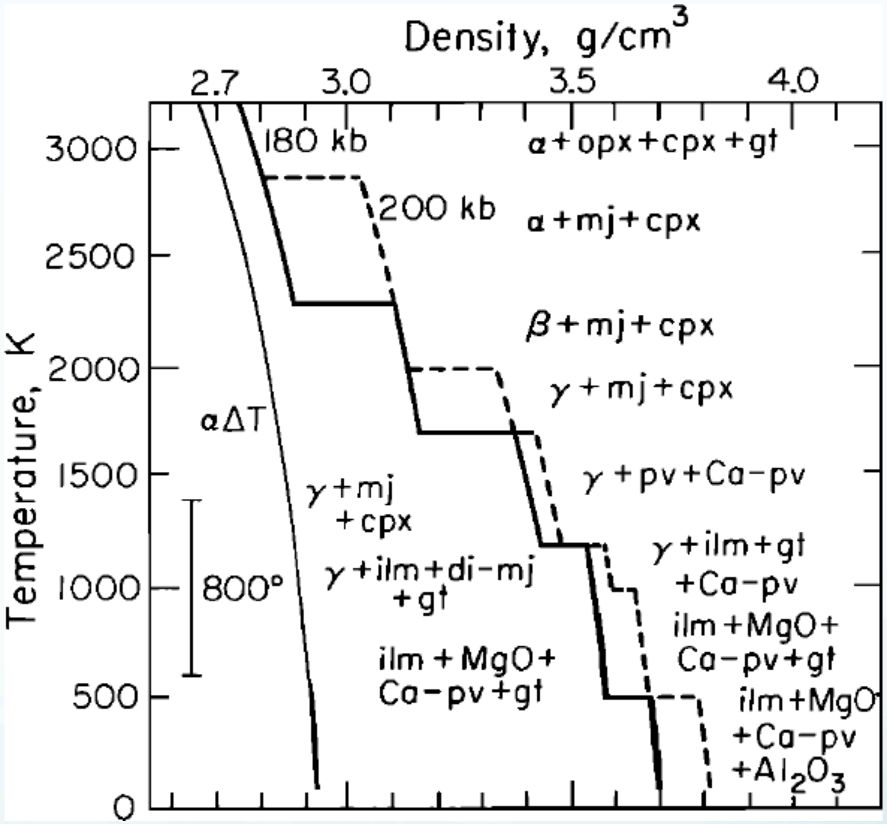
Origin of velocity anomalies



Importance of Phase

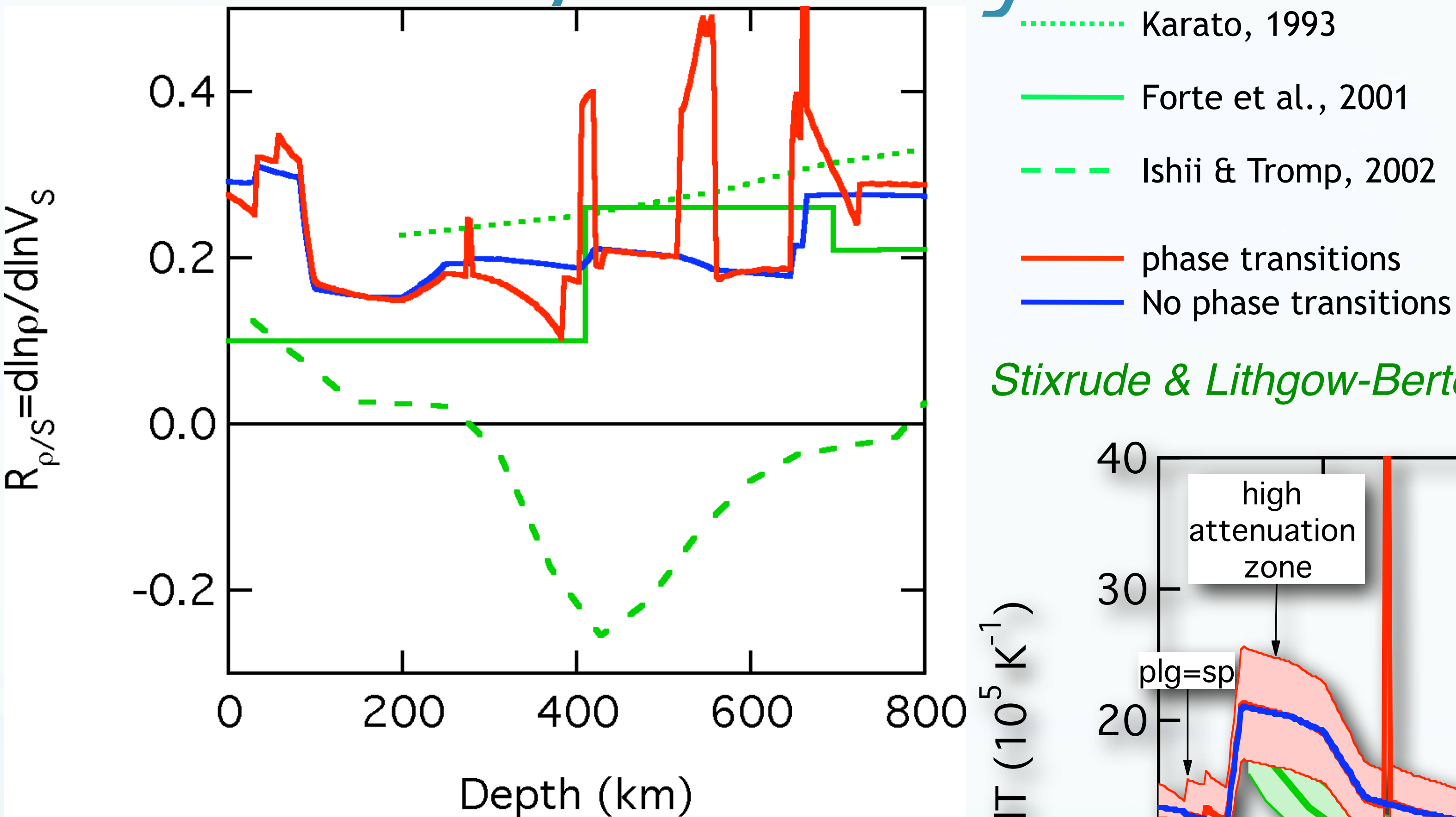
- Phase transformations are likely to be important radially and laterally



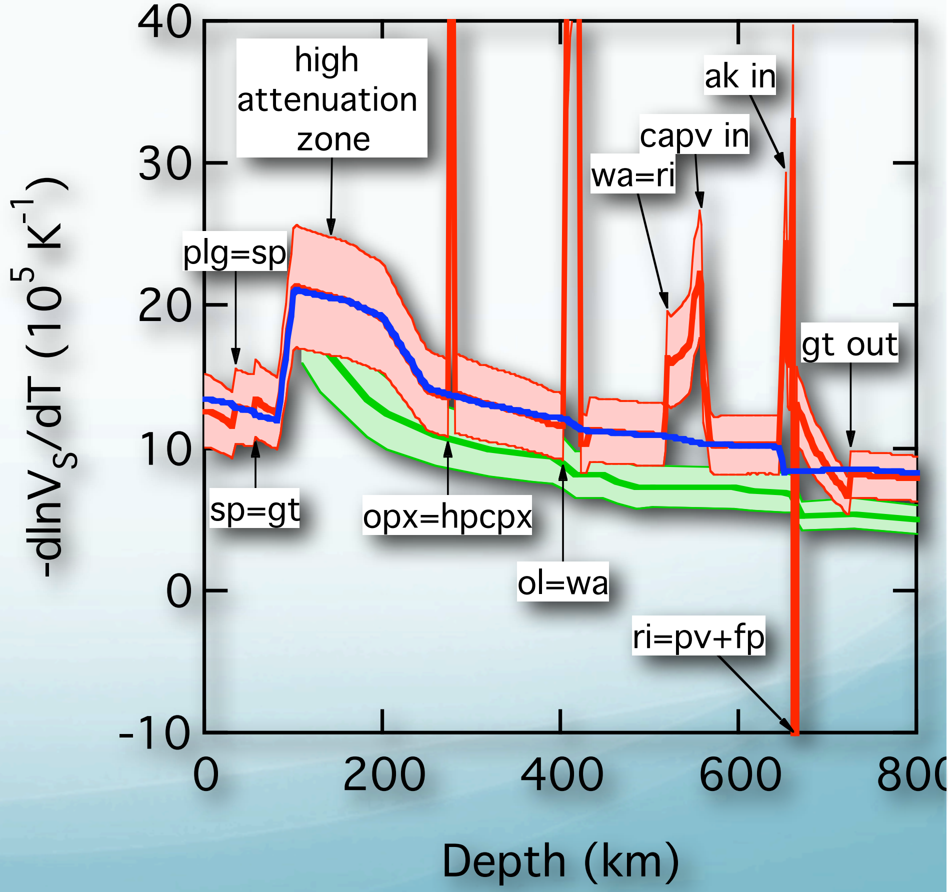


Dziewonski & Anderson (1981) PEPI; Anderson (1987) JGR

Velocity-Density/T Scalings



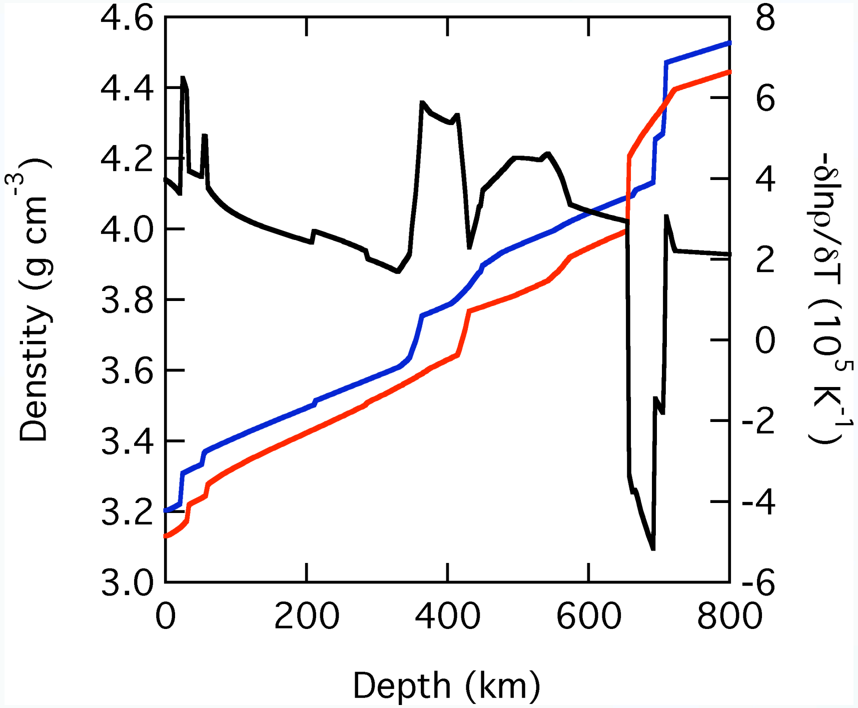
Stixrude & Lithgow-Bertelloni (2007) EPSL



- Metamorphic term increases velocity sensitivity throughout upper mantle and transition zone
- Reduces lateral temperature variations inferred from tomography

Phase transitions and dynamics

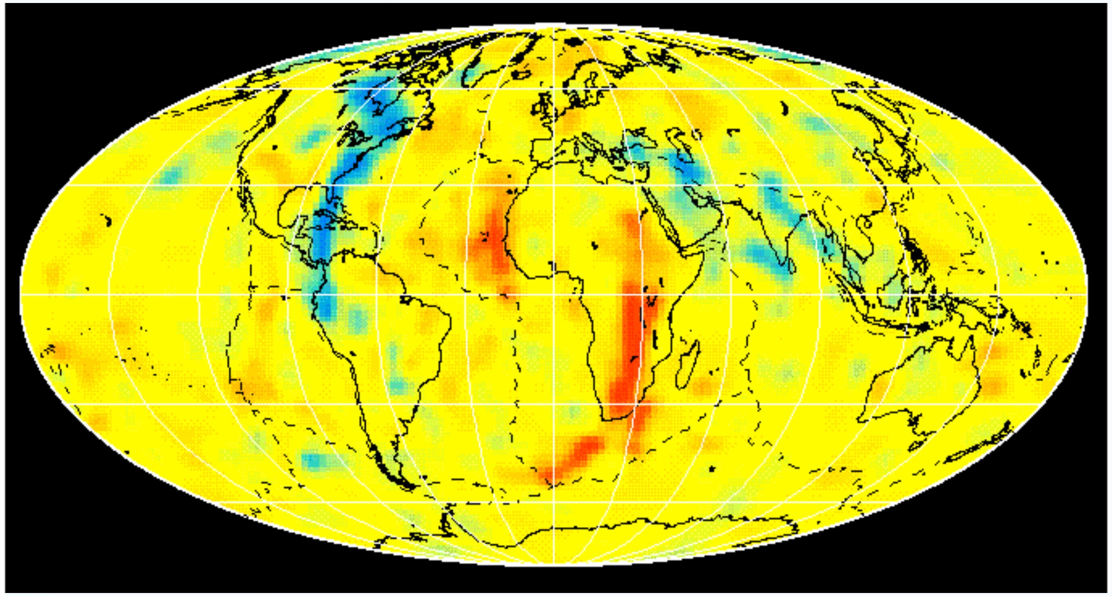
- Phase transformations influence dynamics
- Destabilizing throughout transition zone
- Stabilizing at upper-lower mantle boundary
- Typical formulation may be inadequate
- Look-up table



$$\Pi \frac{dY}{dP} = \frac{\alpha_{met}}{\alpha_{iso}}$$

Modeling Mantle Flow

Seismic Tomography- Convert velocity to density



[*Grand et al.*, 1997]

Mantle Density Heterogeneity Model

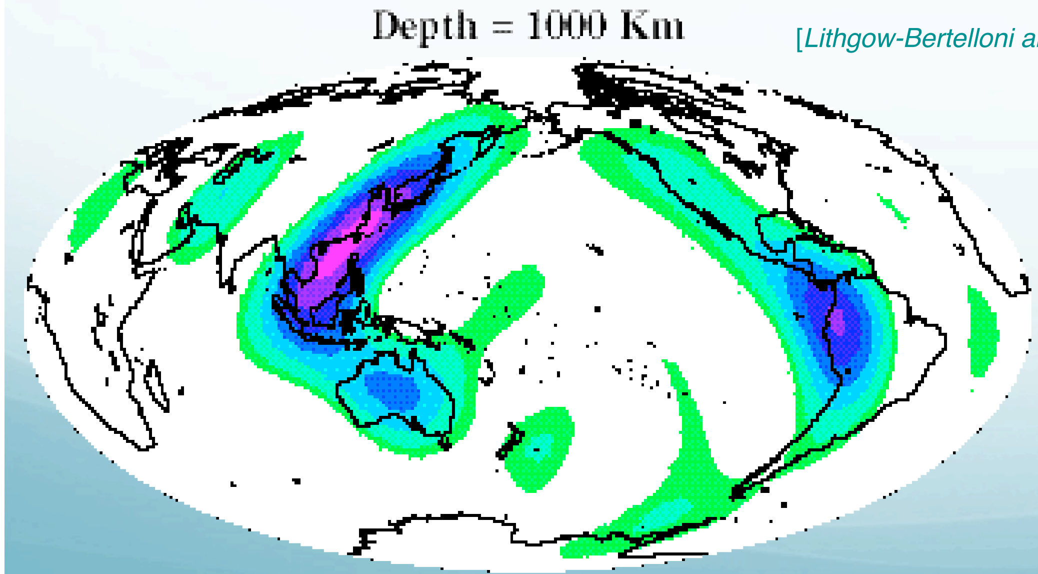
$$\nabla \bullet \vec{v} = 0$$

$$\nabla \bullet \mathbf{T} + \delta\rho g\hat{z} = 0$$

$$\mathbf{T} = -p\mathbf{I} + 2\eta\dot{\varepsilon}$$

$$\nabla^2 V = 4\pi G\delta\rho$$

Based on Geologic Information-Plate Motion History



[*Lithgow-Bertelloni and Richards* 1998]

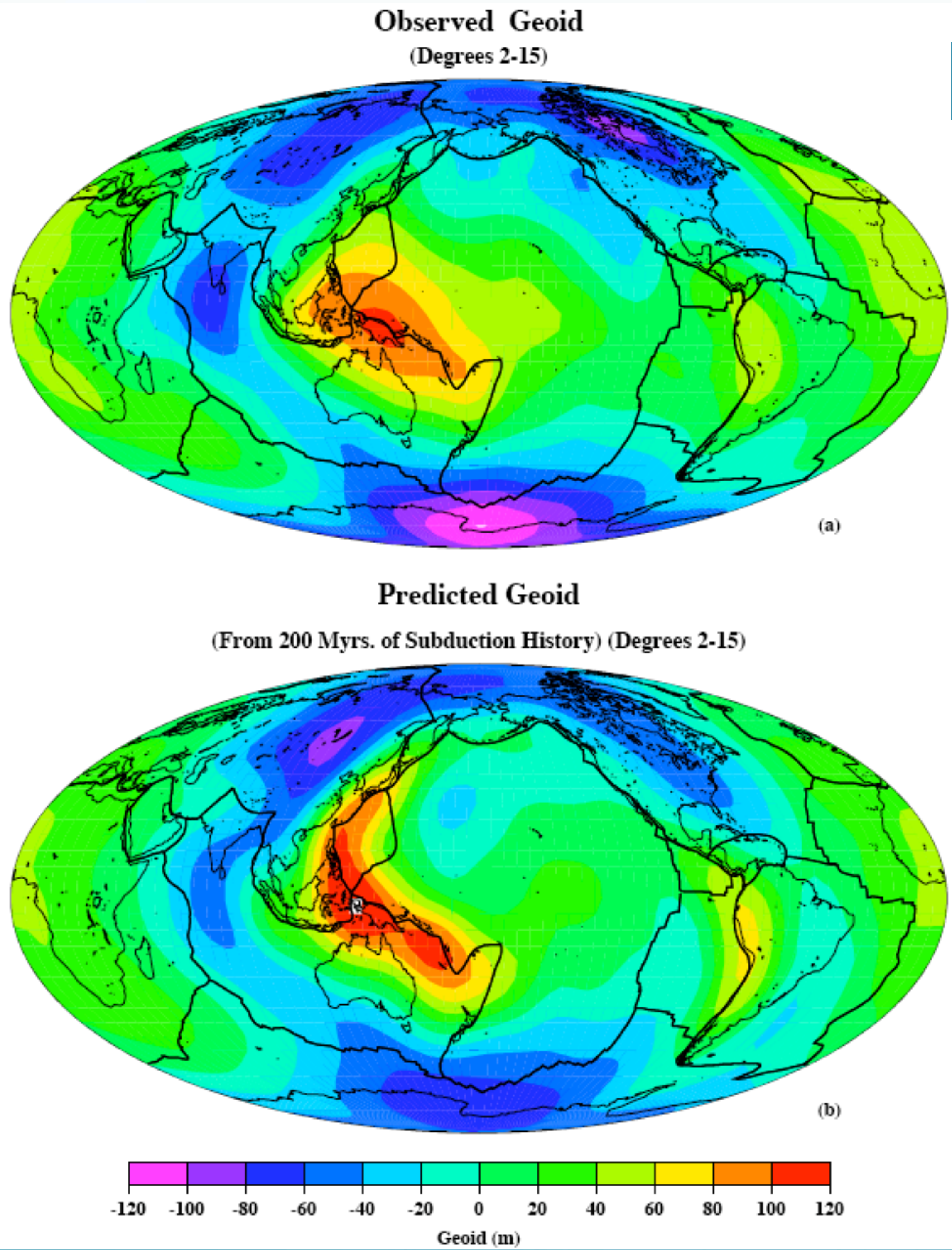
-Induced Viscous Flow

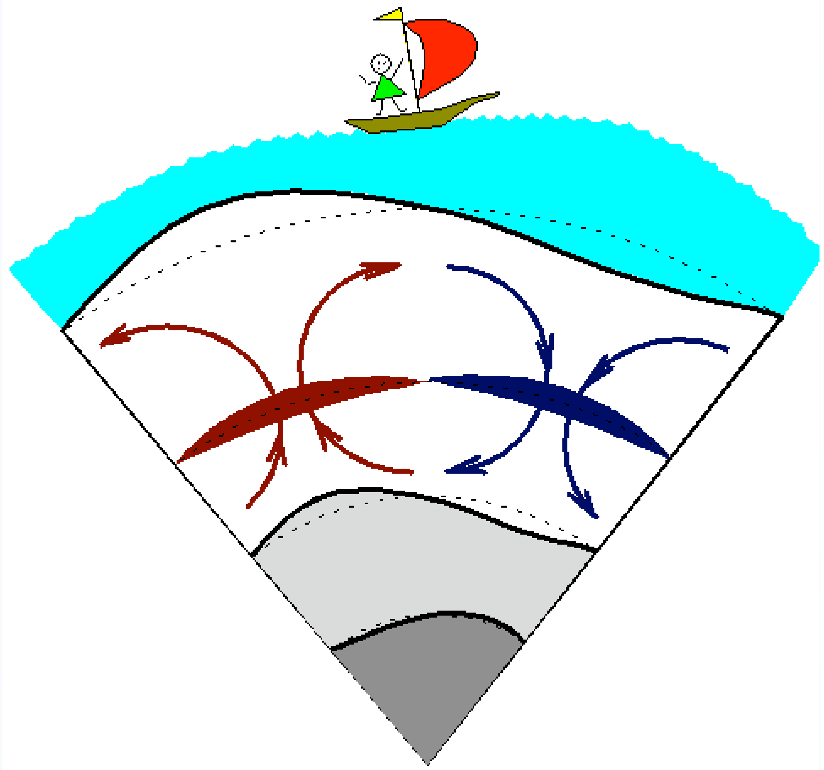
-Can be solved analytically
For a spherical shell

-Predict: Radial Stresses
Dynamic topography

Hager and O'Connell, (1979)

Earth’s Geoid

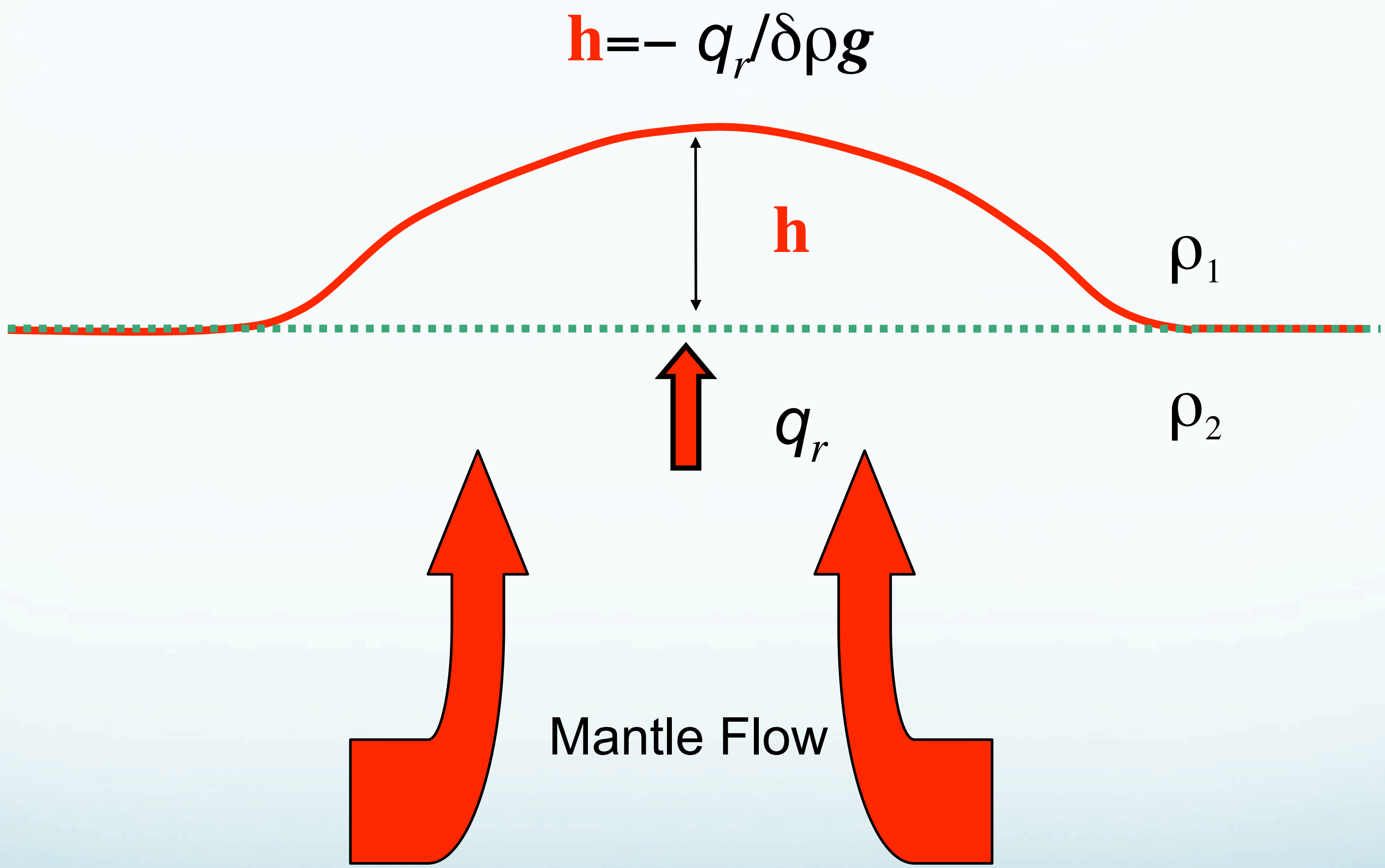




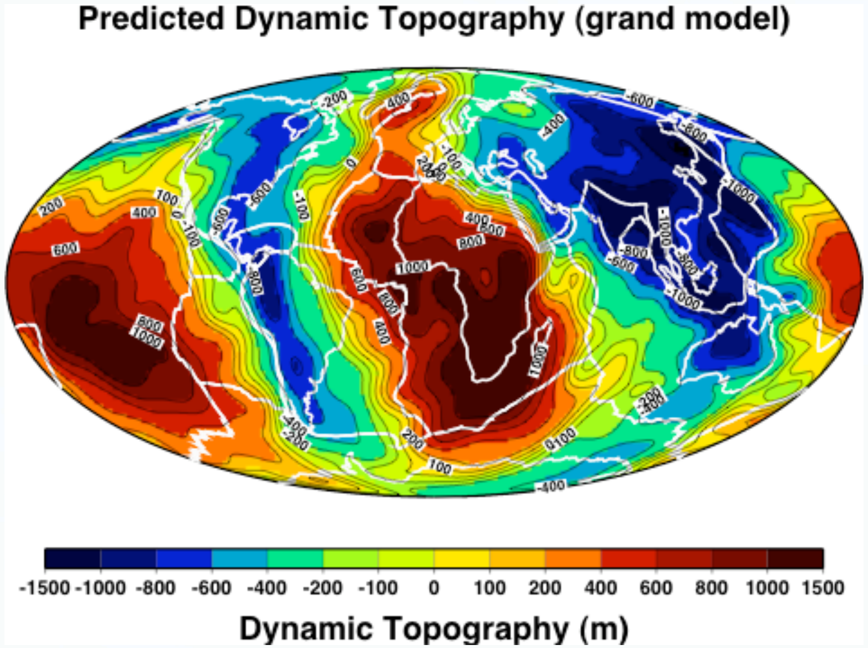
[*cartoon, courtesy of Lana Panasyuk*]

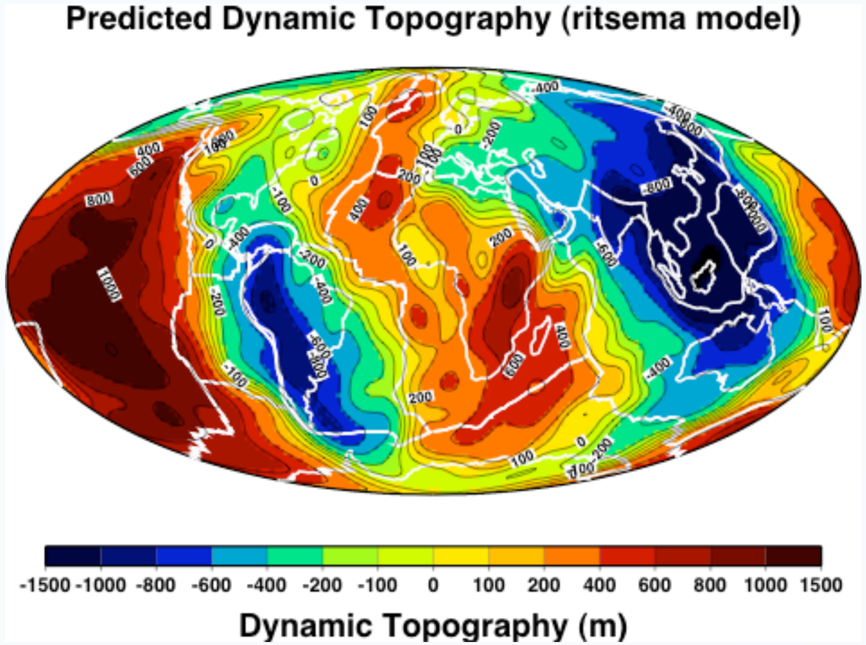
[*Lithgow-Bertelloni and Richards, 1998*]

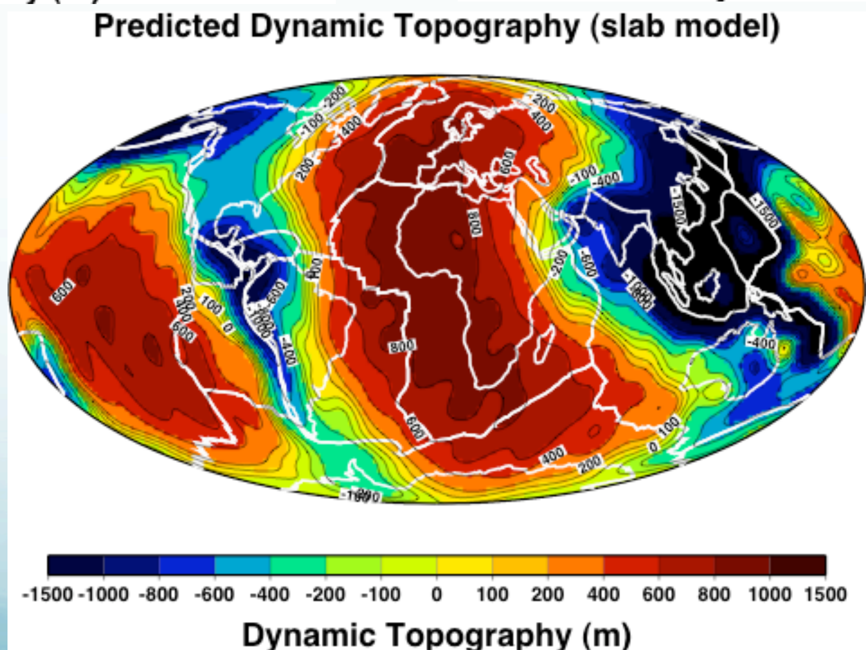
Dynamic Topography



Global Dynamic Topography



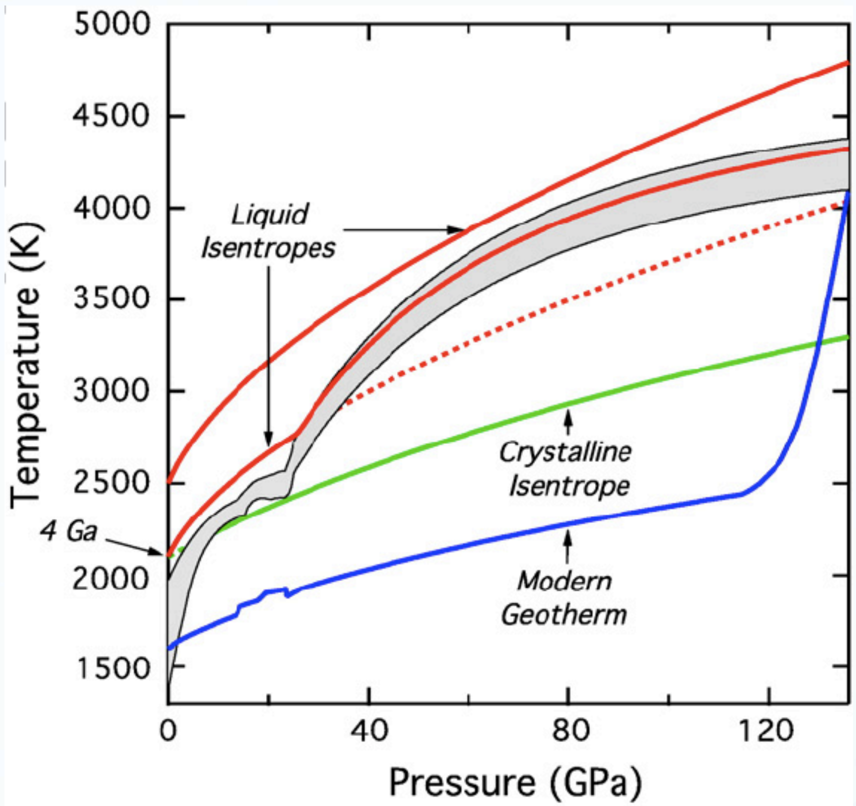


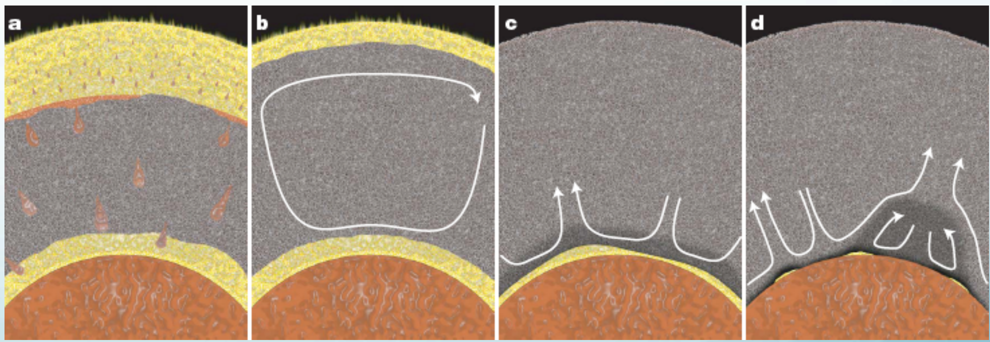


Other Sources of Heterogeneity?

- Differentiation from magma ocean
- Ab initio MD predicts crystallization starts from the middle
- Separates upper and lower magma layers
- Lower layer may have distinct history and may end with a different composition
- Generalization of thermodynamic model to include
  - All relevant lower mantle physics

Stixrude and Karki (2005) Science; Labrosse et al. (2007) Nature





Conclusions

- Basalt fraction a natural metric of major compositional variability
- Two end-members
  - Mechanical mixture of basalt and harzburgite
  - Equilibrium assemblage
- Should be distinguishable based on geophysical observations
  - Differences in radial structure
  - Phase transitions within the lower mantle
  - Scattering
- Radial gradient in basalt fraction
  - Dynamically plausible
  - Should be detectable
  - May explain vanishing slabs
- Importance of full phase equilibria for global geophysical fields
  - Plate acceleration and deceleration
  - Amplitude of dynamic topography