Geophysics of Chemical Heterogeneity in the Mantle

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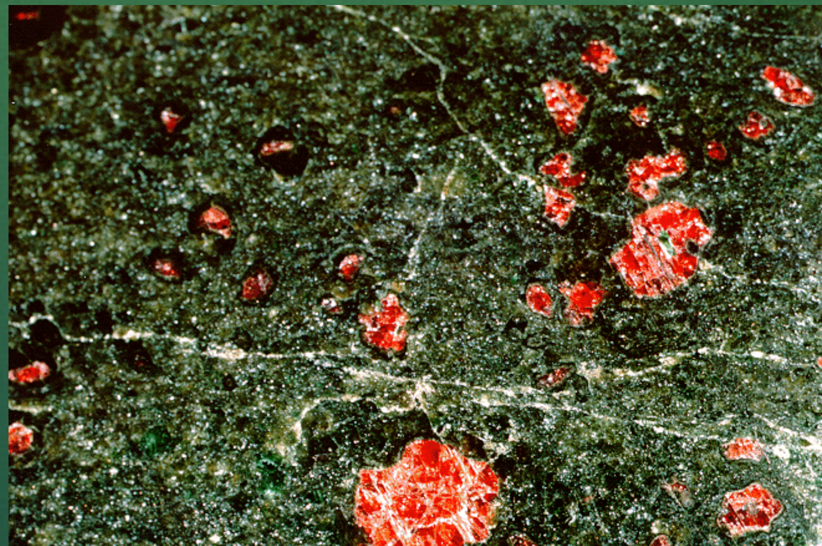
University College London

Heterogeneity



Boundary Layers

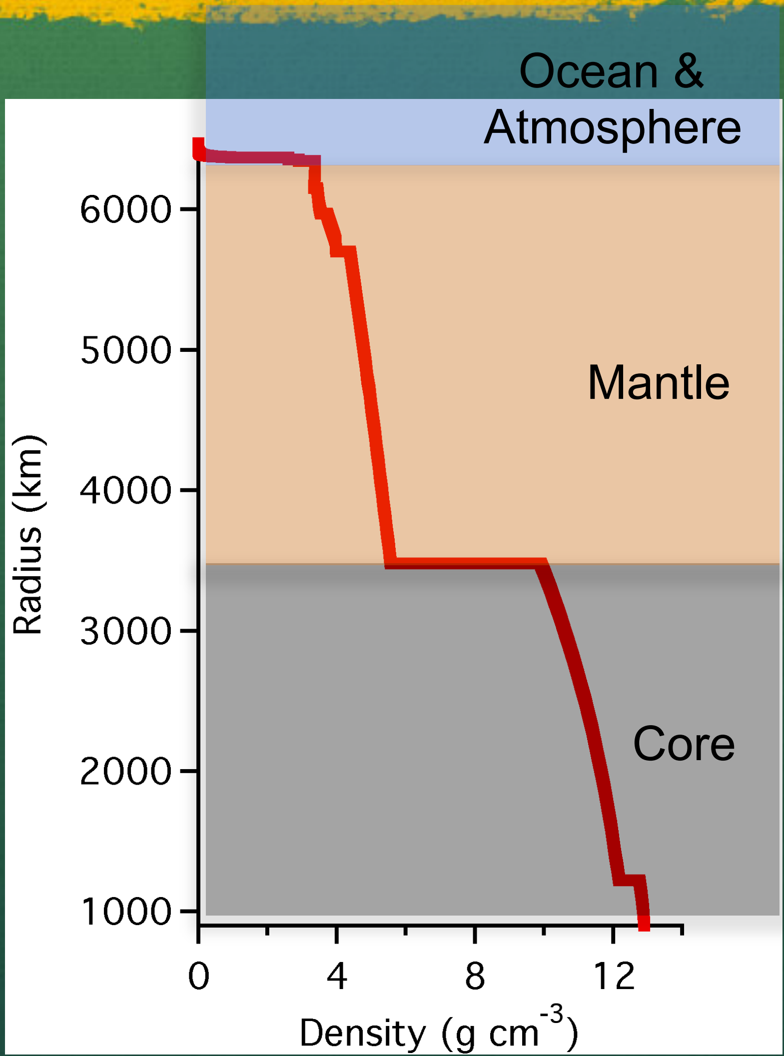
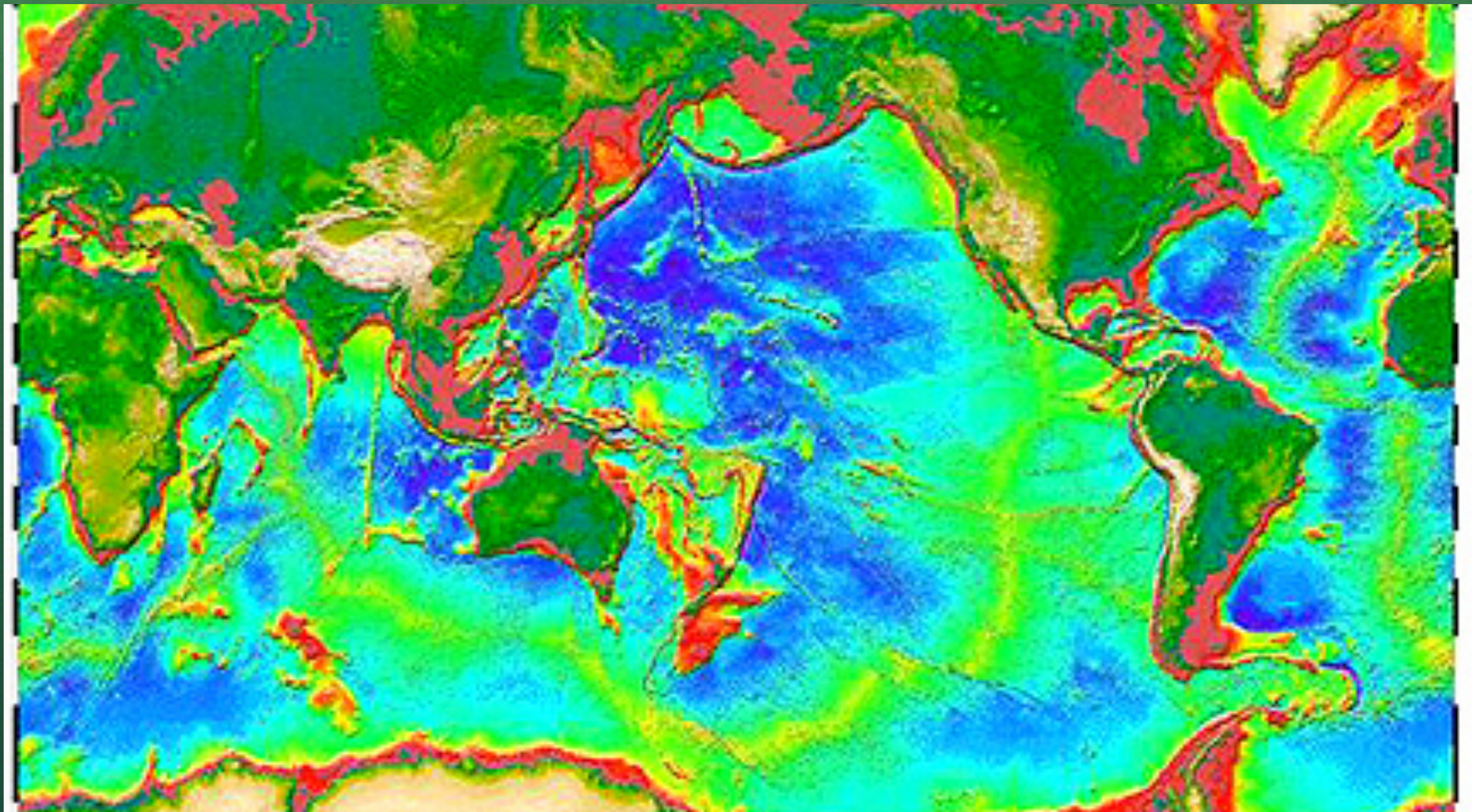


Plate Tectonics



Smith & Sandwell (1997) Science

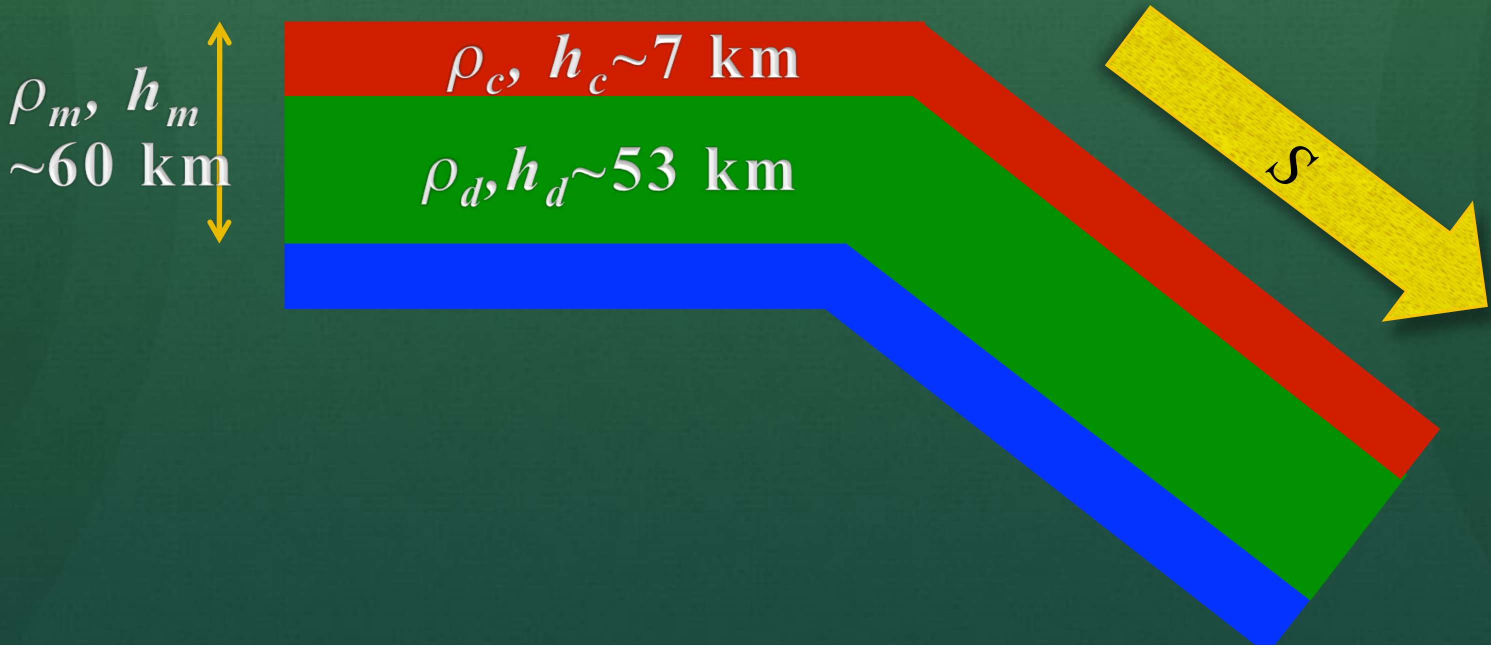
Rate of Production

- Amount of subducted crust
- Amount of subducted depleted
- Amount of mantle processed

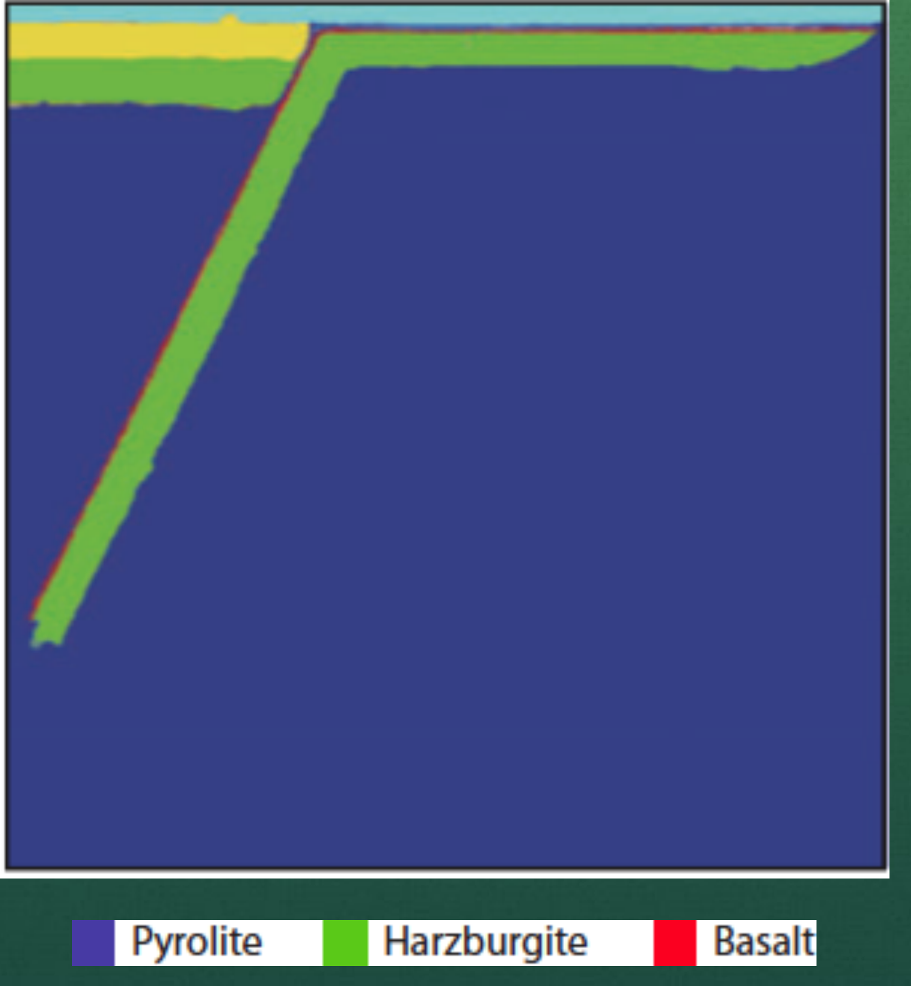
$$C = \int \rho_c h_c S dt$$

$$D = \int \rho_d h_d S dt$$

$$M = \int \rho_m h_m S dt$$



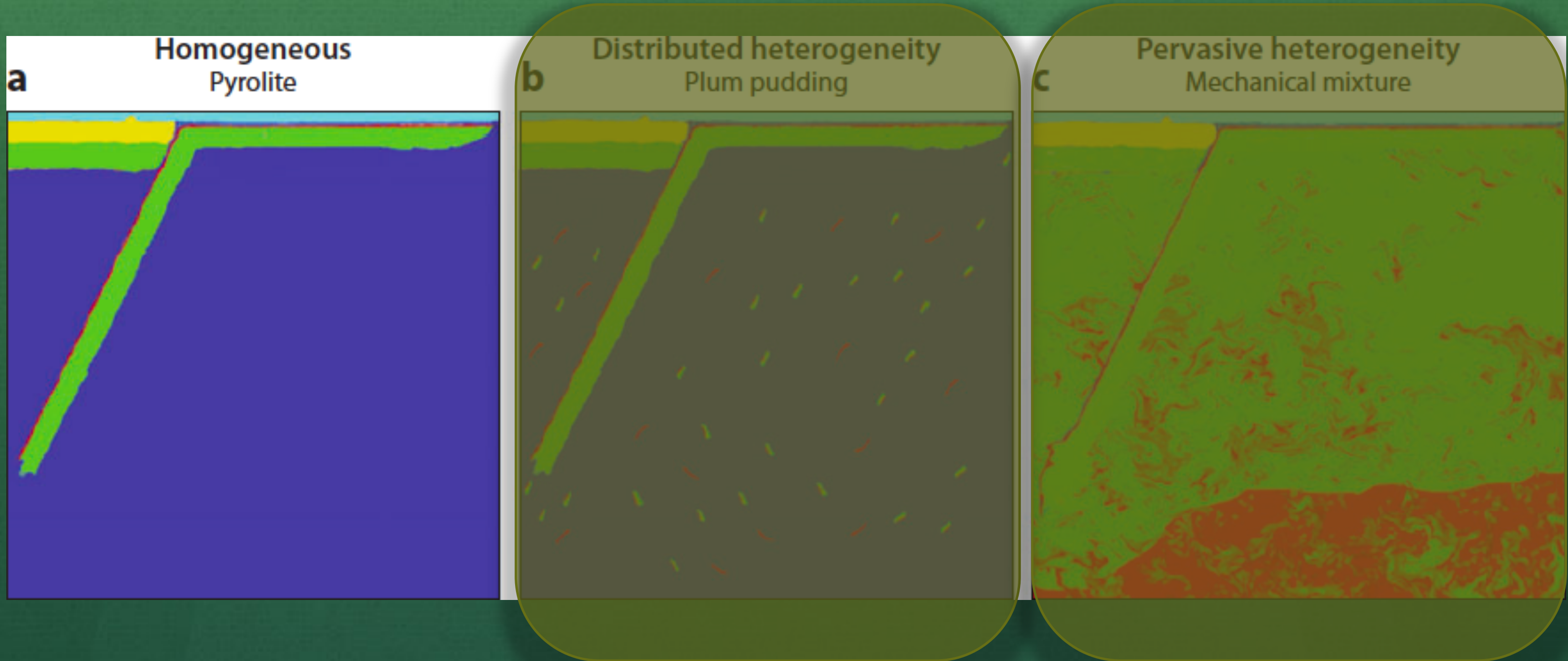
Mantle Heterogeneity



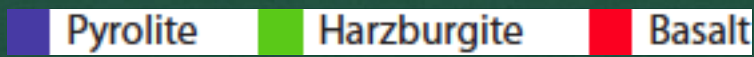
Mantle Heterogeneity

- Heterogeneity is continuously generated in surface boundary layer
- Heterogeneity once produced is difficult to destroy
- Heterogeneity is returned to the mantle
- Subduction may be an ancient process (3 Ga; Shirey et al., 2011, Science)

Mantle Heterogeneity

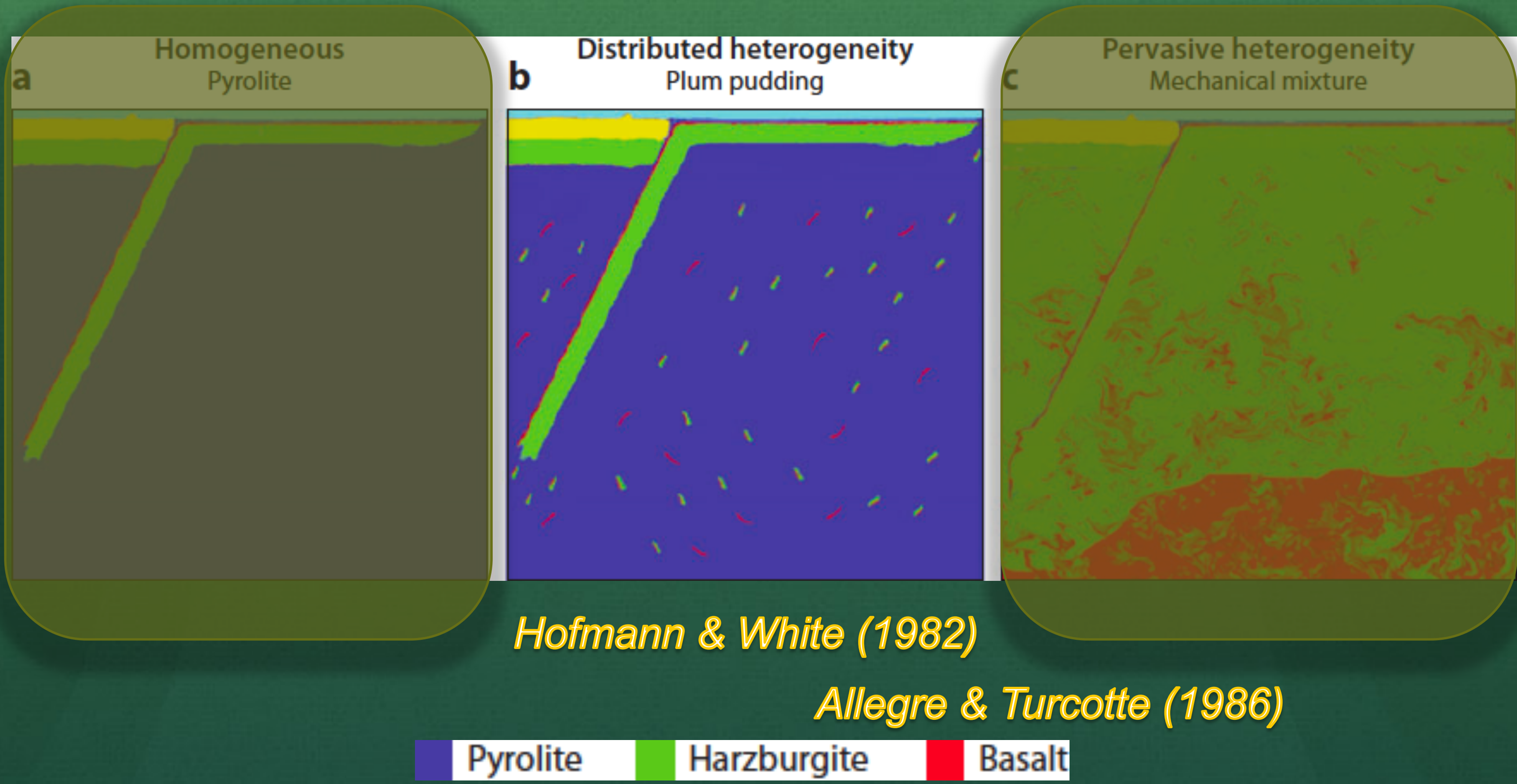


Green & Ringwood (1967)



Stixrude & Lithgow-Bertelloni (2012) AREPS

Mantle Heterogeneity

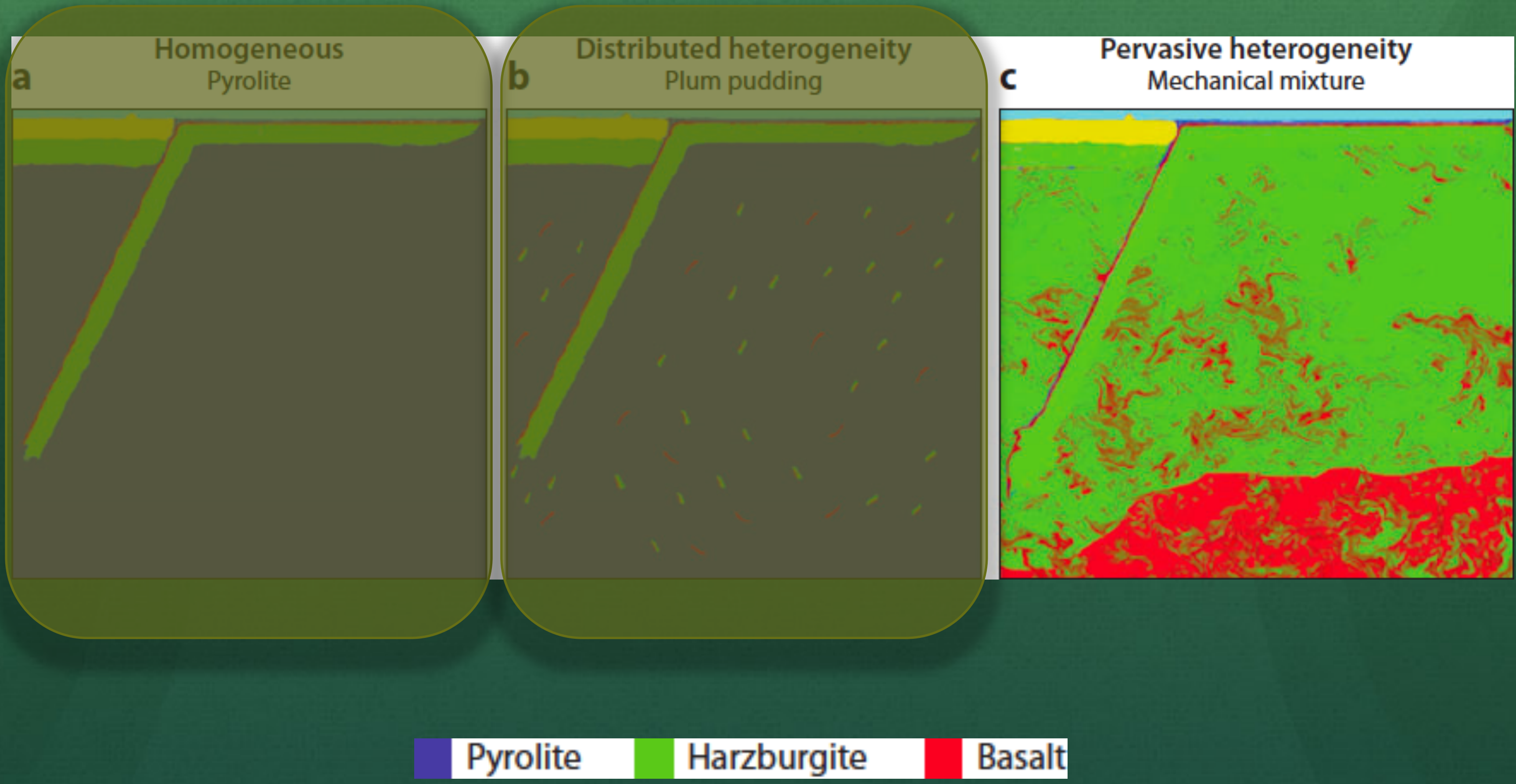


Hofmann & White (1982)

Allegre & Turcotte (1986)

Stixrude & Lithgow-Bertelloni (2012) AREPS

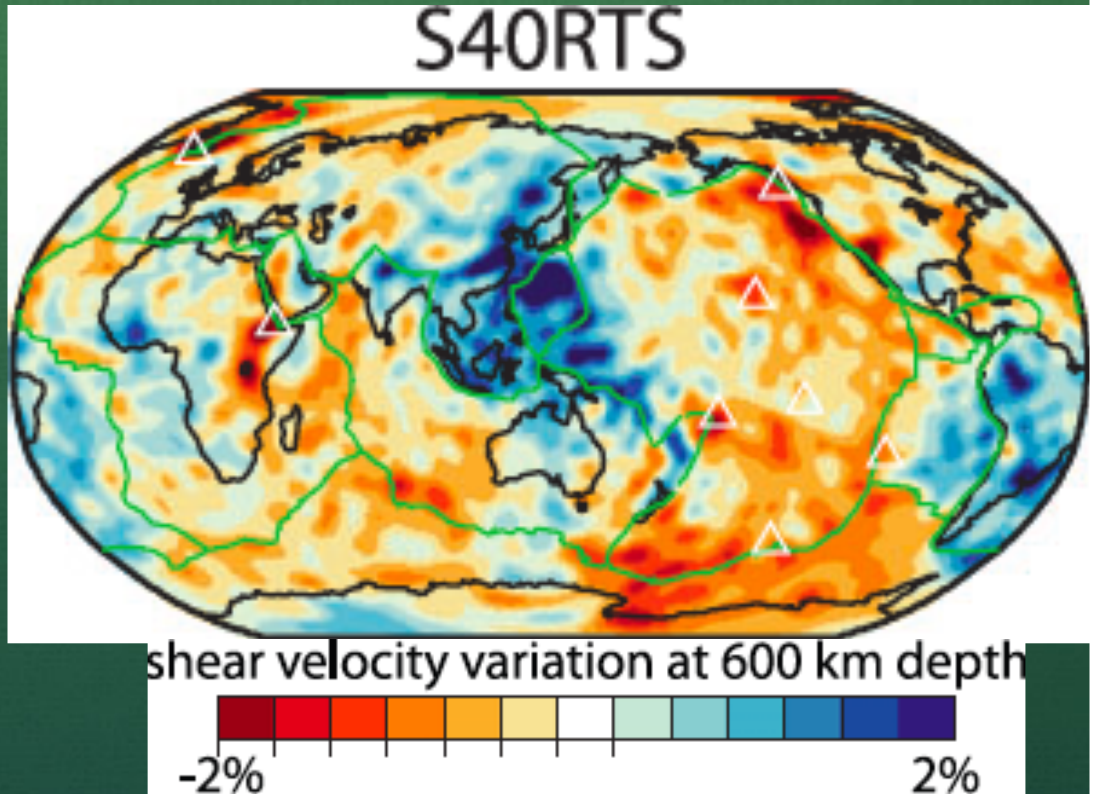
Mantle Heterogeneity



Stixrude & Lithgow-Bertelloni (2012) AREPS

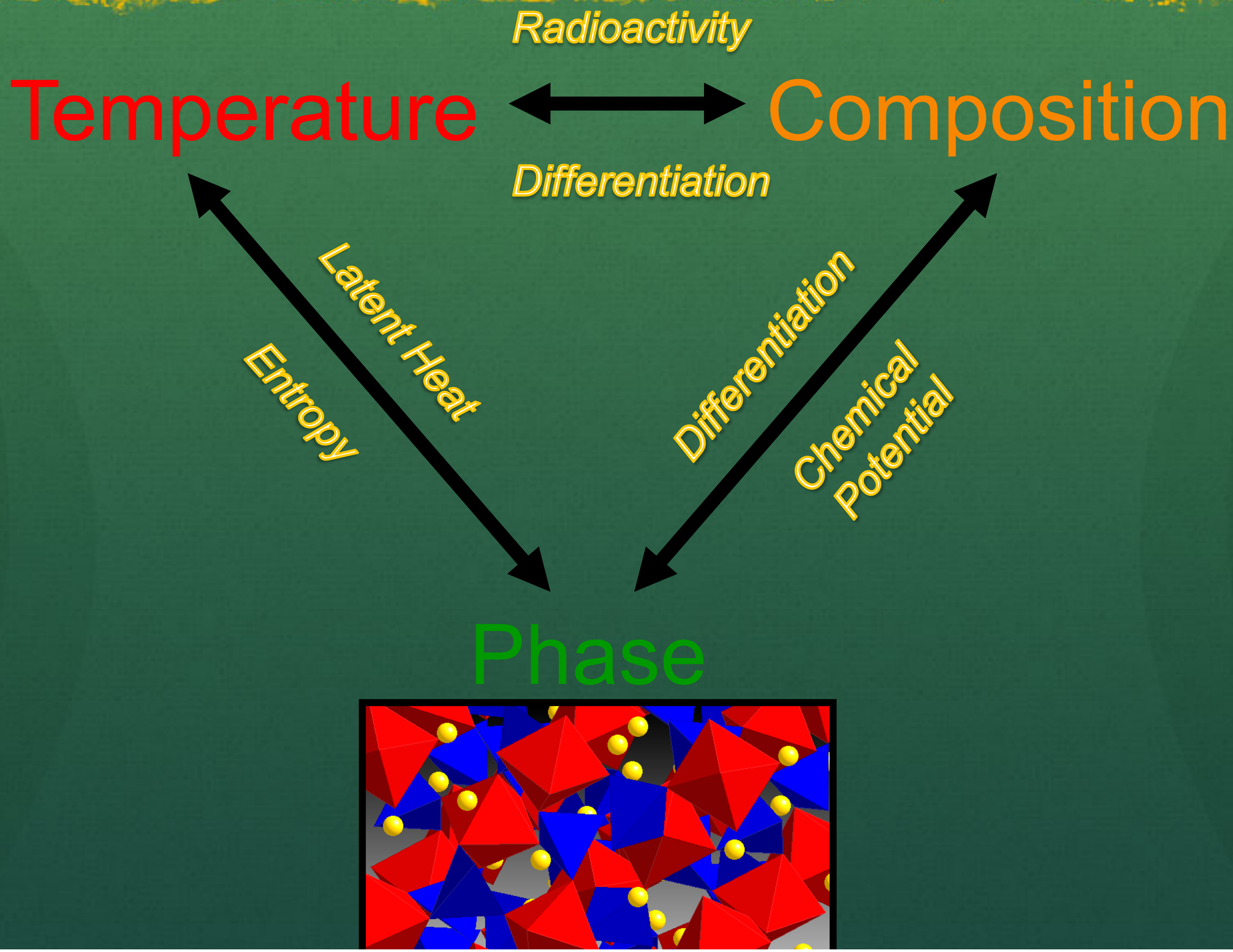
Probing Chemical Heterogeneity

- Tomographic models show lateral heterogeneity
- Broad agreement among models
- Limitations
  - Spatial resolution
  - Multiple sources of heterogeneity

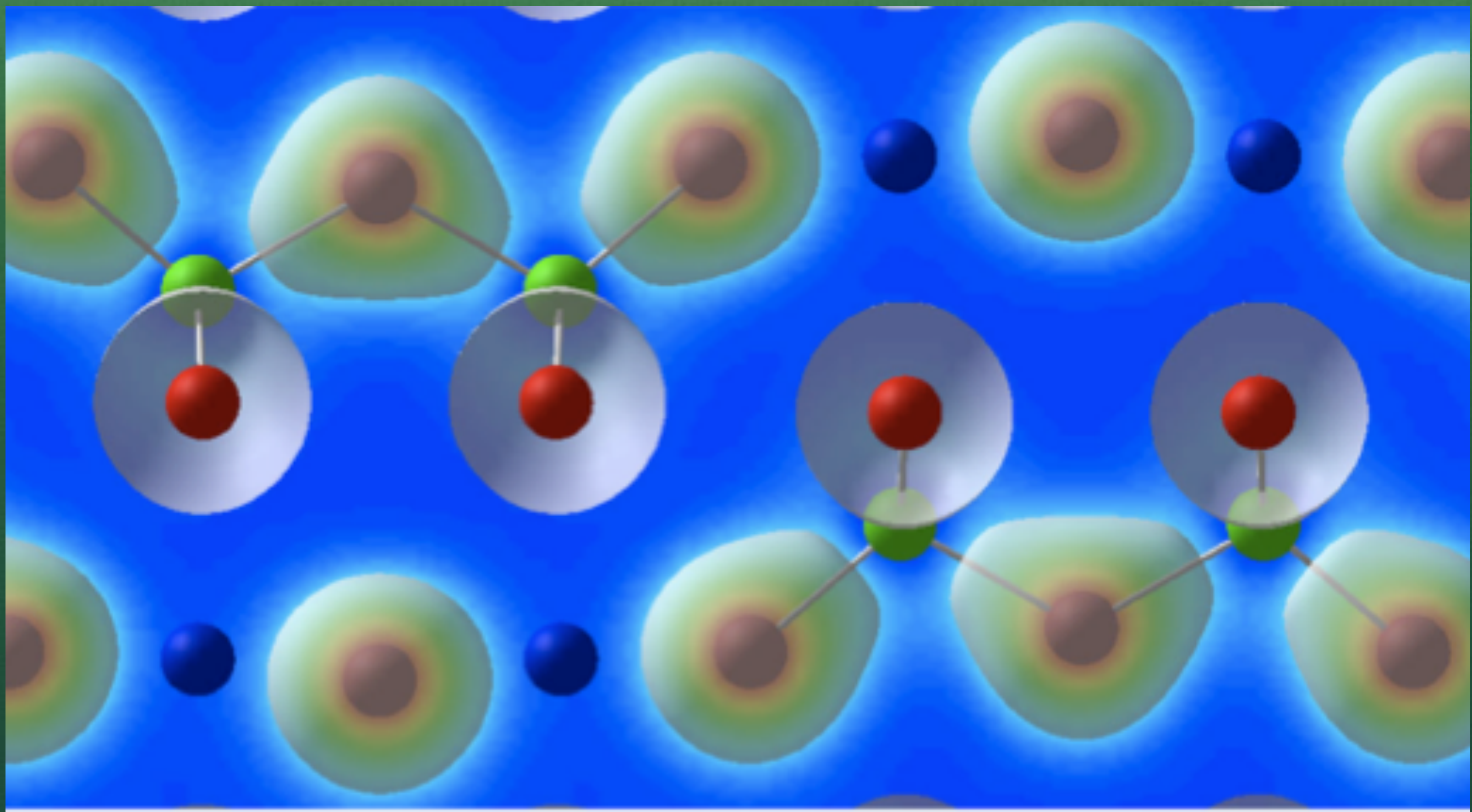


Ritsema et al. (2011) GJI

Origins of Mantle Heterogeneity

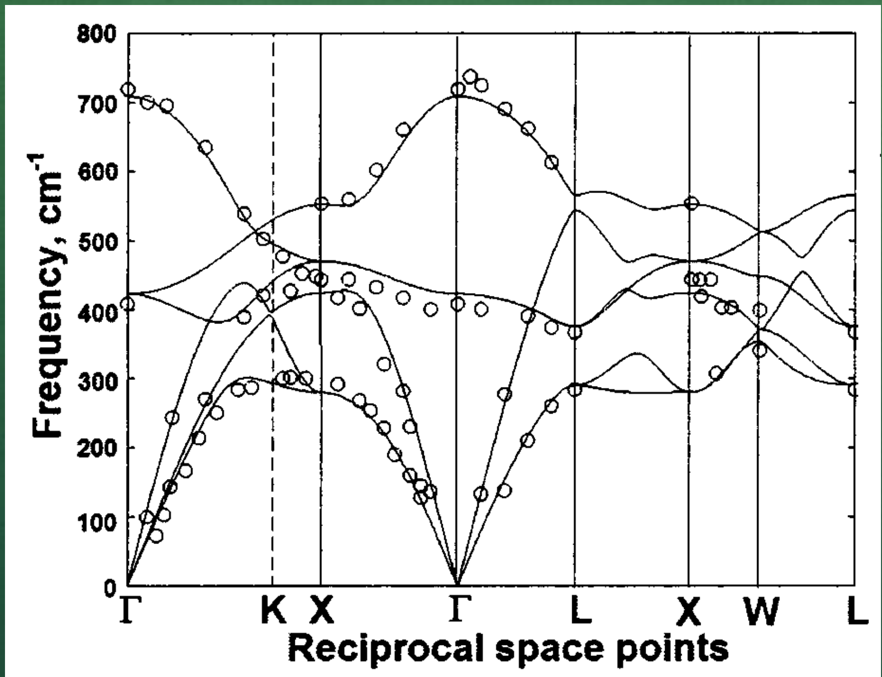


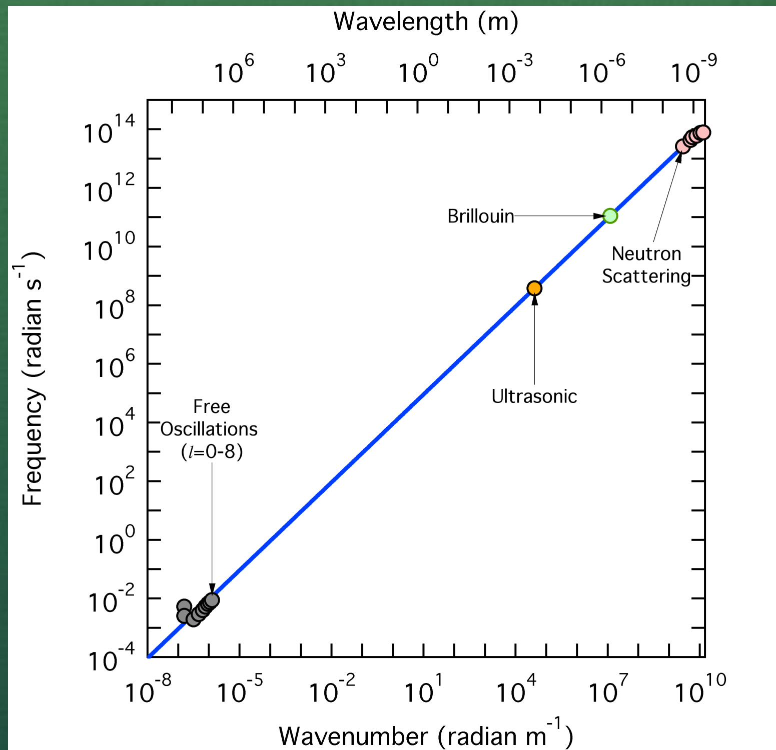
Length Scales of Heterogeneity



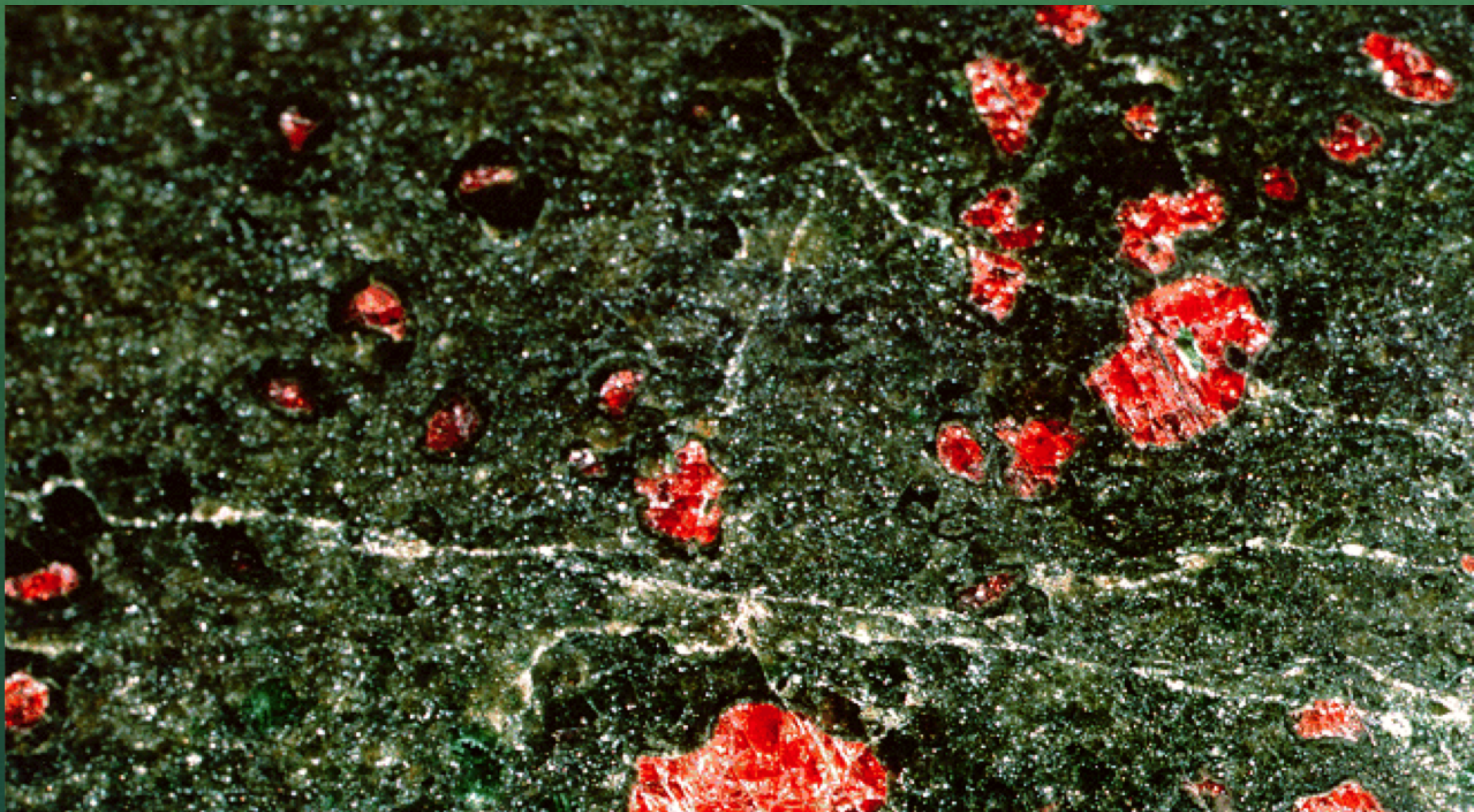
Nico de Koker, Bayreuth

Length Scaling: Atom to Planet



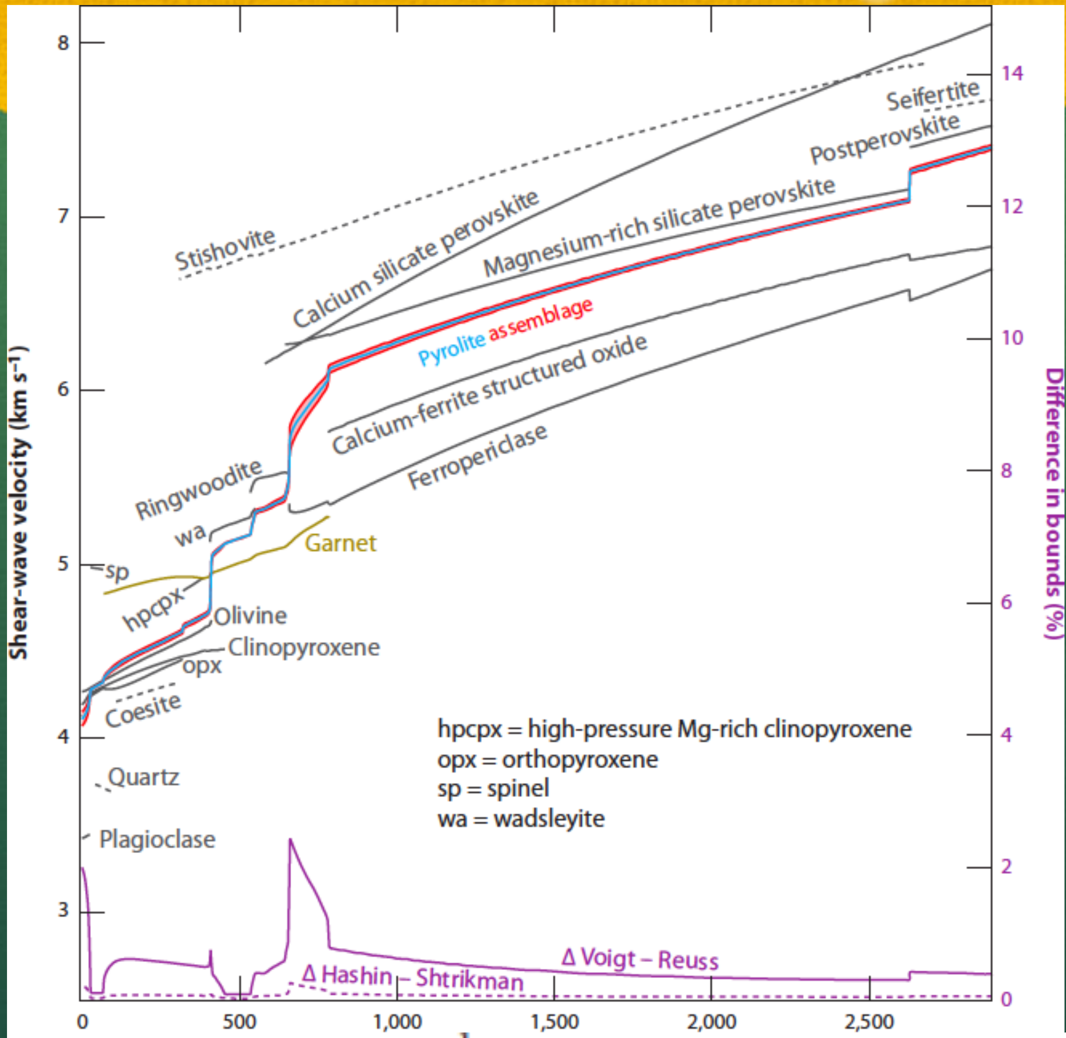


Grain Scale Heterogeneity



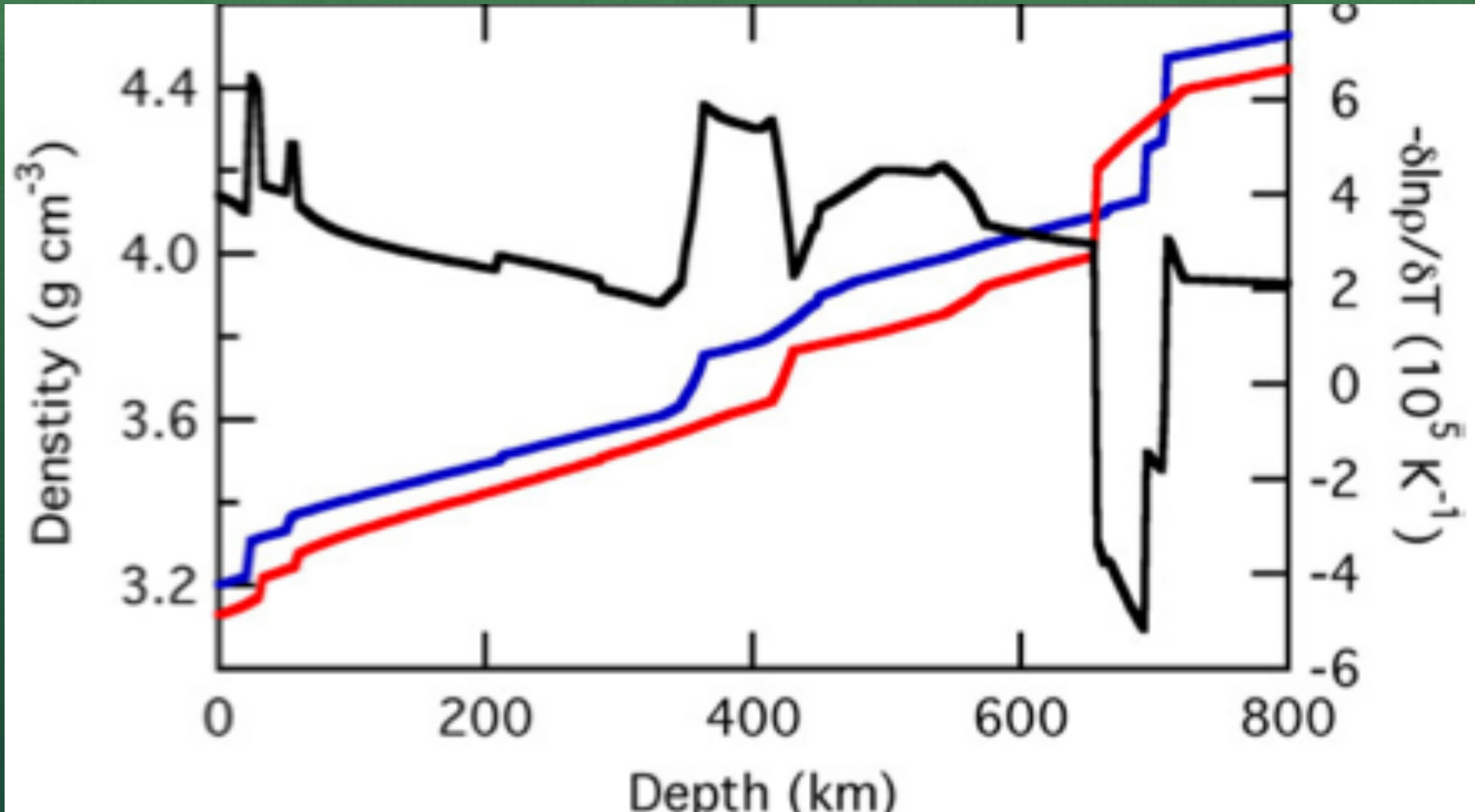
Stixrude & Lithgow-Bertelloni (2012) AREPS

Grain Scale Heterogeneity



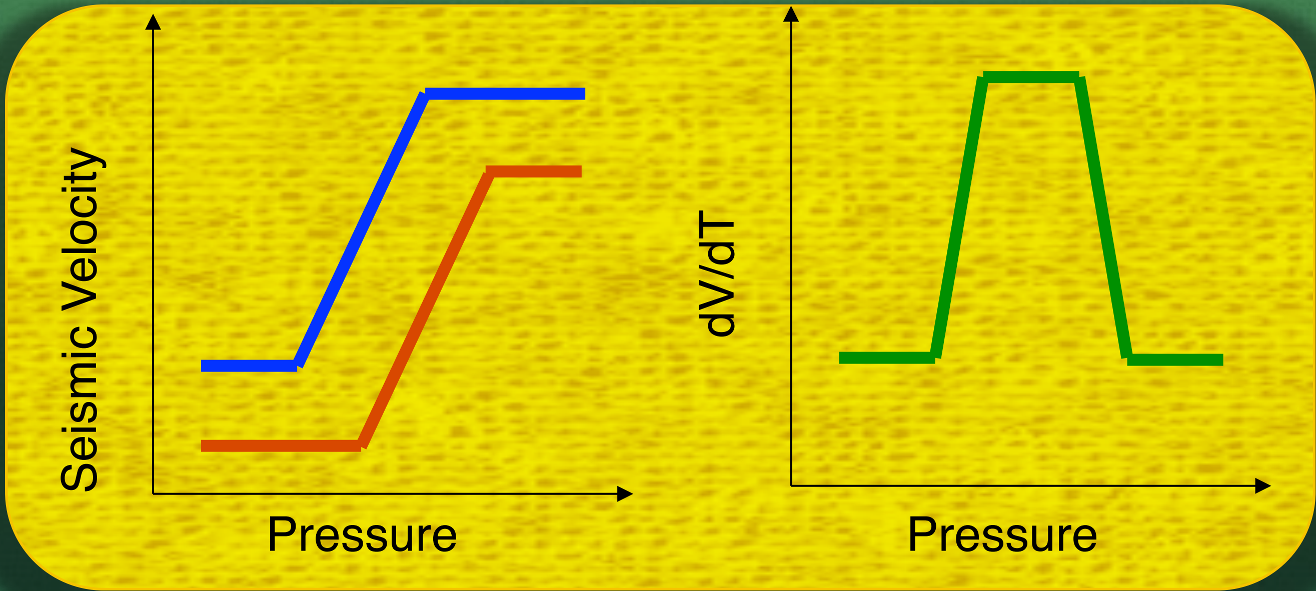
$$M_R^* = \left(\sum_\alpha \frac{\phi^\alpha}{M^\alpha}\right)^{-1} < M^* < \sum_\alpha \phi^\alpha M^\alpha = M_V^*,$$

Grain Scale Heterogeneity



Stixrude & Lithgow-Bertelloni (2007) EPSL

Mantle Heterogeneity: Phase

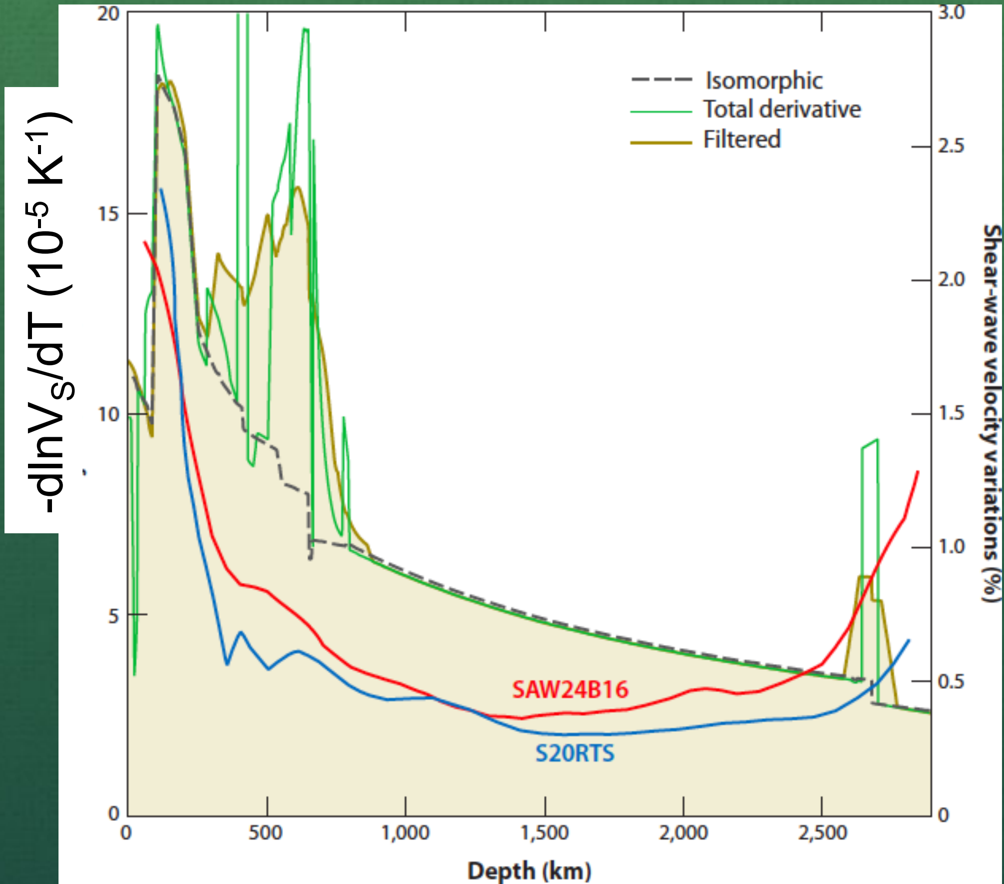


$$\left(\frac{\partial \ln \rho}{\partial T}\right)_P = \left(\frac{\partial \ln \rho}{\partial T}\right)_{P,n_i} + \left(\frac{\partial \ln \rho}{\partial n_i}\right)_P \left(\frac{\partial n_i}{\partial T}\right)_{eq}$$

Total **Isomorphic** **Metamorphic**

Stixrude & Lithgow-Bertelloni (2007) EPSL

Grain Scale Heterogeneity



Stixrude & Lithgow-Bertelloni (2012) AREPS

Melting and differentiation

Melting and differentiation

Oxide wt %	Mantle	Oceanic Crust	Continental Crust
SiO_2	44.9	47.8	58.0
MgO	42.6	17.8	3.5
FeO	7.9	9.0	7.5
Al_2O_3	1.4	12.1	18.0
CaO	0.8	11.2	7.5
Na_2O	0.11	1.31	3.5
K_2O	0.04	0.03	1.5
H_2O (ppm)	150	2,000	10,000
Mean Atomic Mass	21.1	21.6	21.1

Maaløe and Aoki (1977)
Elthon (1979)
Taylor and McLennan (1985)
Hirschmann (2006)
Wedepohl (1995)

Incompatibility

•Ionic radius

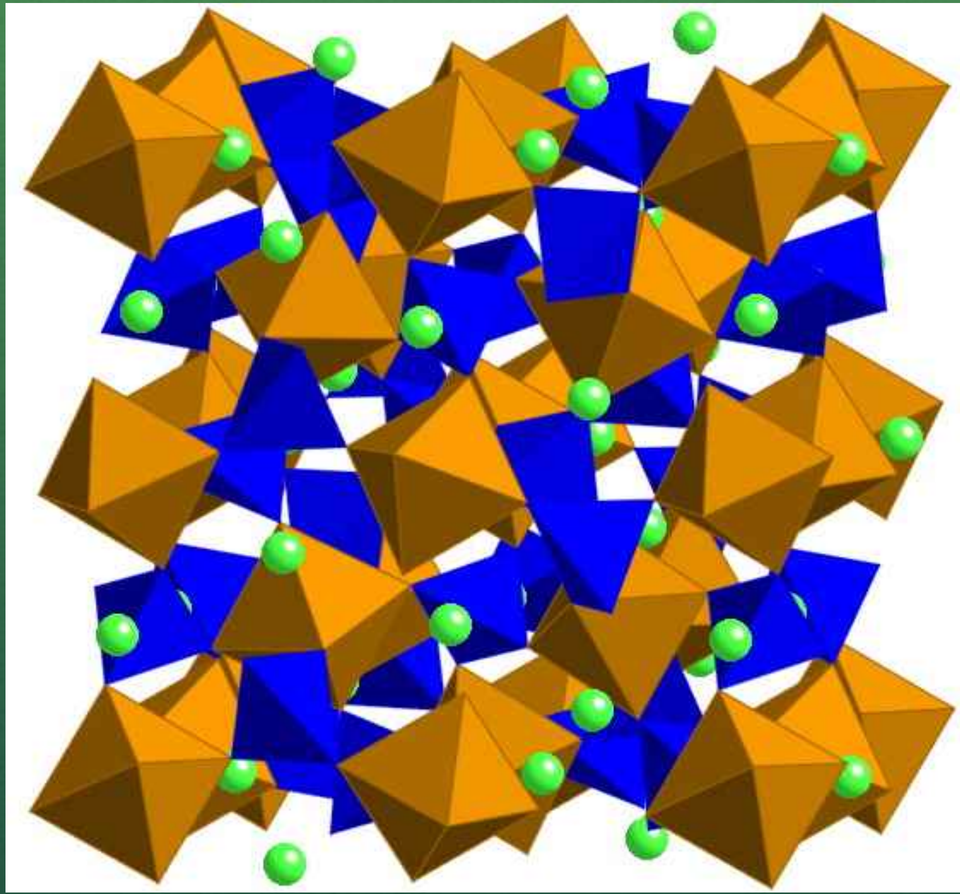
•e.g. alkalis are large

•Structure of coexisting crystals

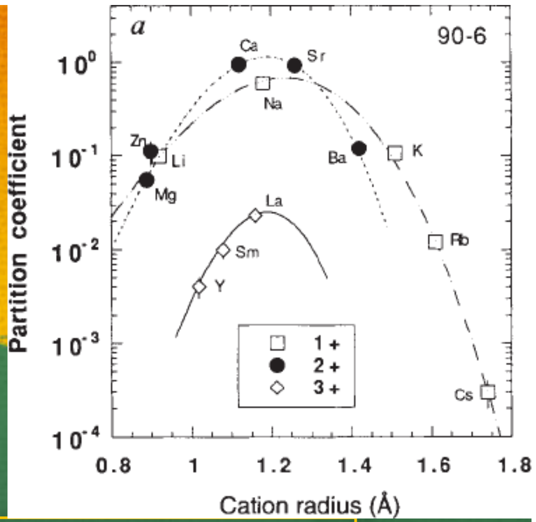
•e.g. garnet retains incompatibles much more completely than other phases

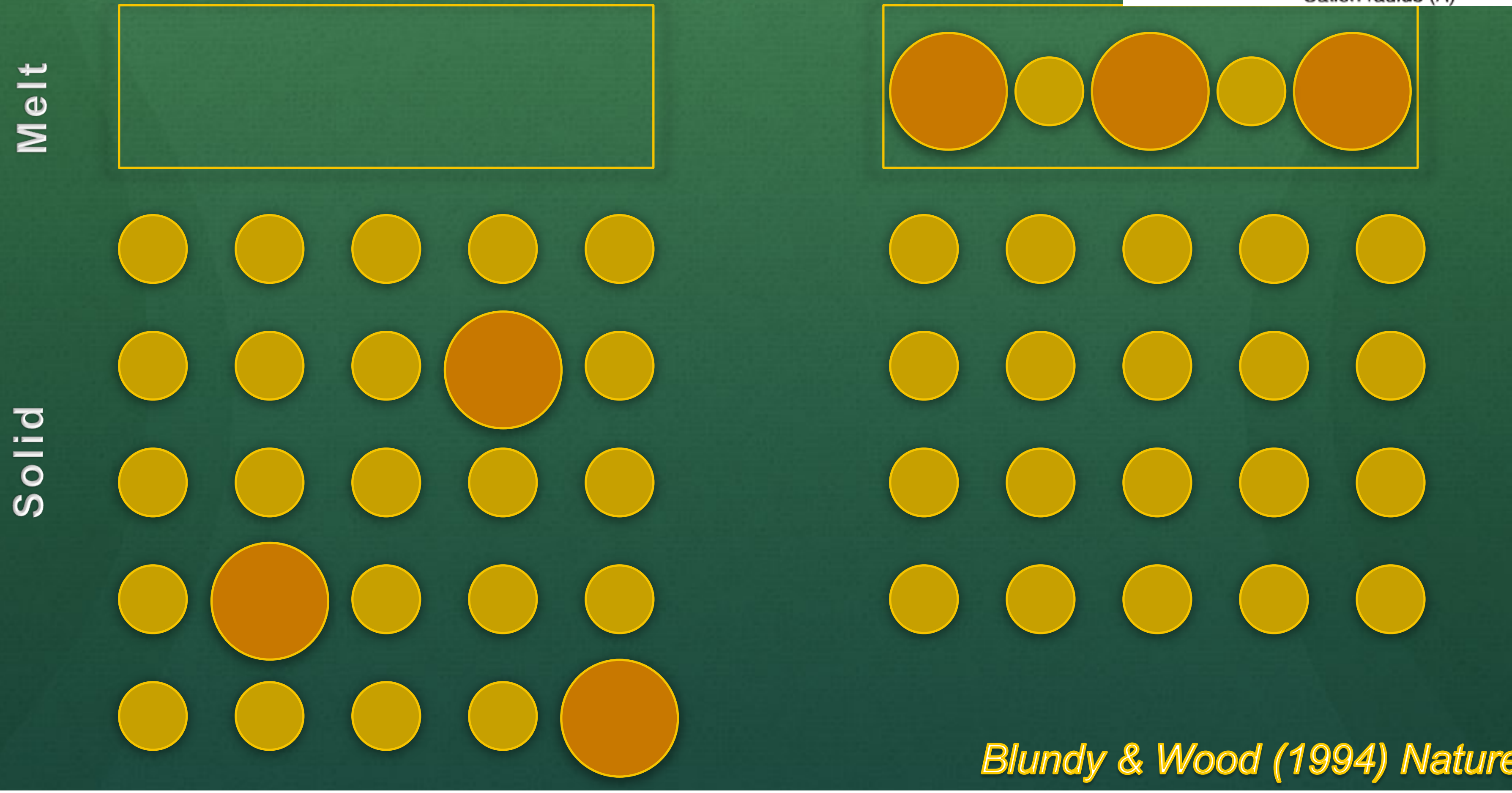
•Garnet signature of MORB

•MORB genesis begins at depths > 80 km



Increasing Length Scale of Heterogeneity

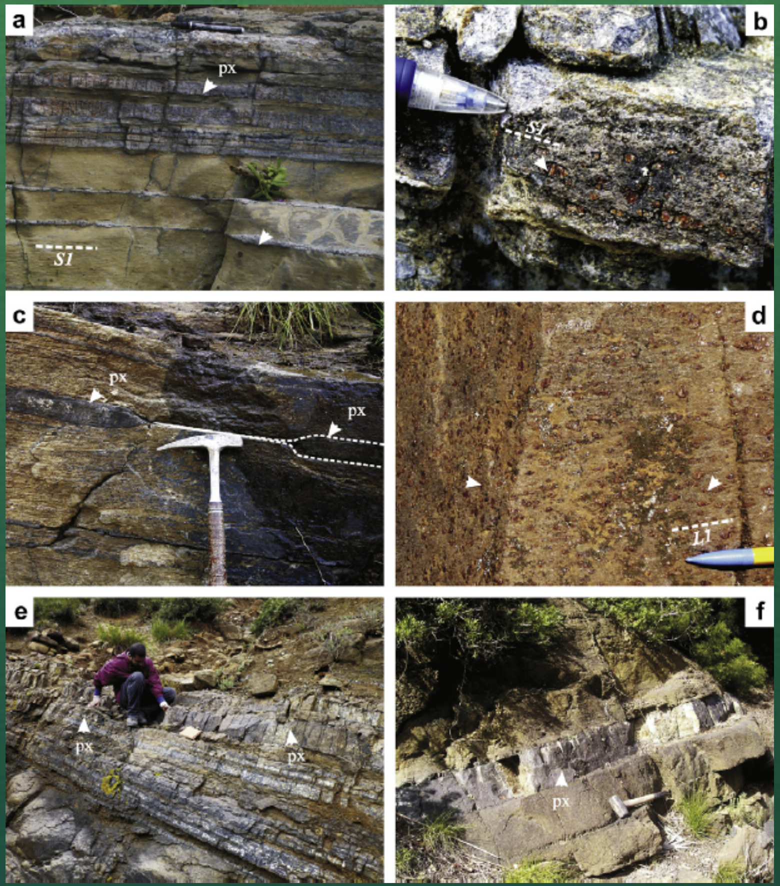




Blundy & Wood (1994) Nature

Lithologic Heterogeneity

- Origin in disequilibrium
- Details of melt extraction
- Stirring
- Diffusion
- Buoyancy



Frets et al. (2012) J. Struc. Geol.

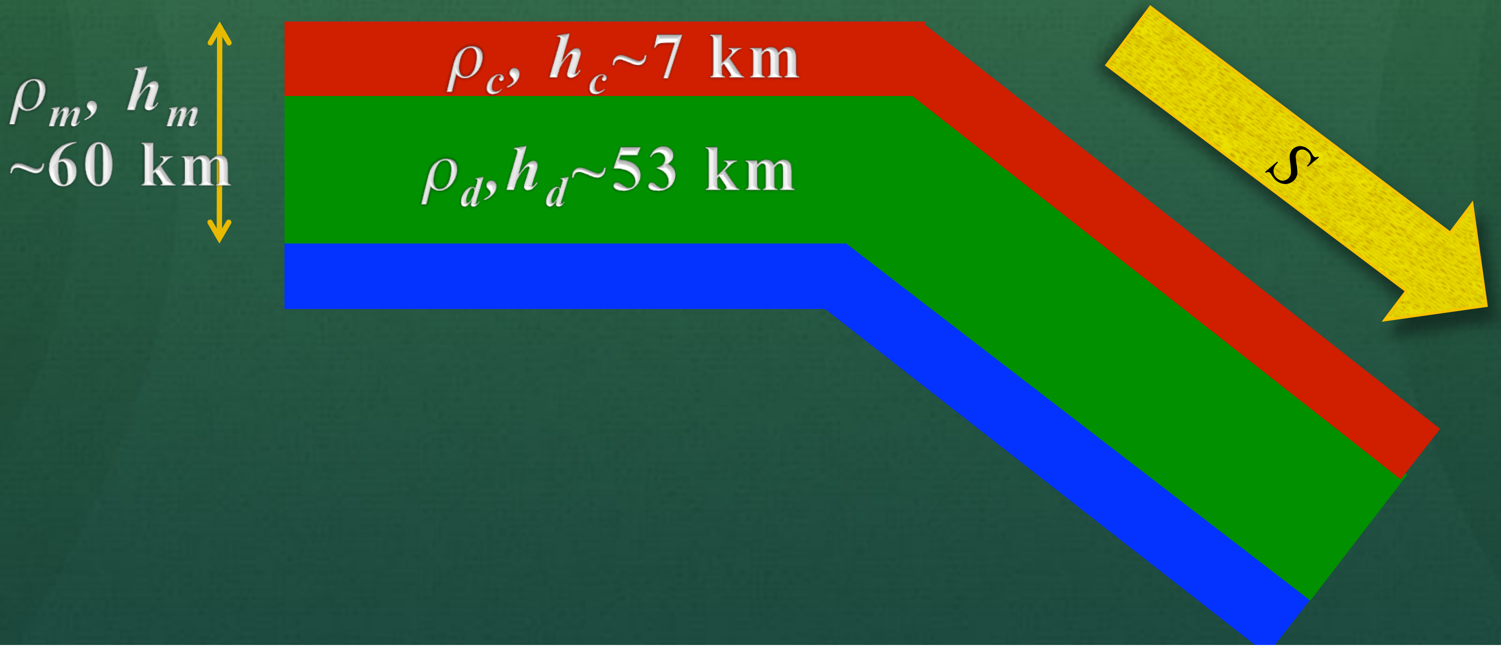
Rate of Production

- Amount of subducted crust
- Amount of subducted depleted
- Amount of mantle processed

$$C = \int \rho_c h_c S dt$$

$$D = \int \rho_d h_d S dt$$

$$M = \int \rho_m h_m S dt$$

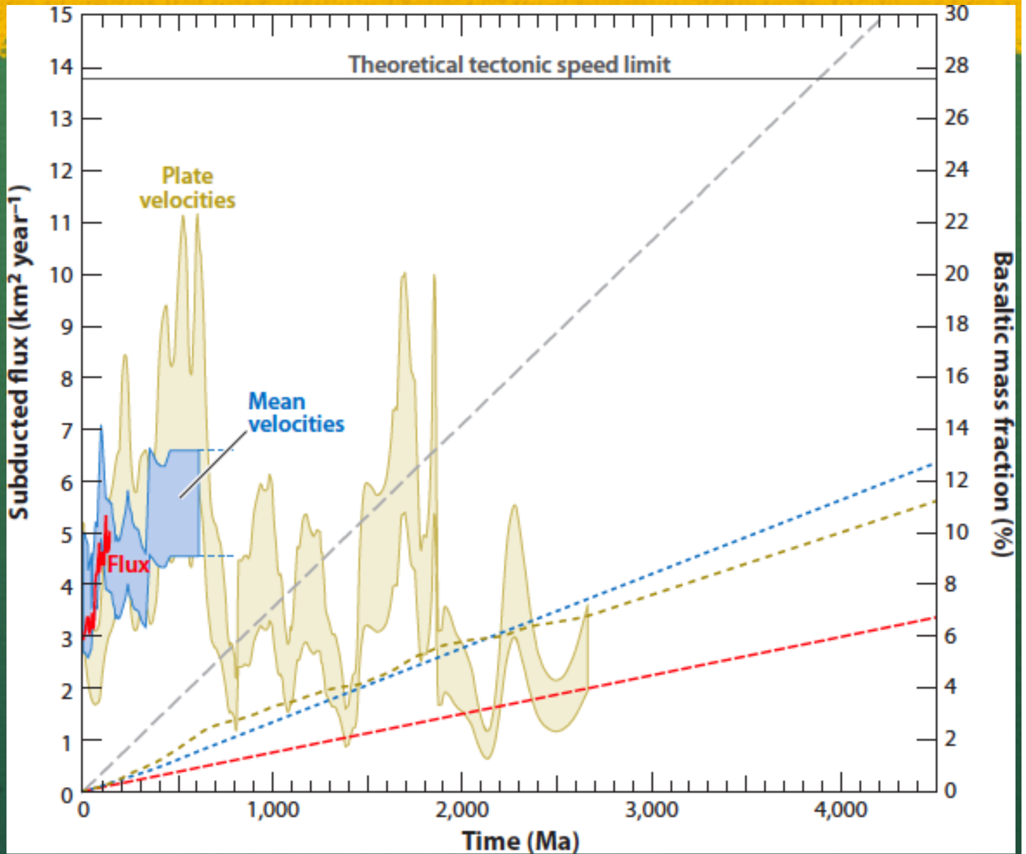


Rate of production

- Amount of subducted crust ~ 12 % of mantle
- Ratio of crust to depleted

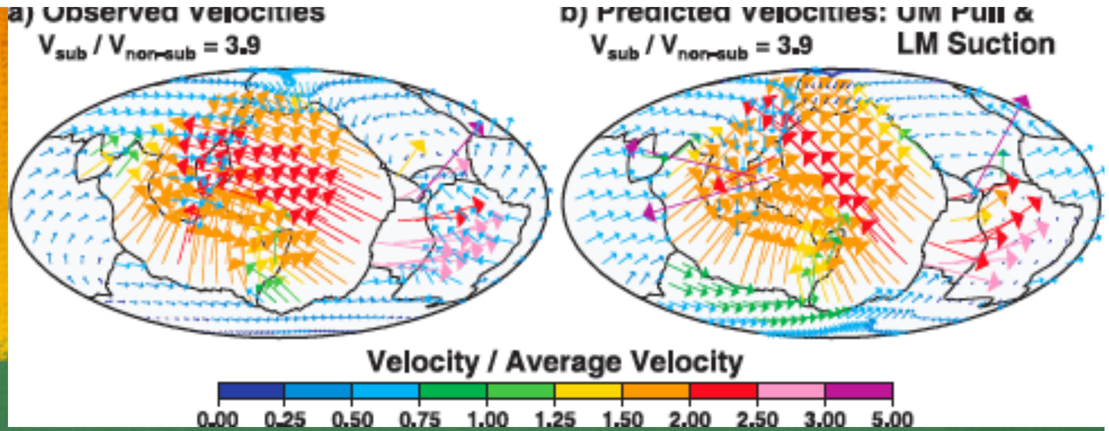
  ~ 7/53~12 %

- Mass balance basalt and harzburgite (18 %)
- Amount of mantle processed ~ 100 %

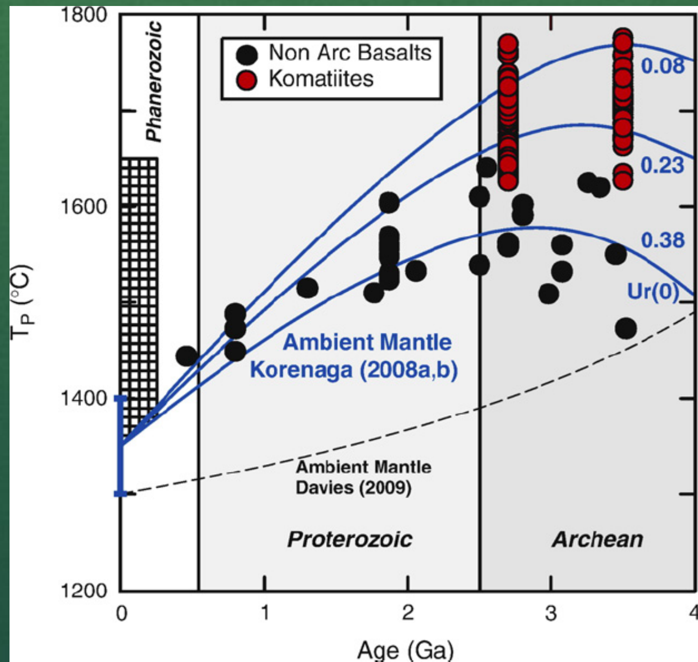


Becker et al. (2009) EPSL
Zhang et al. (2010) JGR
Ulrich & Van der Voo (1981) Tectonophys.
Conrad & Hager (1999)
Stixrude & Lithgow-Bertelloni (2012) AREPS

Production



- Proterozoic rates a lower bound
- Plates with slabs attached tend to move faster
- Earth probably hotter in the past
- Were plate speeds greater?
- Product Sh_C may be more constant (*Klein and Langmuir, 1987*)
- Reprocessing



Conrad & Lithgow-Bertelloni (2004) JGR
Herzberg et al. (2010) EPSL

Survival of Heterogeneity

Survival of heterogeneity

- Diffusion

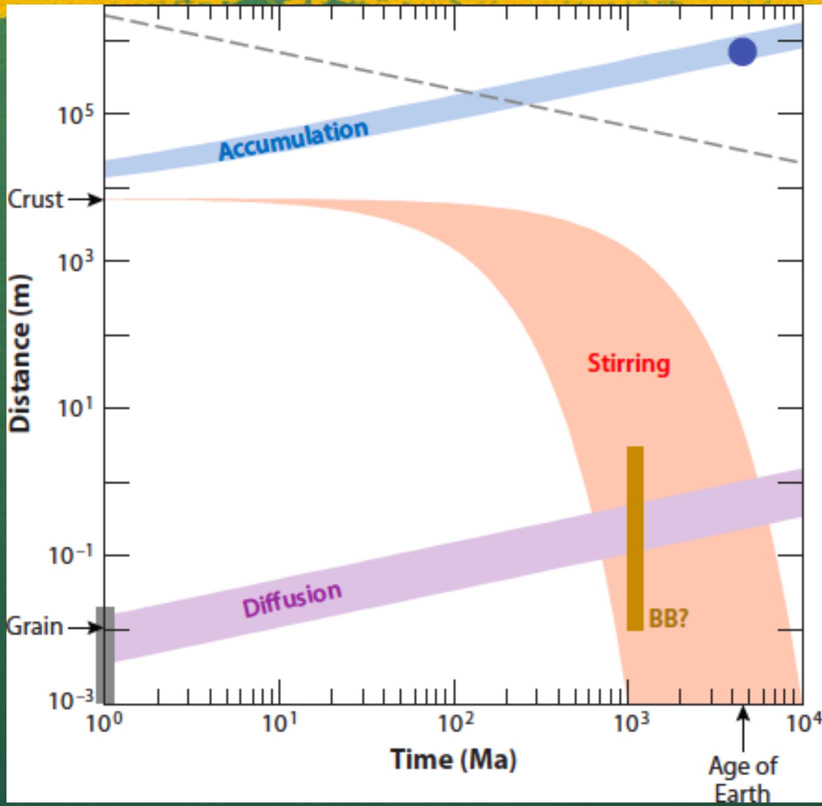
$$h \sim \sqrt{\kappa t}$$

- Stirring

$$h = h_c \exp(-\dot{\varepsilon} t)$$

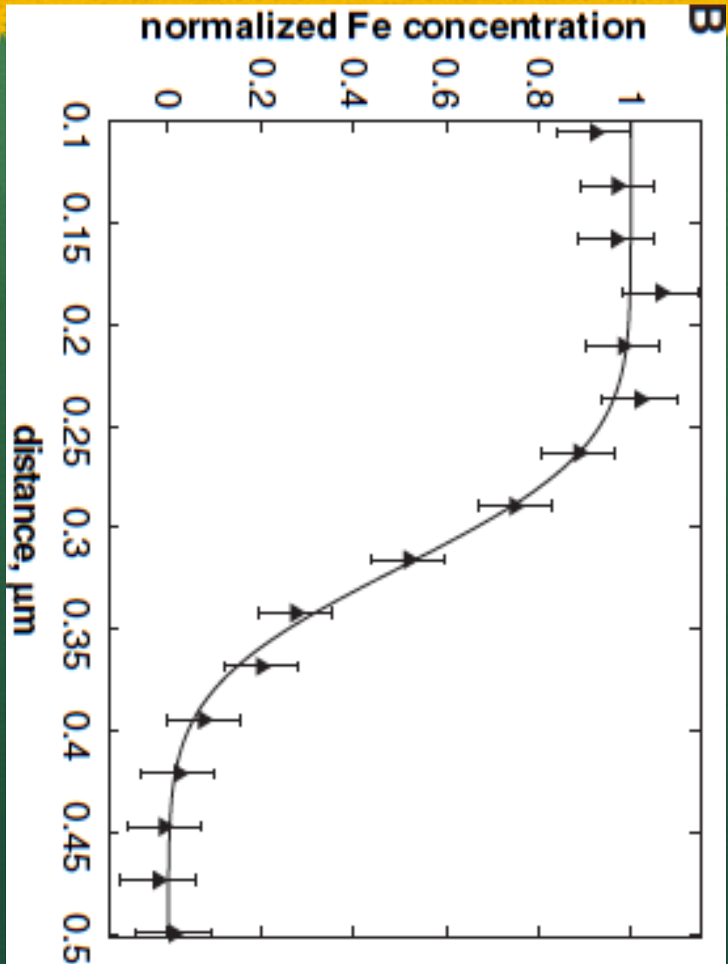
- Buoyant accumulation

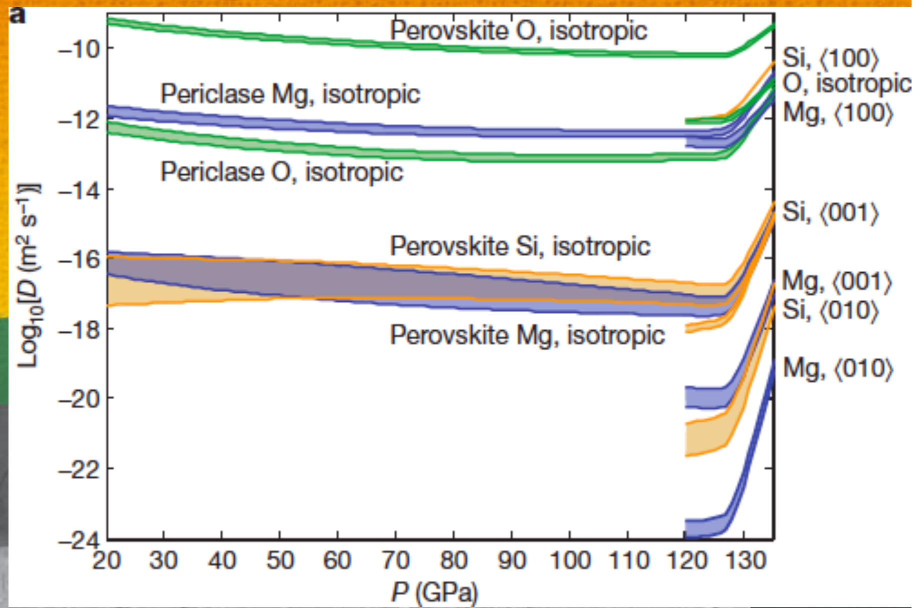
$$h = \sqrt{v h_c t}$$

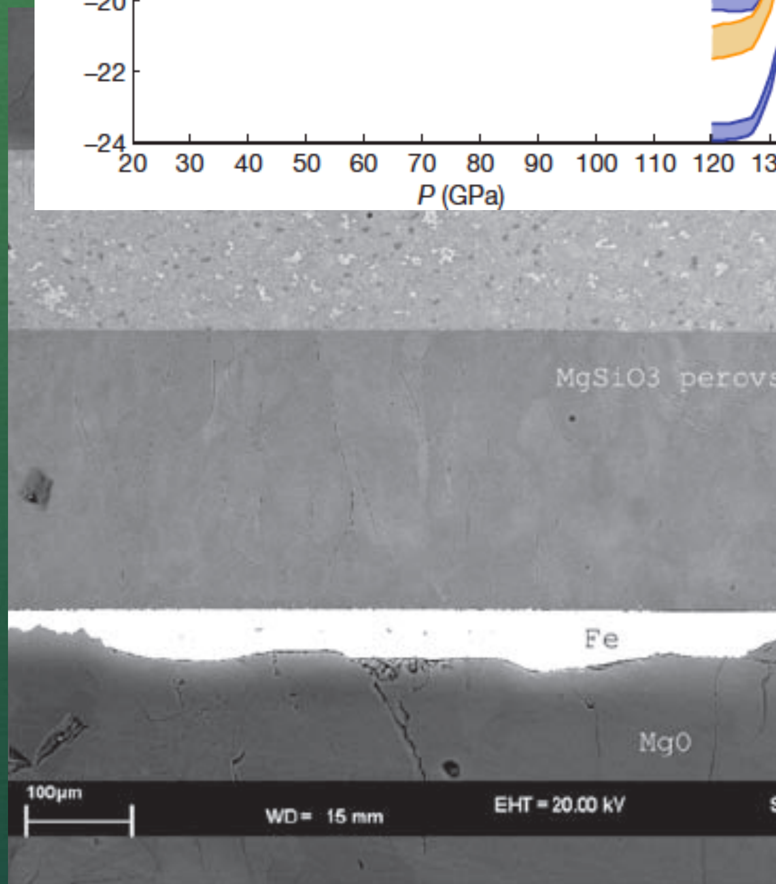


Holzapfel et al. (2005) Science
Spence et al. (1988) GJI
Nakagawa et al. (2010) EPSL
Pearson & Nowell (2004) J. Petrol.
Stixrude & Lithgow-Bertelloni (2012) AREPS

Survival: Diffusion





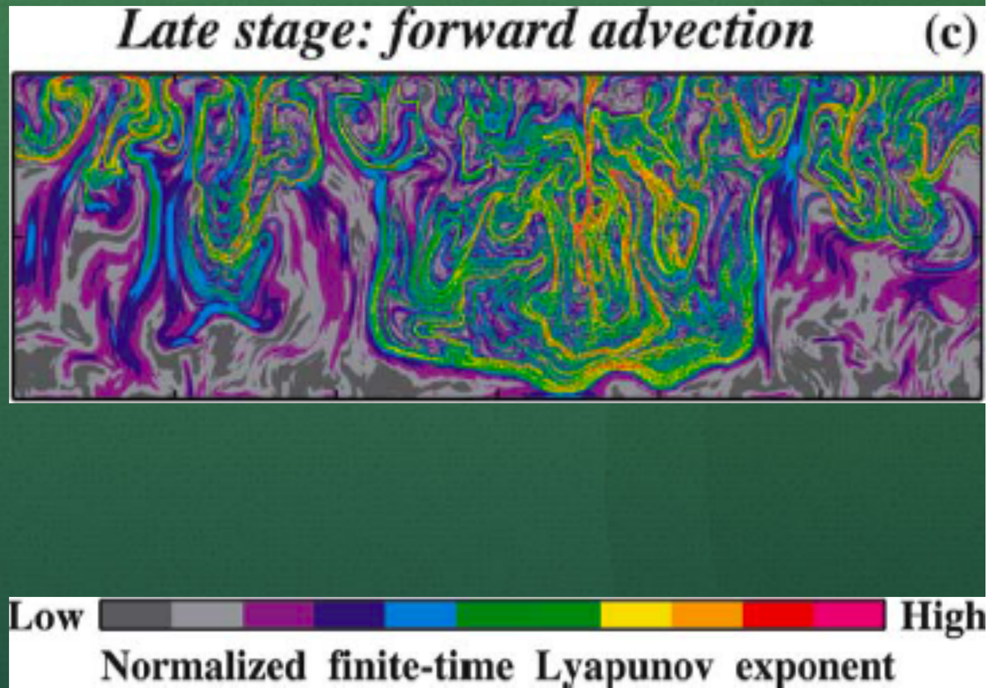


Holzapfel et al. (2005) Science
Ammann et al. (2010) Science

Survival: Stirring

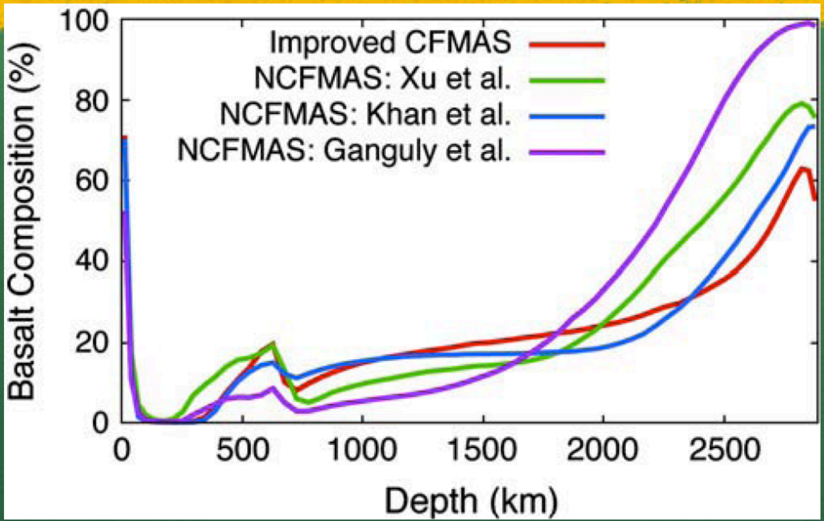
Survival: Stirring

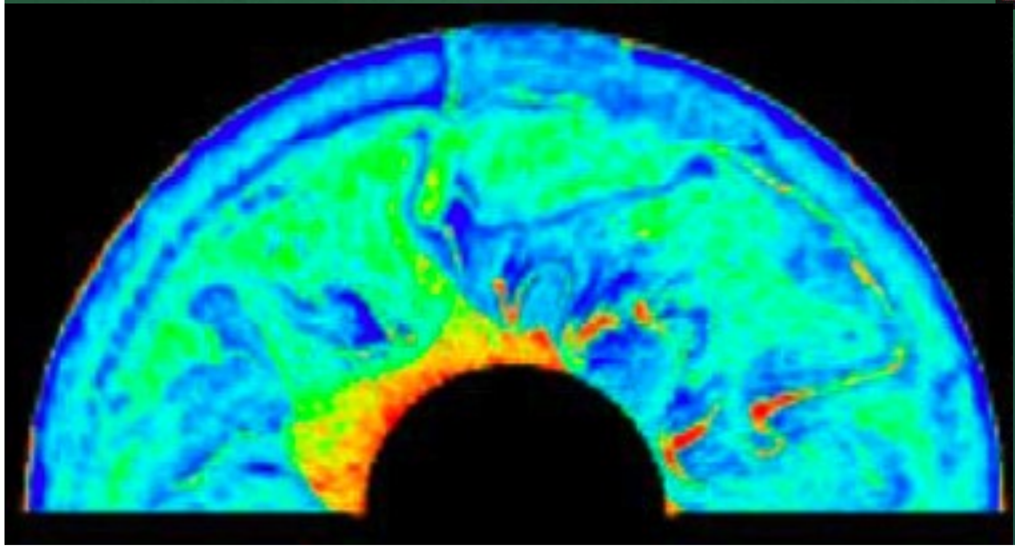
- Rate depends on:
- Amount of pure vs. shear strain
- Amount of toroidal flow
- Chaotic vs. laminar
- Space
- Time



Farnetani & Samuel (2003) EPSL

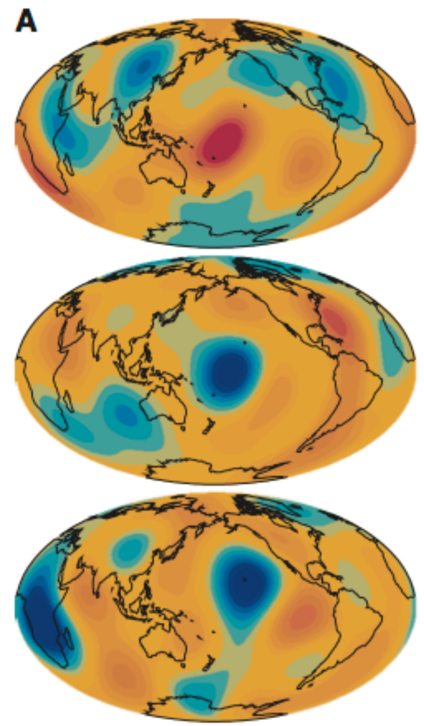
Survival: Accumulation

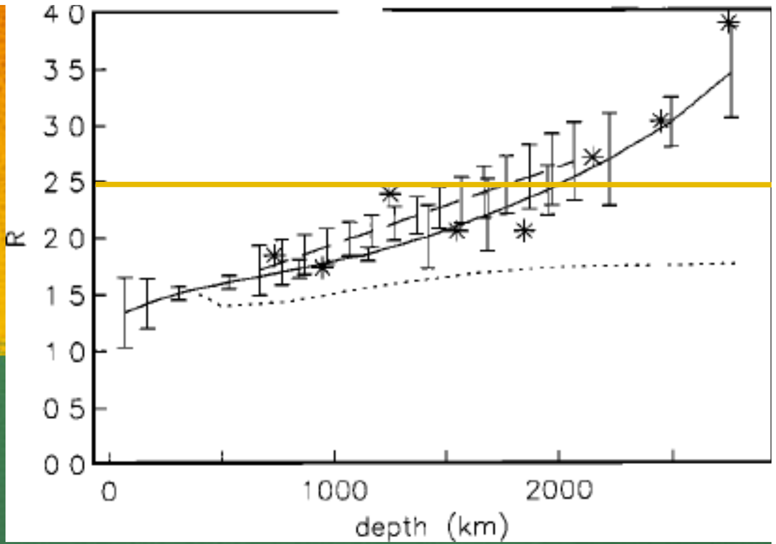


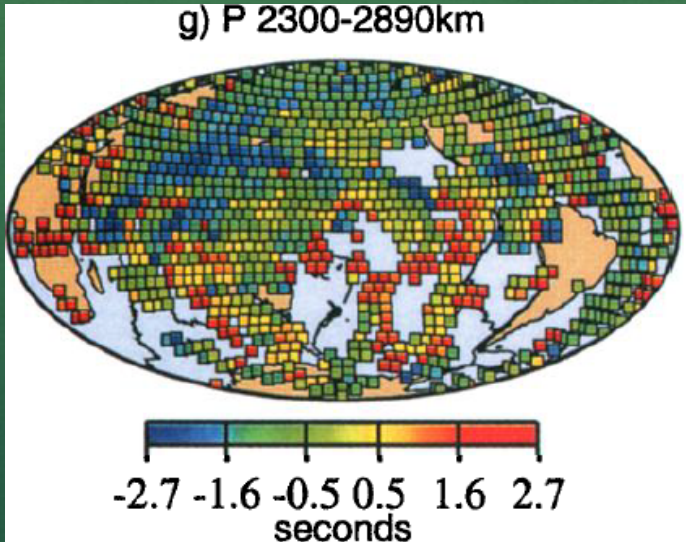


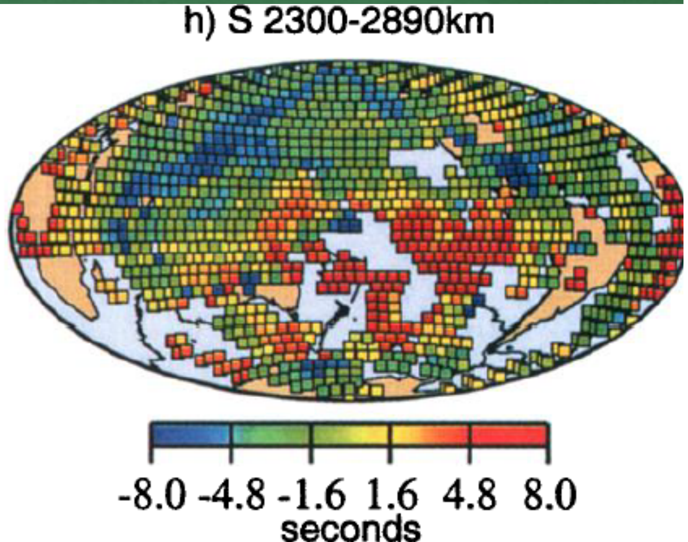
Christensen & Hofmann (1994) JGR
Nakagawa & Buffett (2005) EPSL
Nakagawa et al. (2010) EPSL

Detecting Chemical Heterogeneity









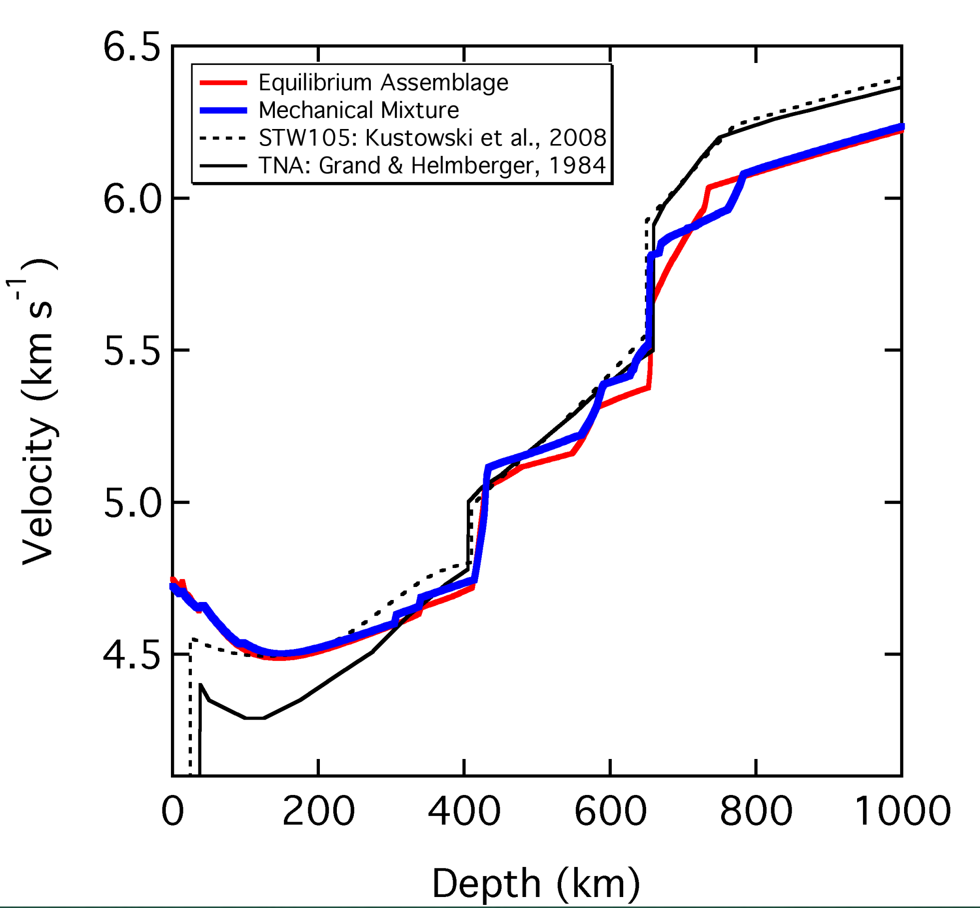
$$R = \left(\frac{\partial \ln V_S}{\partial \ln V_P}\right)_z = \left[\frac{(1-A)(\delta_S - 1)}{\Gamma - 1} + A\right]^{-1} \le 2.5$$

$$A = \frac{4}{3}\frac{V_S^2}{V_P^2}, \quad \delta_S = \left(\frac{\partial \ln K_S}{\partial \ln \rho}\right)_P, \quad \Gamma = \left(\frac{\partial \ln G}{\partial \ln \rho}\right)_P$$

Ishii & Tromp (1999) Science
Bolton & Masters (2001) JGR
Robertson & Woodhouse (1996) JGR

Detecting Chemical Heterogeneity

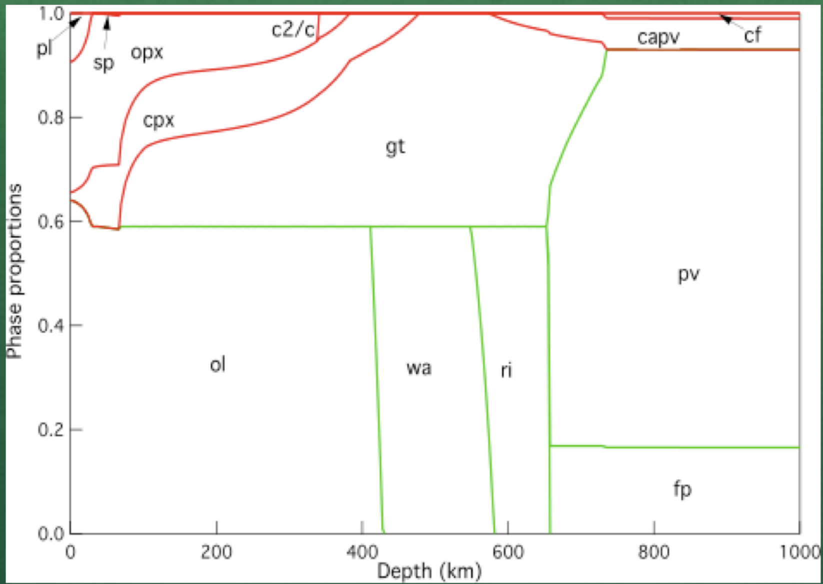
- Lithologically heterogeneous mantle
  - Faster
  - Higher velocity gradient
  - agrees better with seismological models
- Why?
  - Olivine and stishovite faster than pyroxene/garnet



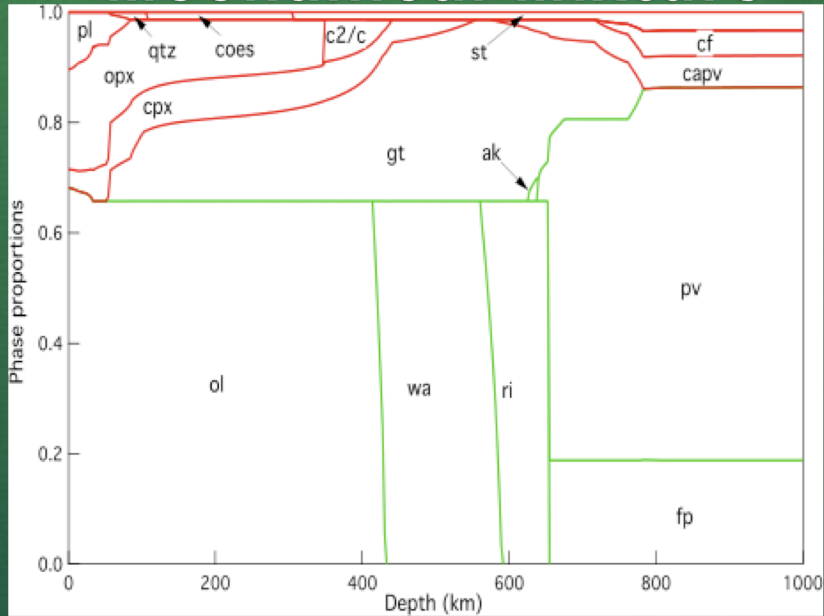
Xu et al. (2008) EPSL

Detecting Chemical Heterogeneity

Equiilbrium Assemblage



Mechanical Mixture



Schematically

$$2MgSiO_3 = Mg_2SiO_4 + SiO_2$$

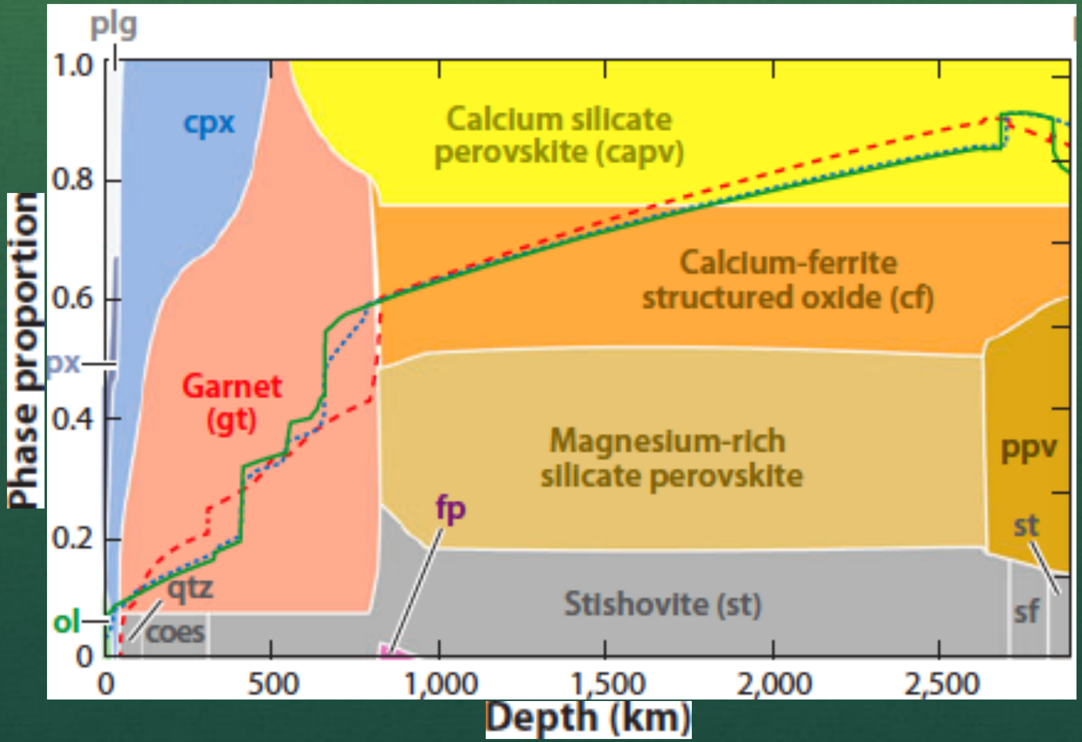
EA Harz. Bas.

Xu et al. (2008) EPSL

Stixrude & Lithgow-Bertelloni (2012) AREPS

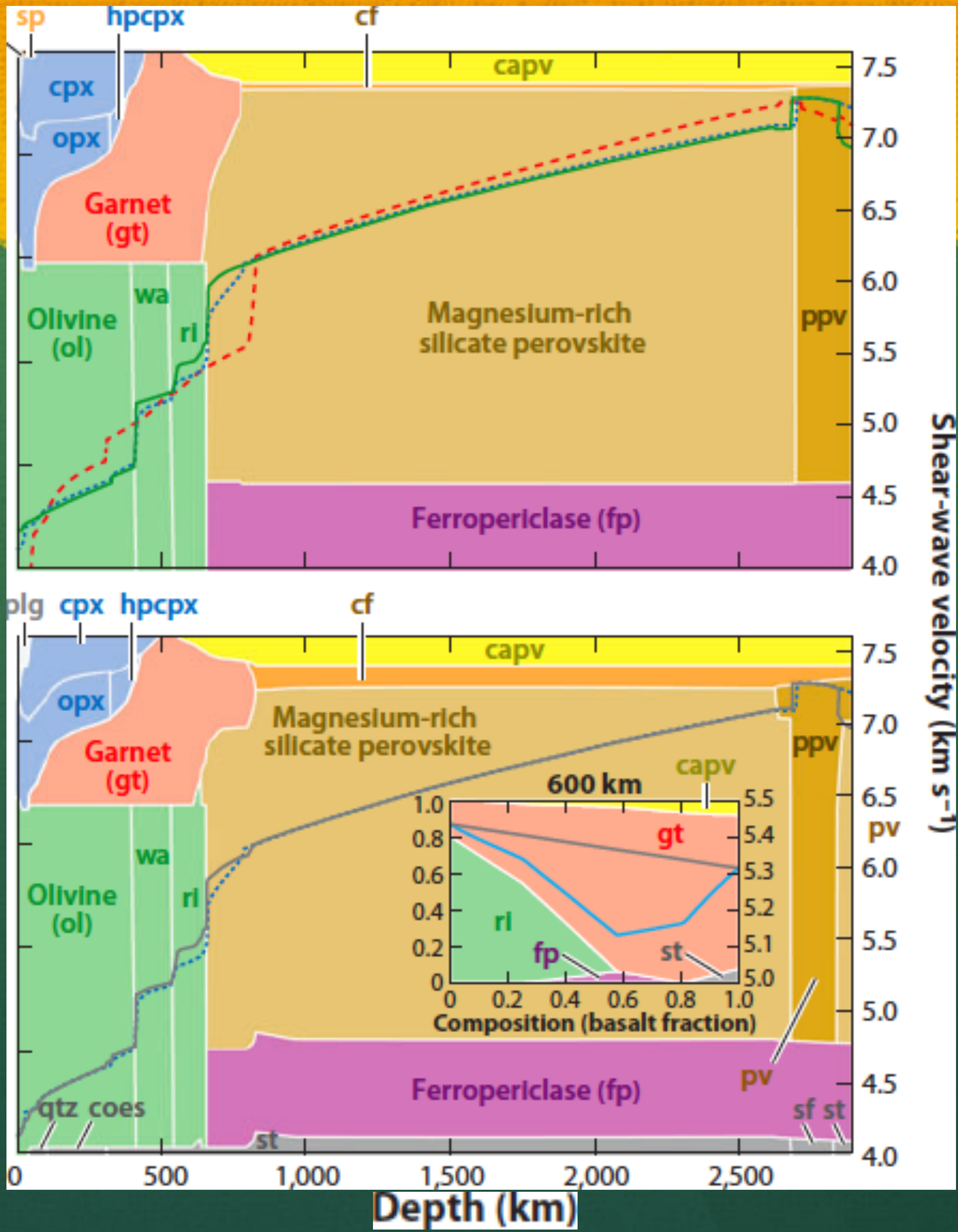
Detection: Reflectors

- Lithologic components show different mid-mantle reflectors
- Basalt: 310 km, 820 km
- Pyrolite/Harzburgite: 410 km, 660 km



Detection: Reflectors

- Post-perovskite
- Single crossing in homogeneous mantle
- Double crossing in heterogeneous mantle
- Experiment (Grocholski et al., 2012, PNAS)
    - No crossing in homogeneous mantle

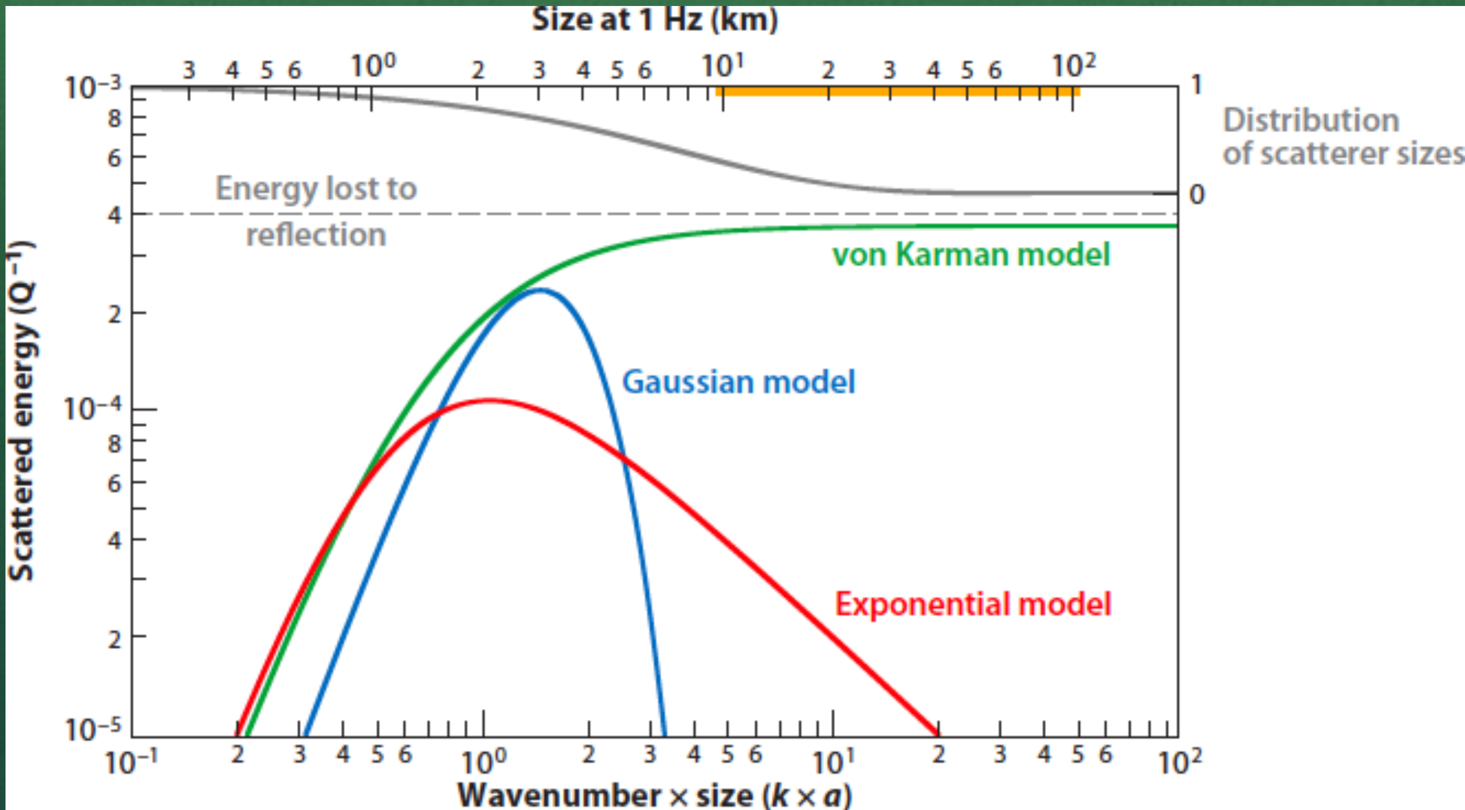


Stixrude & Lithgow-Bertelloni (2012) AREPS

Detection: Scattering

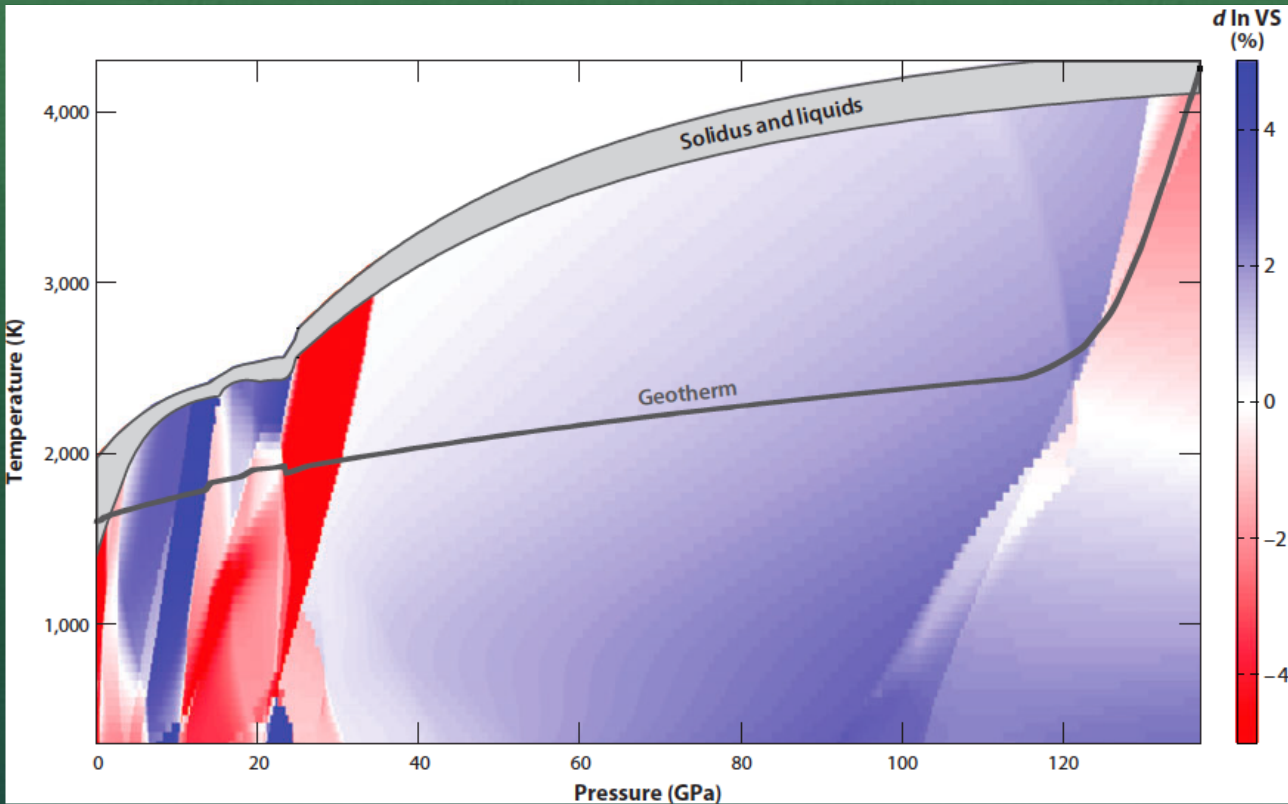
Hedlin et al. (1997) Science
Shearer & Earle (2008) Adv. Geophys.
Kaneshima & Helffrich (1998) JGR
Stixrude & Lithgow-Bertelloni (2012) AREPS

- Analyze in terms of distributed heterogeneity with a range of length scales
- Length scales 1-100 km; Velocity contrast 1-2 %



Detection: Scattering

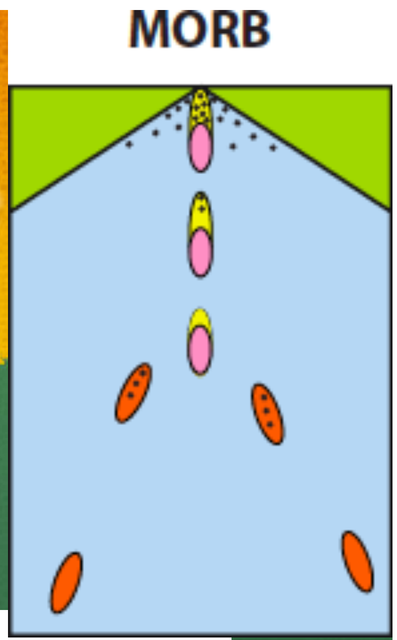
- Scattering analyses agree with expected properties of heterogeneity
- Length scale; Velocity contrast

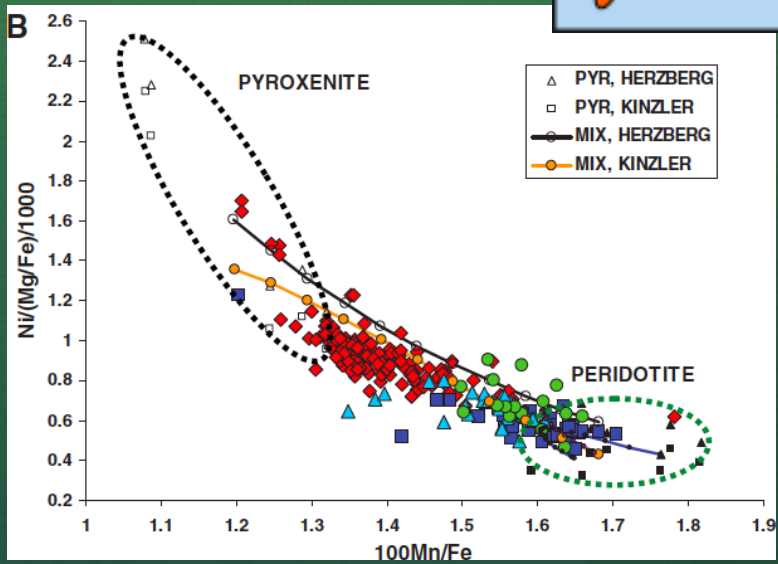


Stixrude & Lithgow-Bertelloni (2012) AREPS

Geochemical Evidence

- Recycled oceanic crust in source of lavas
- Consistent with pervasive heterogeneity
- Usually viewed in terms of plum pudding model, rather than pervasive heterogeneity
- Can a completely differentiated mantle make MORB?





Sobolev et al. (2007) Science

Future Outlook

- Mineral physics ties seismic observation to chemistry
- Reconcile geochemists and geophysicists views of heterogeneity
- Geophysical characterization of geometry and magnitude of heterogeneity
- Geochemical characterization of major element heterogeneity