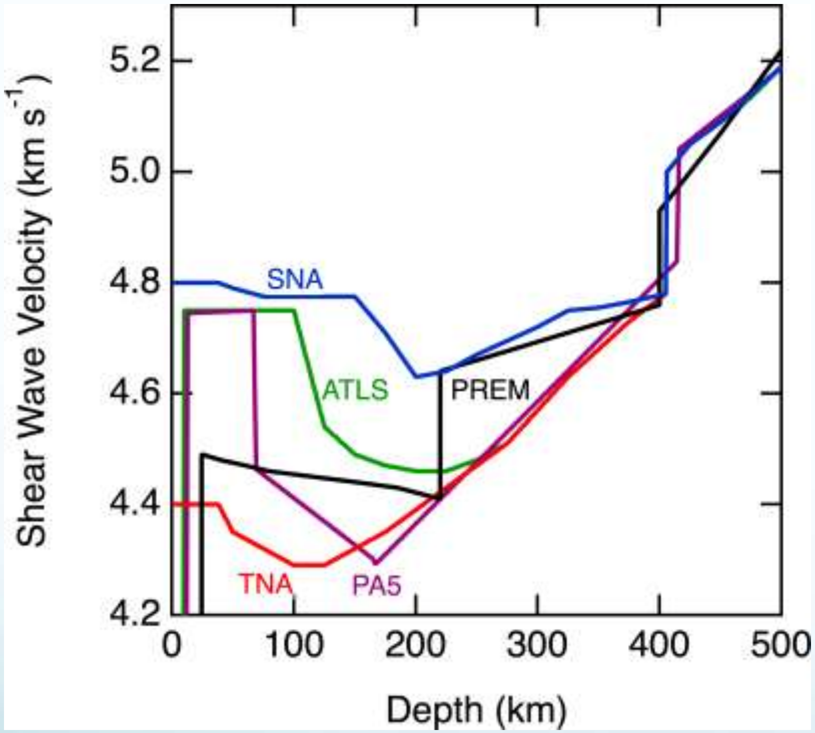
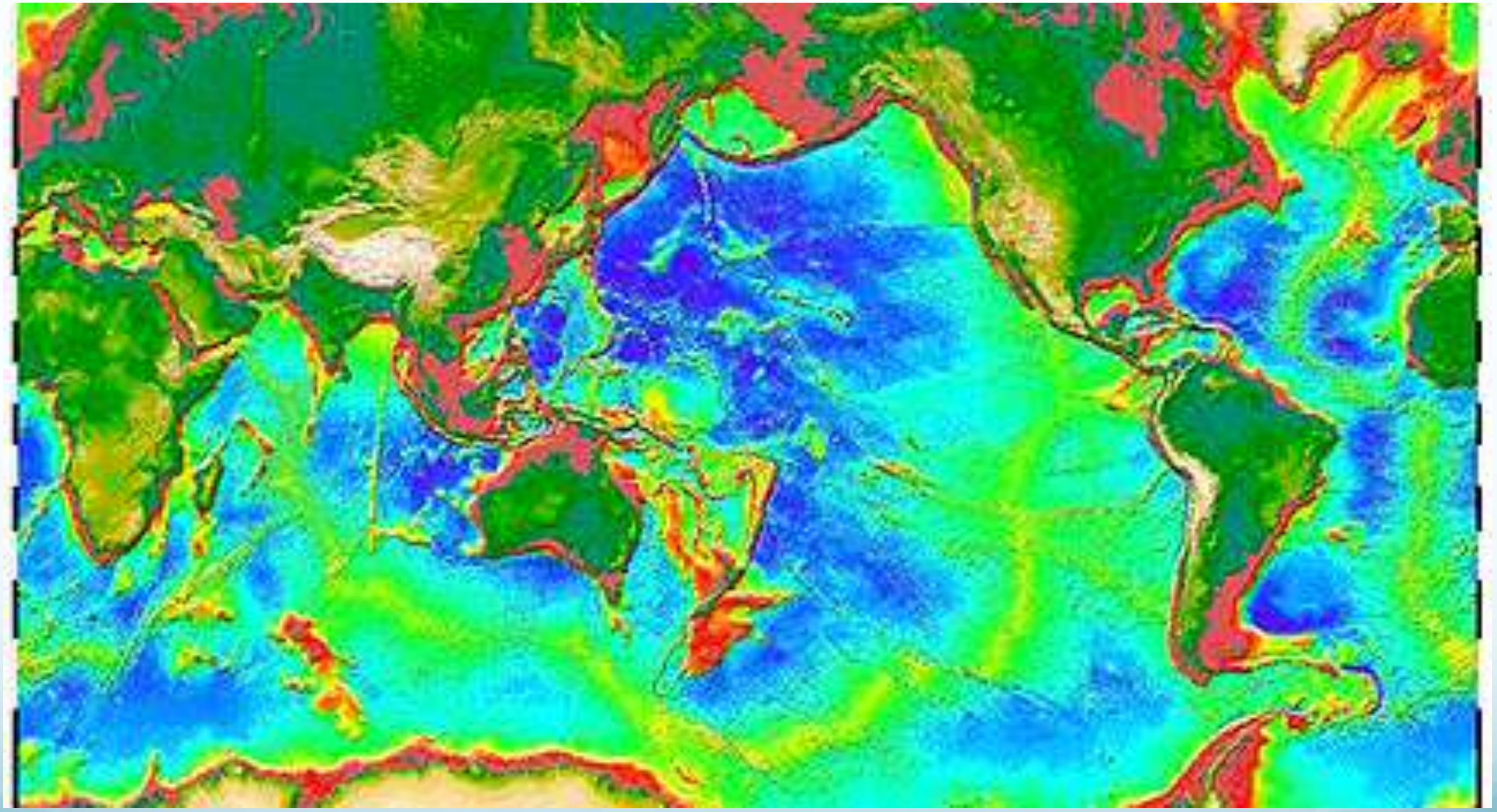
Origin of the Low Velocity Zone

Lars Stixrude
University College London

Nature of the low velocity zone



- Local minimum in seismic wave velocity
- Negative velocity gradient
- Velocity decreases with increasing depth
- Associated with
  - High seismic wave attenuation
  - High electrical conductivity
  - Low viscosity



Smith & Sandwell (1997 Science)

Origin of Low Velocity Zone

$$\left(\frac{\partial T}{\partial P}\right)_{geo} > \beta_S = -\left(\frac{\partial V}{\partial P}\right)_T \Big/ \left(\frac{\partial V}{\partial T}\right)_P$$

- Lithospheric temperature gradient is much greater than β_S for the upper mantle
- Low velocity zone should be widespread on the basis of heat flow observations
- How low is low?

Null Hypothesis

- Minimum of variables
- Experimentally and theoretically well defined
- Captures seismic structure outside of LVZ

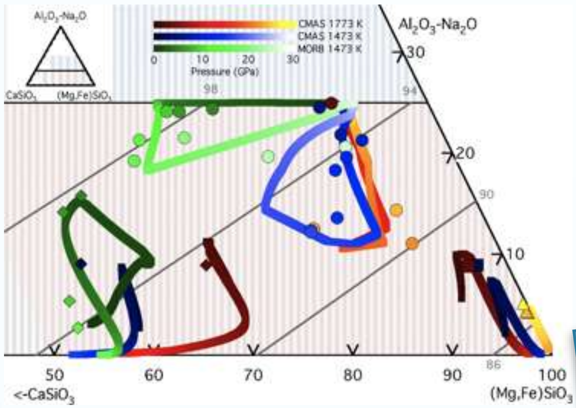
- Definition
  - Elastic limit
  - Fixed bulk composition
  - Thermodynamic equilibrium
  - Depends on P, T, and major element composition

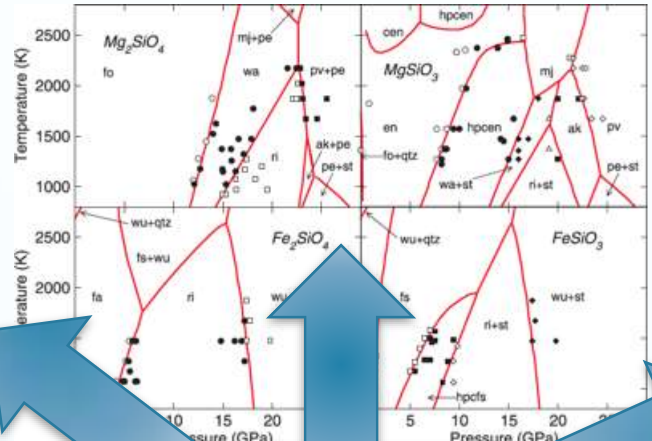
Stixrude & Lithgow-Bertelloni (2005 JGR)

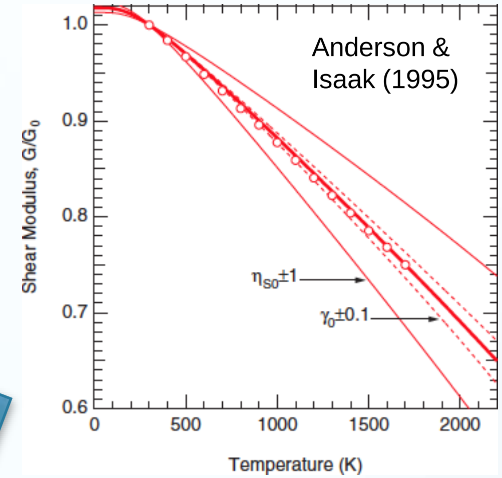
Stixrude & Lithgow-Bertelloni (2005 JGR; 2005 GJI; 2011 GJI)

HeFESTo

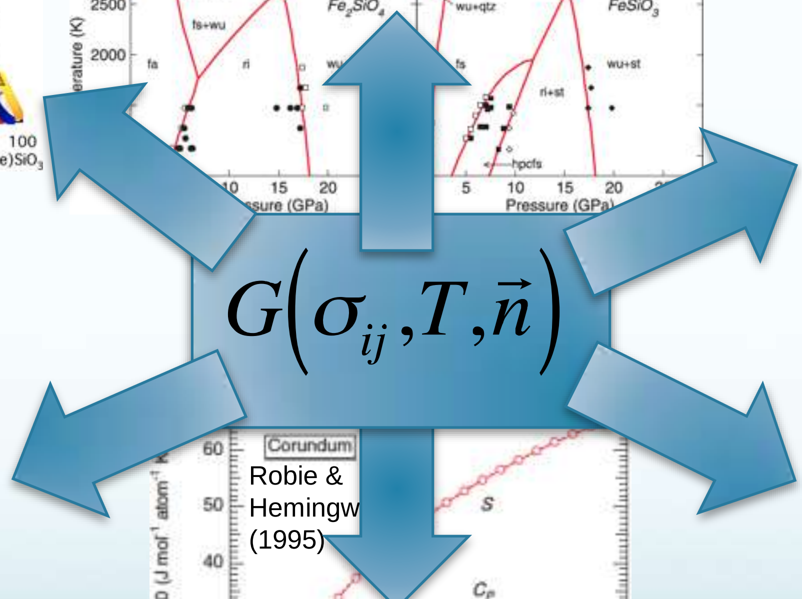
Morishima et al. (1994); Suzuki et al. (2000); Fei et al. (2004); Yang & Ghose (1995); Boyd et al. (1964); Pacalo & Gasparik (1990); Presnall et al. (1998); Ita & Navrotsky (1985); Hirose et al. (2001); Woodland & Angel (1997); Bohlen et al. (1980); Akimoto & Syono (1970); Katsura et al. (1998); Yagi et al. (1987)



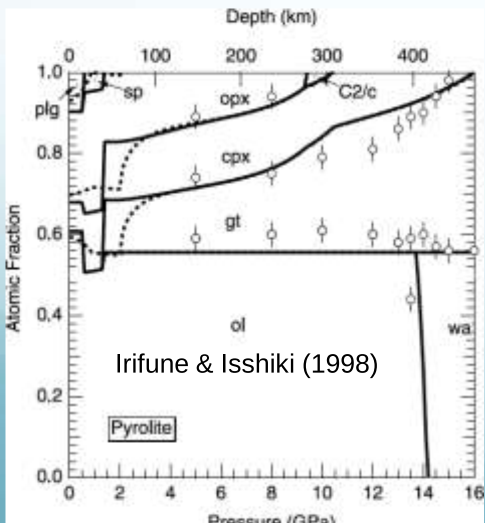


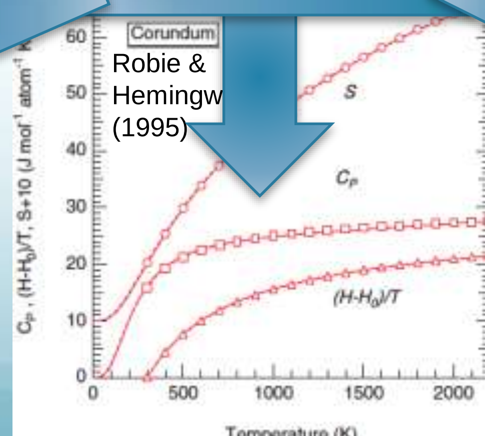


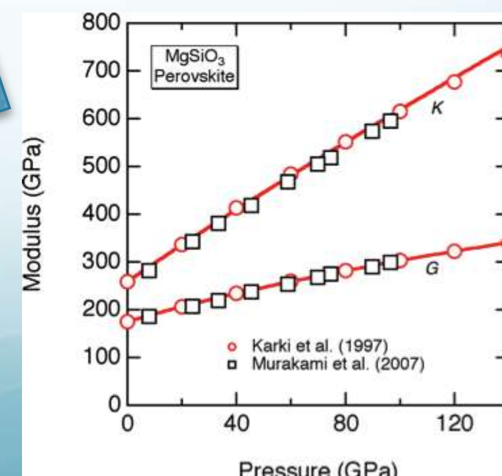
Sen (1985); Irifune et al. (1986); Irifune (1987, 1994); Klemme & O'Neill (2000)



$$G\left(\sigma_{ij},T,\vec{n}\right)$$

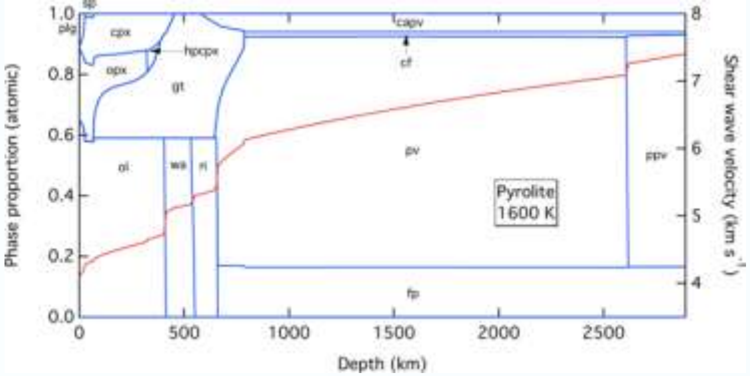


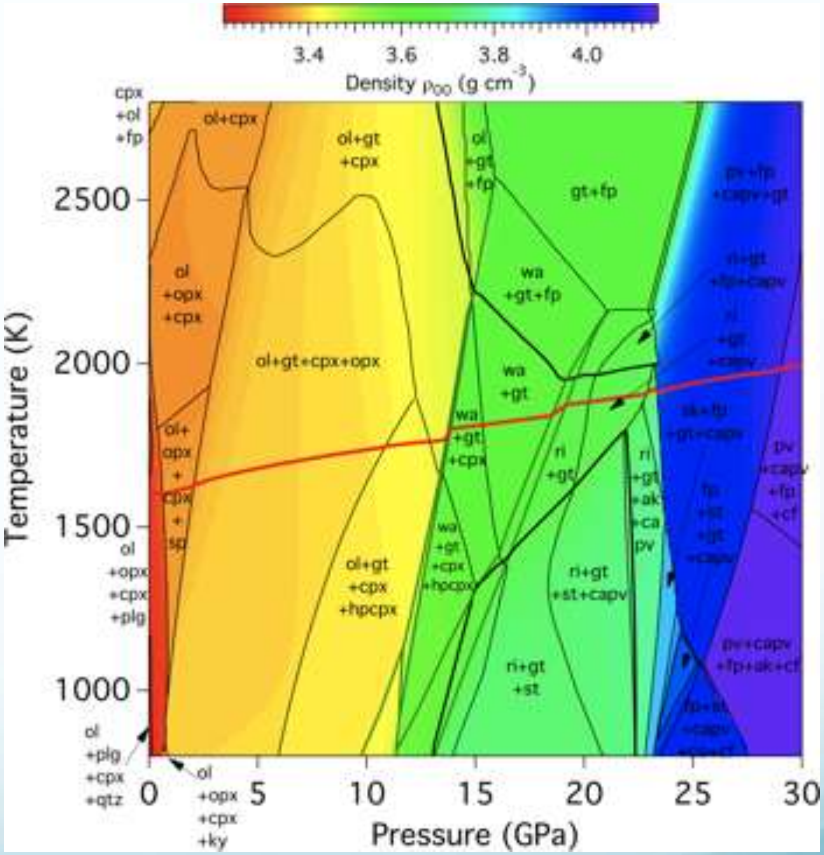




HeFESTo

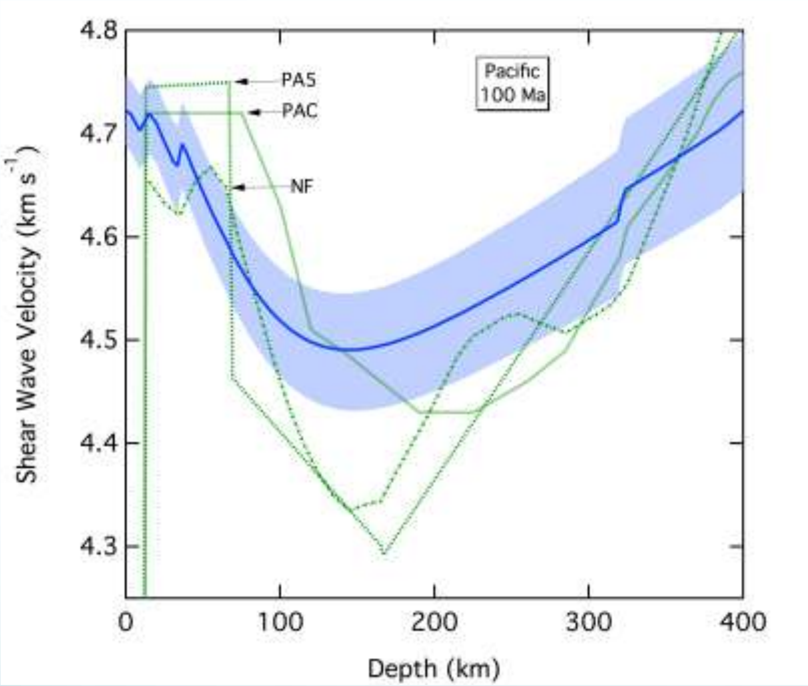
- Helmholtz free energy formulation with Legendre transformation
- Euler form for robust computation across Earth pressure-temperature range
- Generalized to fully anisotropic stress/strain
- Efficient Gibbs free energy minimization with automatic phase addition/subtraction
- 6 Components (NCFMAS)
- 21 Phases
- 47 Species
- Data from ~200 experimental and ab initio studies





Stixrude & Lithgow-Bertelloni (2011 GJI)

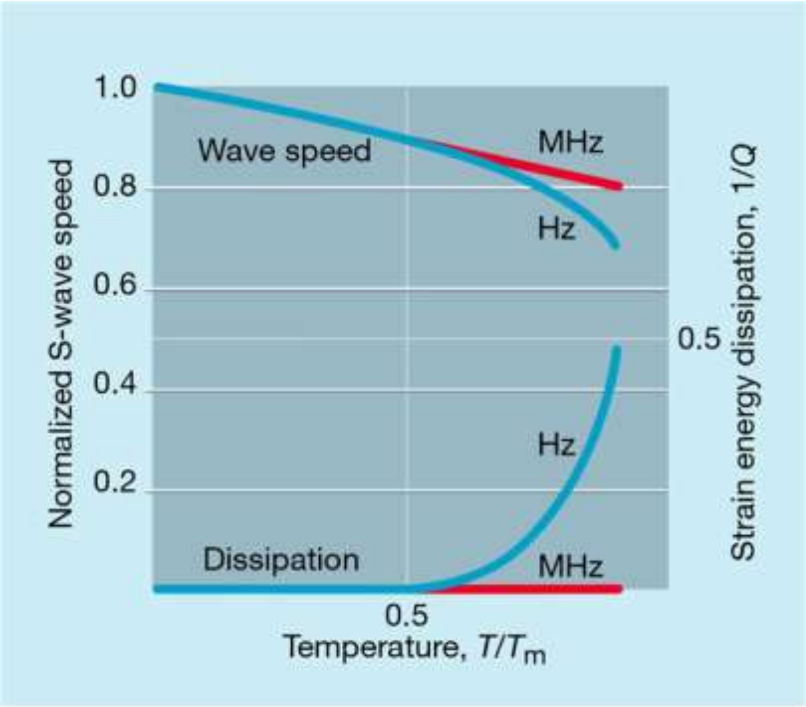
Comparison with Seismology



- Low velocity zone in the null hypothesis is
  - Well defined
  - At the right depth
  - Residual velocity deficit
  - 0.1-0.2 km/s

Stixrude & Lithgow-Bertelloni (2005 JGR; 2011 GJI)

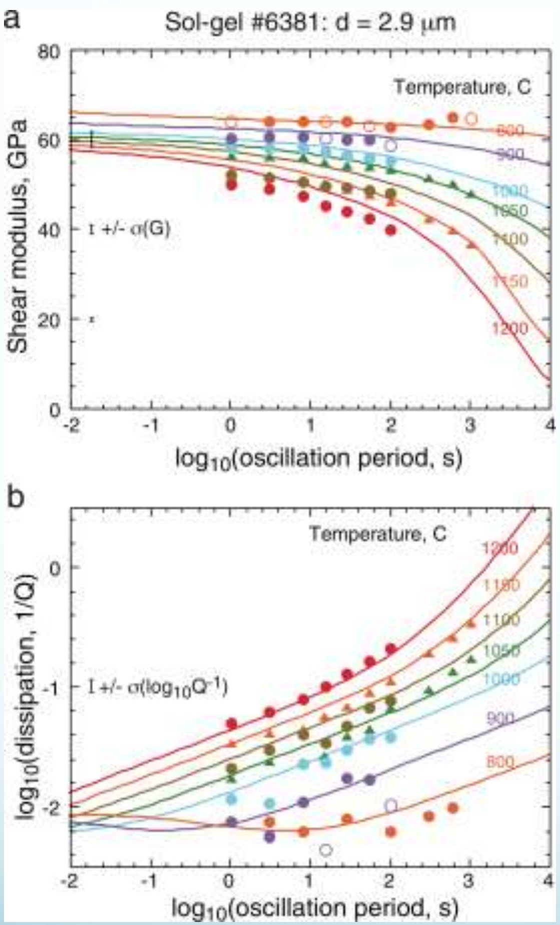
Attenuation and Dispersion



- Seismic observations at finite frequency
- Energy is dissipated
- Entails dispersion
- $V_S(\omega) < V_S(\infty)$

Jackson (2000 Nature)

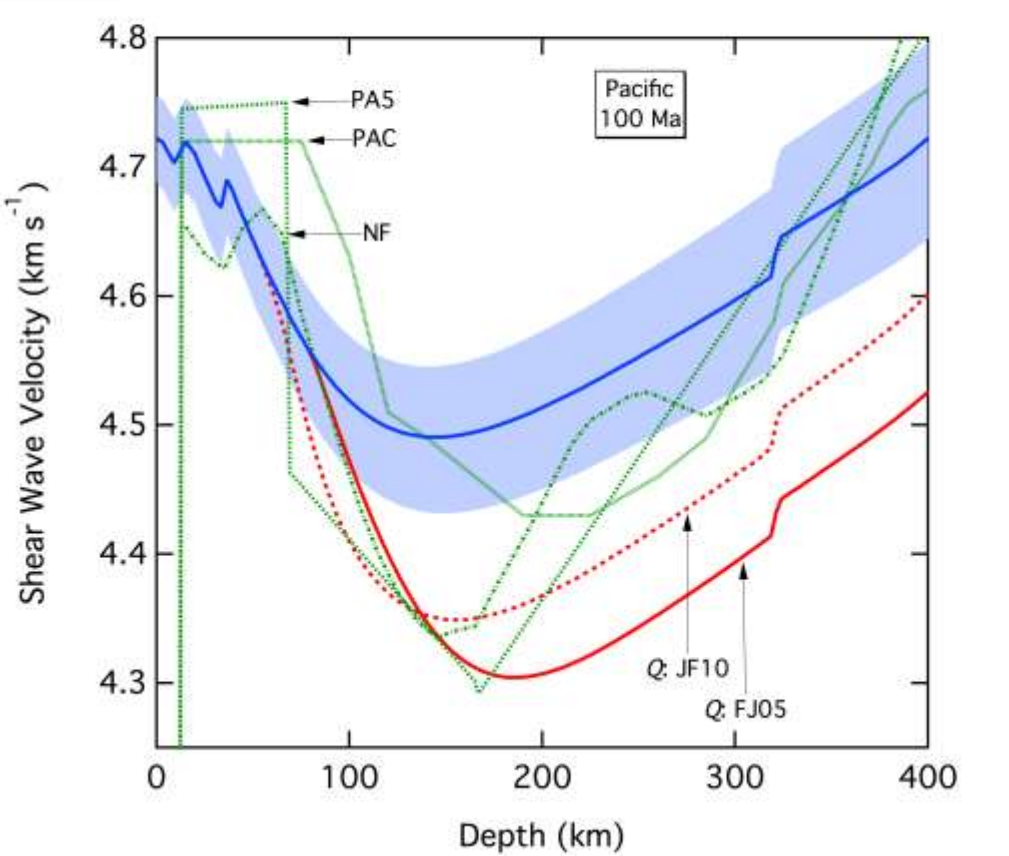
Attenuation and Dispersion



- Experimental measurements
- Seismic frequencies and mantle temperature
- Pressure and grain size are small

Faul & Jackson (2005 EPSL)

Comparison with Seismology



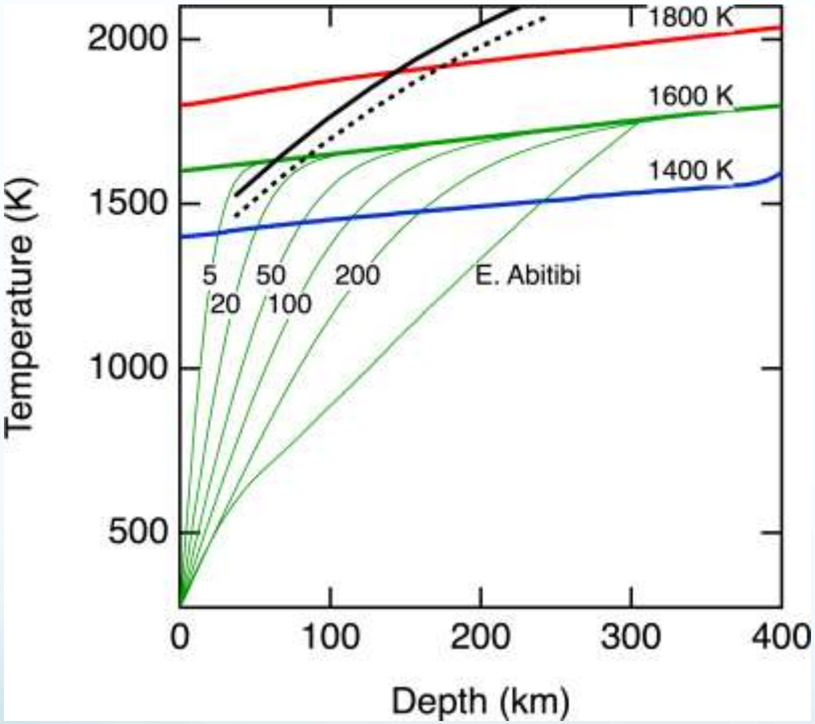
- Attenuation explains residual velocity deficit
- Velocity drops more steeply at top of LVZ
- Magnitude matches G discontinuity
- Is the drop sufficiently sharp to explain receiver function observations?

Stixrude & Lithgow-Bertelloni (2005 JGR; 2011 GJI)

Origin of G Discontinuity (LAB)

- Partial melt?
- Water?
- Anisotropy?
- Extra-band absorption

Partial Melt?

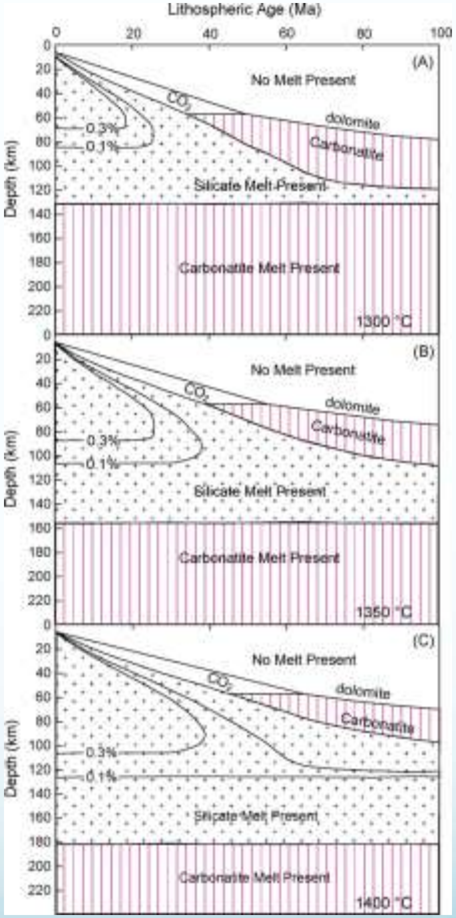


- LVZ is below the wet solidus for ages>20 Ma
- Partial melt is not thermodynamically stable
- If partial melt migrates or accumulates in the LVZ it will freeze
- Partial melt can only be stabilized by anomalous heating

Stixrude & Lithgow-Bertelloni (2005 JGR); Hirschmann (2010 PEPI)

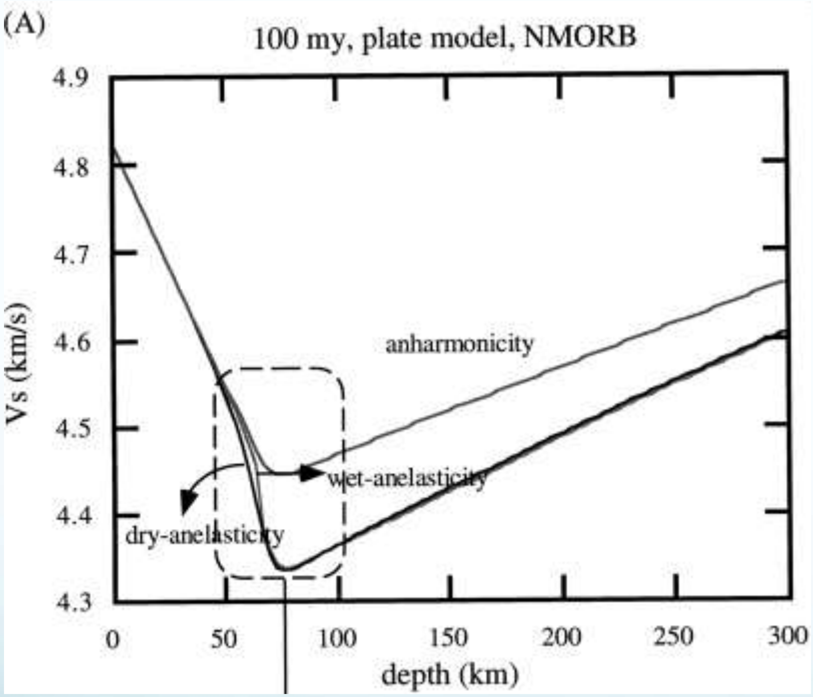
Partial Melt?

- Partial melt may be stable in the LVZ if CO_2 is present
- Amounts of fluid/melt are very small (<0.1 %)
- This is too small to significantly influence seismic wave velocities



Hirschmann (2010 PEPI)

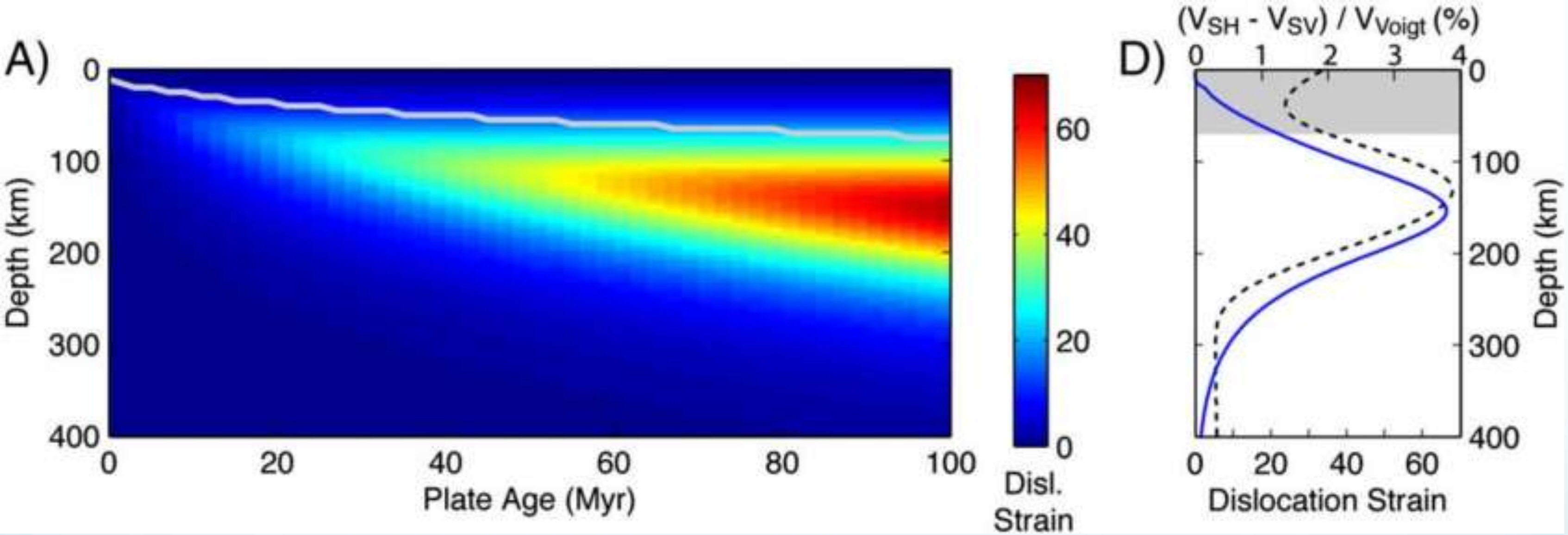
Water?



- Water removed at the melting front
- Attenuation decreases sharply
- But the effect on velocity is small
- Limited by seismically observed attenuation to <2 %

Karato & Jung (1998 EPSL)

Anisotropy

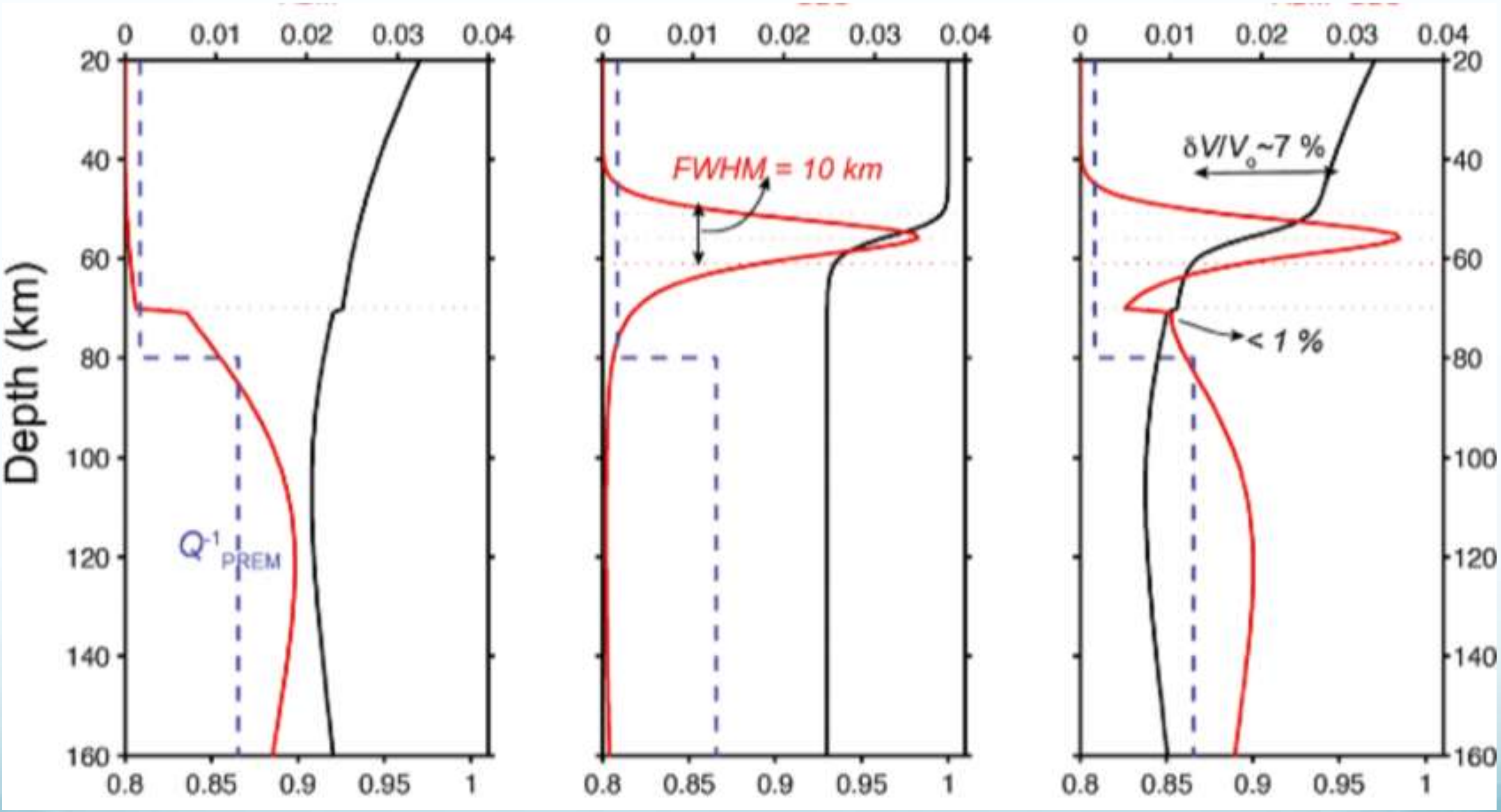


Receiver functions sense the slower polarization in the LVZ
Anisotropy makes the LVZ look slower to receiver functions

Behn et al. (2009 EPSL)

Olugboji et al. (2013 G^3)

Extra-band Absorption



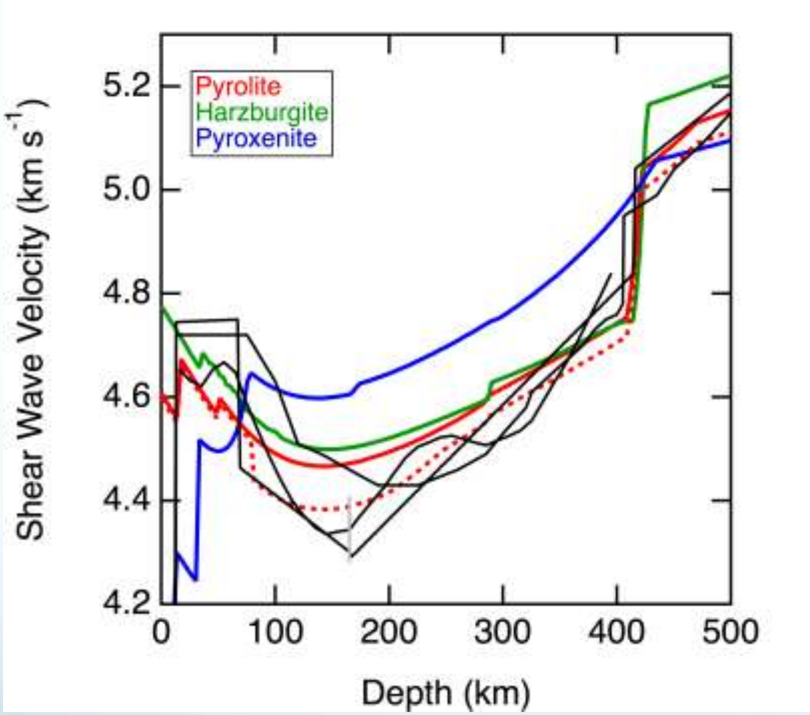
Absorption peak lurks at the high frequency edge of observations

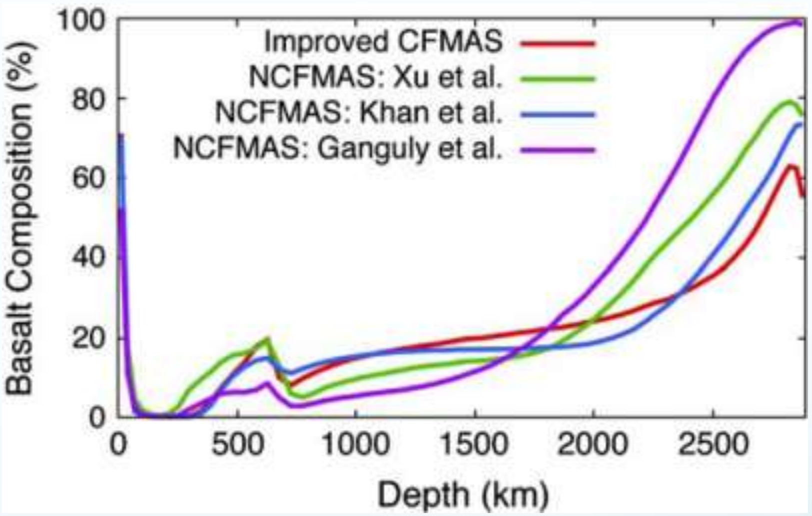
May move across seismic band with changes in P, T, H_2O, etc.

Origin of High Gradient Zone

- Composition varies with depth?
- Grain size varies with depth?
- Potential temperature (entropy) varies with depth?

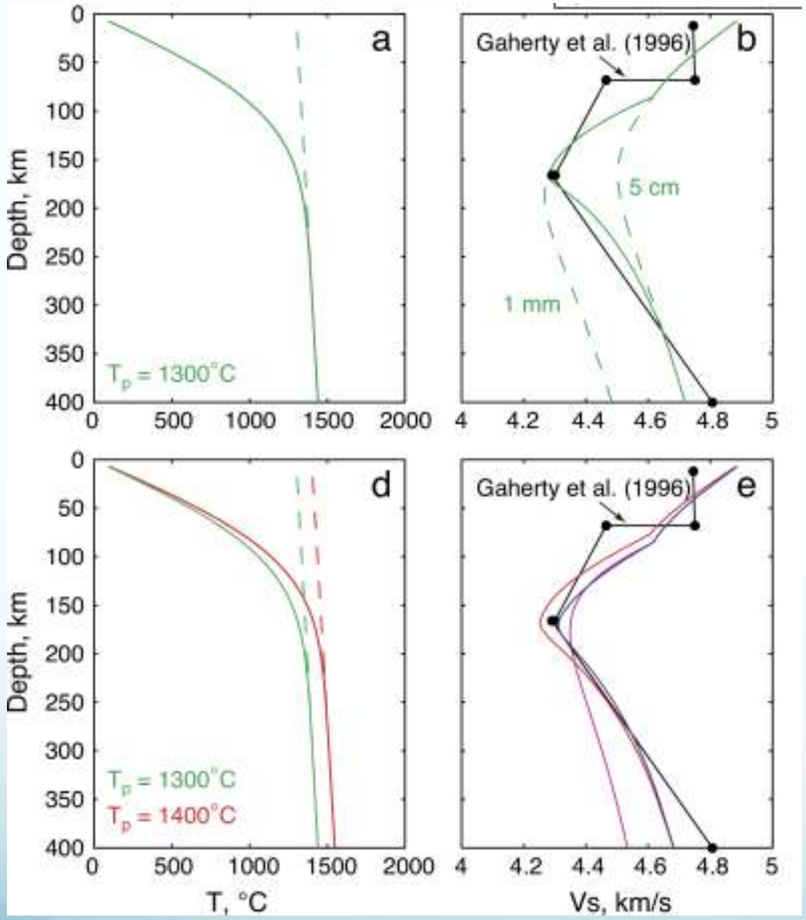
Composition

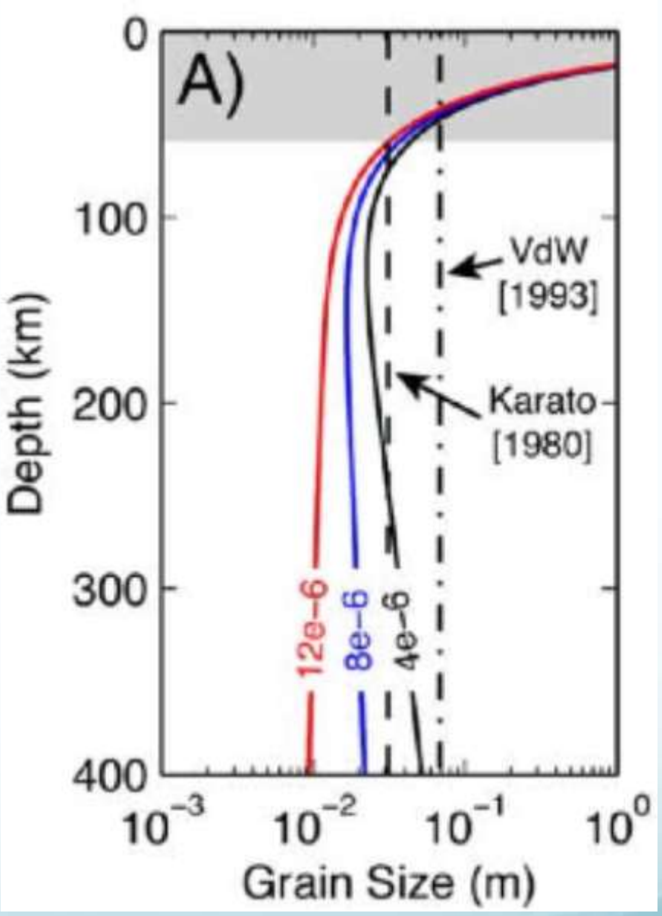




Stixrude & Lithgow-Bertelloni (2005 JGR); Nakagawa et al. (20110 EPSL)

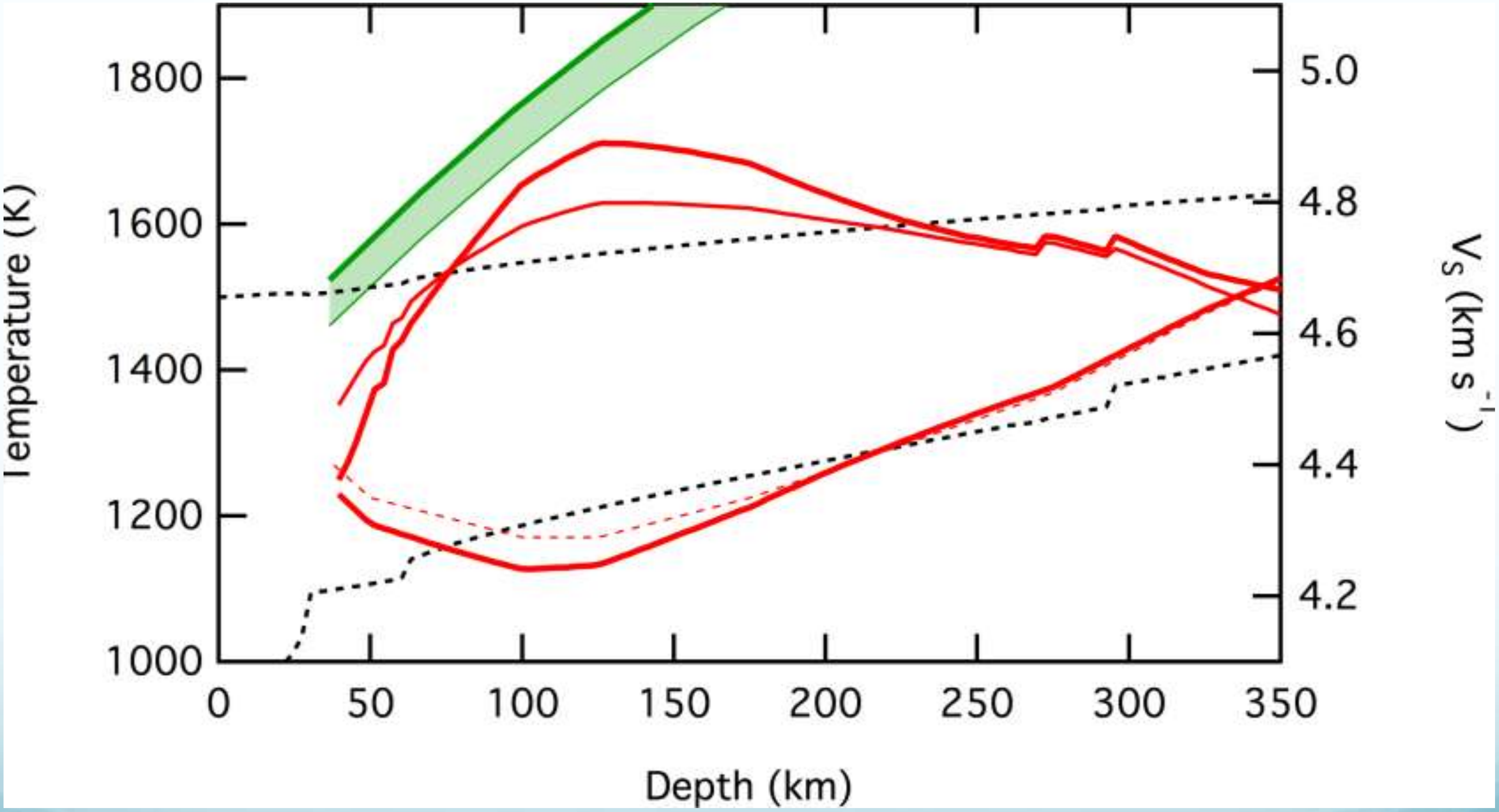
Grain Size





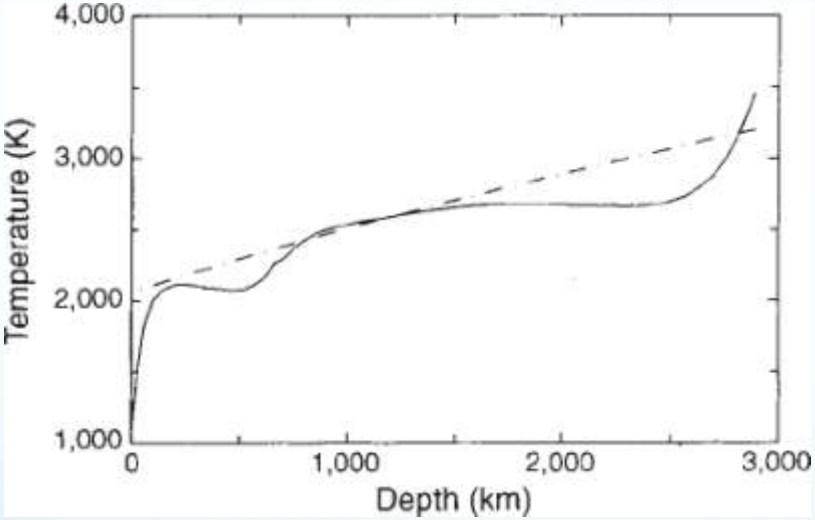
Faul & Jackson (2005 EPSL); Behn et al. (2009 EPSL)

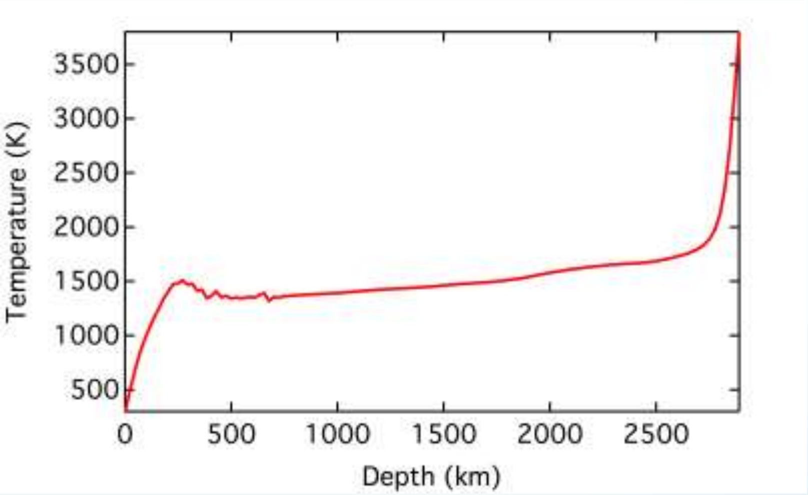
Entropy



Xu et al. (to be published)

Entropy



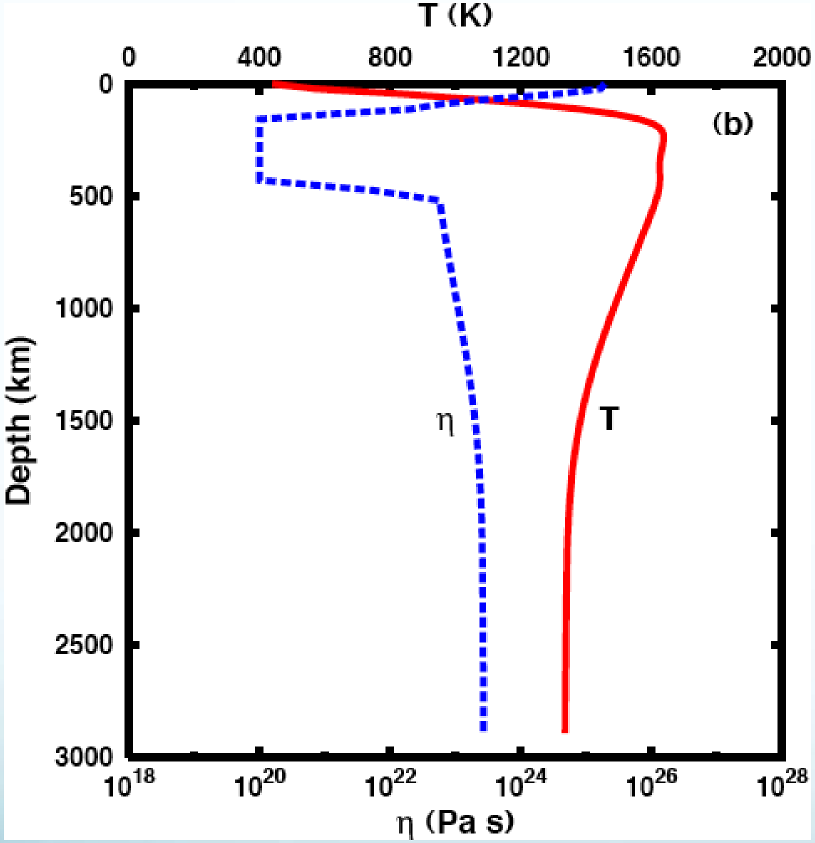


Tackley et al. (1993 Nature); Davies et al. (to be published)

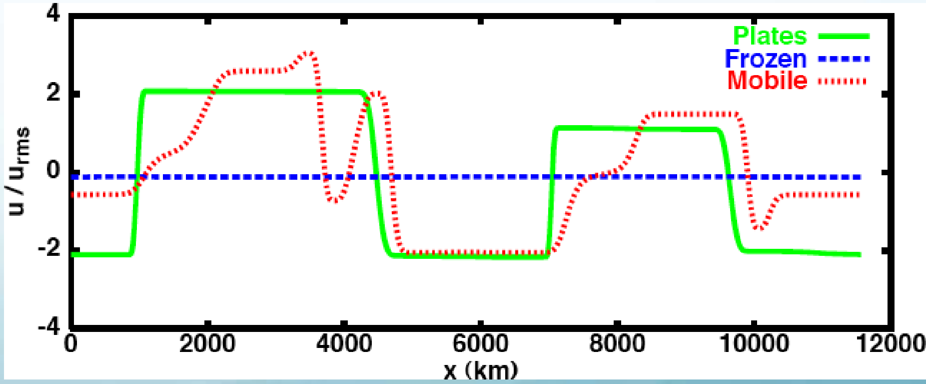
Conclusions

- Null hypothesis produces a well defined LVZ with observed age-dependent behavior
- Attenuation satisfies the residual velocity deficit
- Attenuation produces a large magnitude drop in velocity at the top of the LVZ
- Partial melt in the LVZ is difficult to reconcile with thermodynamics
- HGZ may be explained by variations in entropy with depth

Significance



- Plate-like behavior only in the presence of a low viscosity channel



Richards et al. (2001 G³)