Partial melting, water, rheological properties and **the origin of the asthenosphere**

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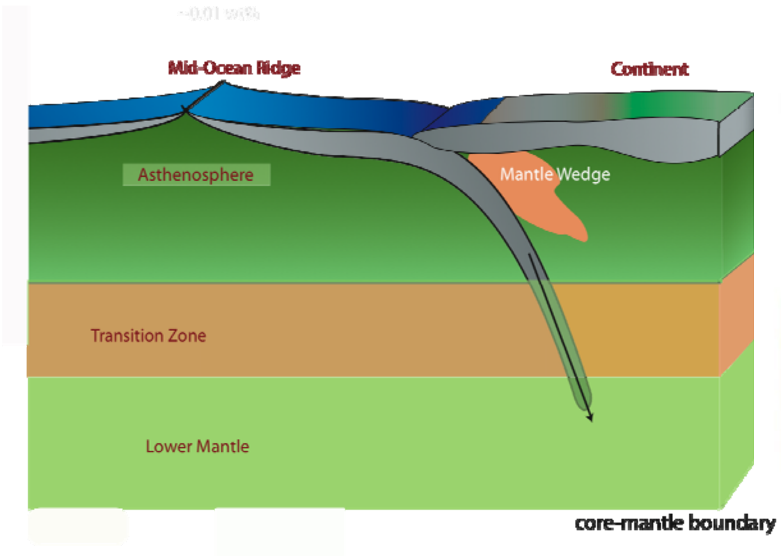
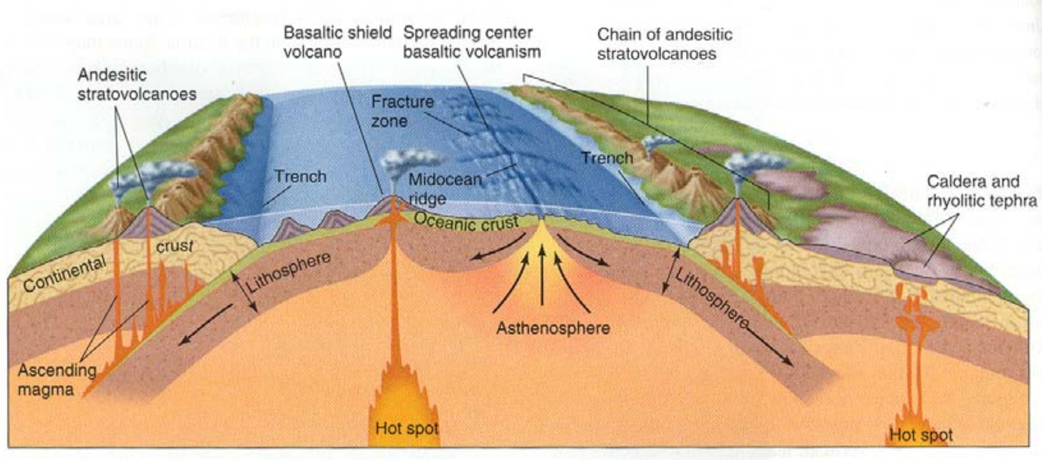




The weak asthenosphere helps plate tectonics to operate.

why is the asthenosphere weak? (T effect, partial melting?)

Partial melting occurs in the asthenosphere beneath mid-ocean ridges.
→ formation of the oceanic crust + the lithosphere

MORB (mid-ocean ridge) is homogeneous and modestly depleted.
→ **why?**

Are they boring questions?

New observations (sharp and shallow LAB), a large rheological contrast between depleted and undepleted materials → challenges to conventional models

A brief history of the study of the asthenosphere

- 1914 (Barrell): "the asthenosphere"
- **1926- (Gutenberg**): the low velocity zone below the lithosphere **(asthenosphere = partial melt)**
- 1964 (Mizutani-Kanamori): experimental study on the elasticity of a partially melt
- 1973 (Gueguen-Mercier): importance of solid state relaxation for low velocity and high attenuation
- 1975 (**Stocker-Gordon**)**: importance of the geometry of melt** (dihedral angle)
- 1979- (Waff, Faul, Kohlstedt): experimental studies on melt geometry
- 1984 **(McKenzie**): **theory of compaction (difficulty of melt retention)**
- 1984 (**Cooper-Kohsltedt**): **modest effect of partial melting on creep**
- 1986- (Karato, Kohlstedt: Paterson): **strong weakening effects of hydrogen**
- **1986 (Karato): partial melt hardening model** (due to hydrogen removal)
- **1988 (Hofmann): a model of depleted upper mantle (residue of continental crust)**
- 1992 (Plank-Langmuir): difficulty of partial melting away from the ridges
- 1992- **(Jackson**): experimental study on anelasticity of dunite
- **1995 (Karato): hydrogen weakening model of the asthenosphere**
- 1996 (**Hirth-Kohlsedt**): extension of Karato (1986, 1995) model
- 1996 (Gaherty et al.)**: sharp LAB** (lithosphere-asthenosphere boundary)
- 1998 (Karato-Jung): further extension of Karato (1995)
- 2003 (Holtzman et al.): deformation of partially molten peridotite
- 2003 (Bercovici-Karato): 410-km melting model for global material circulation
- 2007 (Yoshino et al.): **complete wetting at high P**
- **2009 (Kawakatsu et al.): a new partial melt model (based on Holtzman et al., 2003)**
- 2010 (**Jackson-Faul): a model of anelasticity including high-frequency relaxation**
- 2010- (Tauzin, Karato): **evidence for (global) 410-km melting**

Summary

- **Partial melting** redistributes **water** → rheological contrast (Karato, 1986, 1995; Hirth-Kohlstedt, 1996)

→ mixing of depleted and undepleted components is difficult

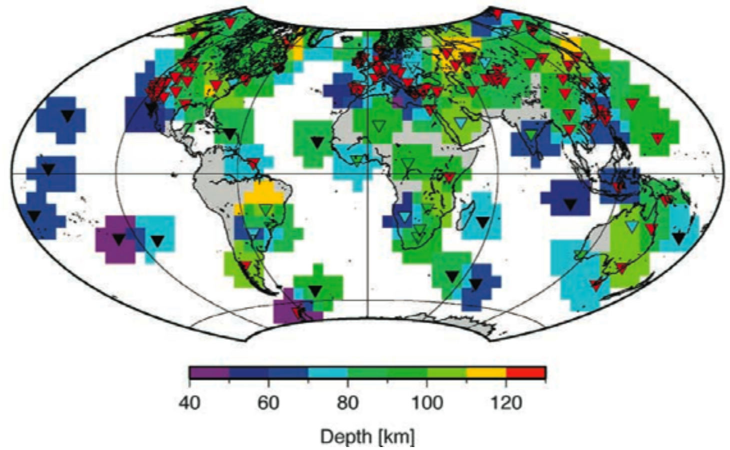
→ large and sharp change in seismic velocities

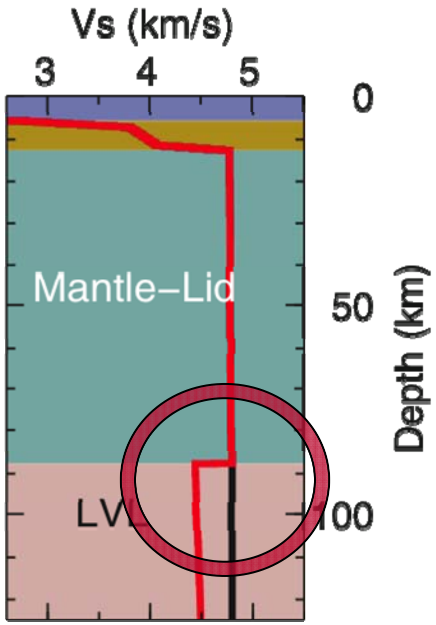
- Direct mechanical effects of partial melting are small (if the melt fraction is small, <1 %, and if melt does not wet grain-boundaries)
- **Seismological** LAB (lithosphere-asthenosphere boundary) is caused by the sub-solidus processes.
- **Geochemical** character of the asthenosphere (moderately depleted and nearly homogeneous composition) is due to partial melting at ~410-km.

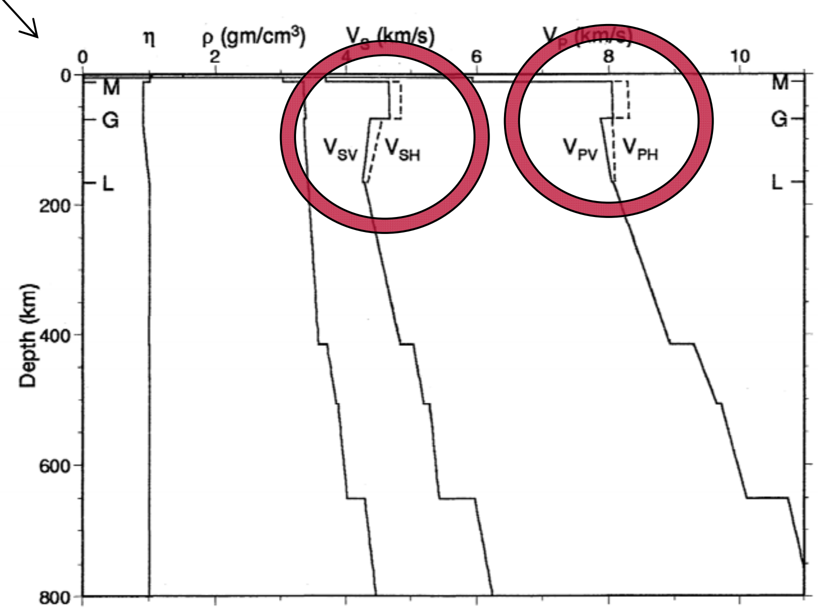
Mid-mantle melting is important.

A **sharp** and **large** velocity drop at the LAB
(shallow LAB in the old oceanic mantle)

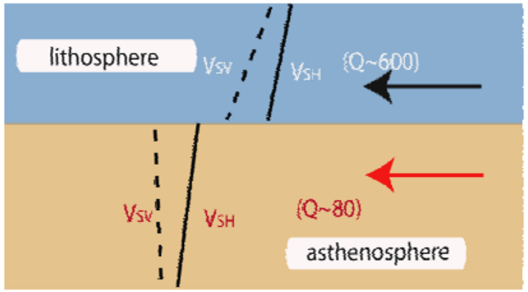
- Revenaugh-Jordan (1991)
- Gaherty et al. (1996)
- Rychert et al. (2005)
- Rychert-Shearer (2009)
- Kawakatsu et al. (2009)

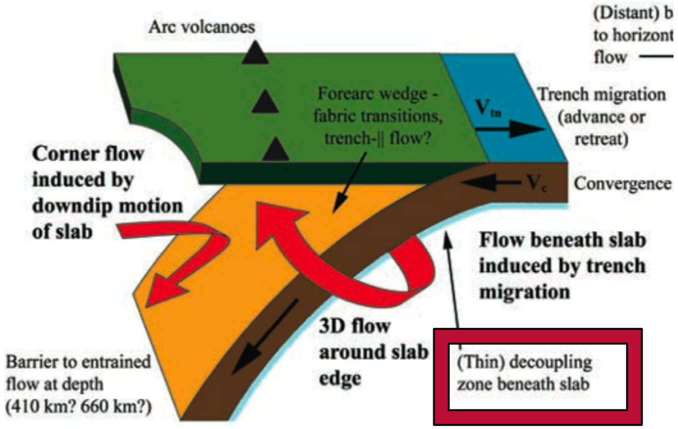




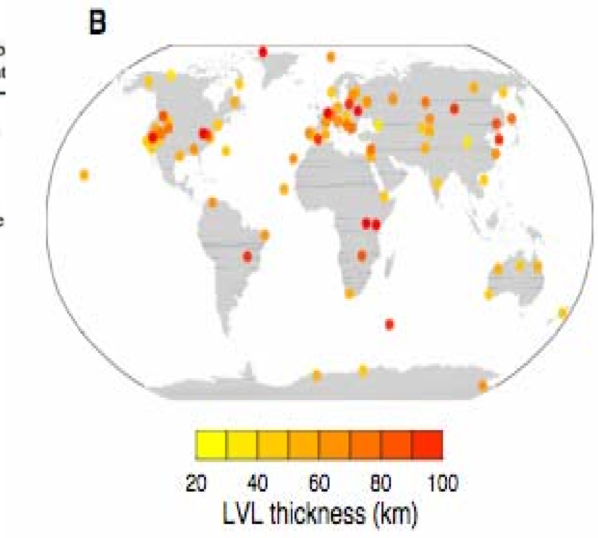


Key seismological observations on the lithosphere-asthenosphere system





(Long-Silver, 2009)



Tauzin et al. (2010)

- A sharp and large velocity drop at the LAB (shallow)
- dV-Q discrepancy (too large dV for the observed Q)
- Anisotropy
  - depth-dependent, modest anisotropy (~2-4 %)
  - fast direction ~// flow direction (in most regions)
  - trench parallel flow (below some slabs) → decoupling
- low velocity region above 410-km

What is the Asthenosphere?
[What do we need to explain?]

- Geophysical aspects
  - low velocity, high attenuation (high electrical conductivity, low viscosity)
  - **a sharp and large velocity drop** at the LAB (Lithosphere-Asthenosphere-Boundary)
  - Decoupling between the lithosphere and the asthenosphere
  - A thick low velocity layer above 410-km
- Geochemical aspects
  - **homogeneous**, **modestly** **depleted** composition

[water content ~ 0.01 wt% (+/- a factor of 2)]

- Is **partial melting** needed or a likely mechanism to explain anomalies of the asthenosphere? No
- Can **continental crust formation** explain the homogeneity of the asthenosphere? No

→ **revisit sub-solidus model of the asthenosphere**

→ **an alternative model to explain the geochemical characteristics of the asthenosphere**

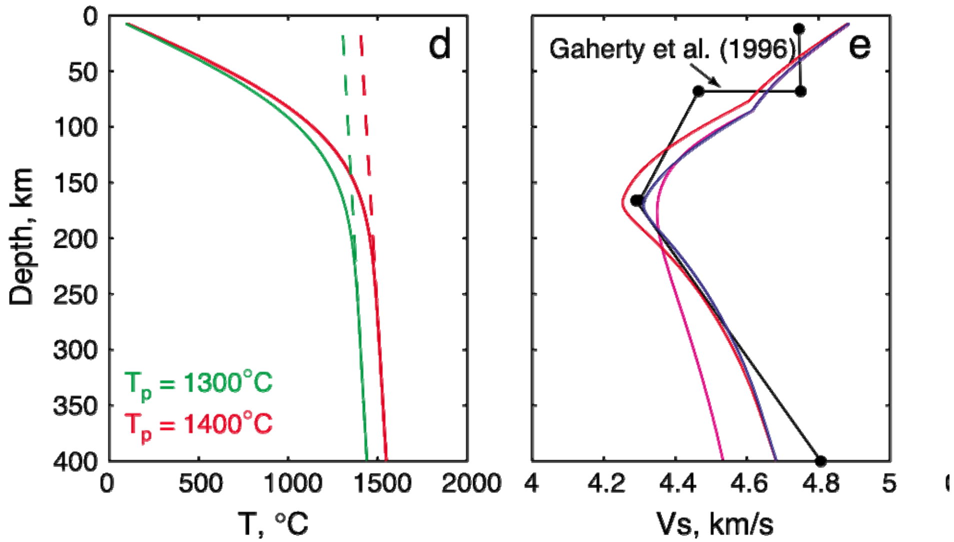
→ possible mechanism of lubrication at the LAB

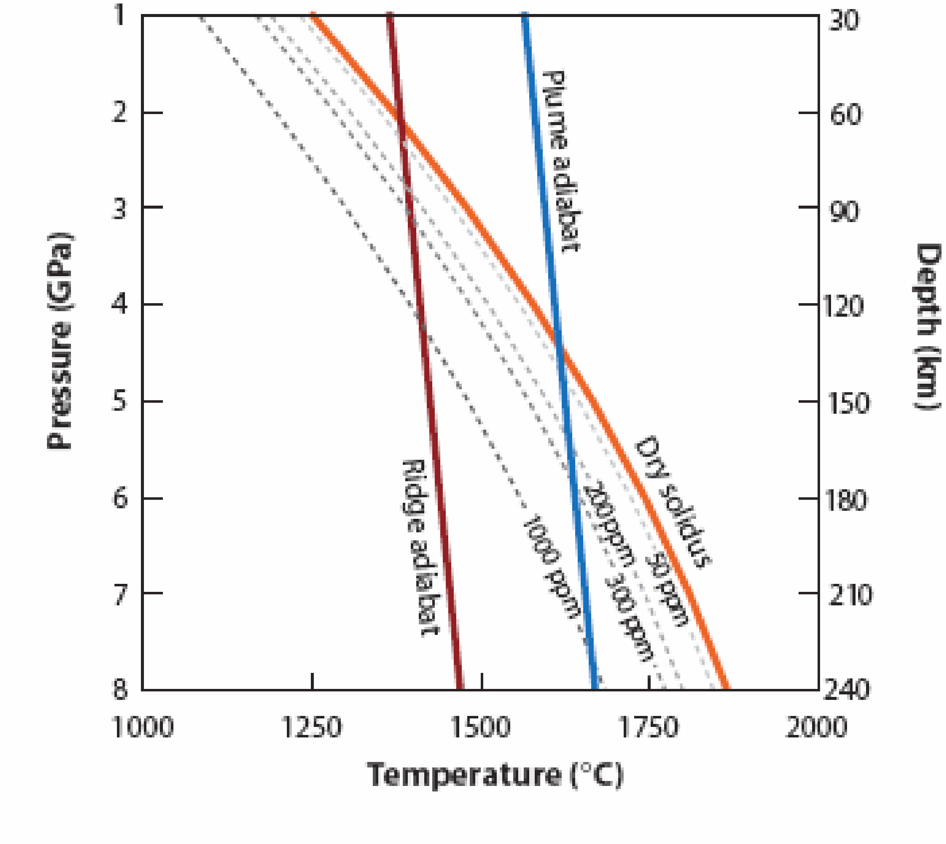
Models for geophysical aspects

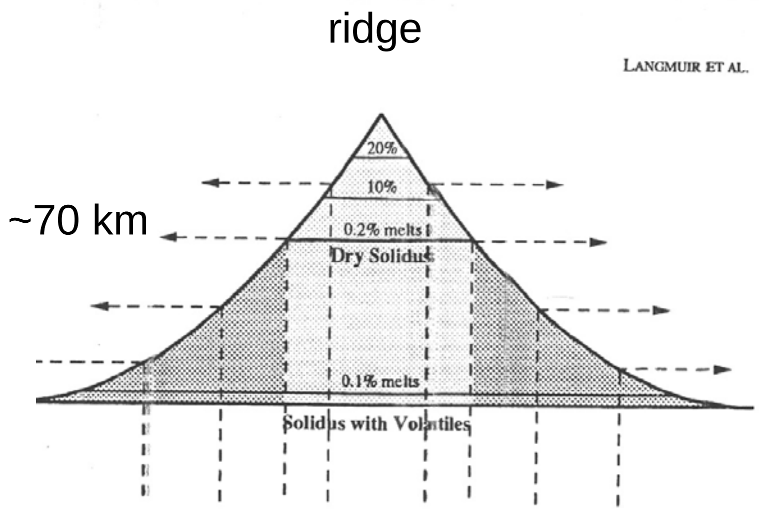
- Purely thermal model (Birch, 1952; Schubert et al., 1976; Faul and Jackson, 2005) → Diffuse (age-dependent) LAB → need "**something else**"
- **Conventional model**: asthenosphere = partially molten layer (Gutenberg, 1926; Lambert-Anderson, 1970)

  but (1) partial melting is difficult away from the ridges

  (2) no strong effect of partial melting on mechanical properties

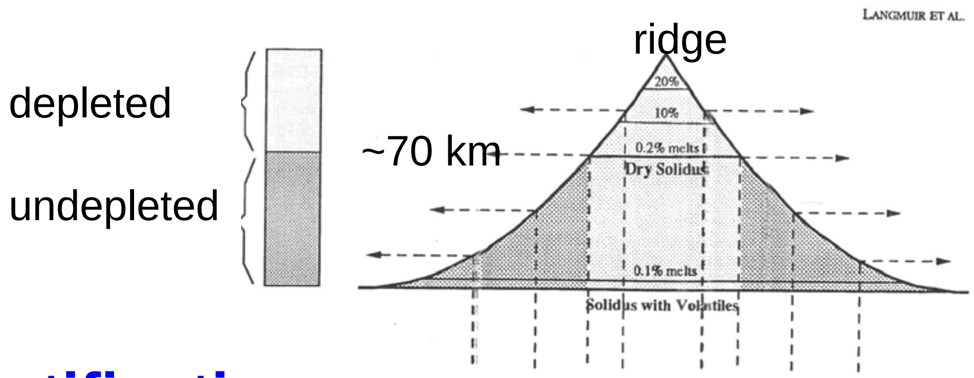






- Extensive partial melting is likely beneath the ridge (above ~70 km), but the melt fraction is expected to be small in the asthenosphere away from the ridge.
- **Melting at 60-80 km depth in the old oceanic upper mantle is difficult**.

A sub-solidus (hydrogen) model



- **Karato-Jung (1998)**:
  partial melting below a ridge
  → **A sharp water content stratification**:
  water-rich asthenosphere, water-poor lithosphere
  (by partial melting below ridges (Karato, 1986; Hirth-Kohlstedt, 1996))
  – A sharp LAB at a constant depth ~70 km (**age indep.**)
  – A small $\delta V/V$~1 % ← absorption band model

→ **Don't agree with obs.??**

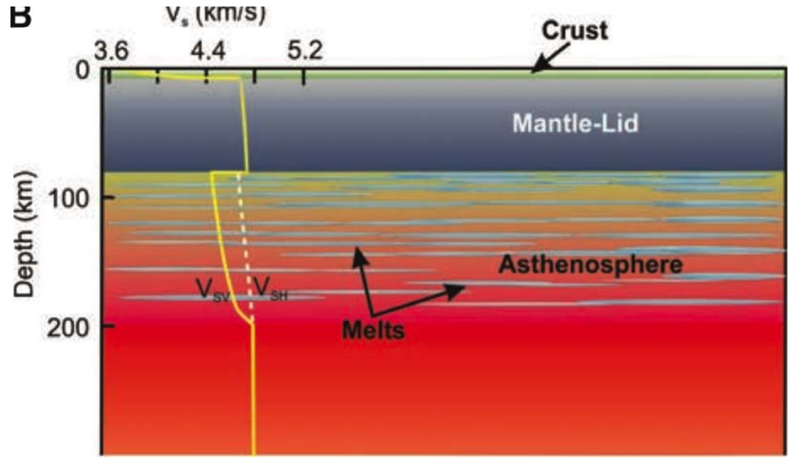
→ **A new partial melt model** (Kawakatsu et al., 2009)

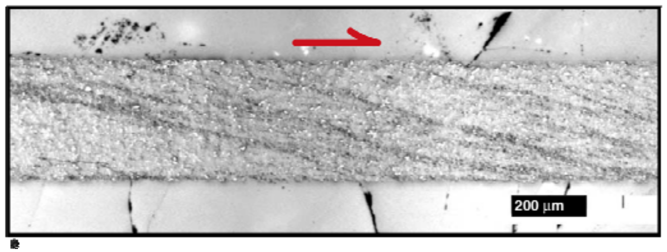
A new partial melt model

- **Kawakatsu et al. (2009)**
  (based on Holtzman-Kohlstedt model)
  - Partial melting below ~60-80 km
  - Average melt fraction is small but there are thin horizontal layers with high melt fraction (very low velocity)

  → low SV velocity, no melt segregation

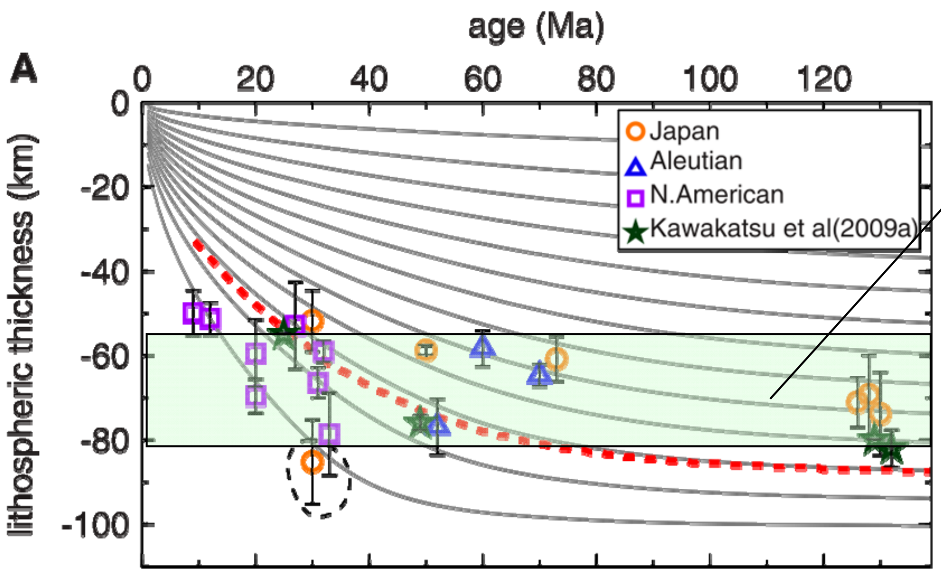
  → age-dependent LAB



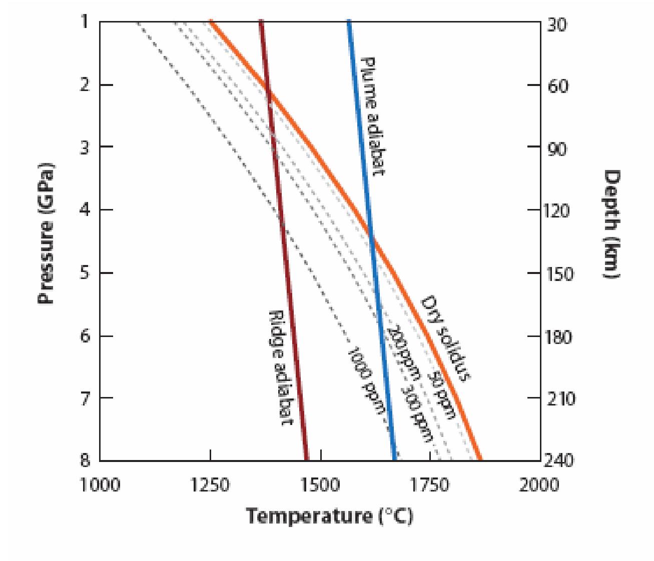


- Is this model consistent with the observations and the physics of partial melt?

Can partial melting occur at 60-80 km depth (~900 C) ?
Is the LAB depth age-dependent ?



900 C !

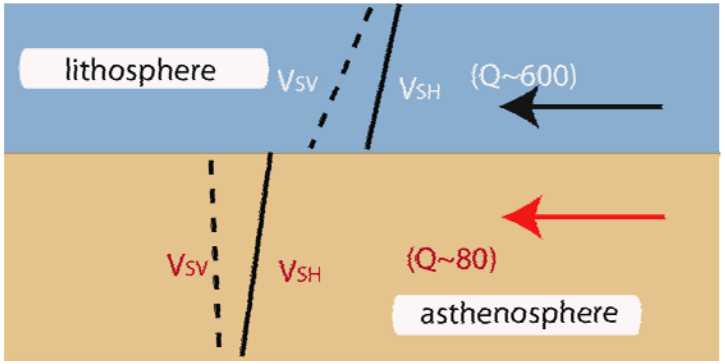


dT=100 K ←→ dz=30 km

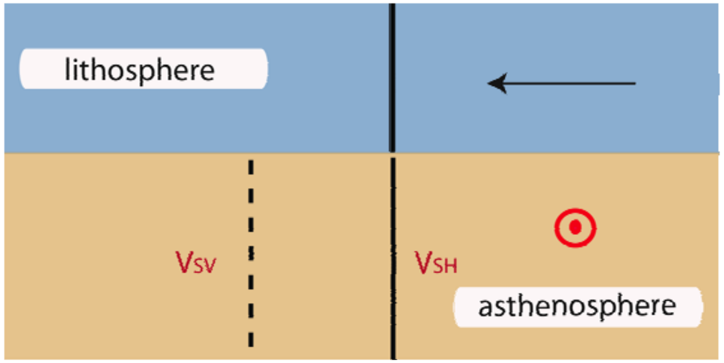
Kumar-Kawakatsu (2011)

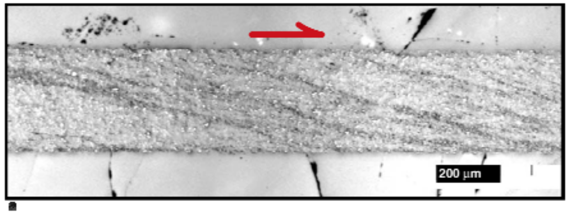
Melting at 60-80 km is very difficult.
"Age-dependent LAB" is questionable.

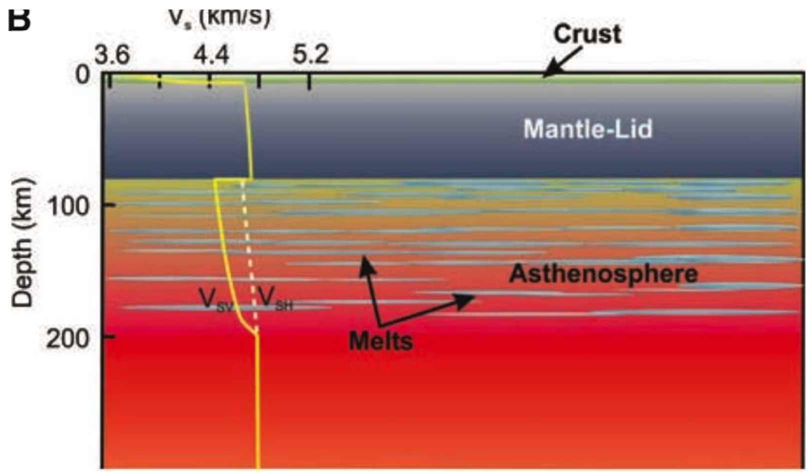
observed structure



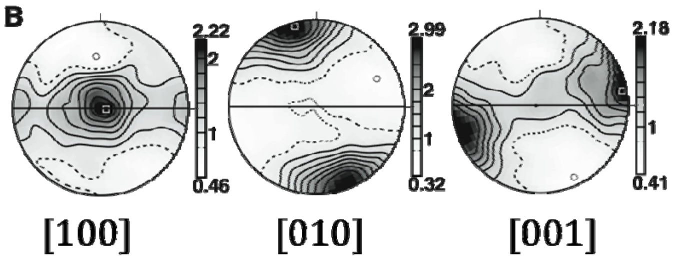
Kawakatsu et al. (2009) model







Holtzman et al. (2003), Kohlstedt-Holtzman (2009)



→ Kawakatsu model is inconsistent with geophysical, petrological and mineral physics observations.

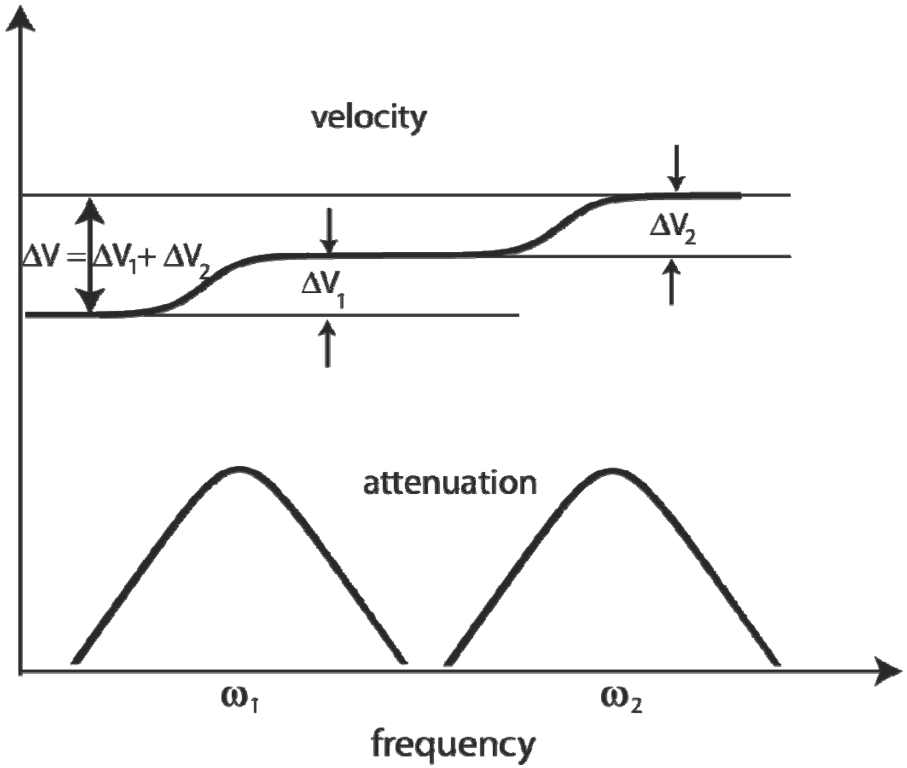
Sub-solidus model?

- **How can we explain a sharp and large velocity reduction?**
- Karato-Jung (1998): sharp LAB but $\delta V/V \sim 1$ % ← absorption band model

$$V_{P(S,\phi)} \approx V^{\infty}_{P(S,\phi)}\left[1 - Q^{-1}_{P(S,\phi)}\right]$$

- Absorption band model is inconsistent with seismological observations (Karato, 1977: Yang et al., 2007) → high-frequency relaxation mechanisms (confirmed by Jackson-Faul (2010))
- Are there any plausible **high-frequency** relaxation mechanisms that have **large relaxation strength**?

Possible role of high-frequency relaxation

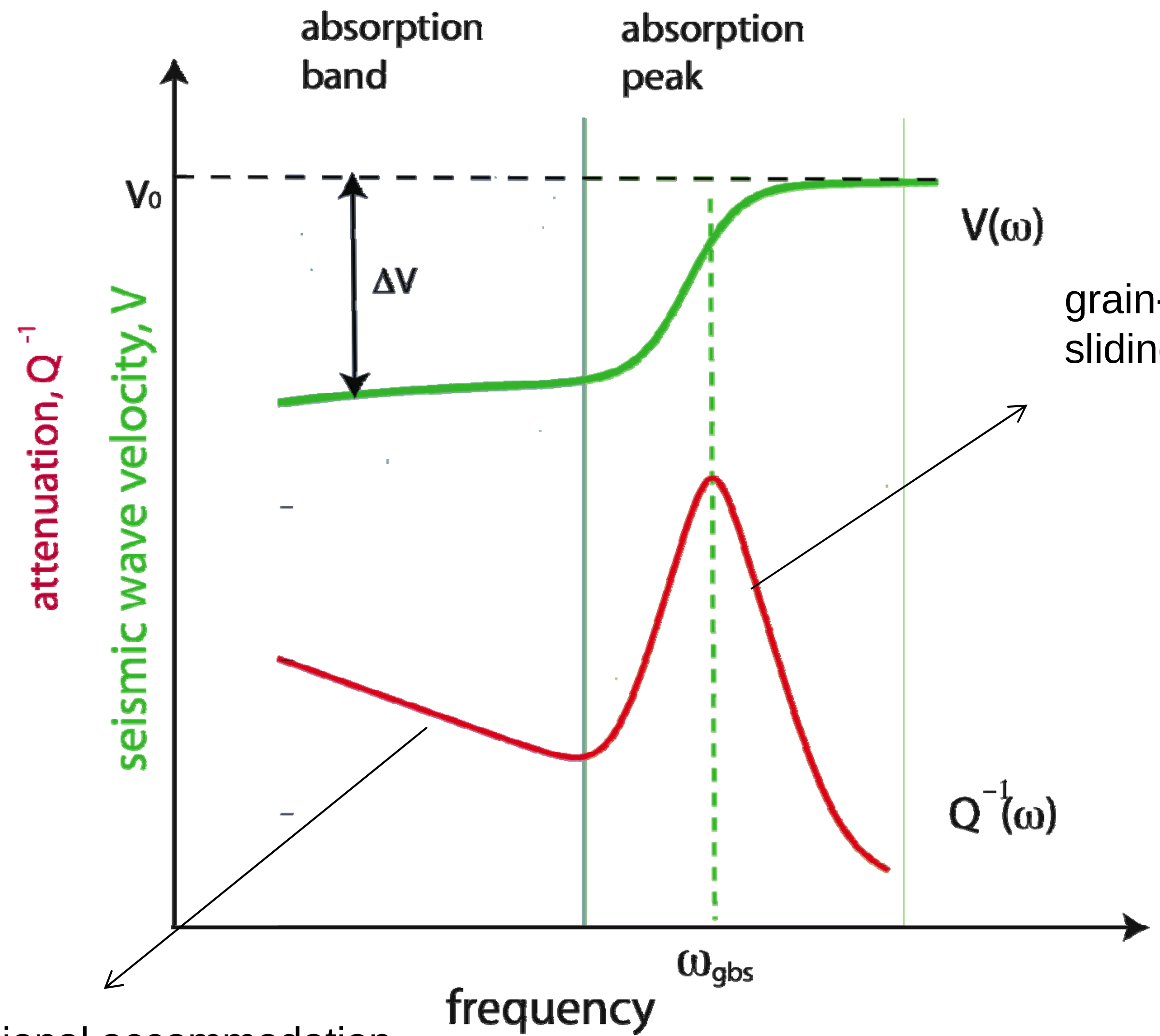


$$V_{P(S,\phi)} \approx V^{\infty}_{P(S,\phi)}\left[1 - Q^{-1}_{P(S,\phi)}\right]$$

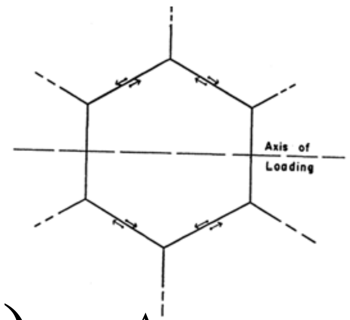
If high-frequency relaxation mechanisms exist, then dV/V can be larger than expected from Q.

Grain-boundary relaxation

$$V_{P(S,\phi)} \approx V^{\infty}_{P(S,\phi)}\left[1 - Q^{-1}_{P(S,\phi)}\right]$$



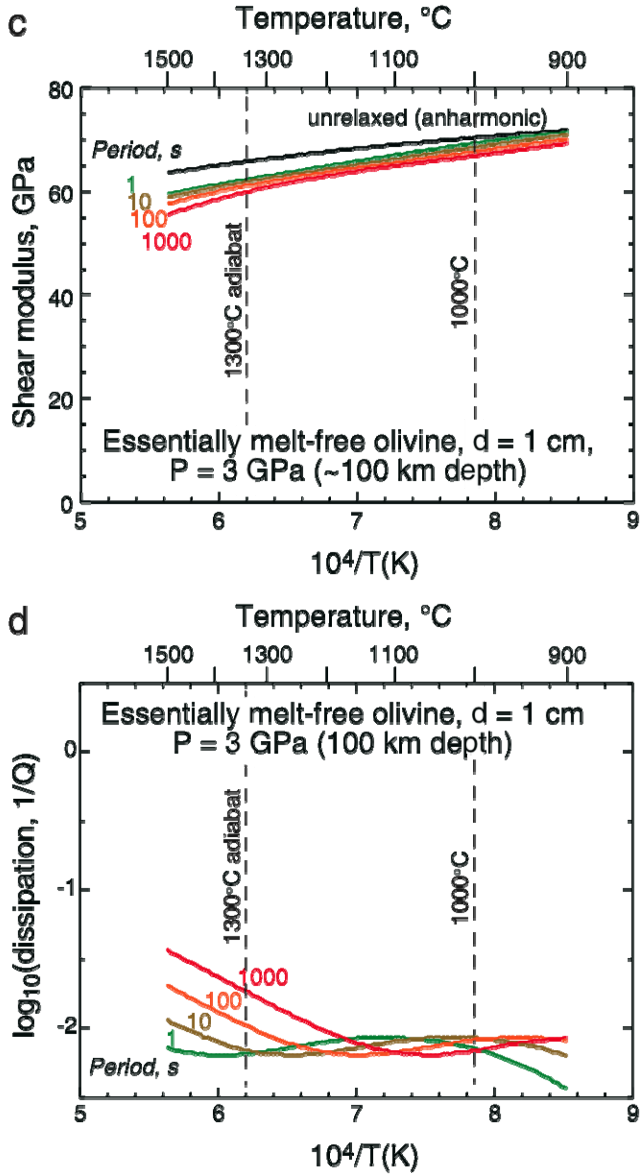
grain-boundary sliding



$$\left(\frac{\Delta V}{V}\right)_{max} = \frac{\Delta}{2} \approx 10\ \%$$

diffusional accommodation

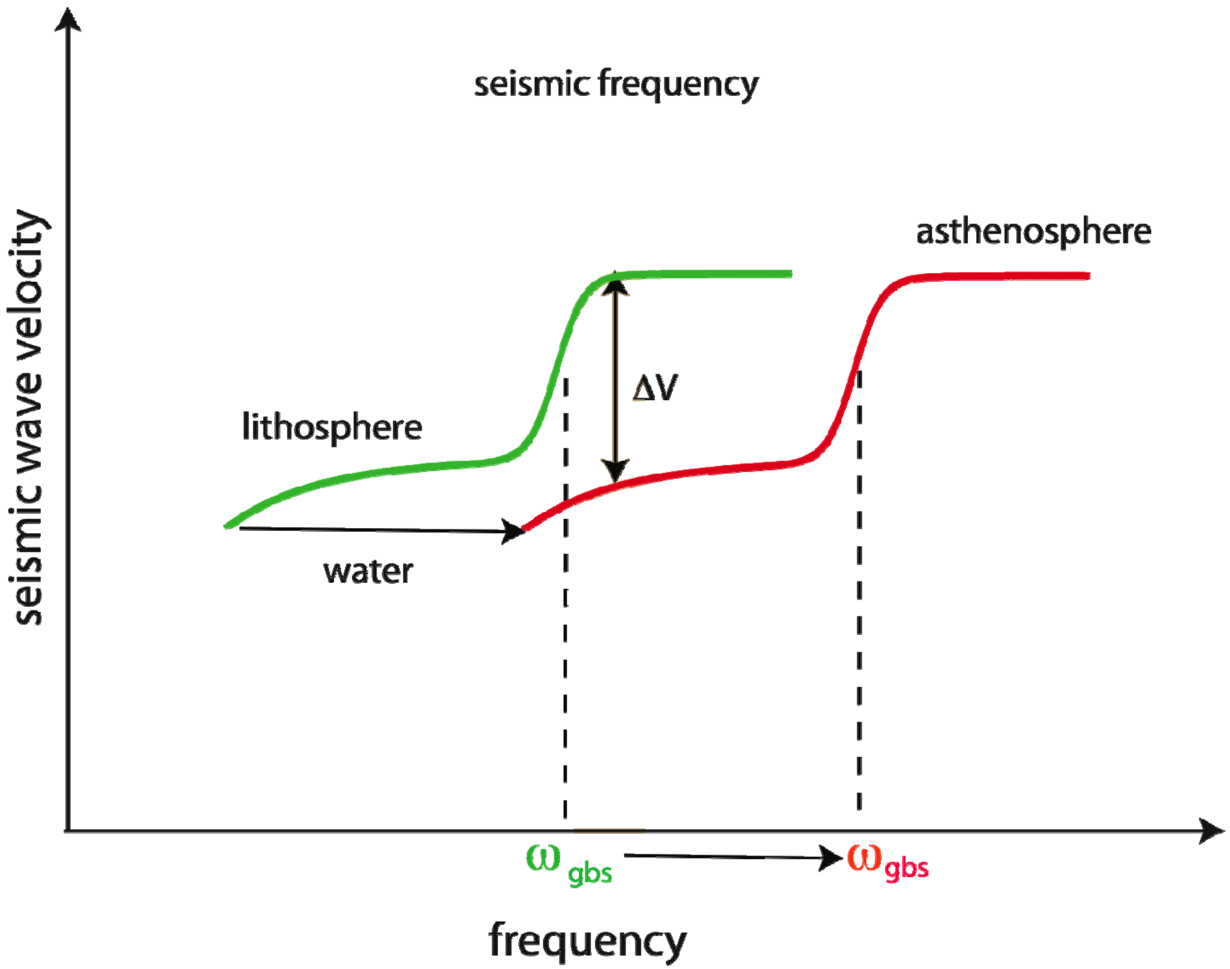
[based on Morris-Jackson (2009) model]



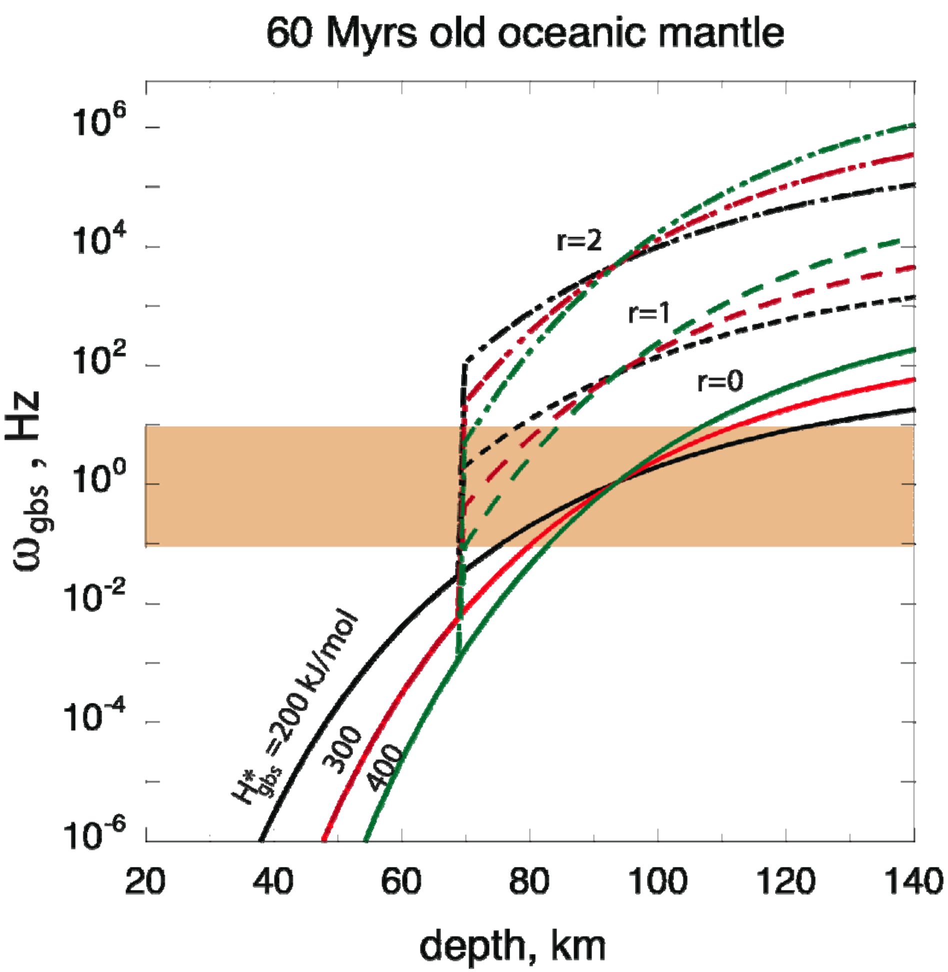
High-frequency peak
←→ 5-10% δV/V

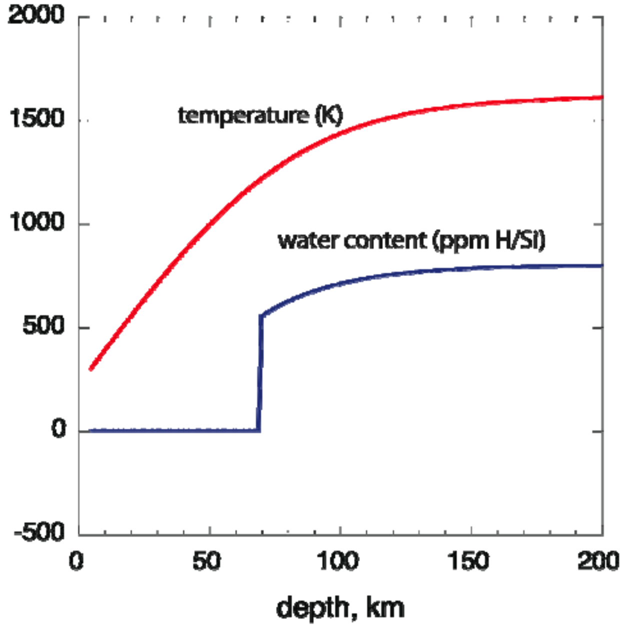
(Jackson-Faul (2010))

Water content is stratified → shift in the peak freq.

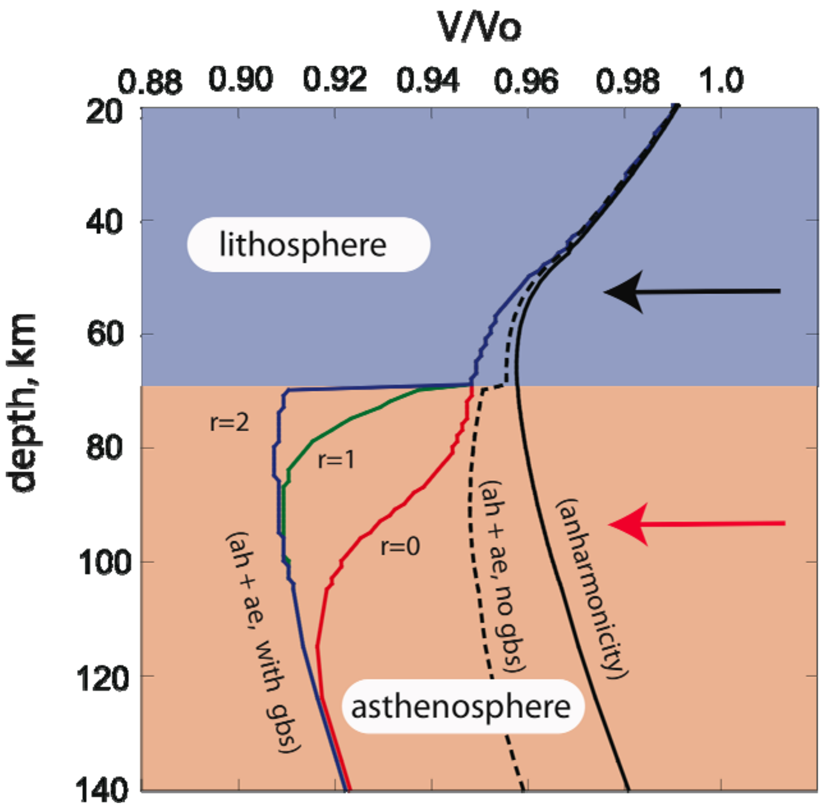


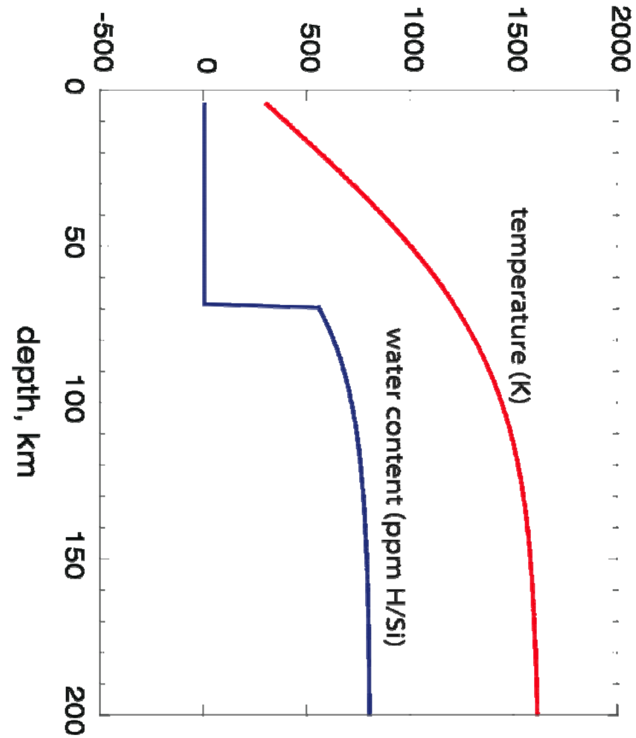
$$\frac{\omega_{gbs}(T, C_W)}{\omega_{gbs}\left(T_o, C_W^o\right)} = \left(\frac{C_W}{C_W^o}\right)^r exp\left[-\frac{H_{gbs}^*}{RT_o}\left(\frac{T_o}{T} - 1\right)\right]$$





Sub-solidus model
(water content layering)

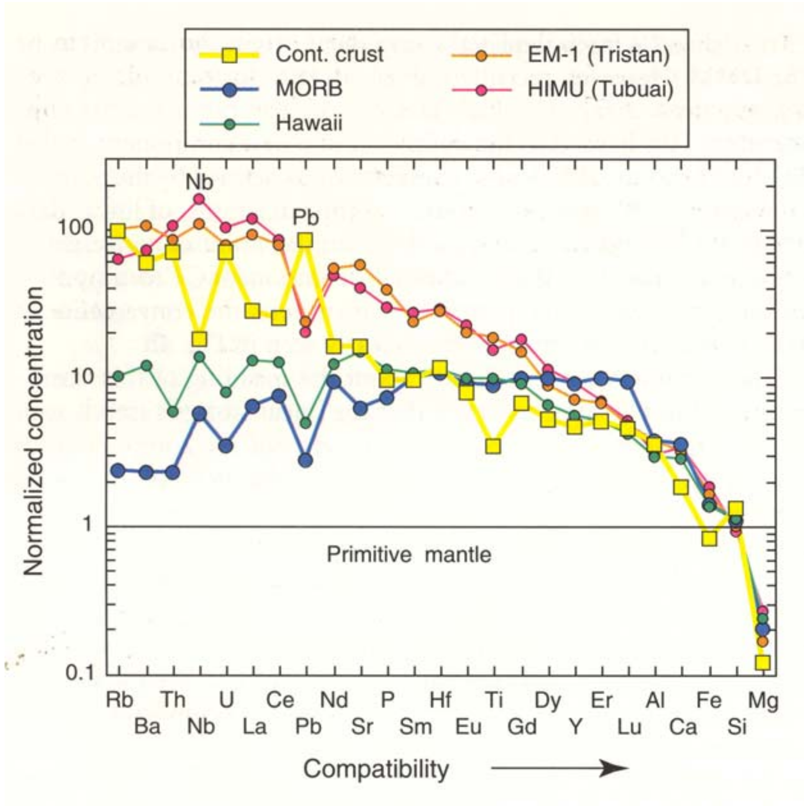


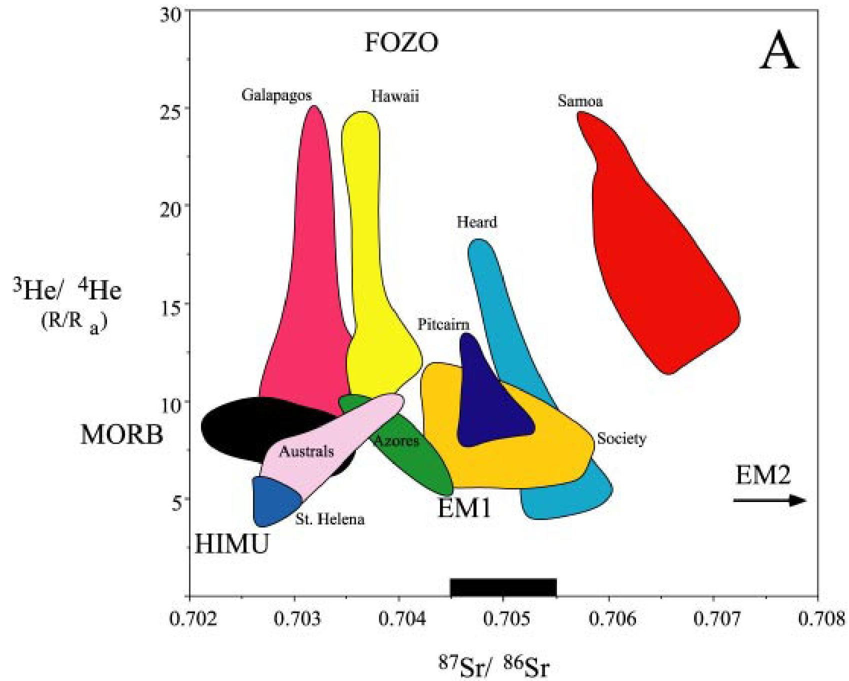


With plausible water effects (r=1-2), the velocity-depth profile is consistent with obs. including anisotropy.

Geochemical aspects

• MORB has homogeneous, modestly depleted composition.
• MORB and continental crust have complementary trace element abundance pattern.

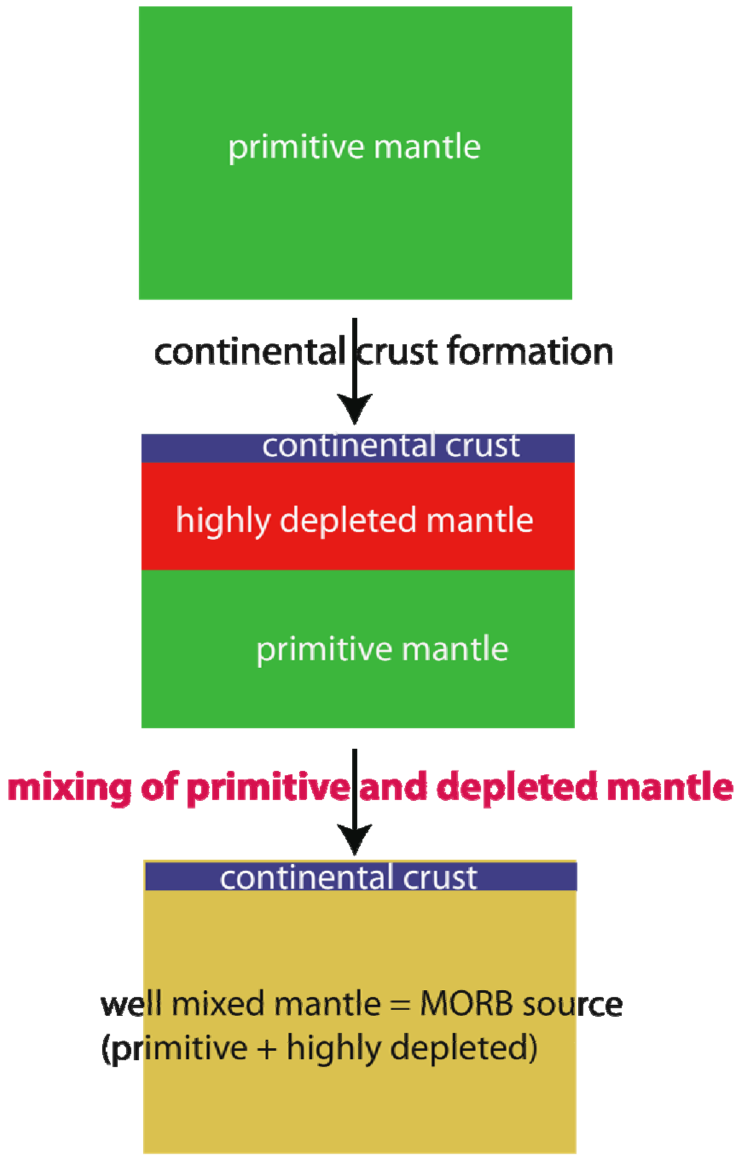


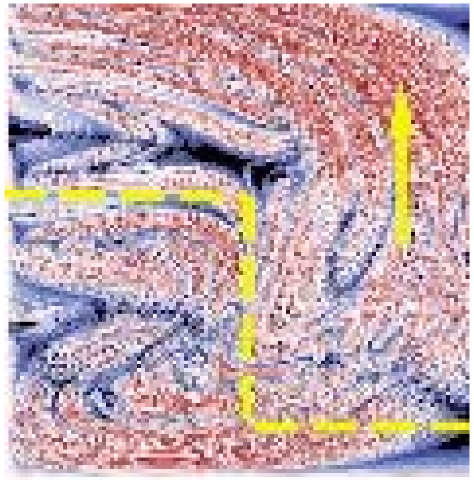


→ asthenosphere (MORB source region) = a residue of extensive partial melting that formed the continental crust (Hofmann, 1988)

"After separation of the bulk of the continental crust, the residual portion of the mantle was **rehomogenized**, and the present-day internal heterogeneities between MORB and OIB sources were generated subsequently by processes involving only oceanic crust and mantle." (Hofmann, 1988)

Hofmann (1988) model of chemical evolution





Can mixing occur effectively?

[+ subsequent plate tectonics cycling]

- **Can mixing occur so effectively ??**
  - Depleted and un-depleted rocks have largely different viscosity (a factor of 10^2-10^3)

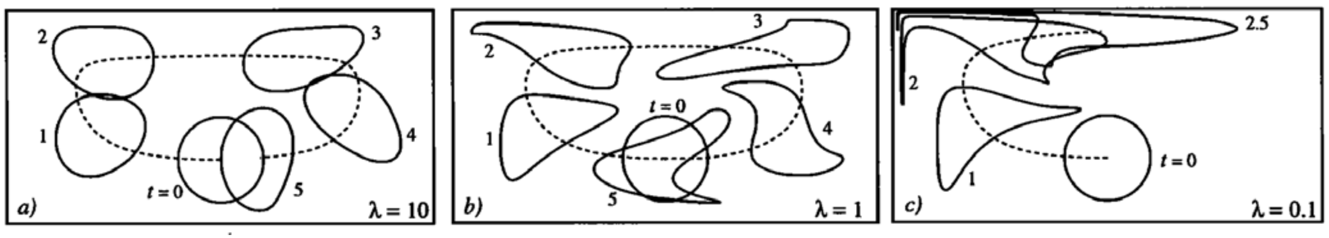
    [preservation of the continental lithosphere]
  - Materials with largely different viscosities do not mix

[For efficient mixing, strain larger than ~10 is needed.

For a viscosity contrast larger than 10^2, the hard materials (depleted materials) do not deform more than ~1 strain]

$$\varepsilon_0 = \dot{\varepsilon}_0 \tau \approx 100$$

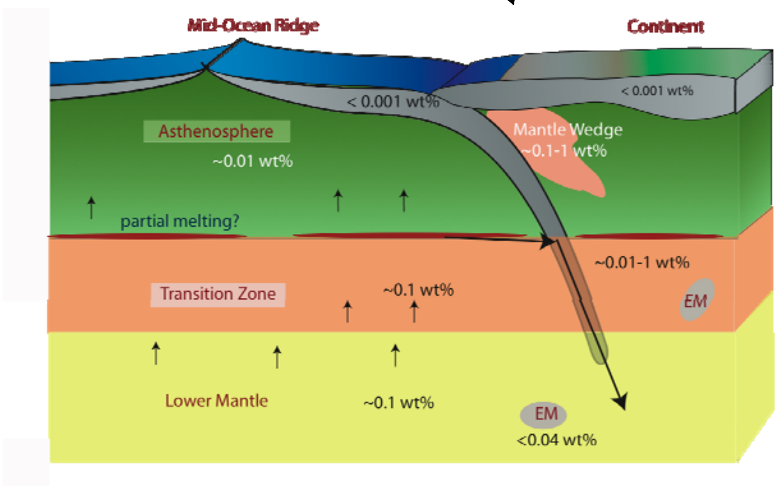
$$\varepsilon_{depleted} = \varepsilon_0 \frac{\eta_0}{\eta_{depleted}} = 0.1 - 1$$



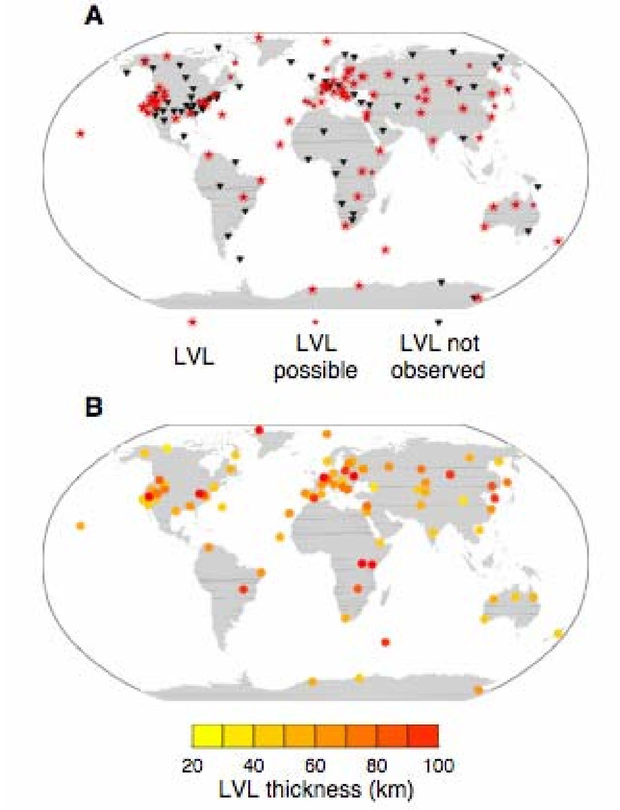
Manga (1996)

Homogeneous, modestly depleted asthenosphere by **mid-mantle melting**

- Evidence for 410-km melting
  - Low velocity layer
  - Water content layering

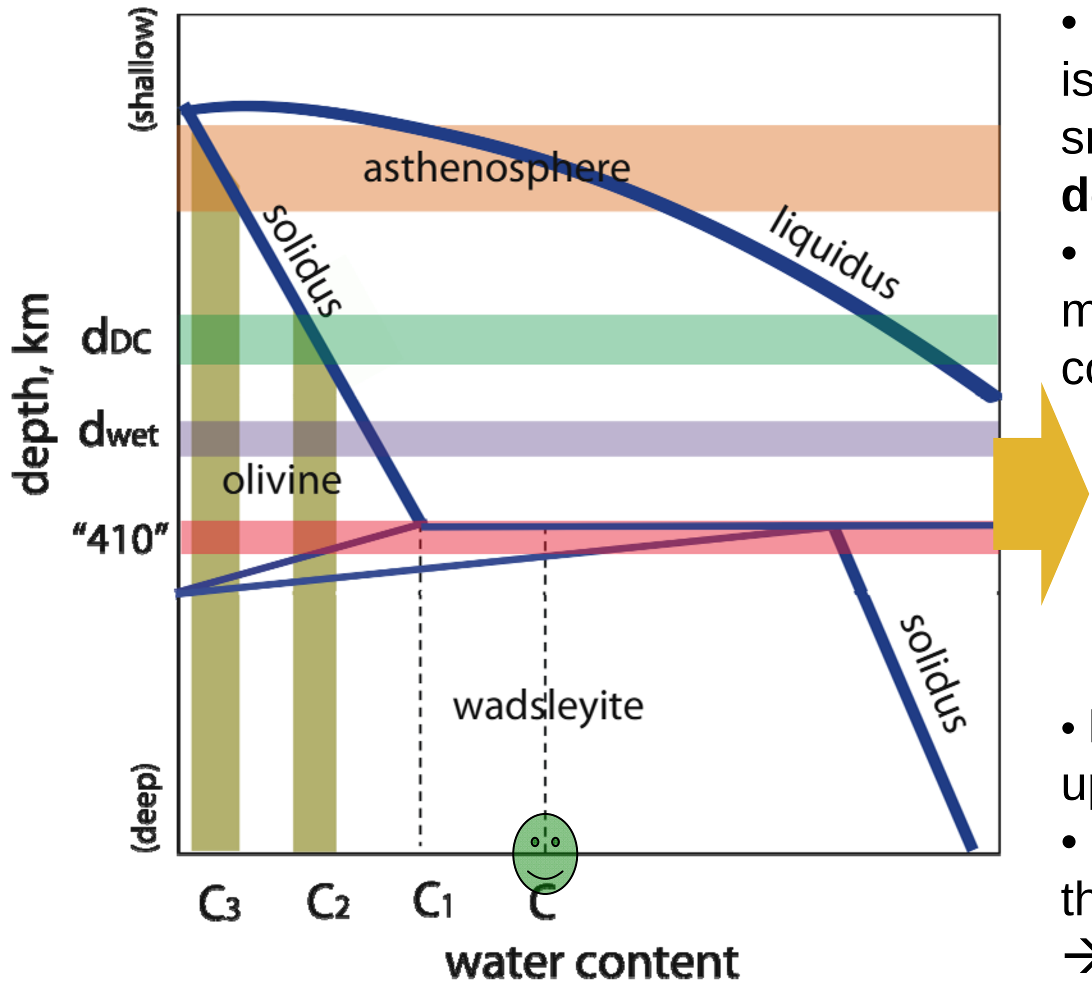


Karato (2011)



Tauzin et al. (2010)

What happens after 410-km melting?



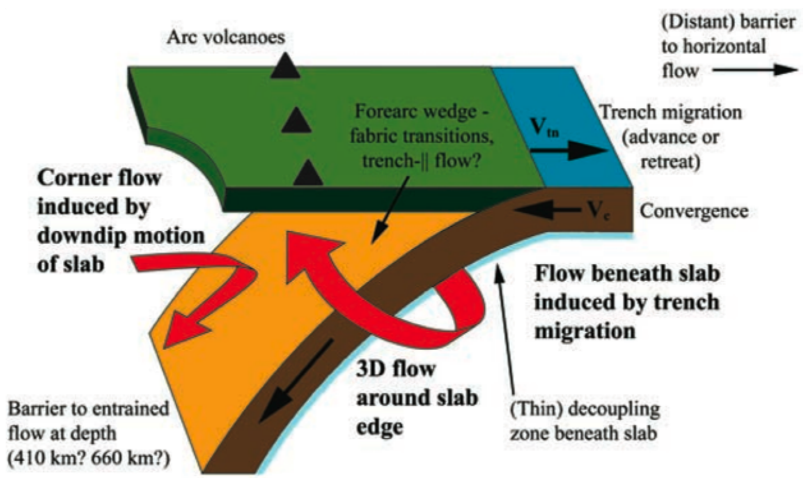
- Most of the upper mantle is partially melted (with a small melt fraction) → **modest depletion**
- Composition of the upper mantle is controlled by solidus composition and **homogeneous**.

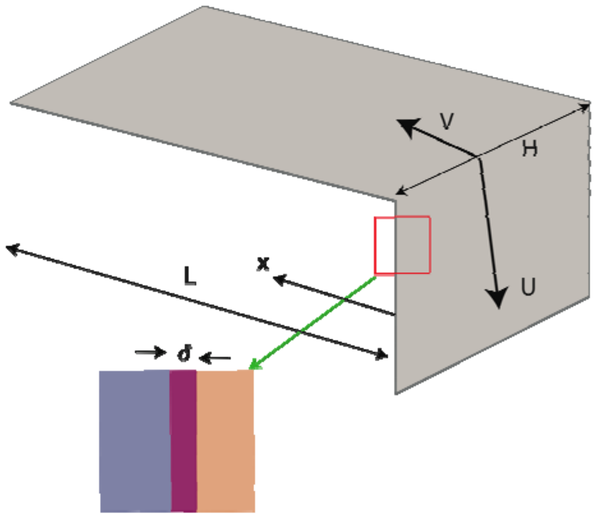
a thick low velocity layer (due to complete wetting)

- Melt sinks in the deep upper mantle.
- Melt rises to the LAB in the shallow asthenosphere.

→ frozen wet gabbro

Trench parallel anisotropy helped by lubrication by a wet gabbro?





U: subduction velocity → trench normal flow

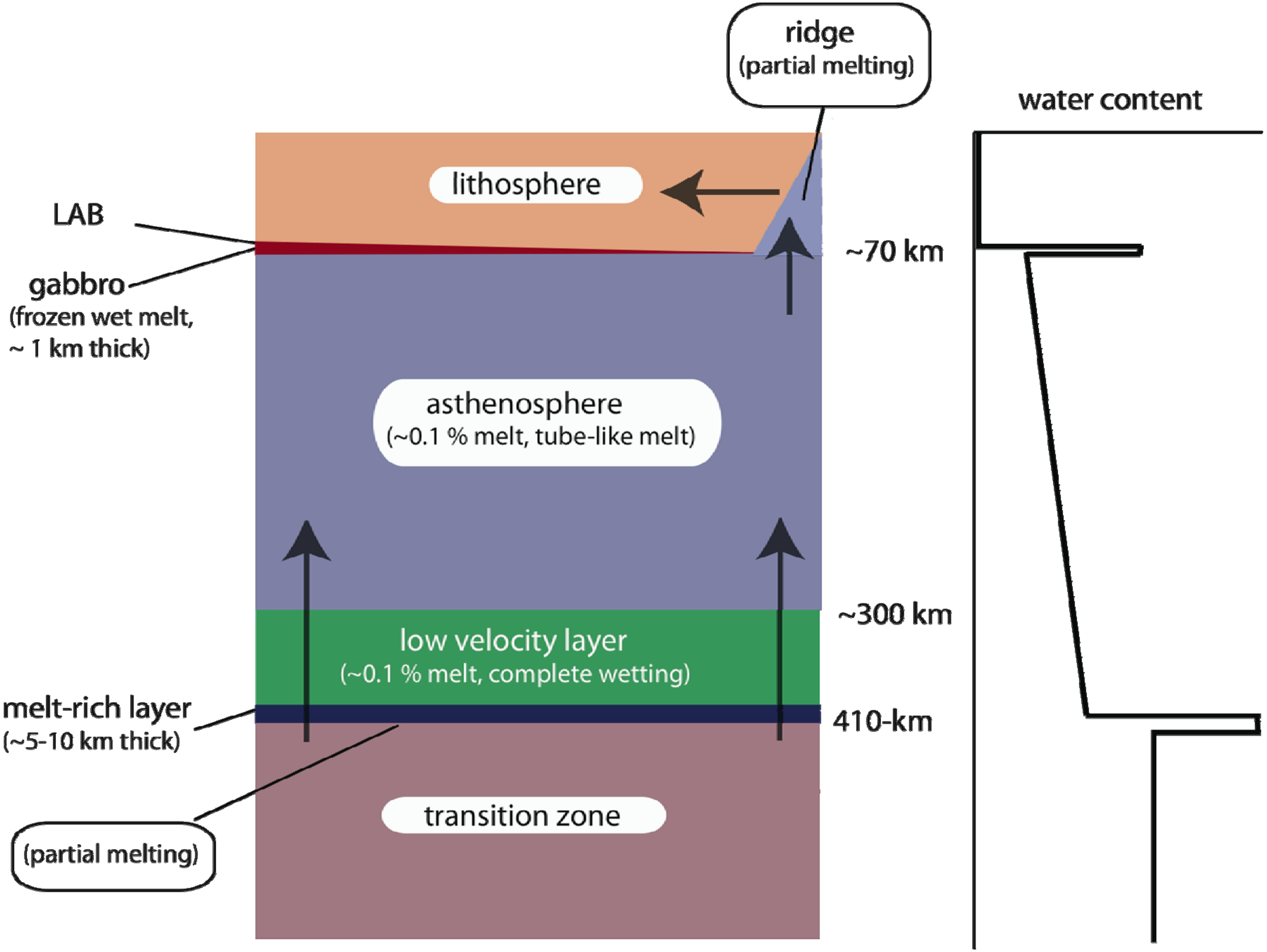
V: trench migration velocity → trench parallel flow

U>>V

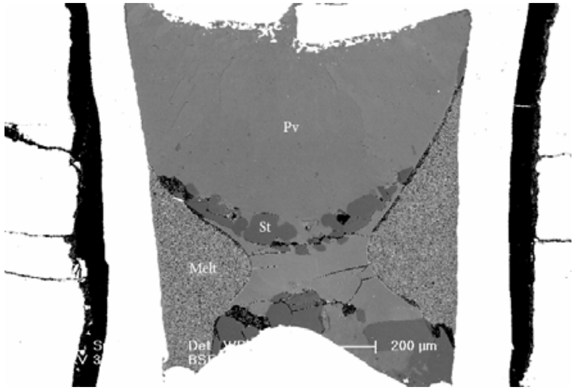
→ how could trench parallel flow dominate?

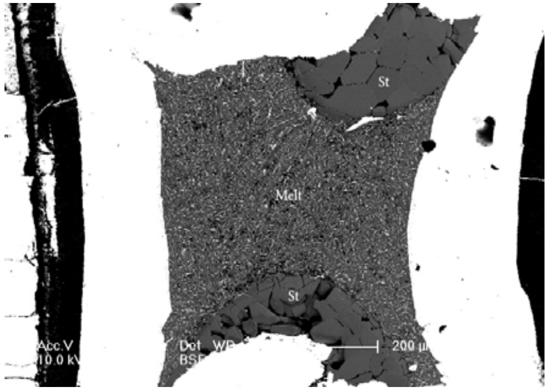
→ decoupling by lubrication

→ How? shear heating (Long-Silver, 2009)
a wet gabbro


ridge
(partial melting)
water content
lithosphere
LAB
~70 km
gabbro
(frozen wet melt,
~ 1 km thick)
asthenosphere
(~0.1 % melt, tube-like melt)
~300 km
low velocity layer
(~0.1 % melt, complete wetting)
melt-rich layer
(~5-10 km thick)
410-km
transition zone
(partial melting)

Melting in the lower mantle (~700 km)





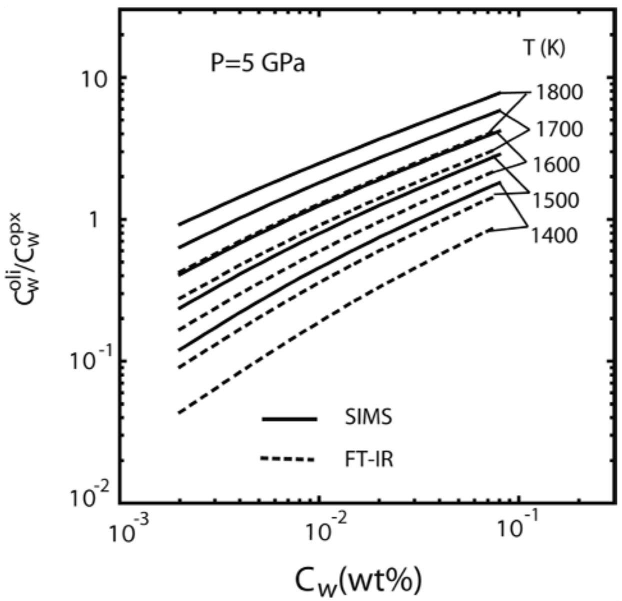
Expt	Pressure (GPa)	Temperature (°C)	Time (Hrs)	Phase assemblage
K994	24 – 25	1500 - 1600	5	Pv, St, melt
K1073	24 - 25	1500 - 1600	5	Pv, melt
K1098	24 - 25	1500 - 1600	5	Pv, melt
K1157	24 - 25	1500 - 1600	5	Pv, St, melt
K1161	24 - 25	1500 - 1600	5	Pv, St, melt
K1182	24 - 25	1500 - 1600	5	St, melt

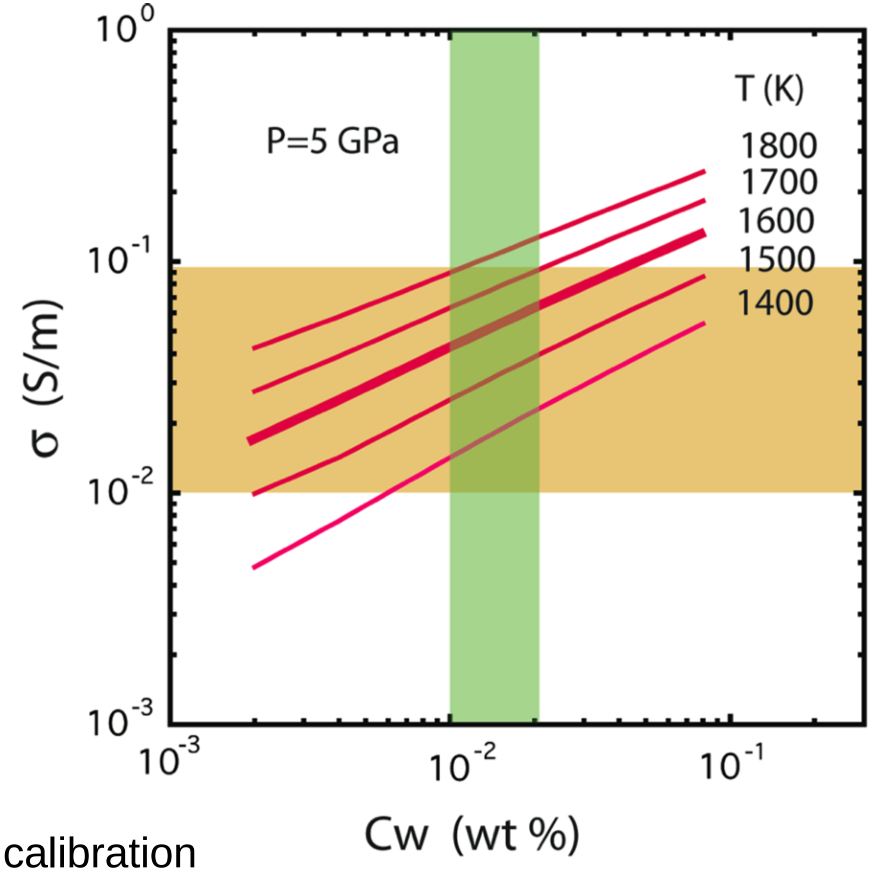
(MgO-FeO-Al_2O_3-SiO_2)

Summary

- Conventional models of the asthenosphere (partial melt, residual of continental crust formation) are inconsistent with geophysics/mineral physics observations**.**
- Most of geophysical and geochemical characteristics of the asthenosphere can be explained as a result of ***indirect*** influence of partial melting (at ~**410-km** and at ~**70** km) that redistributes **water (hydrogen)**.
- Seismic properties (low velocity, anisotropy) are controlled mostly by **water** not by **partial melting** (except just above 410-km)**.**
- **Melting in the mid-mantle has important effects on the geochemical evolution of Earth.**

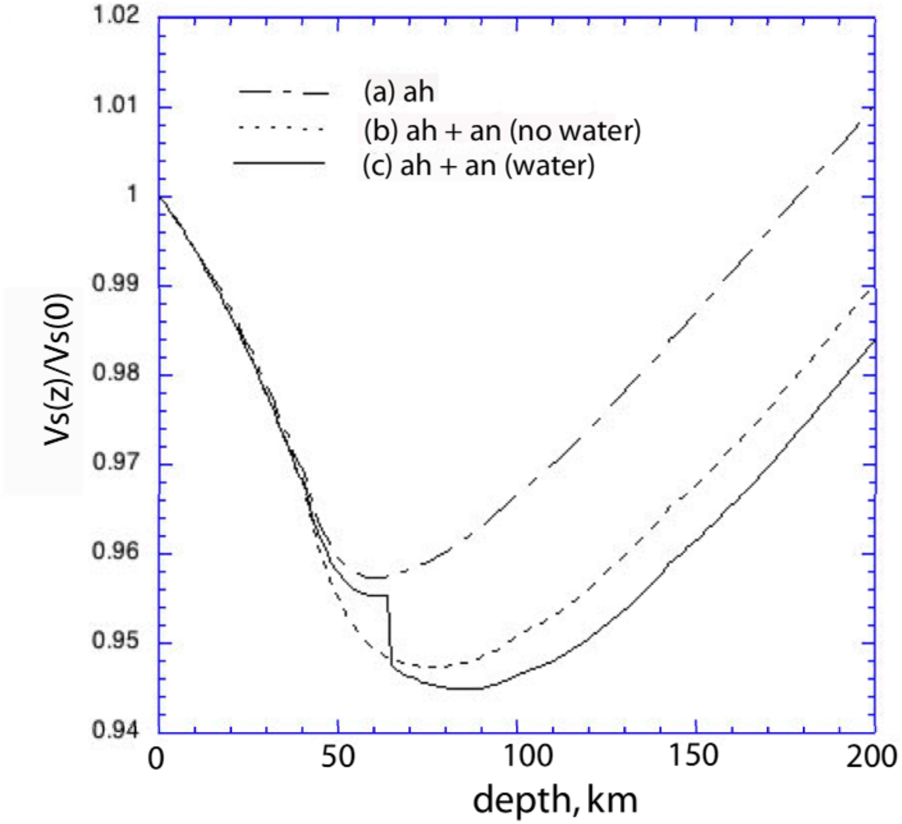
Testing the model for the upper mantle





pyrolite (olivine+opx+pyrope), SIMS water calibration

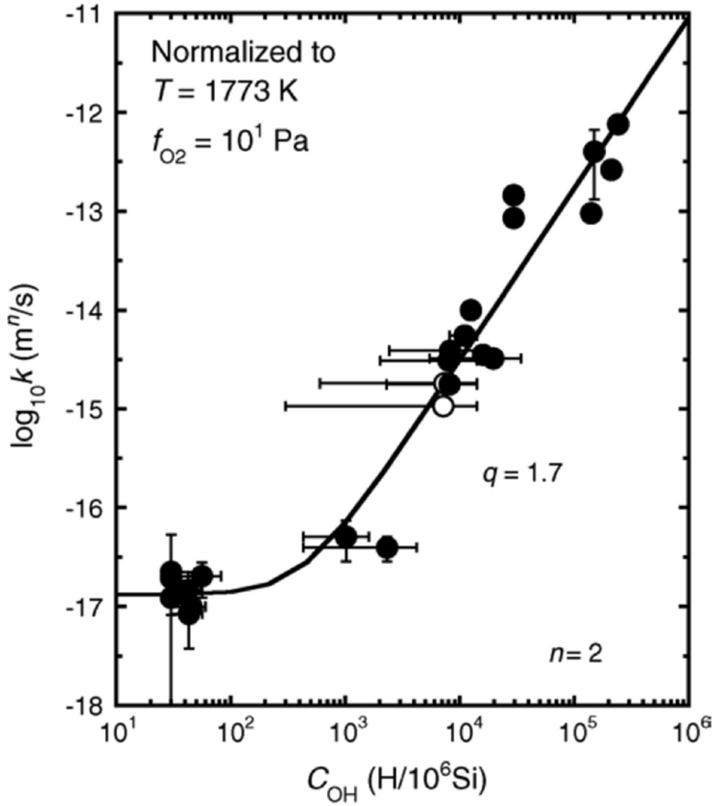
[Dai and Karato (2009)]

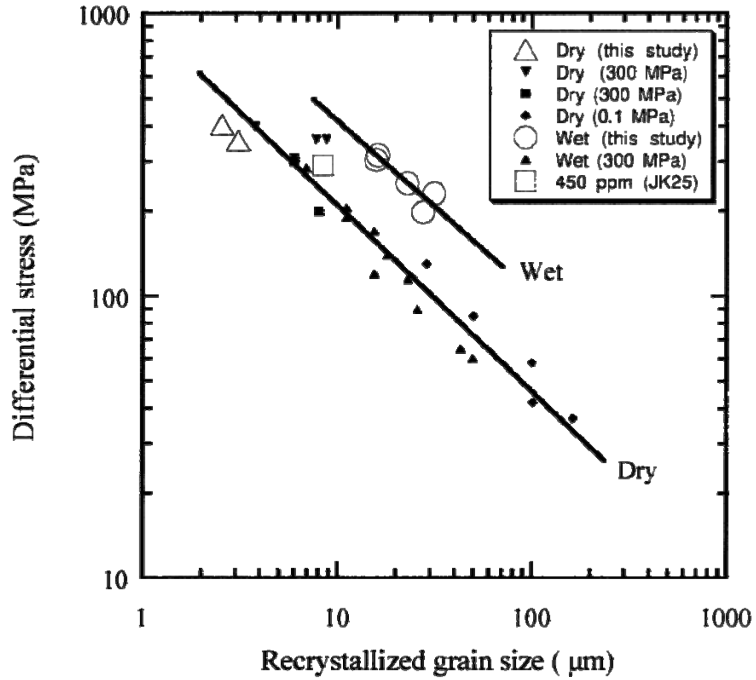


$$V_{P(S,\phi)} = V^{\infty}_{P(S,\phi)}\left[1 - \frac{1}{2}\cot\frac{\alpha\pi}{2} Q^{-1}_{P(S,\phi)}(Cw)\right]$$

A sharp boundary, but a small velocity reduction → need partial melting??

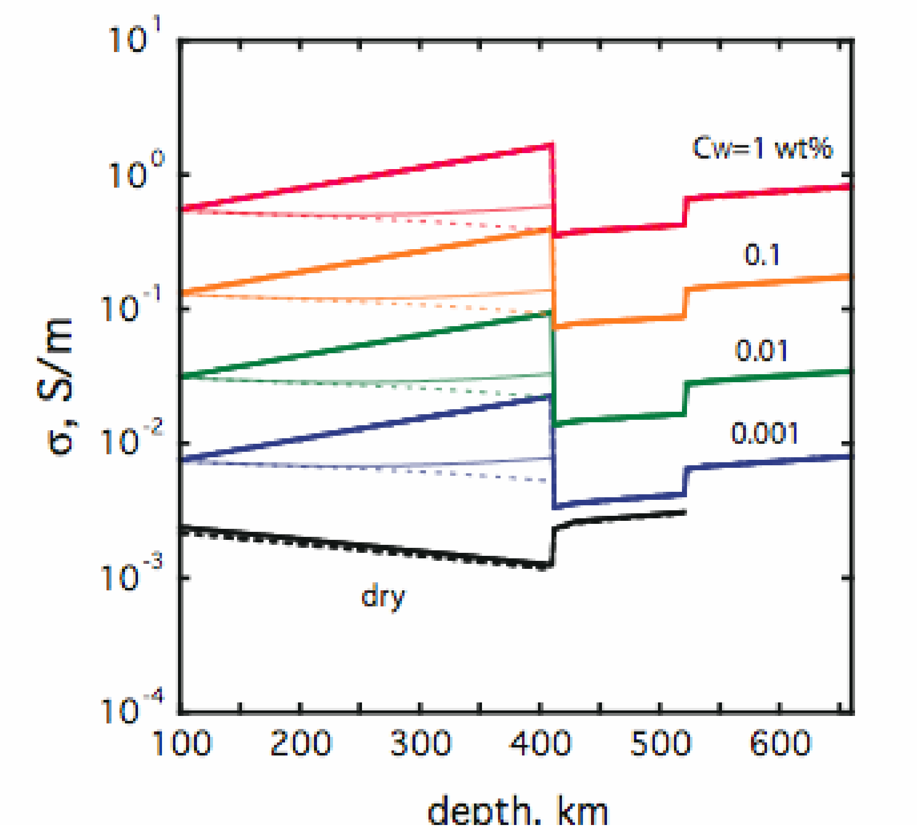
Water weakens grain-boundaries





Electrical conductivity and water in the mantle

Mineral physics model



Geophysical model