Mantle Processes and Geodynamics

Dynamic processes in the mantle wedge

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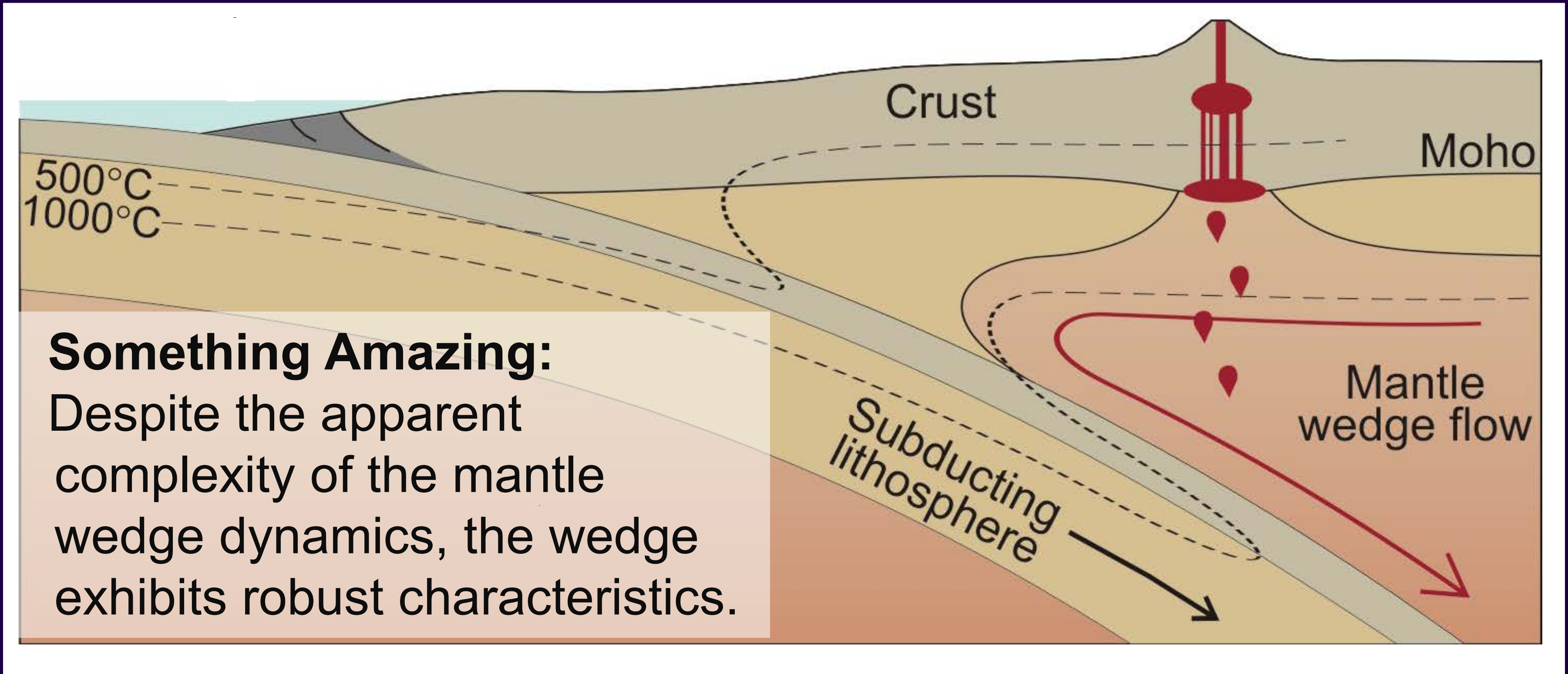
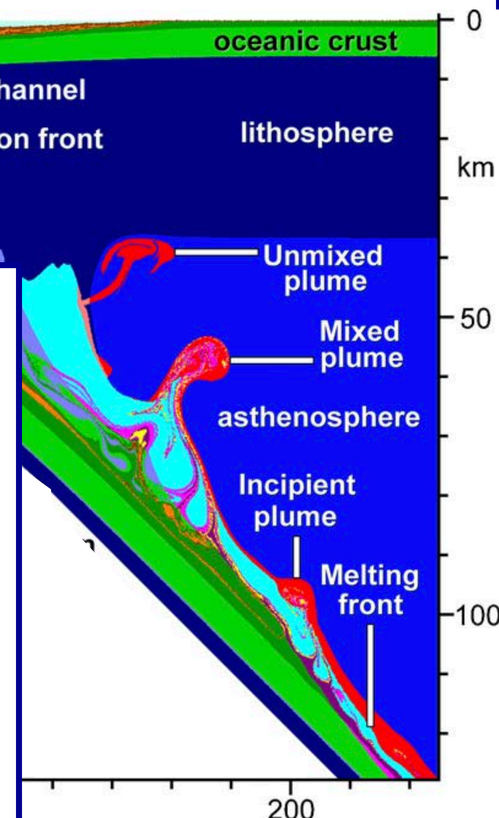


Something Amazing:
Despite the apparent complexity of the mantle wedge dynamics, the wedge exhibits robust characteristics.

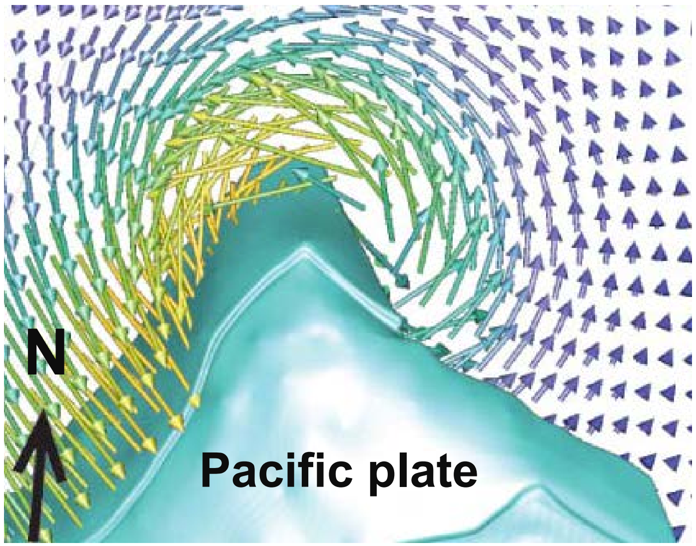
Competition between slab-driven flow and …

- Along-arc variations in slab geometry [*Kneller and van Keken*, 2007] (keynote by Peter van Keken)
- “Cold plumes” [*Gerya and Yuen*, 2003, *Gerya et al*., 2006]
- Slab edge [*Jadamec and Billen*, 2010]
- Foundering of arc lower crust [*Behn et al.*, 2007]
- Slab rollback [*Long and Silver*, 2008]
- …



[*Gerya et al*, 2006]

Slab beneath central Alaska



[*Jadamec and Billen*, 2010]

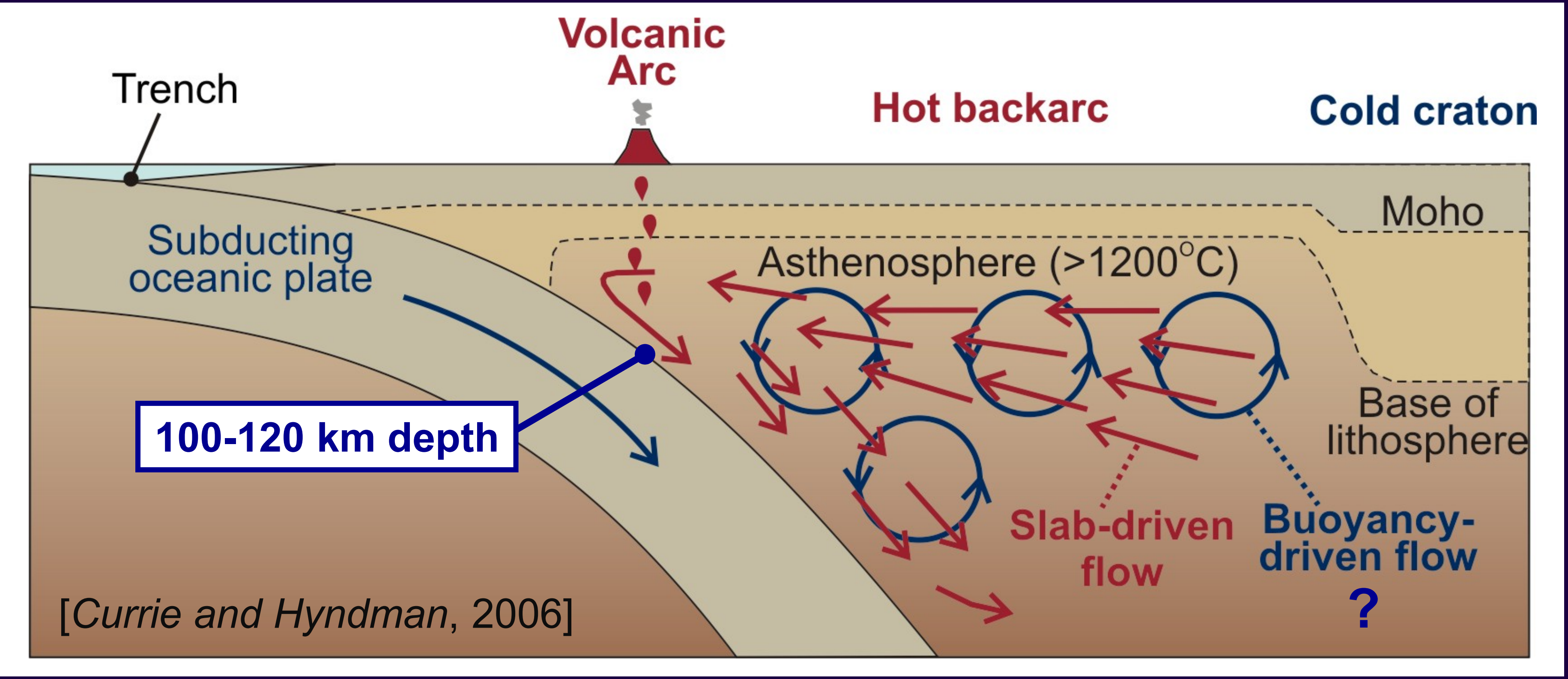
Robustness of Processes in the Mantle Wedge

Location of the Arc

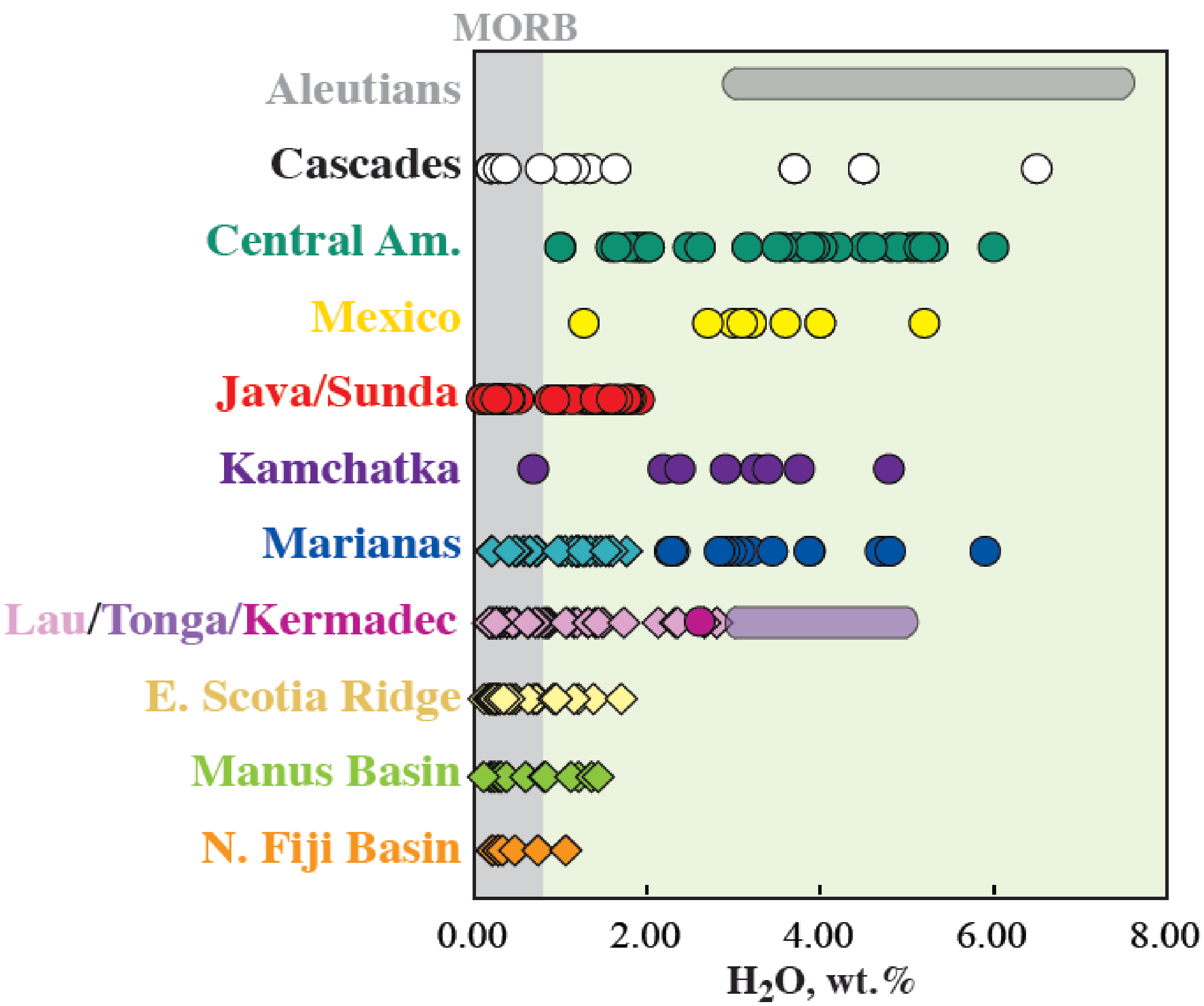
- The arc tends to form where the slab is 100–120 km deep [*England et al.*, 2004; *Syracuse et al.*, 2008].

Hot Backarc

- Shallow part of the mantle is hot [*Currie and Hyndman*, 2006]



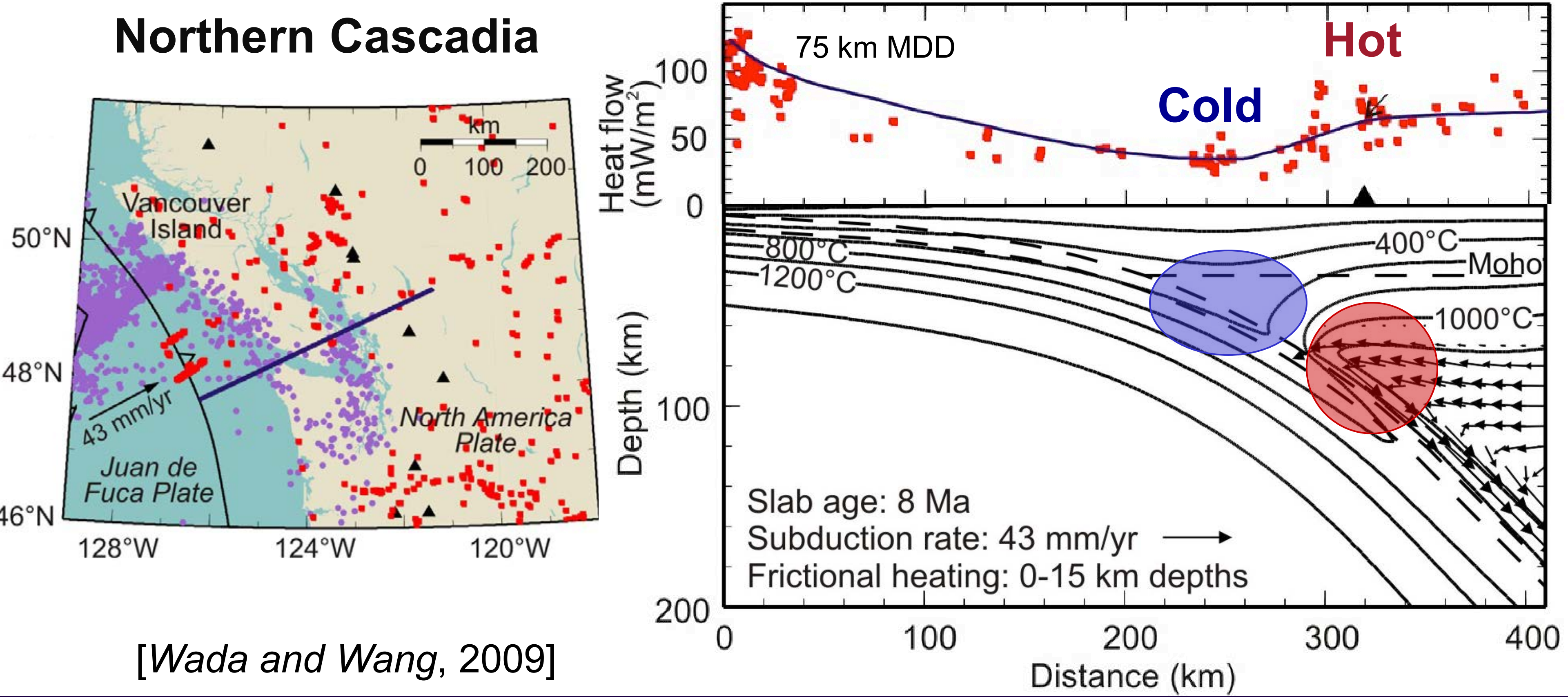
Water in Mafic Arc Magmas: Olivine Melt Inclusions



Compilation by Katie Kelley

"Why mafic arc magmas contain 4 wt% water on average?" – T. Plank et al. at Goldschmidt 2011

Cold to Hot Thermal Transition: Surface Heat Flow



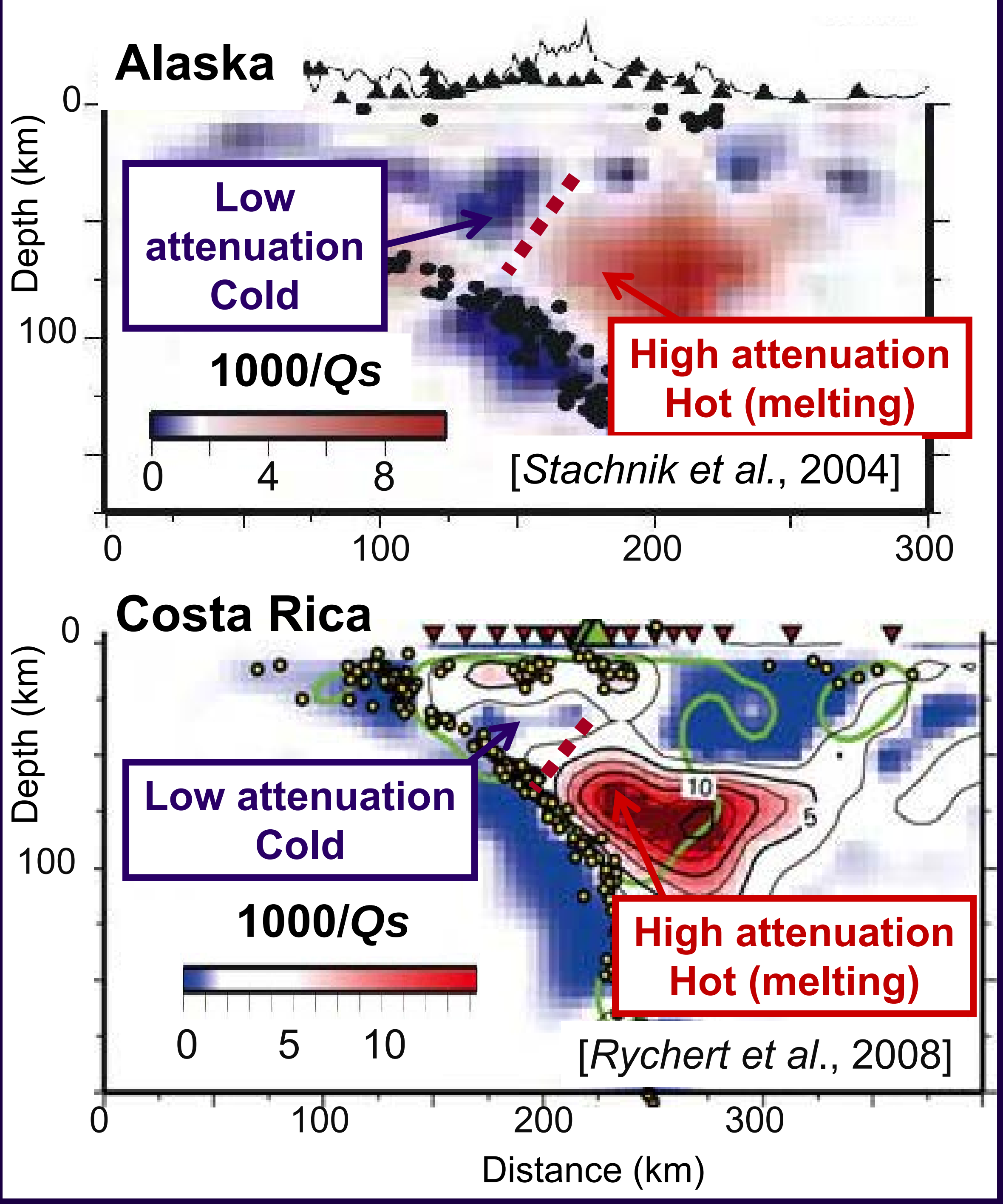
[*Wada and Wang*, 2009]

E.g., *Honda* [1985], *Furukawa* [1993], *Kincaid and Sacks* [1997], *van Keken et al.*, [2002], *Currie et al.* [2004], *Conder* [2005]

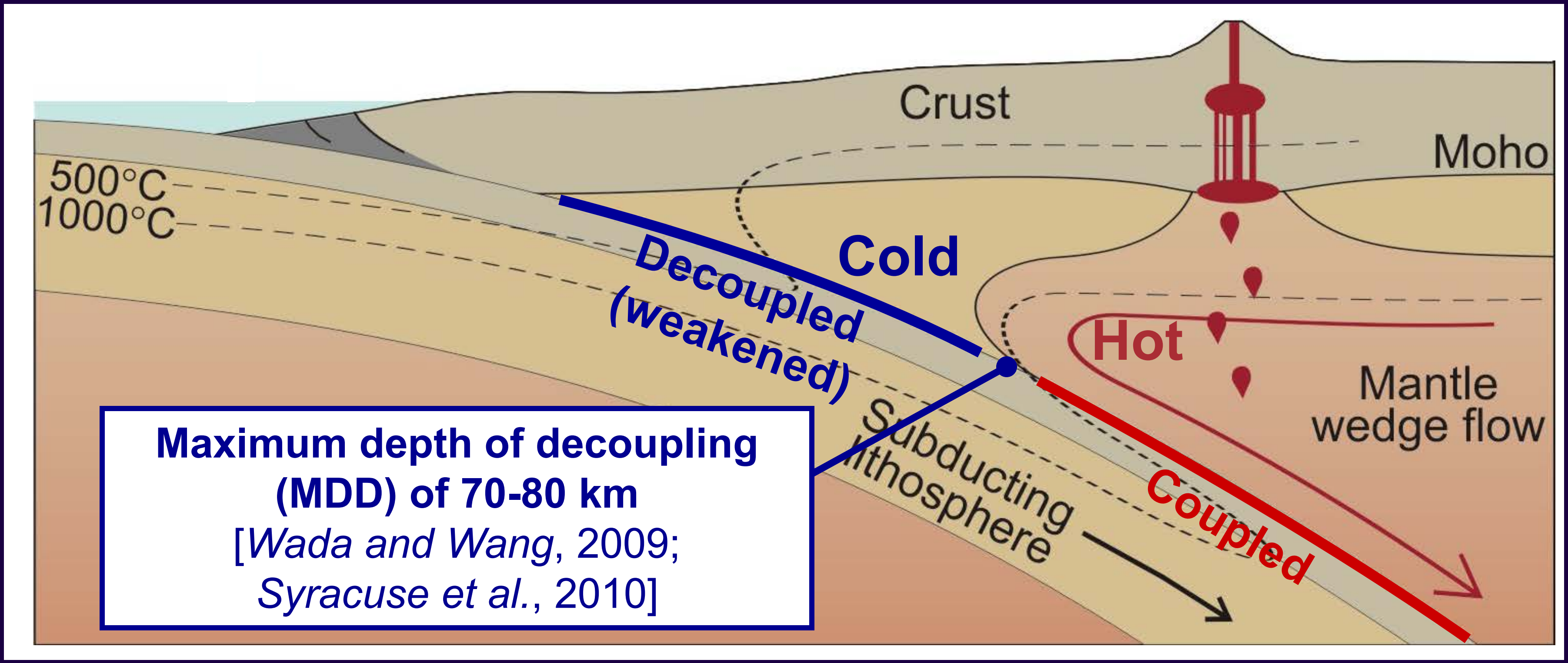
Cold to Hot Thermal Transition: Seismic Attenuation

1. Transition from cold to hot is sharp.

2. Transition tends to occur where the slab is at 70-80 km depth.



Sharp Thermal Transition at 70-80 km depth



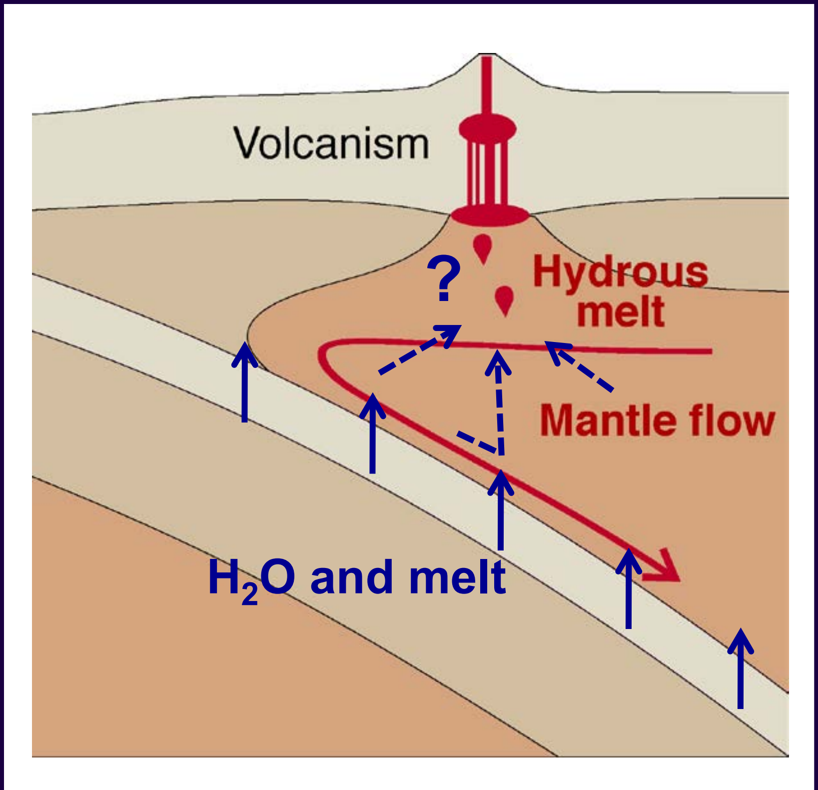
Factors that affect the mantle-interface strength contrast

- T- dependence of the mantle rheology [*Wada et al.*, 2011]
- Rheology of the interface manterial
- Metamorphic changes of the interface material or the mantle
- Variations in fluid and melt content
- Hot backarc – heat supply
- …

Arc Location:
Location of Hydrous Melting

1. Location of fluid release/influx

- Dehydration reactions in the slab and in the hydrous layer at the wedge base [e.g., *Tatsumi,* 1986; *Peacock*, 1990*; Davies and Stevenson*, 1992; *Grove et al*., 2009]

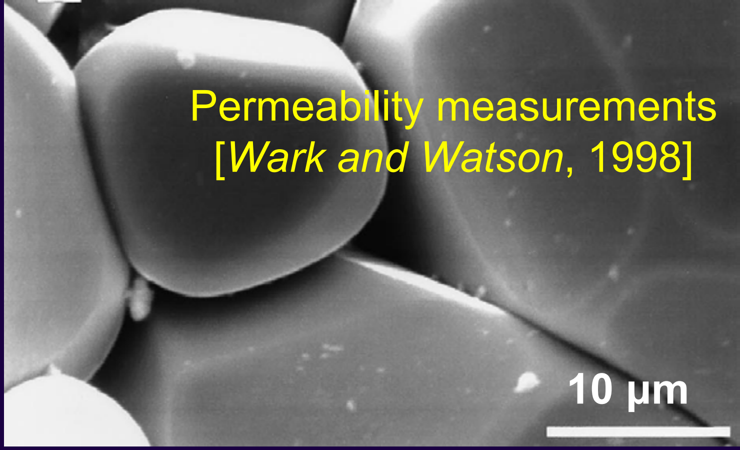


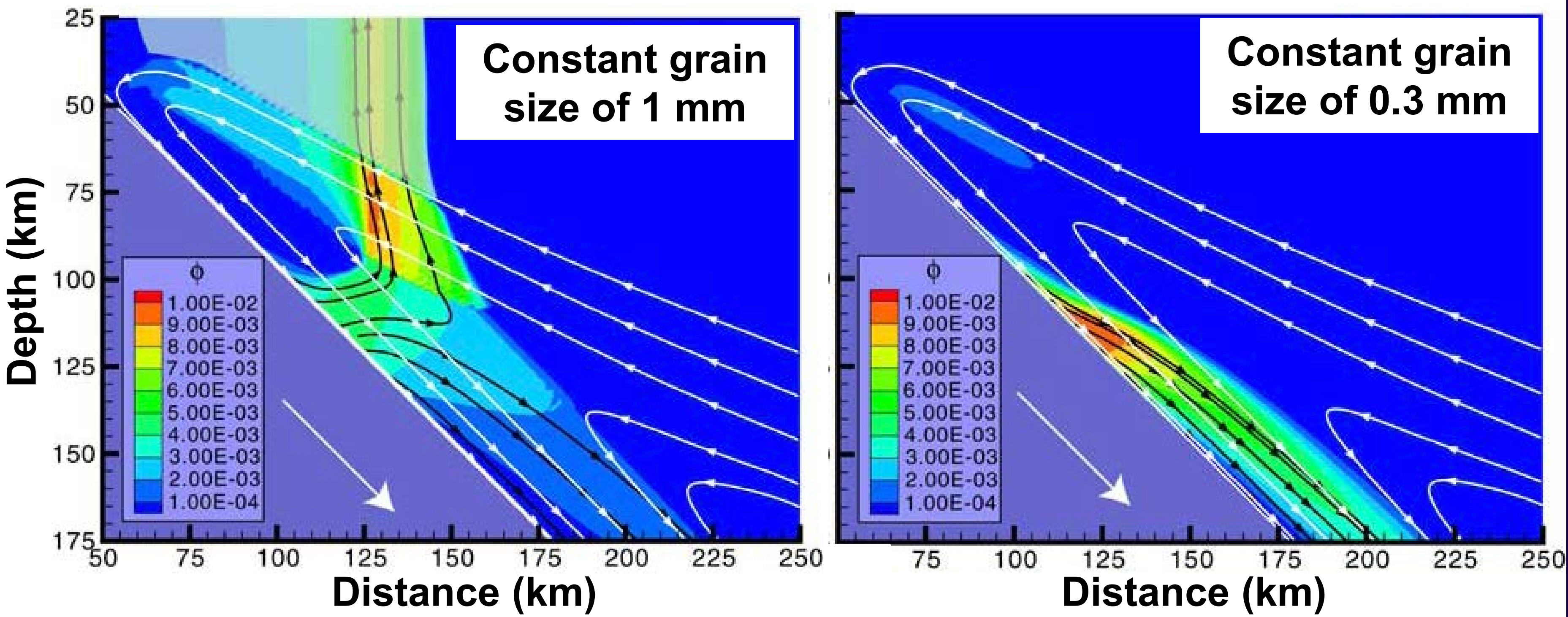
2. Volatile transport to the hot region

- Plumes/diapirs [*Hall and Kincaid*, 2001; *Gerya and Yuen*, 2003; *Currie et al*., 2007; *Behn et al.*, 2011]
- Porous fluid migration within the wedge [*Arcay et al.*, 2005; *Iwamori*, 1998, 2007; *Cagnioncle et al.*, 2007; *Hebert et al.*, 2009]

- Fluid migration occurs through interconnected pores between grains.
- Grain-scale permeability (k) depends on grain size (d) and fluid fraction (ϕ):

$$k = (d^2 \phi^3) / 270$$ [*Wark et al*, 2003]





[*Cagnioncle et al.*, 2007]

Grain Size Evolution Model

[*Austin and Evans*, 2007, 2009; *Behn et al.*, 2009]

Laboratory-derived model for wet olivine

Change in grain size	=	Static grain growth	+	Dynamic recrystallization (by dislocation creep)

$$\dot{d} = \left[\frac{G_0}{p_g} \exp\left(-\frac{E_g}{RT} \right) d^{1-p_g} \right] + \left[-\frac{\chi \sigma \dot{\varepsilon}_{dis}}{c\gamma} d^2 \right]$$

Temperature — Stress × strain rate

- The model does not account for brittle deformation and is valid only for creeping regions (> 600° C).

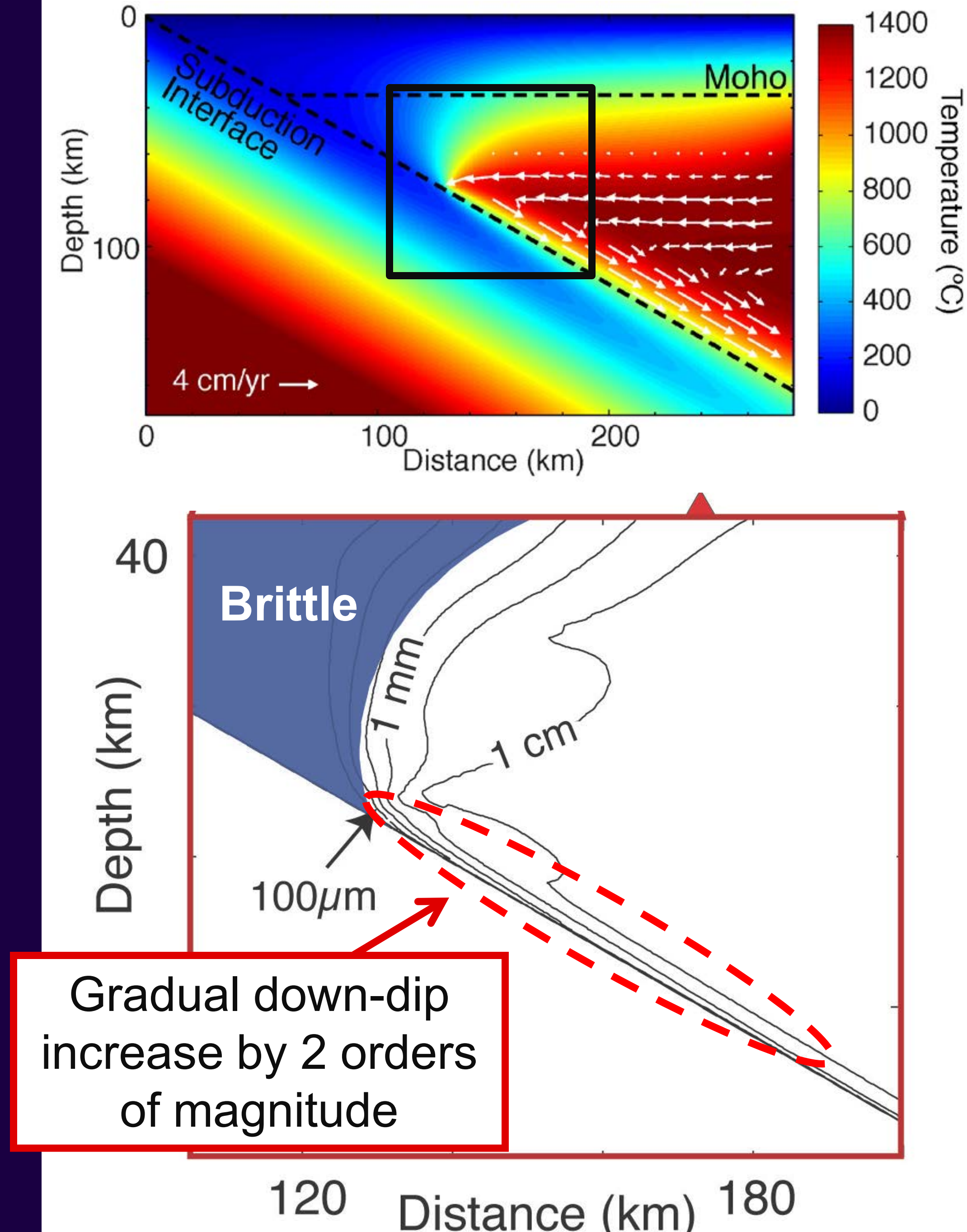
Poster:
"Grain size distribution in the mantle wedge"
[*Wada et al.*, JGR, in press]

Steady State
Grain Size Distribution

Slab age	100 Ma
Subduction rate	4 cm/yr
Slab dip	30°

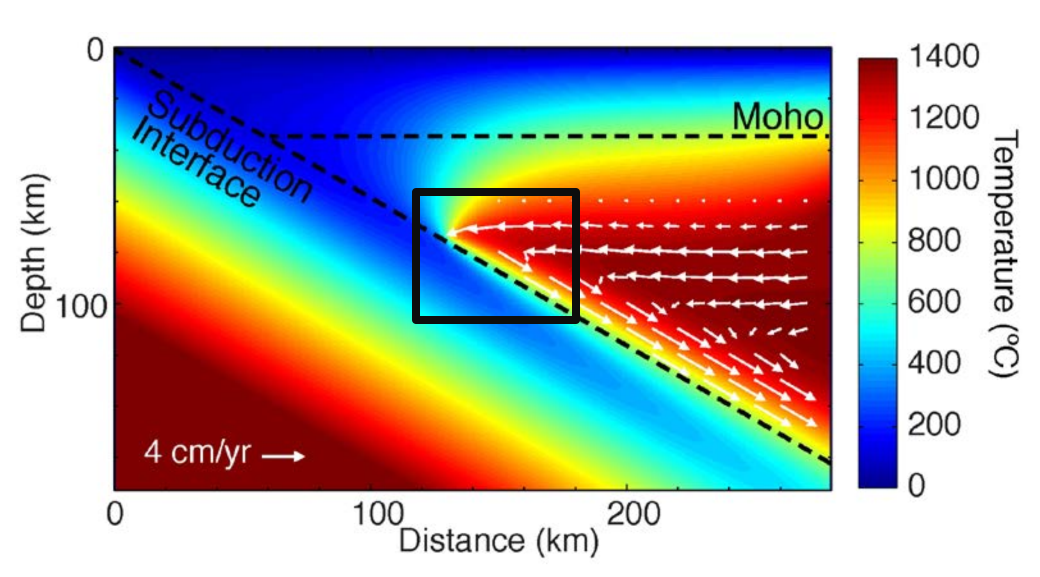
Grain size increases downdip from 10-100 μm to a few cm, by > 2 orders of magnitude, independent of subduction parameters.

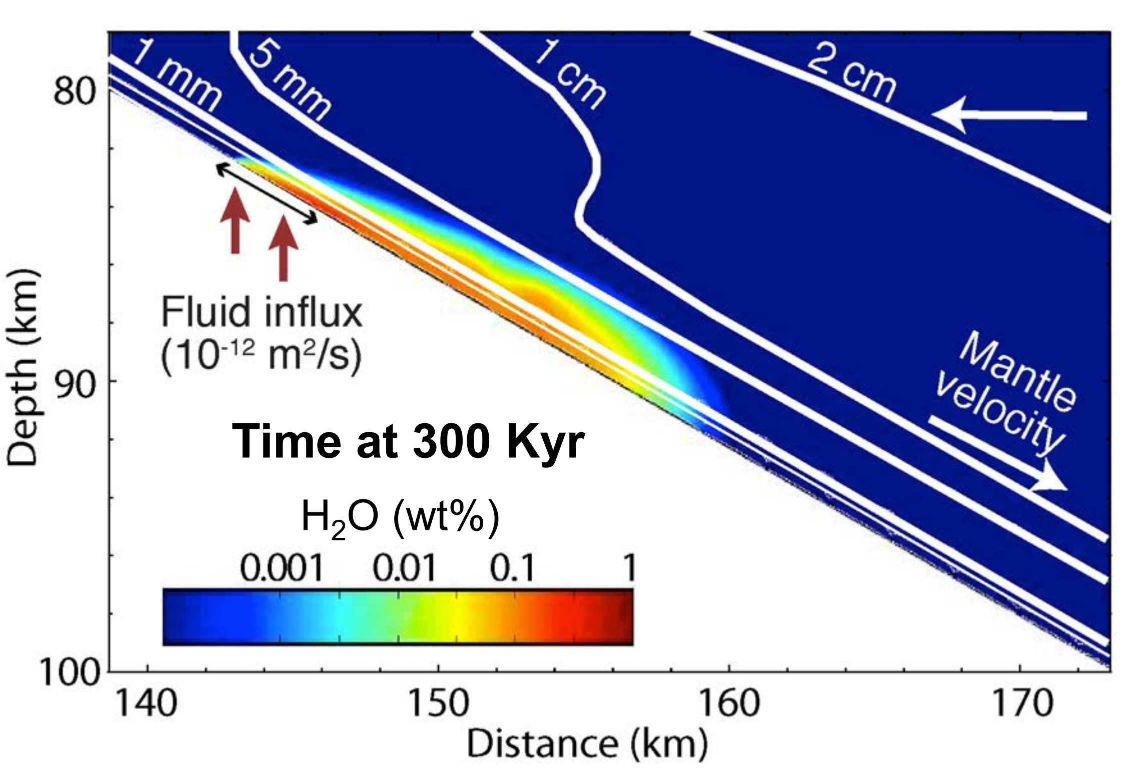
Poster:
“Grain size distribution in the mantle wedge”
[*Wada et al.*, JGR, in press]



Effect of Grain Size Variations

Fluid migration model in progress [I. Wada, M. Behn., and E. M. Parmentier]





Fluid velocity

$$\vec{V}_f = \vec{V}_m + \frac{\vec{S}}{\phi}$$

Darcy's flux

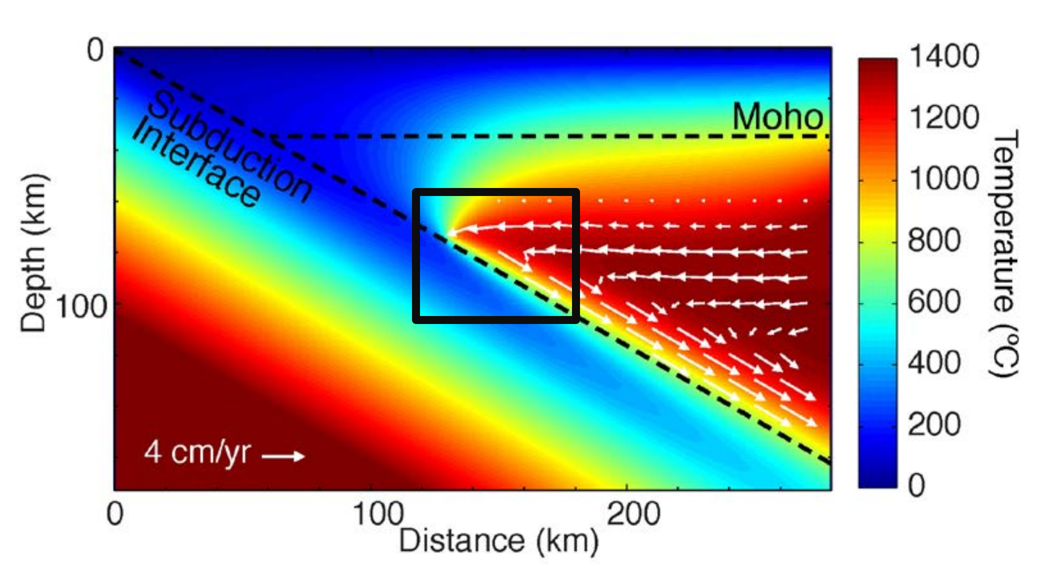
$$\vec{S} = -\frac{k}{\eta}\left[\Delta\rho\vec{g} + \nabla P\right]$$

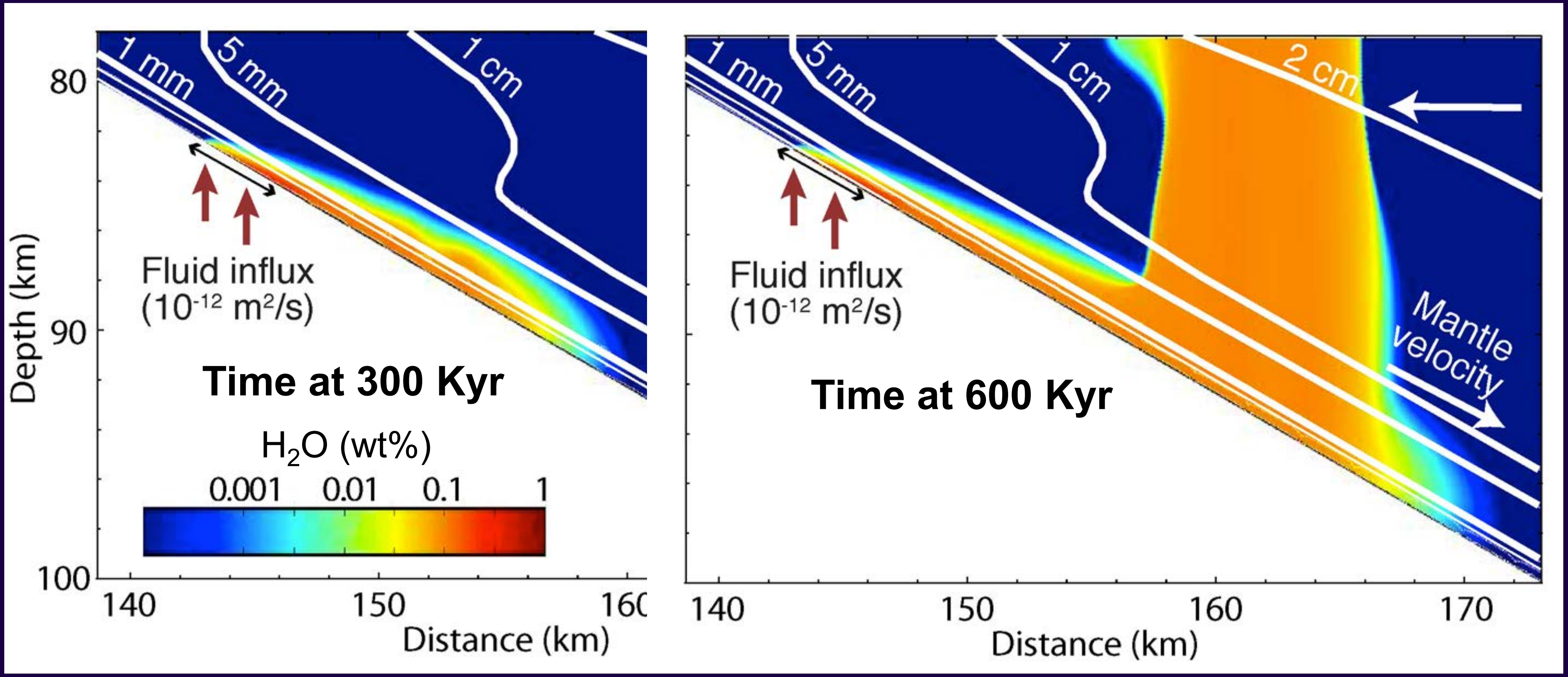
Permeability

$$k = \phi^3 d^2 / 270$$

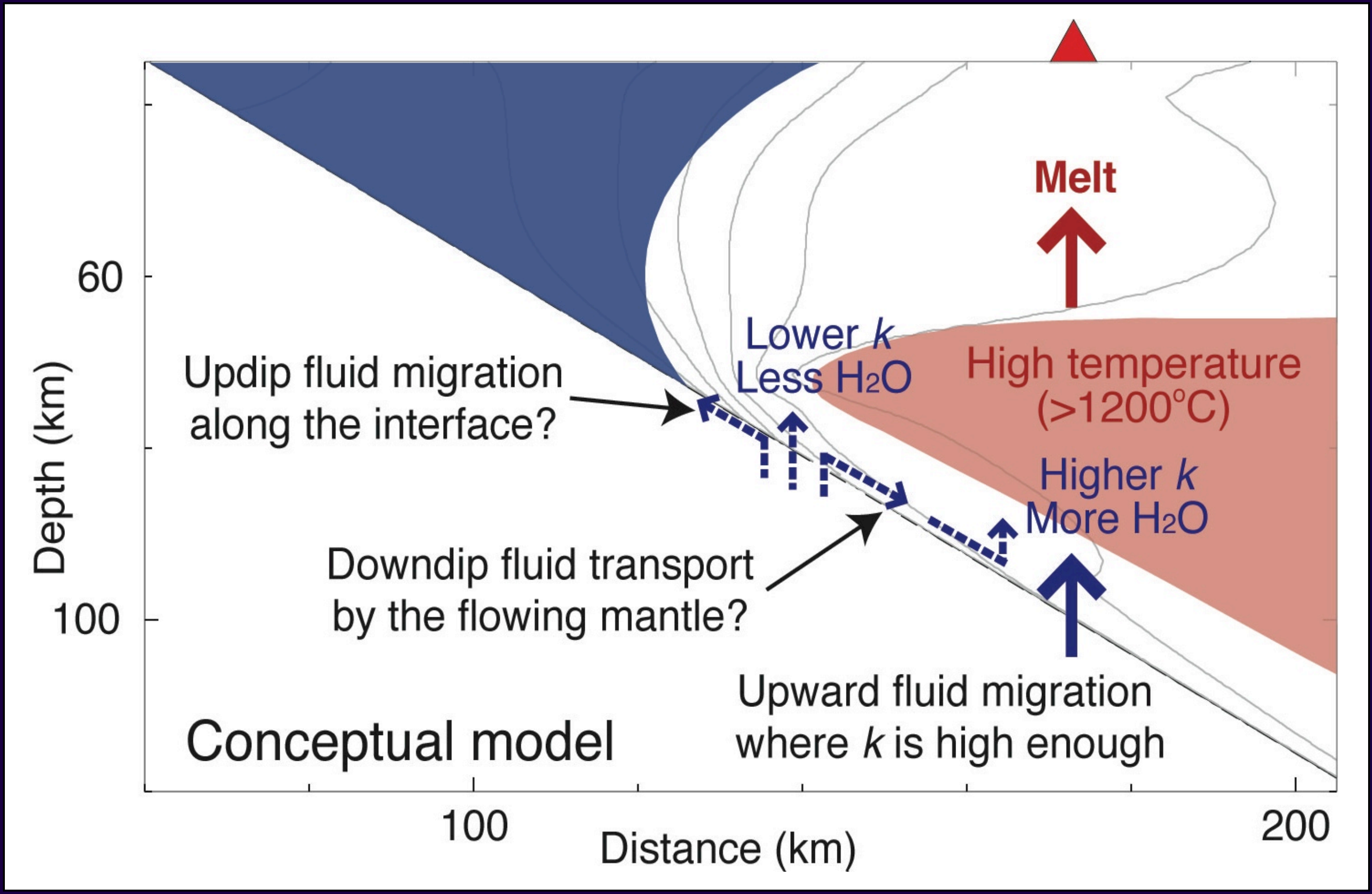
Effect of Grain Size Variations

Fluid migration model in progress [I. Wada, M. Behn., and E. M. Parmentier]





Conceptual Model for Fluid Migration



Concluding Remarks

Despite complex dynamic processes, the mantle wedge exhibits robust features – Clues to understanding the mantle wedge dynamics.

- Maximum depth of slab-mantle decoupling – Disappearance of mantle-interface strength contrast
- Cold wedge nose (<70-80 km depth) – No significant mantle flow
- Hot region – Enough flow to bring heat for melt generation; Competition among viscous coupling and other flow drivers.
- Relatively high water content of mafic arc magmas – Water transfer mechanism.
- Arc location relative to the slab – Focusing of melt where slab is ~110 km deep: Grain size variations may help regulate upward fluid flow.
- Hot backarc – Small scale convection; heat supply regulator?

Robust Feature: Hot Mantle (> 70-80 km depth)

Formation of hydrous phases

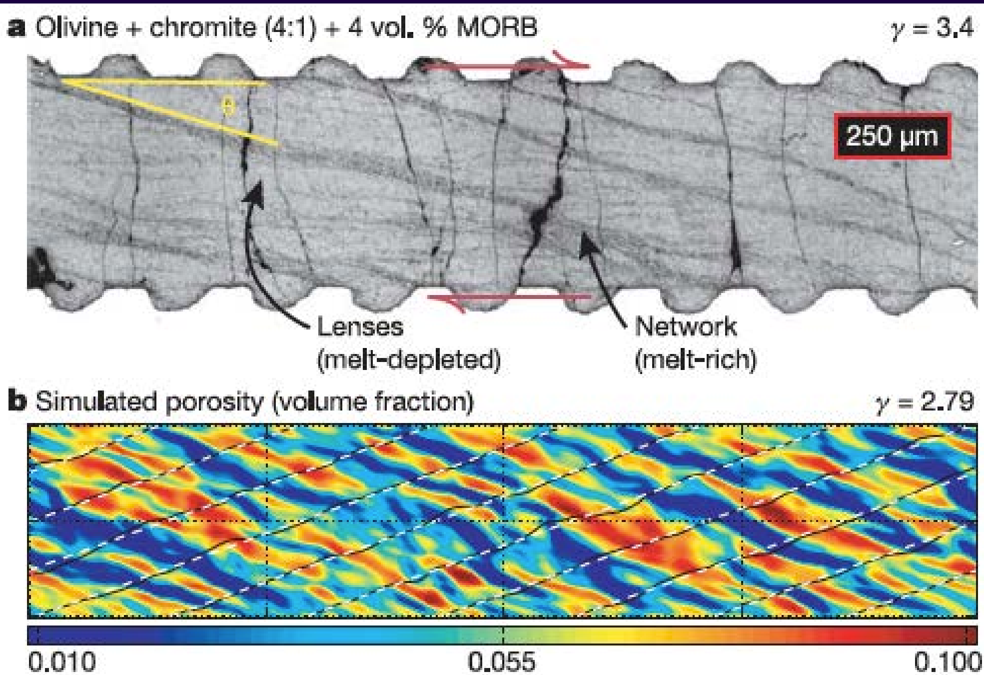
- Thin hydrous boundary layer above the subducting slab [*Kawakatsu and Watada*, 2007; *Grove et al.*, 2009] – weakening effect

Melting

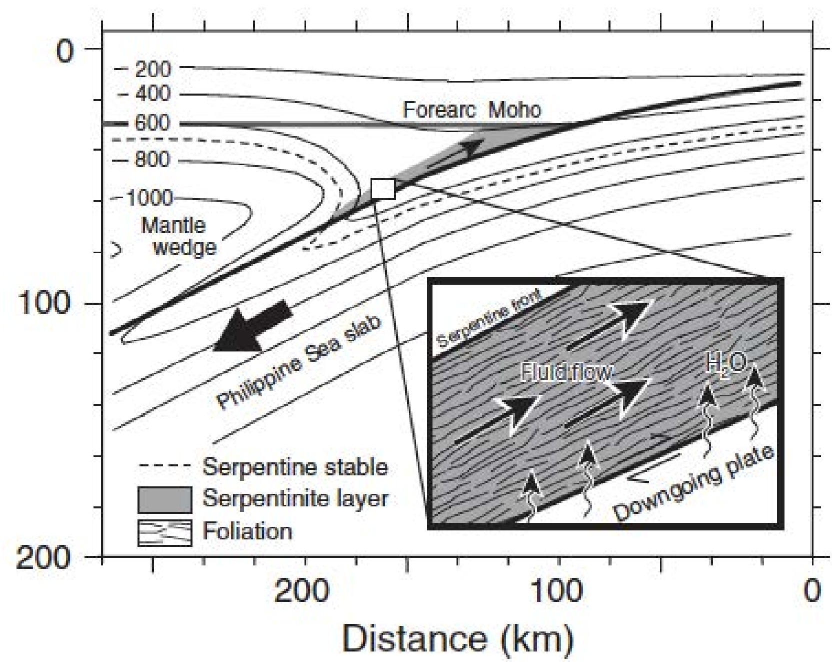
- Anhydrous melting via adiabatic decompression [e.g., *England and Katz*, 2010]
- Hydrous melting [e.g., *Grove et al*., 2006] – Fluid availability

Fluid migration

- Grain size, dynamics pressure gradients due to mantle shear and compaction, variations in fluid influx
- Shear induced melt bands [*Spiegelman*, 1993; *Katz et al.*, 2006; *Butler*, 2009]
- Anisotropic permeability of serpentinites [Kawano et al., 2011]
- …



[*Katz et al*, 2006]

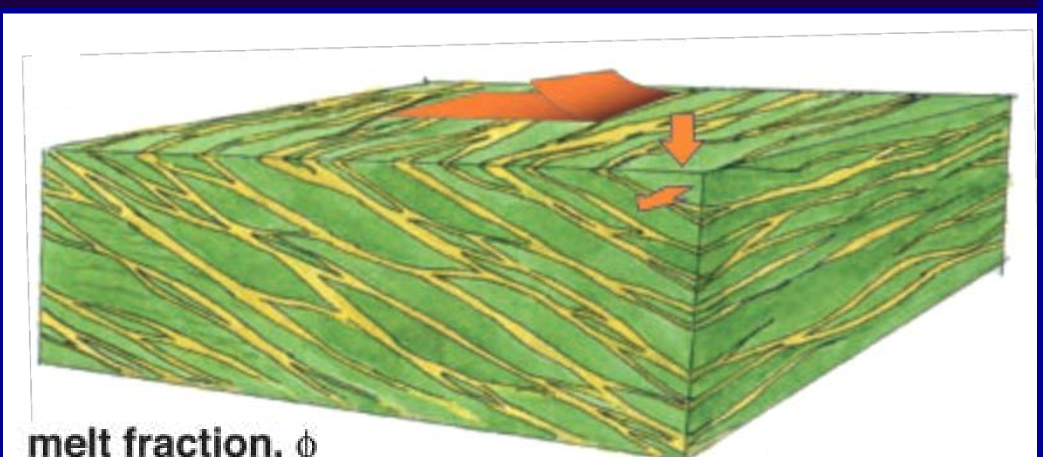


[*Kawano et al*, 20011]

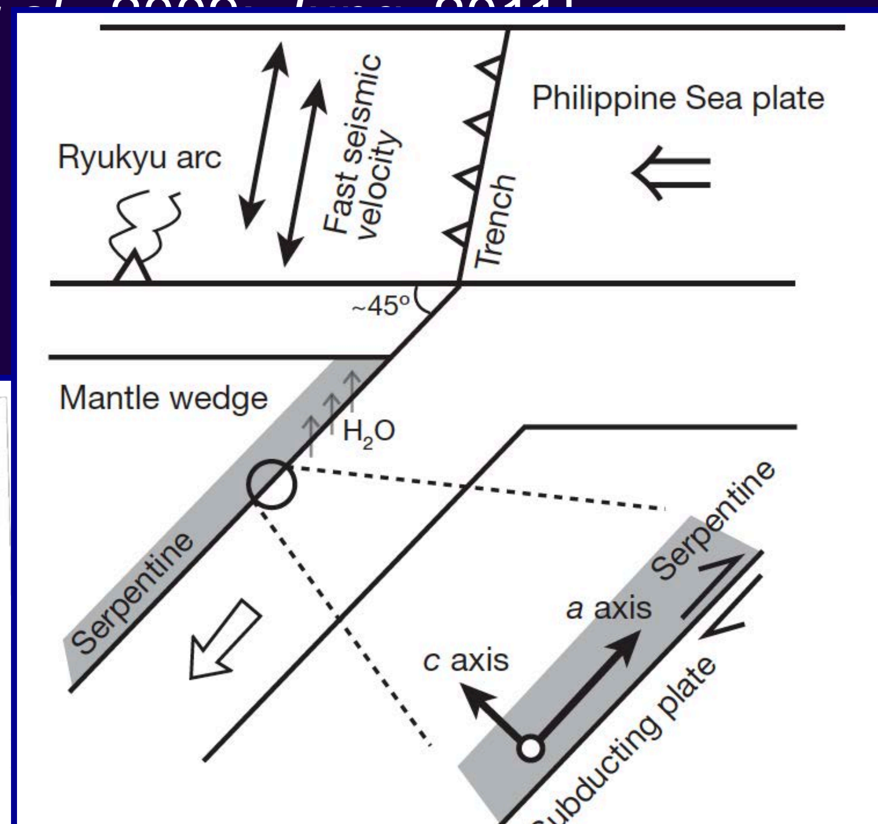
Variable direction of fast direction and magnitude of delay time

What does seismic anisotropy indicate?

- Crystal-preferred orientation (CPO) of olivine: A type vs. B type [*Jung and Karato,* 2001; *Kneller et al.*, 2007].
- CPO of serpentine [*Katayama et al.*, 2009; *Jung*, 2011]
- Fluid filled cracks or melt lenses (e.g, *Holtzman et al.* [2003])
- …



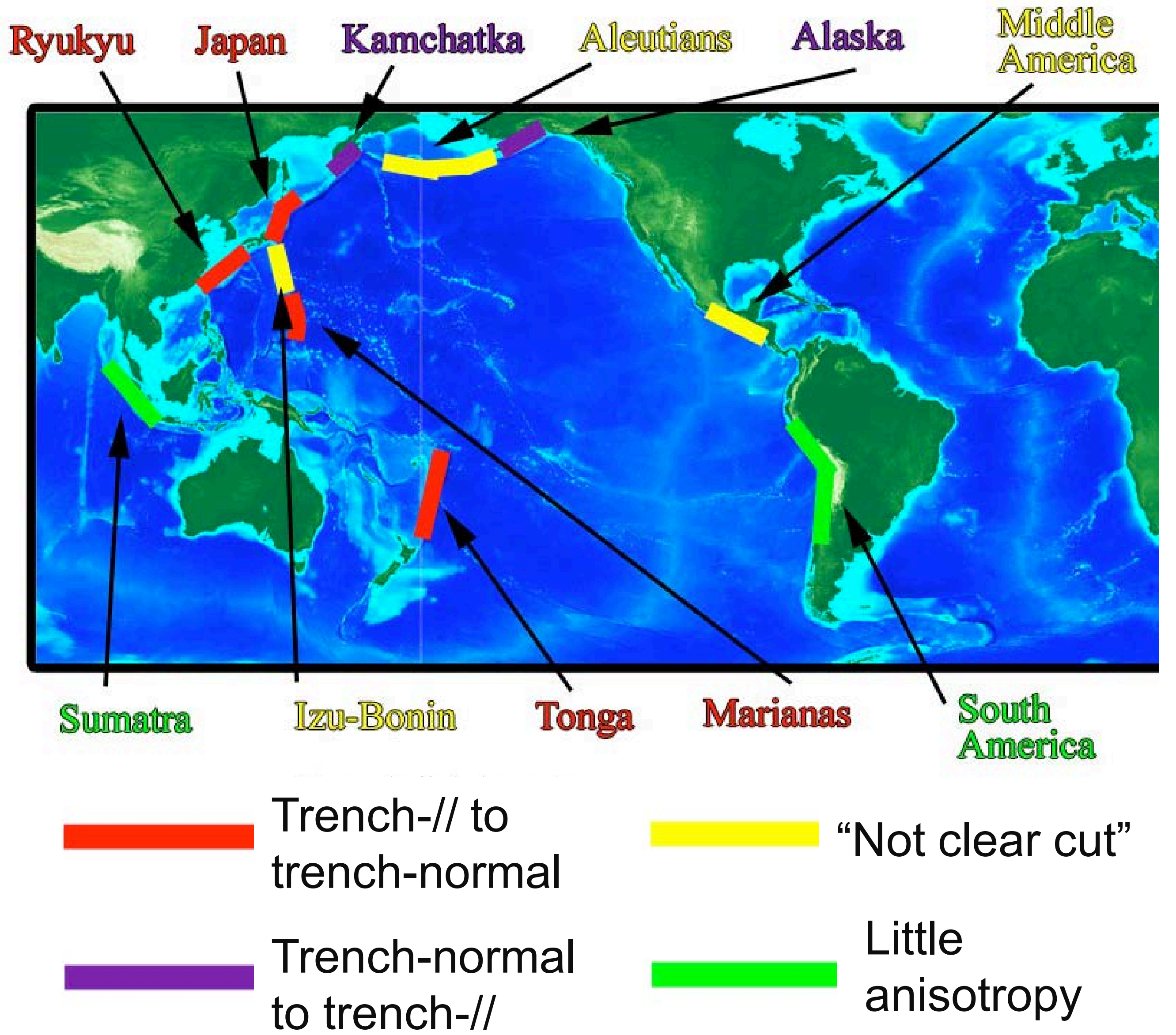
[*Holtzmen et al*, 2003]



[*Katayama et al*, 2009]

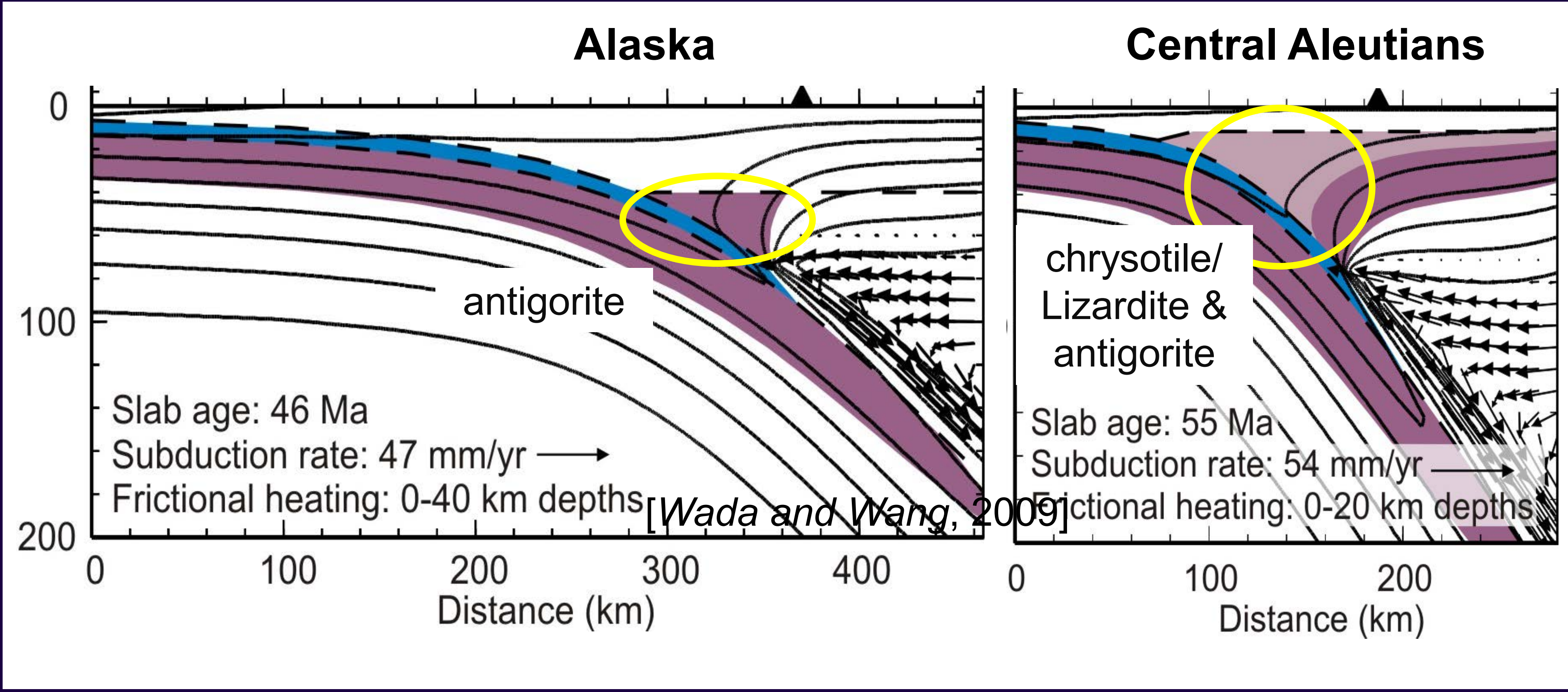
Large Variability in Observables

Seismic Anisotropy



[*Long and Silver*, 2008]

Cold Wedge Nose & Mantle Wedge Serpentinization



[*Wada and Wang*, 2009]