From Reaction-driven to Stress-driven Melt Segregation – Formation of High-permeability Paths through Earth's mantle

David Kohlstedt
University of Minnesota

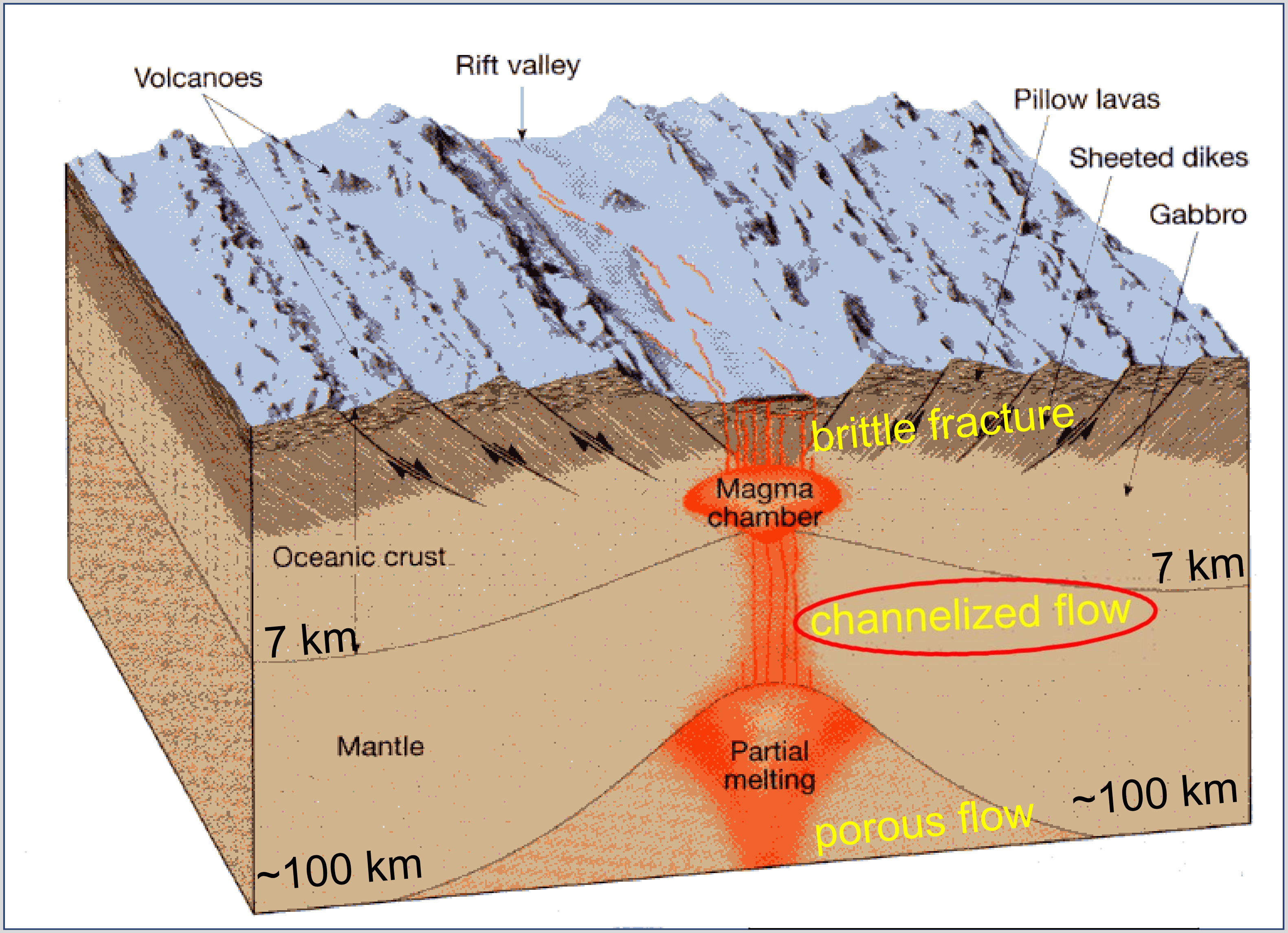
Matěj Peč – MIT
Mark Zimmerman – U Minnesota
Ben Holtzman – Columbia University

Volcanic eruption

Iceland – 2010
Mid-Atlantic Ridge

National Geographic (2010)

Melt transport paths from depth to surface



Tarbuck and Lutgens (2005)

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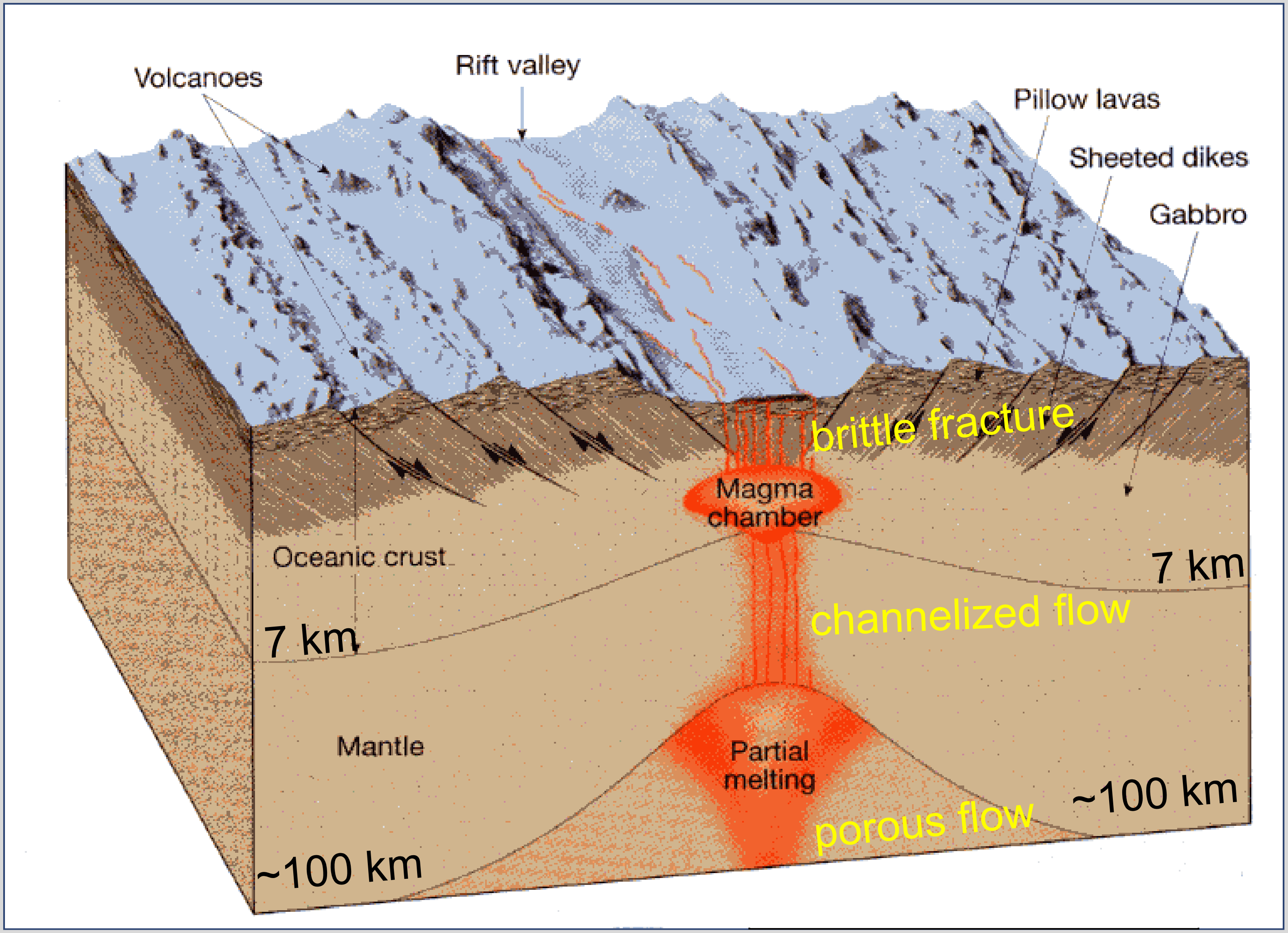
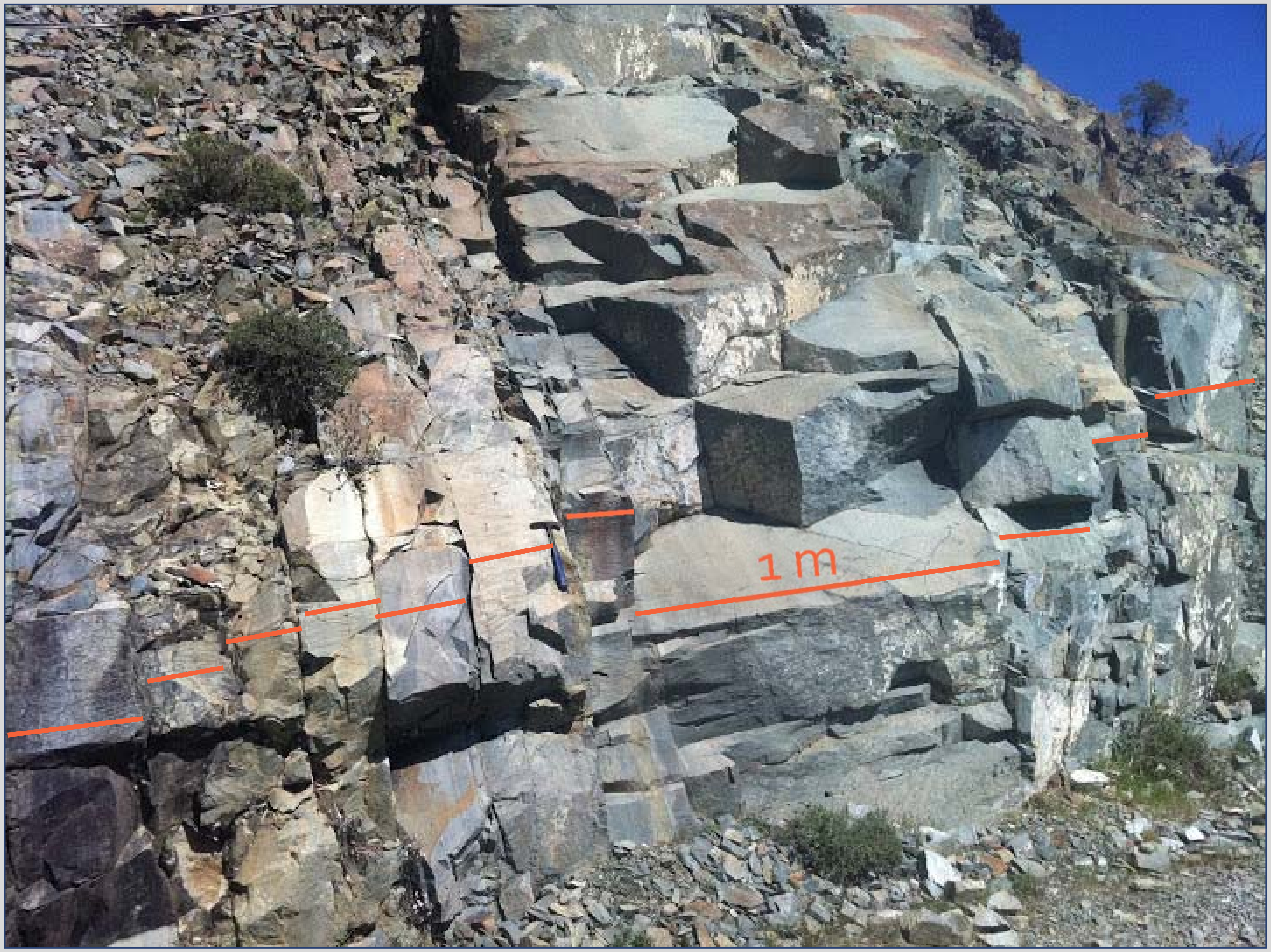


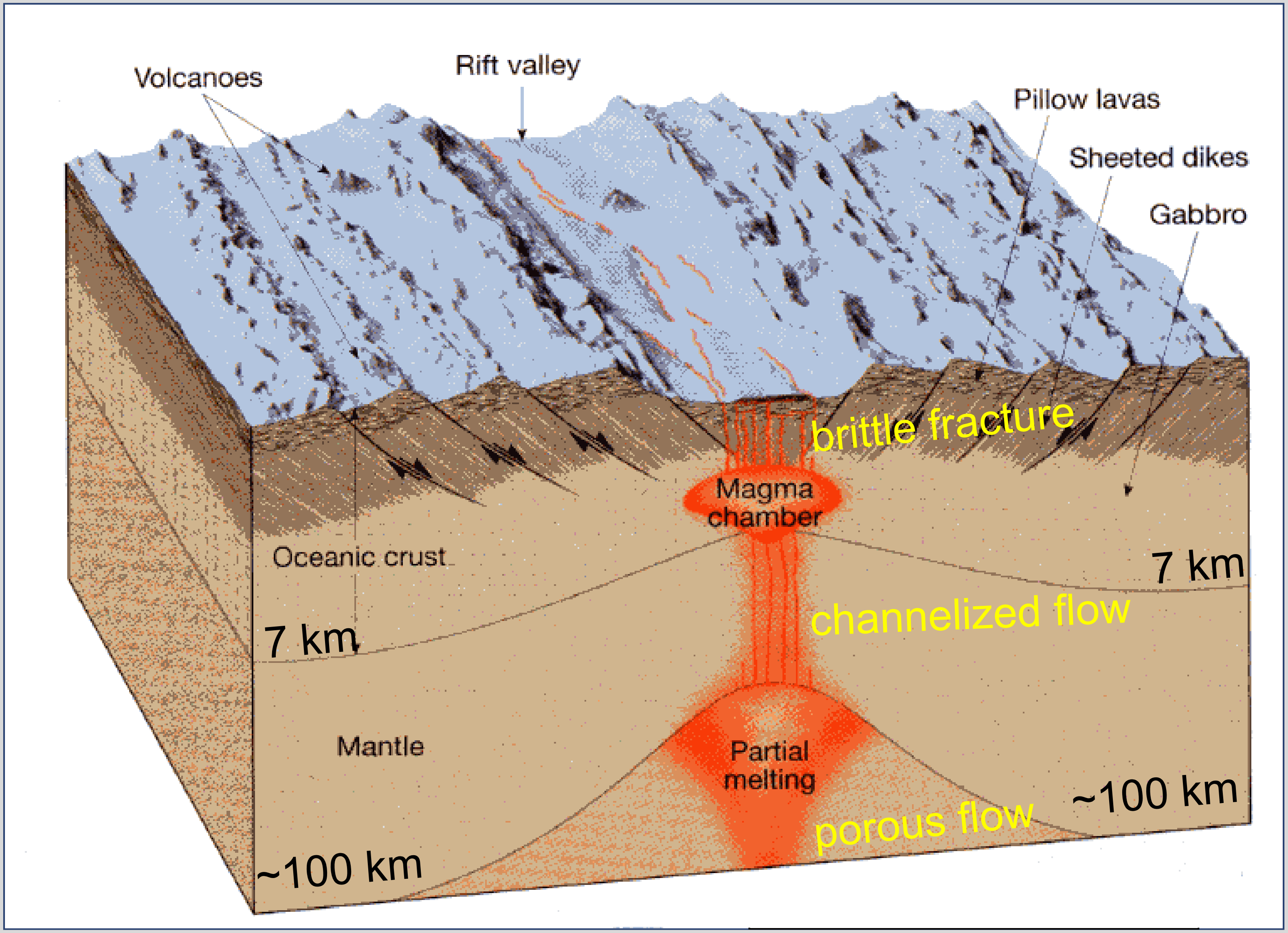
Tarbuck and Lutgens (2005)

Sheeted dikes in the Troodos Ophiolite, Cyprus



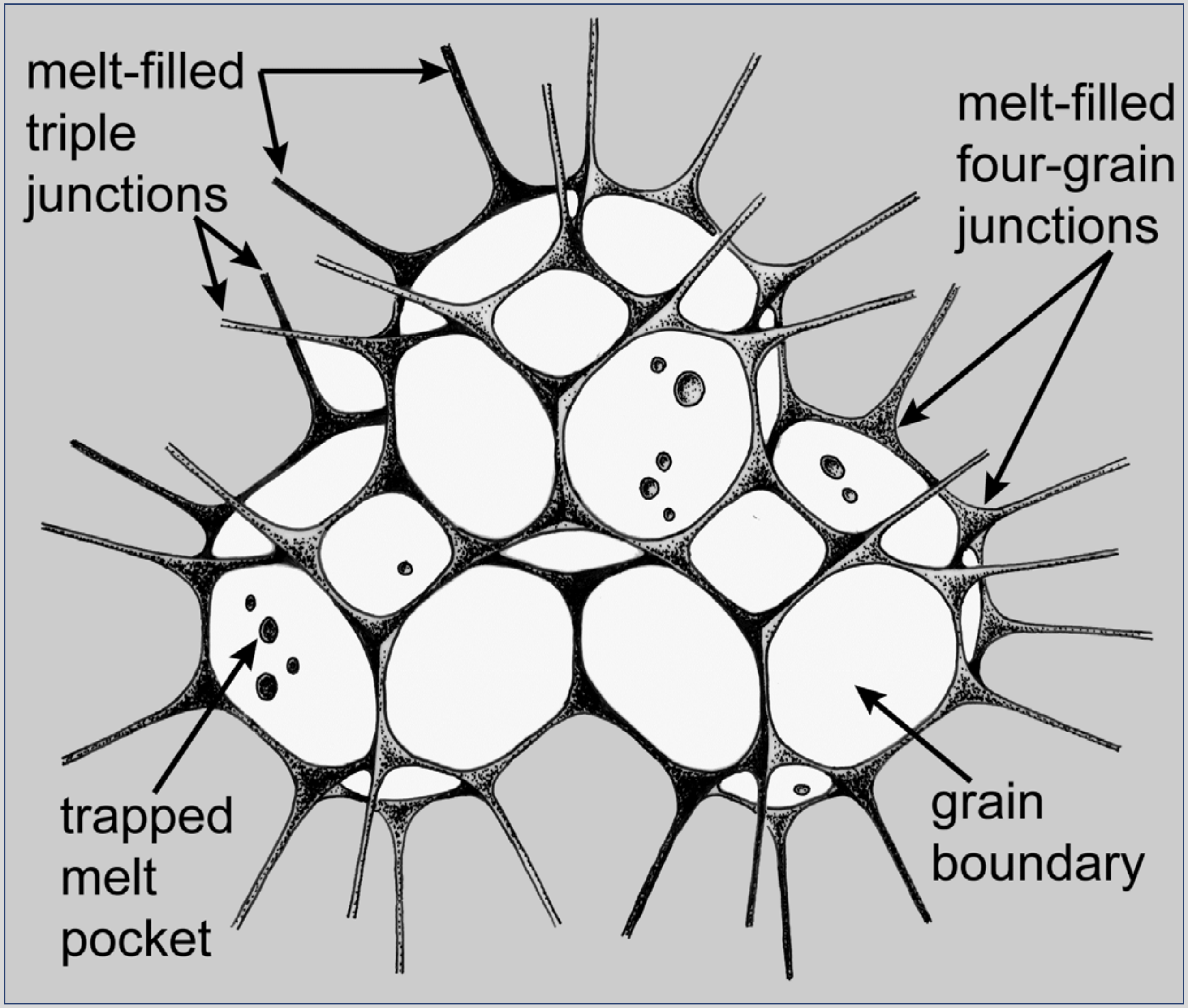
Ophiolite: fragment of oceanic crust and uppermost mantle usually formed at a spreading center and subsequently obducted onto the continental crust

Melt transport paths from depth to surface



Tarbuck and Lutgens (2005)

3-D melt distribution for isotropic interfacial energy



interconnected network of melt along triple junctions permits porous flow

Lee and Mackwell (1991)

3-D melt distribution in olivine-basalt aggregates

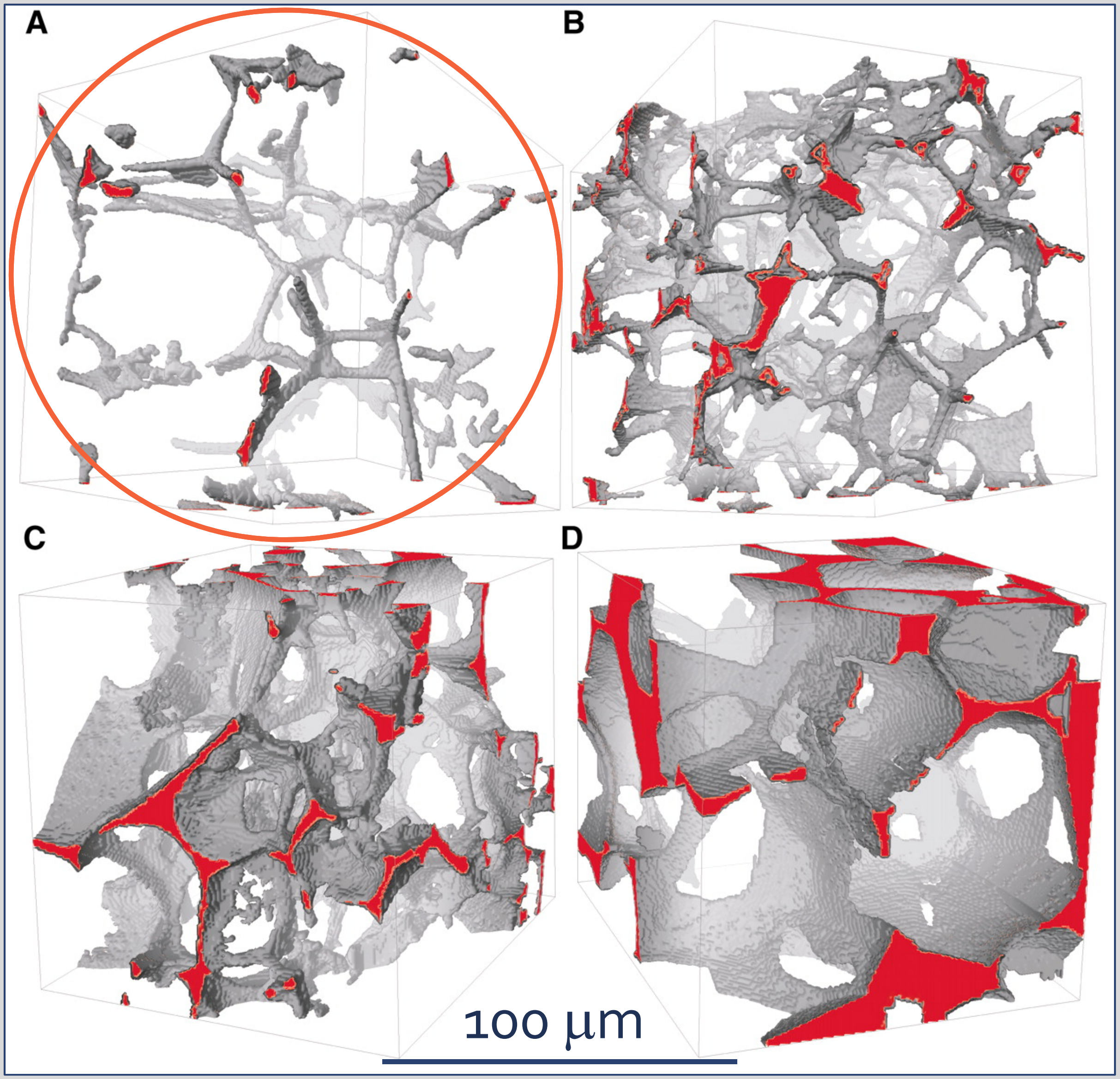
X-ray computed tomography images

$\phi = 0.02$

$\phi = 0.05$

$\phi = 0.10$

$\phi = 0.20$

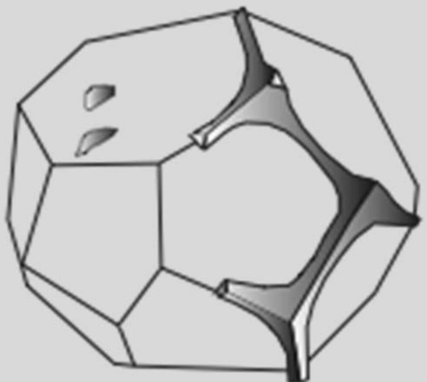


porous flow along melt-filled triple junctions

Zhu et al. (2011)

Porous flow

Melting occurs at the grain scale



$$q = -\frac{k}{\mu}\frac{\partial P_p}{\partial z}$$

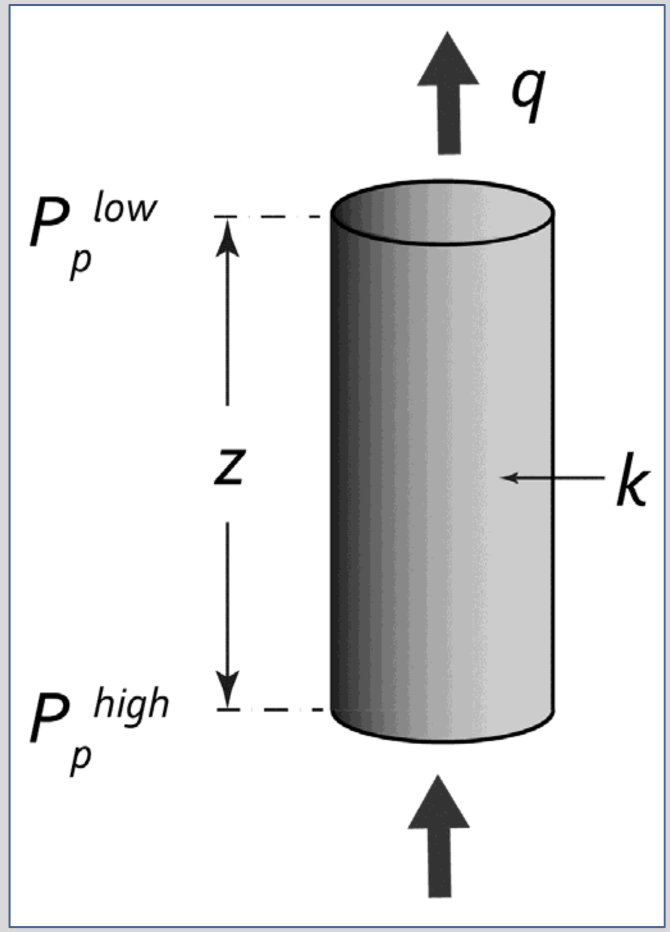
Darcy's law

$$k = \frac{d^2 \phi^s}{C}$$

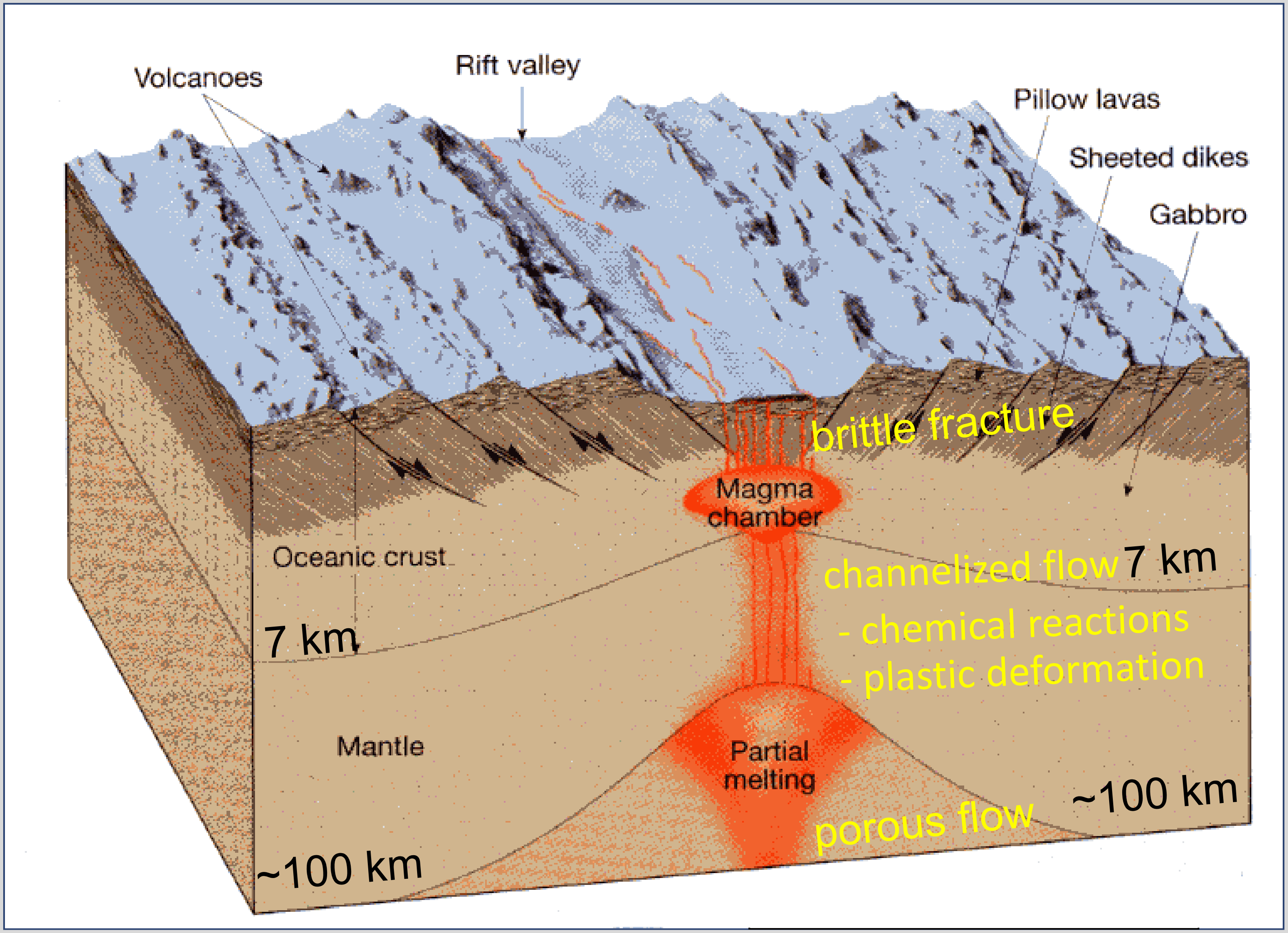
permeability

$$k = \frac{d^2 \phi^{2.6}}{56}$$

Miller et al. (2014)



Melt transport paths from depth to surface

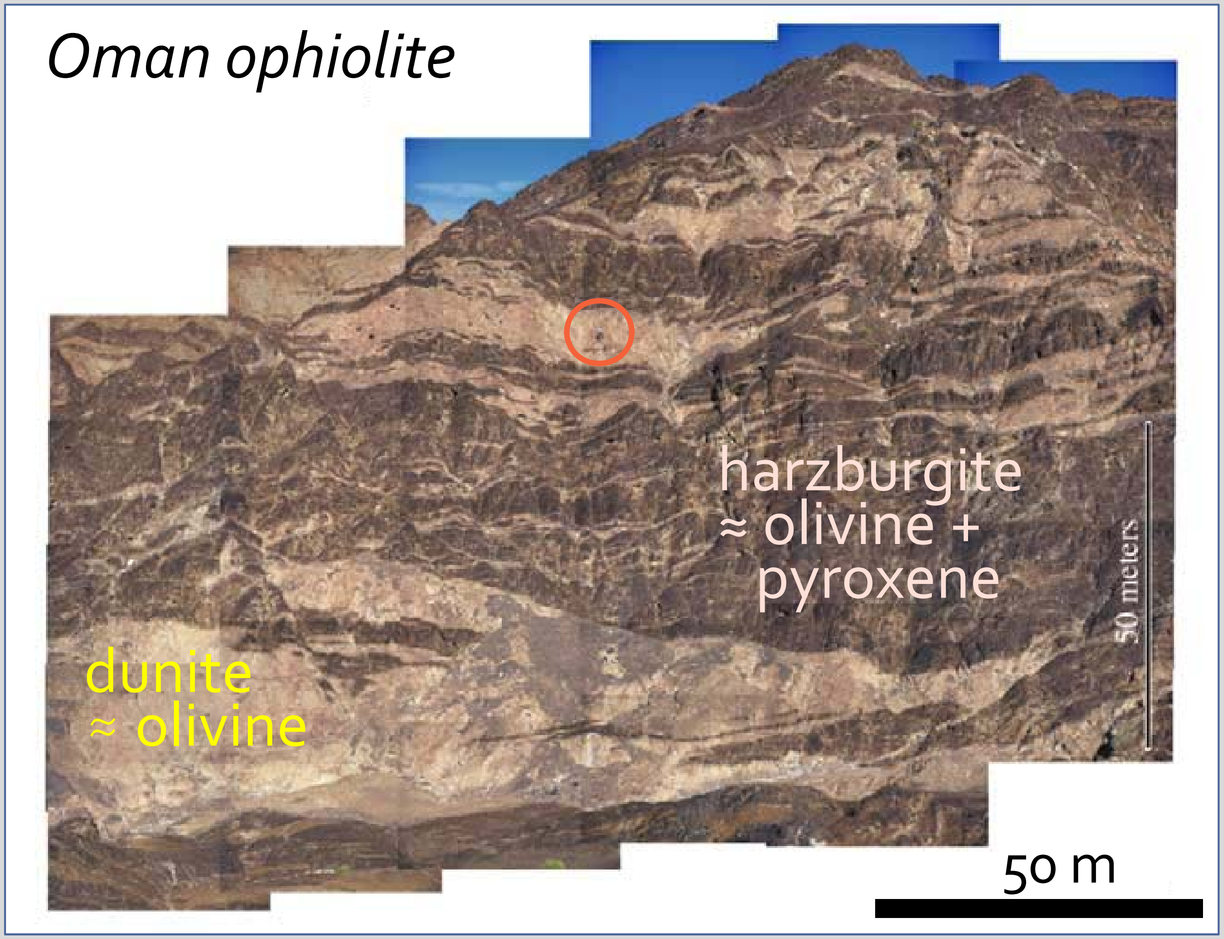


Tarbuck and Lutgens (2005)

Field evidence for channelized flow – geochemical and geophysical observations

– Basaltic melt is in equilibrium with dunite, but not with harzburgite

– Anastomosing network of tabular dunite bodies in harzburgite



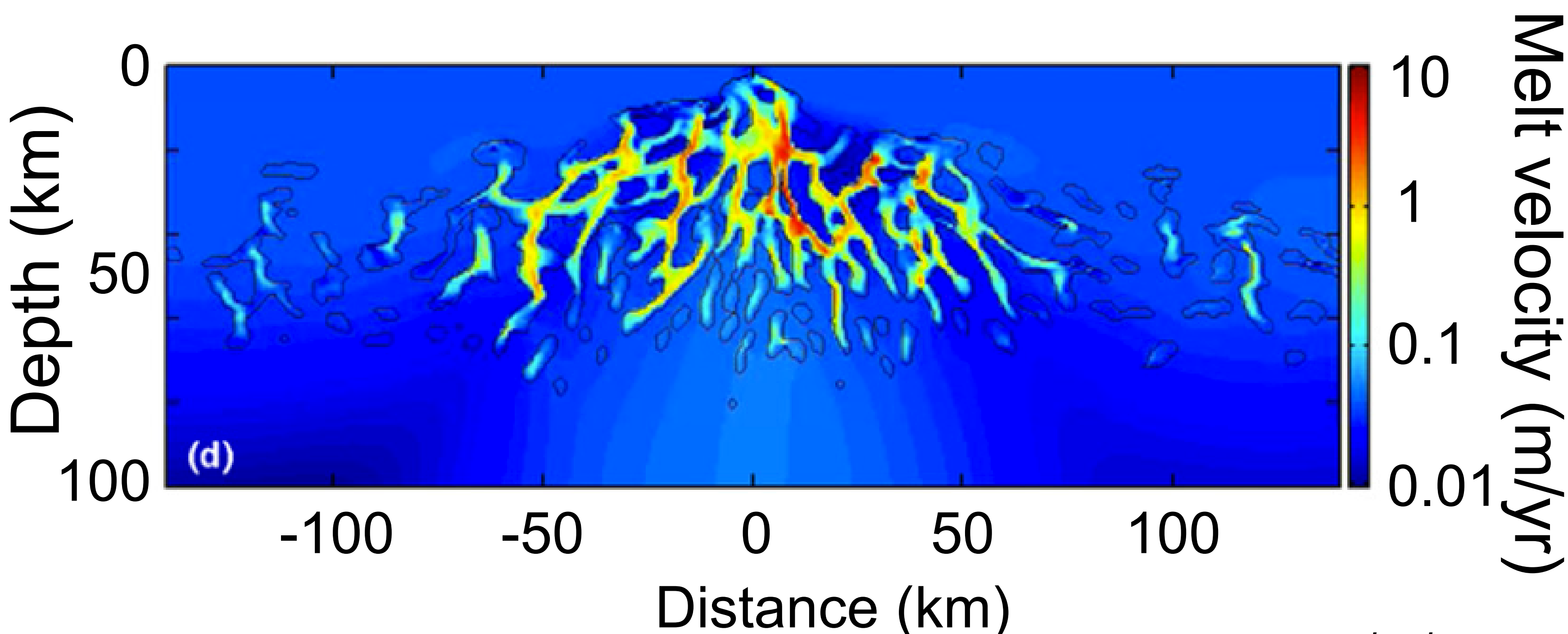
Braun and Kelemen (2002)

Geochemical constraints

- Chemical composition: source + pathway
- Isotopic disequilibria: velocity
- Channelization is necessary
- Produces cylindrical channels

Geophysical constraints

- Deformation produces tabular channels
- Channels are shear zones



Katz & Weatherley (2012)

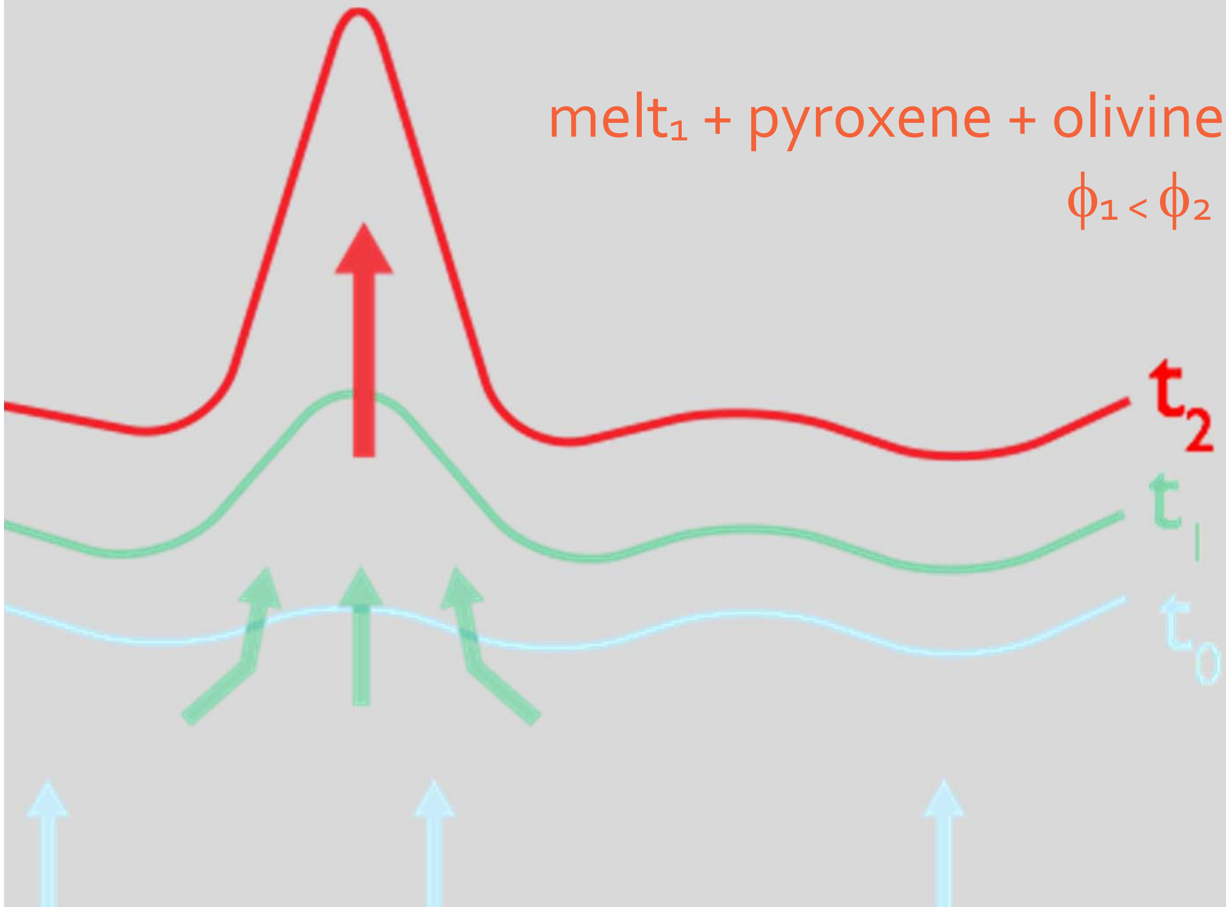
Geochemical aspects of channelization of melt flow – reactive-infiltration instabilities

Reactive-infiltration instabilities

- Channelized flow occurs due to positive feedback between flow and reaction. *Chadam et al.* (1986)
- Melt becomes under saturated in pyroxene and thus reactive as it ascends.

$$\text{melt}_1 + \text{pyroxene} + \text{olivine}_1 \longrightarrow \text{melt}_2 + \text{olivine}_2$$

$$\phi_1 < \phi_2$$



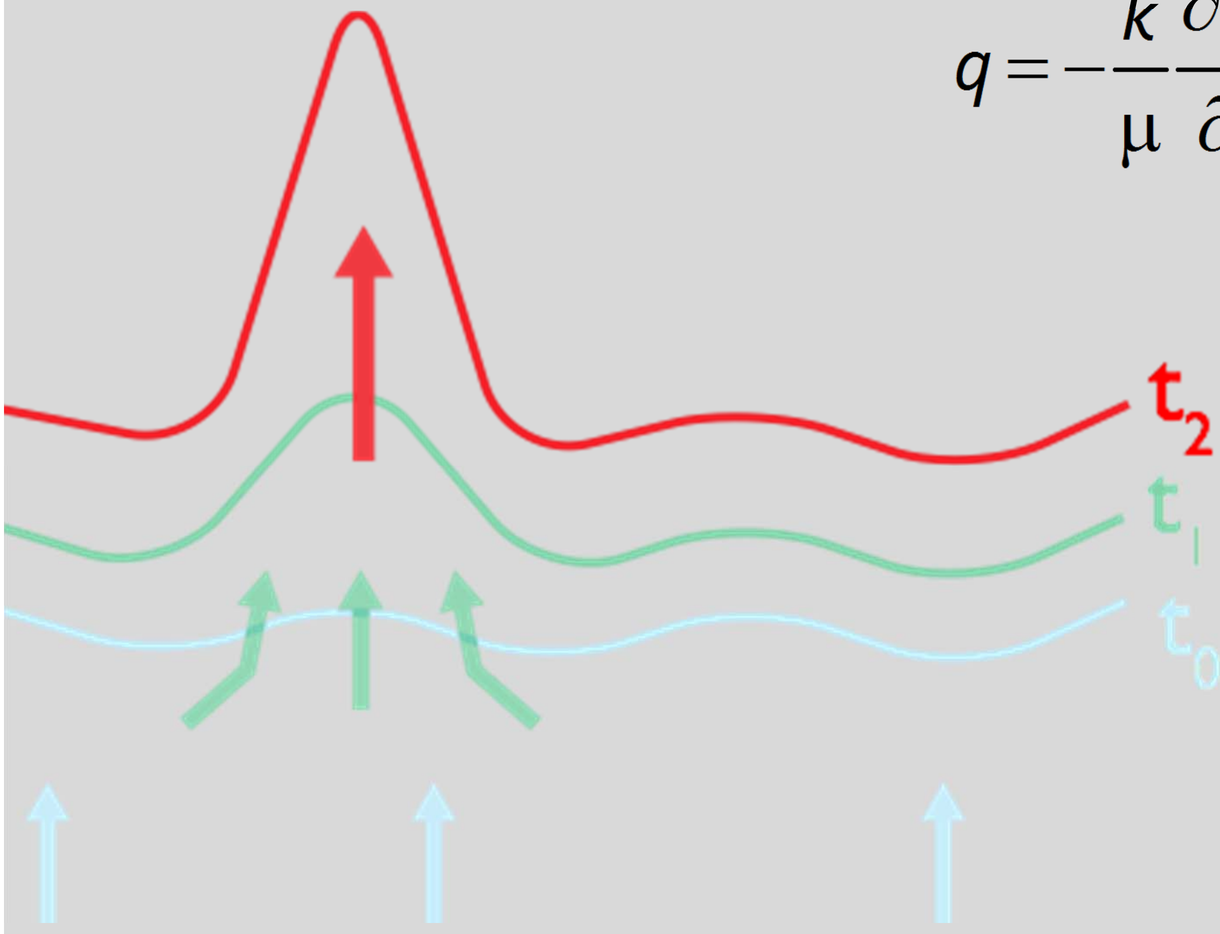
Reactive-infiltration instabilities

Darcy's law

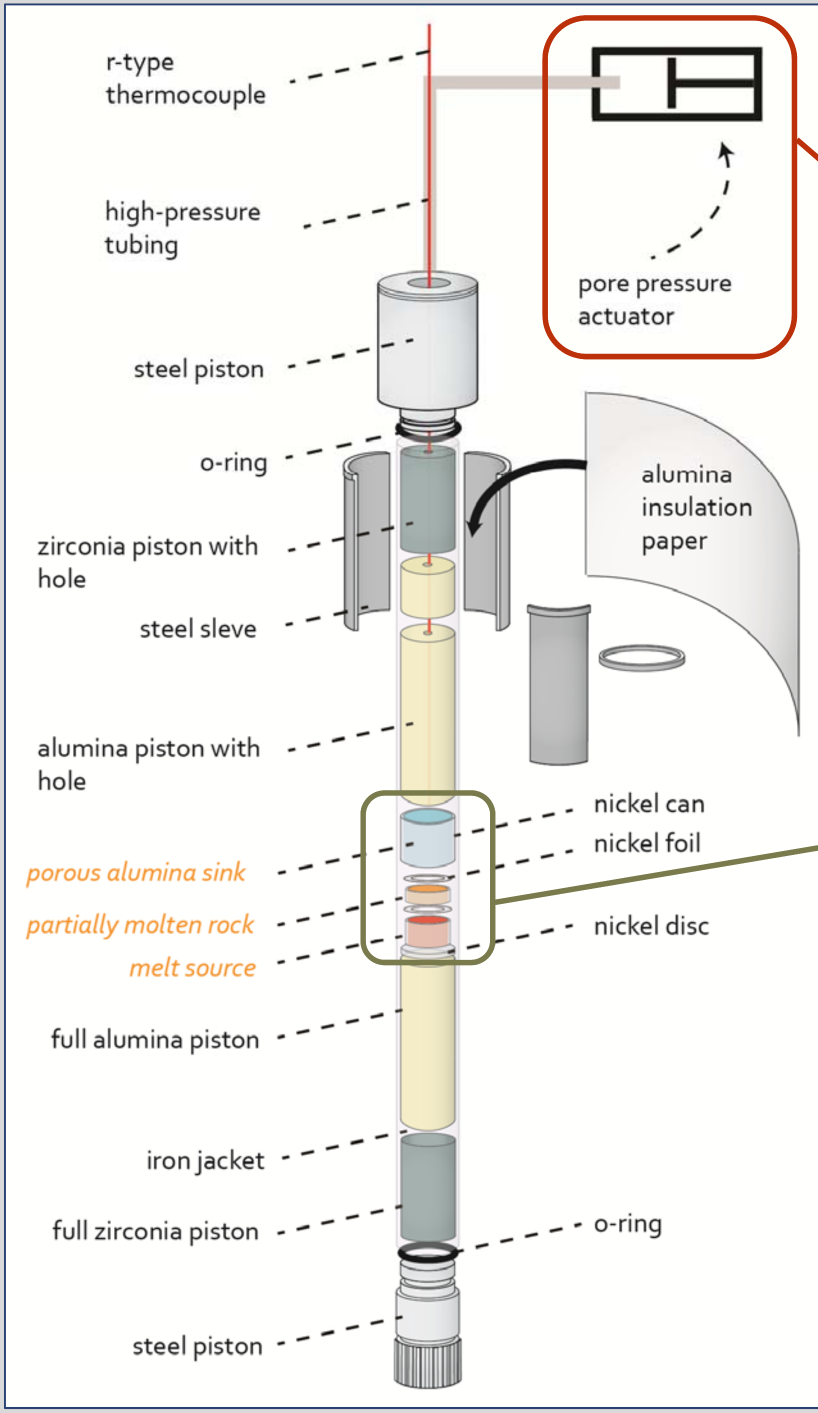
$$q = -\frac{k}{\mu}\frac{\partial P_p}{\partial z}$$

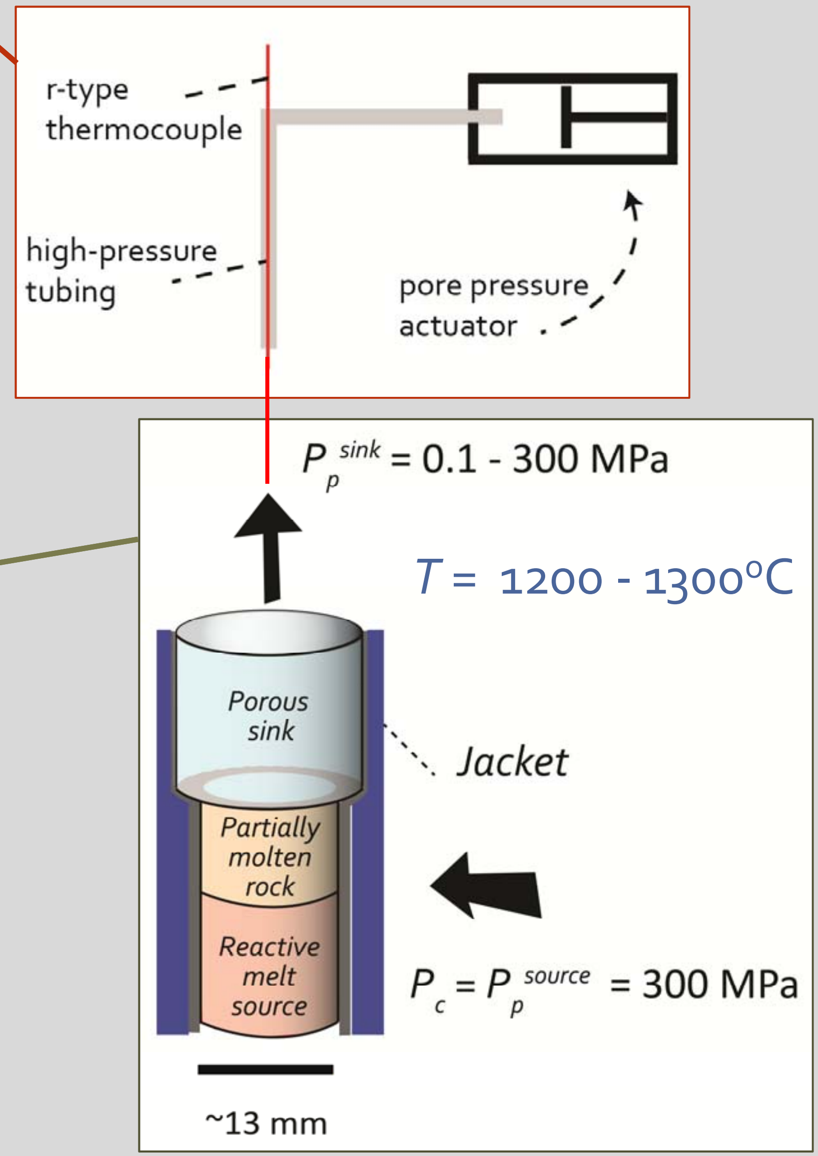
permeability

$$k = \frac{d^2 \phi^s}{C}$$



Experimental setup – flow in a pressure gradient





Starting materials

– porous sink

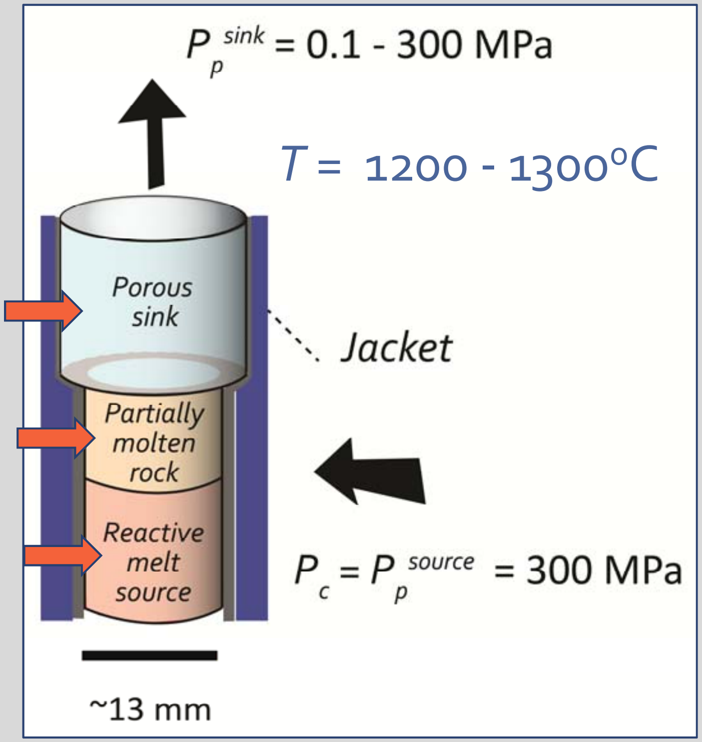
➡ Al_2O_3 with 20 vol% porosity

– partially molten rock

➡ 50:50 olivine:pyroxene + 4, 10 & 20 vol% melt

– reactive melt source

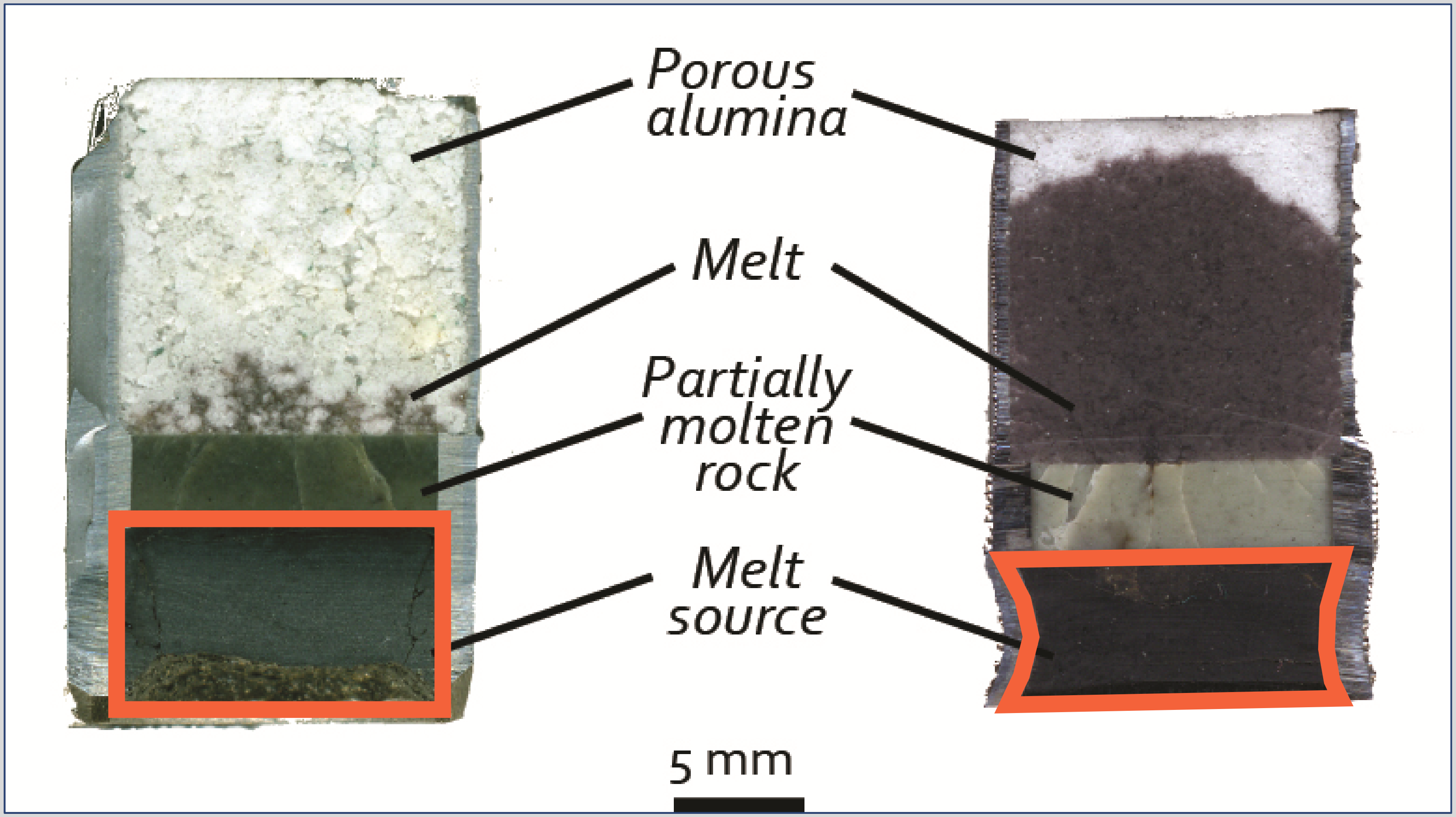
➡ alkali basalt + 1 wt% Yb



Reactive-melt infiltration samples – without and with a pressure gradient

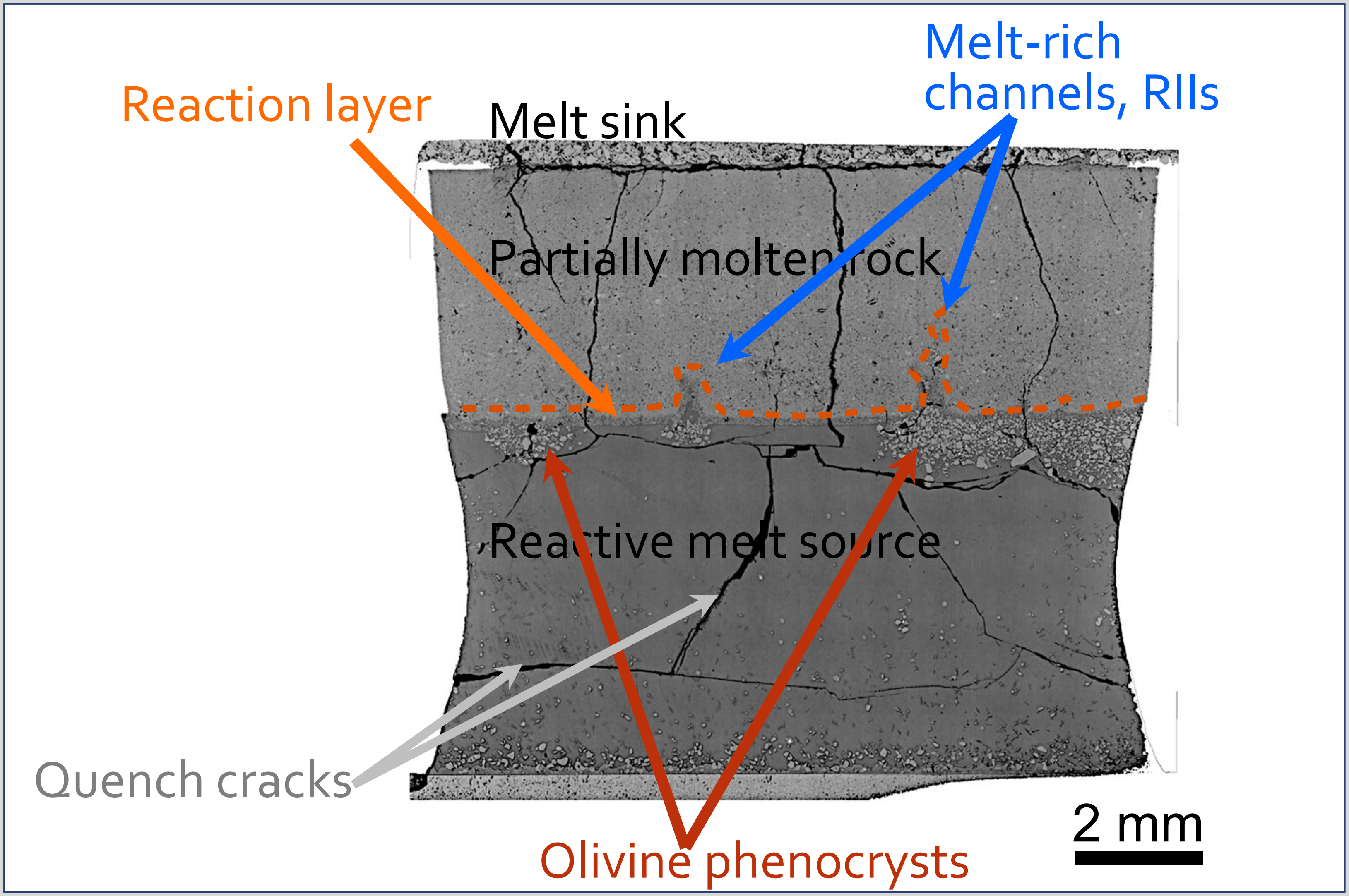
$\Delta P_p/L$ = 0 MPa/mm

$\Delta P_p/L$ = 85 MPa/mm

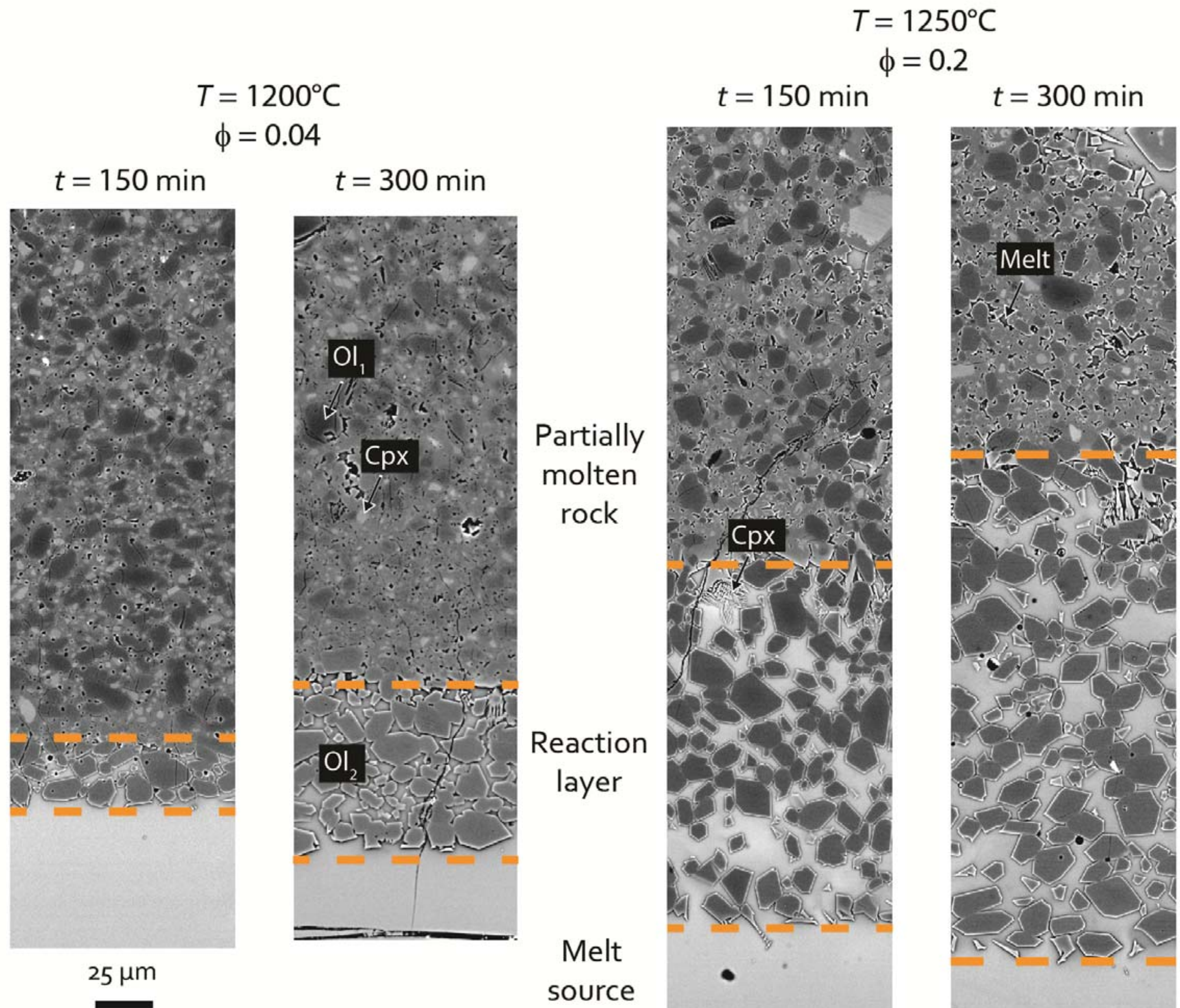


Anatomy of a sample of olivine + pyroxene exposed to a reactive melt

$\Delta P_p/L$ = 72 MPa/mm ϕ = 0.20



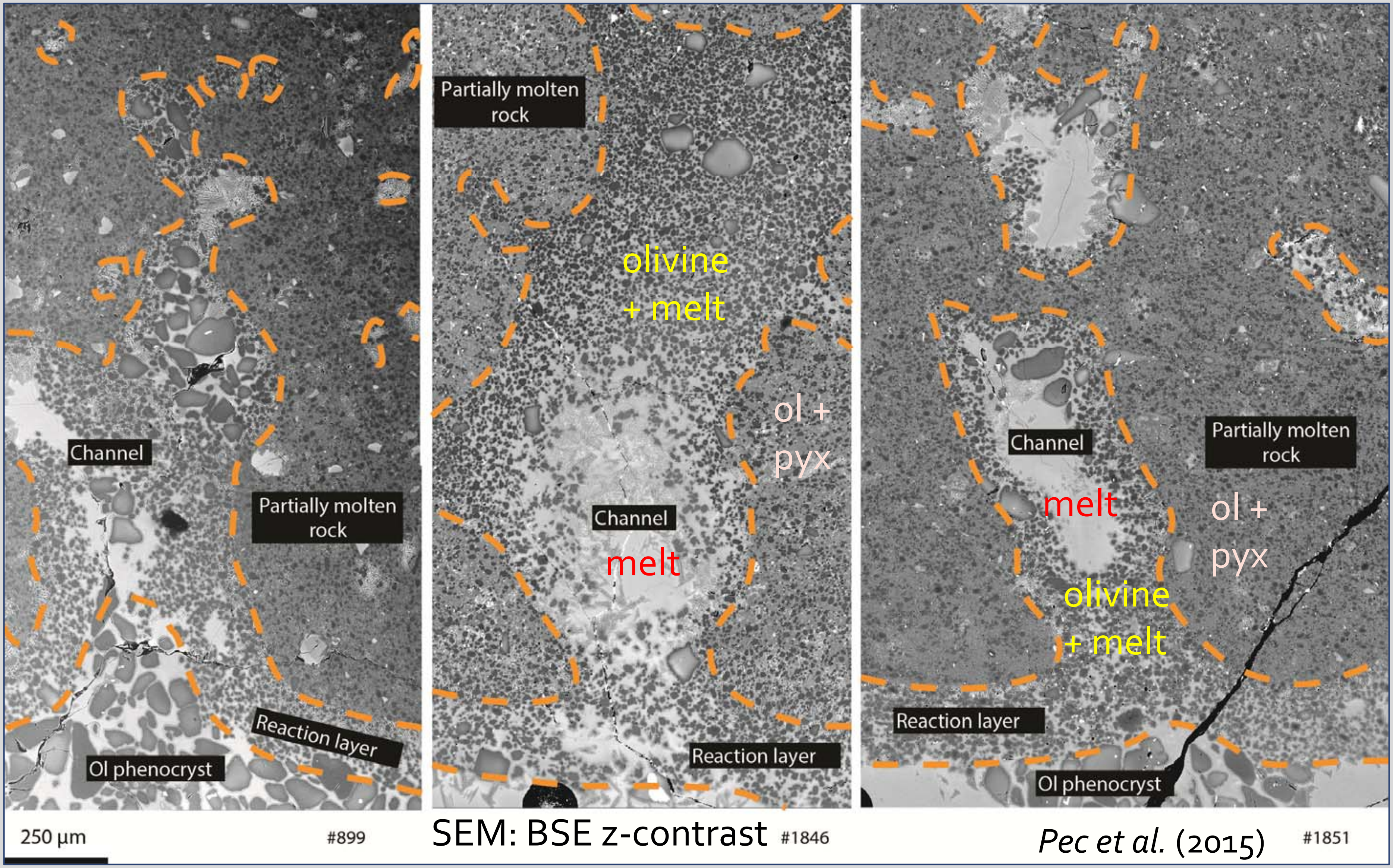
Reaction layer structure



SEM: BSE z-contrast

Structure of channels (RIIs) formed by reactive infiltration

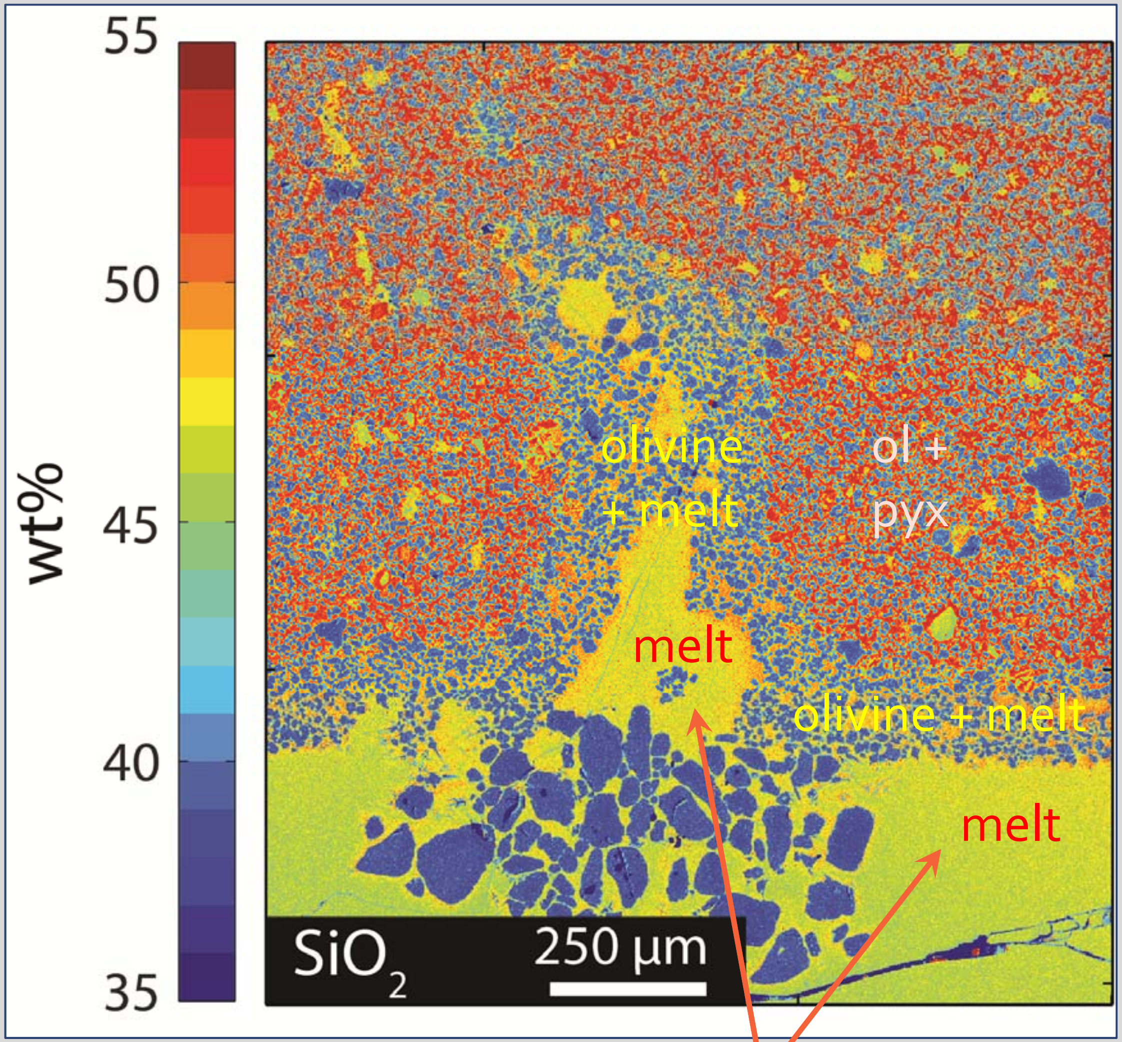
$\phi = 0.2$



SEM: BSE z-contrast

Pec et al. (2015)

Melt chemistry

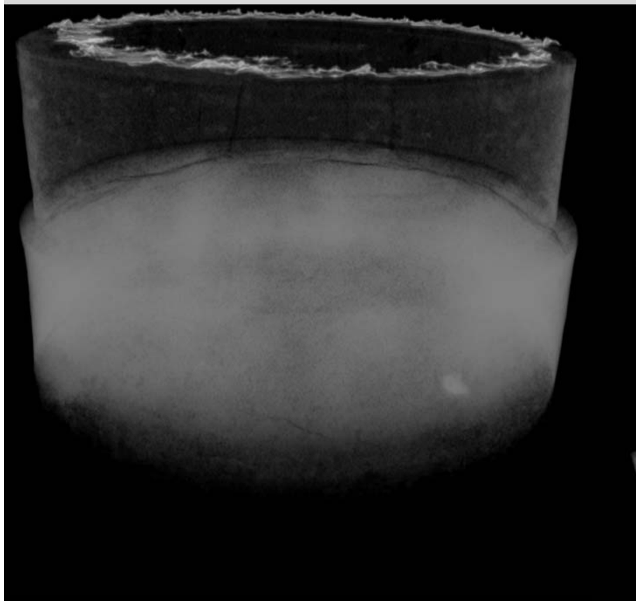


After reaction, melt is more Si-rich in channel than in the melt source.

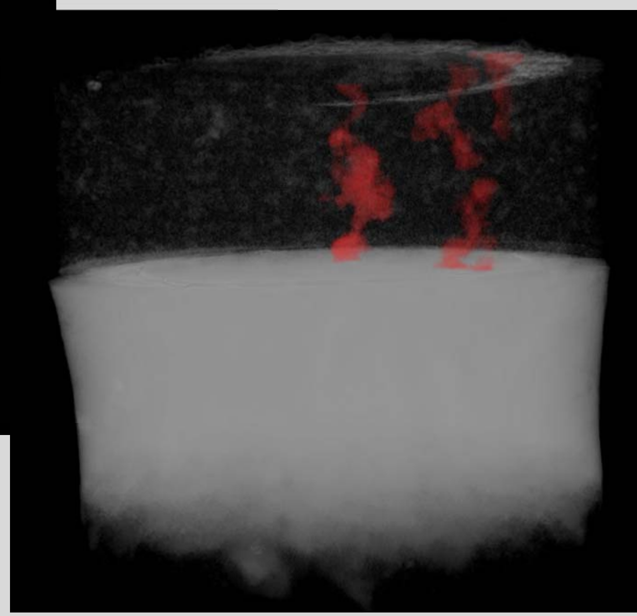
Pec et al. (2015)

X-ray computed tomography of reaction infiltration instabilities

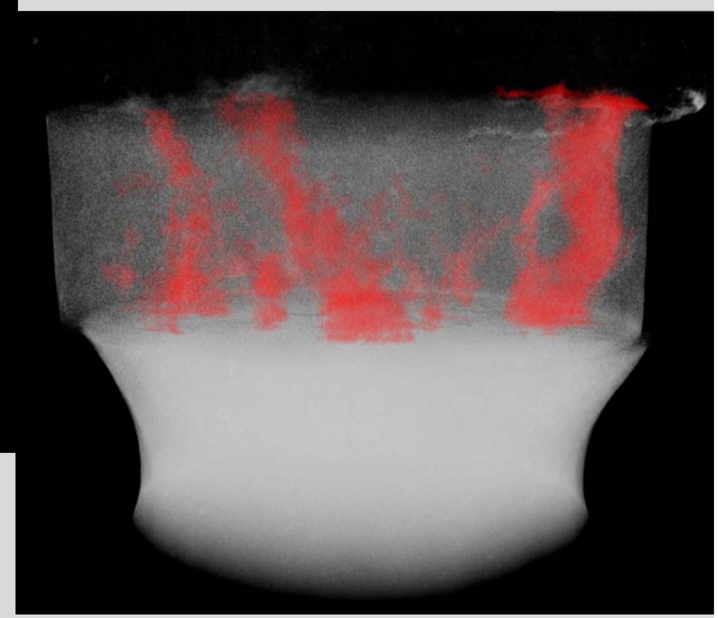
alkali basalt + 1 wt% Yb



$\partial P_p/\partial z = 0$
t long



$\partial P_p/\partial z > 0$
t short



$\partial P_p/\partial z > 0$
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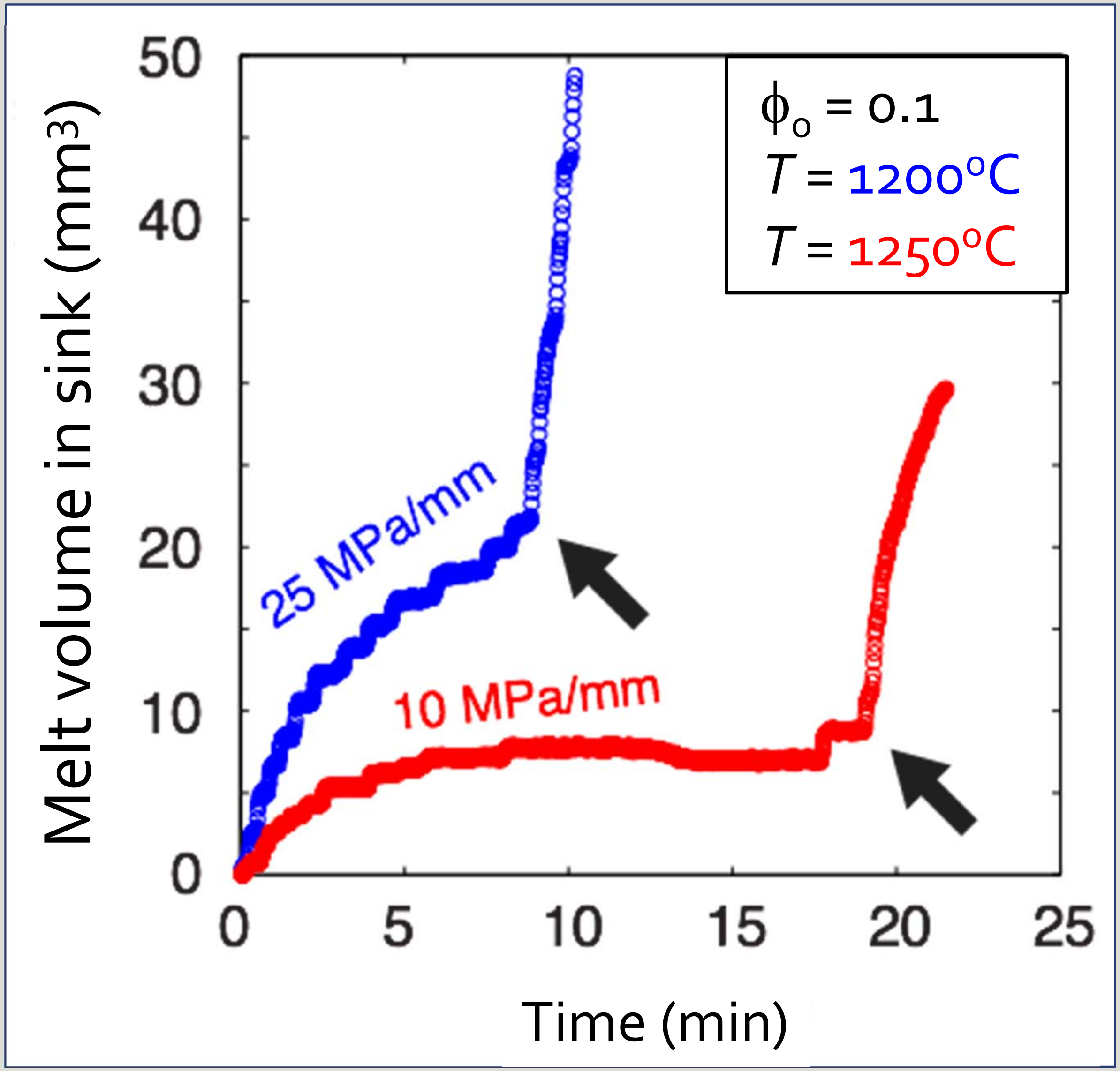
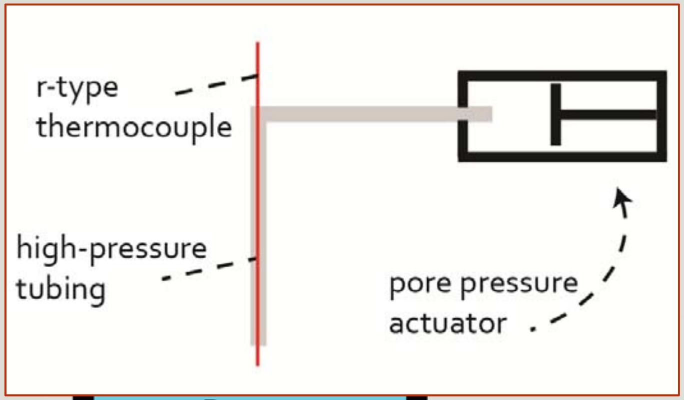
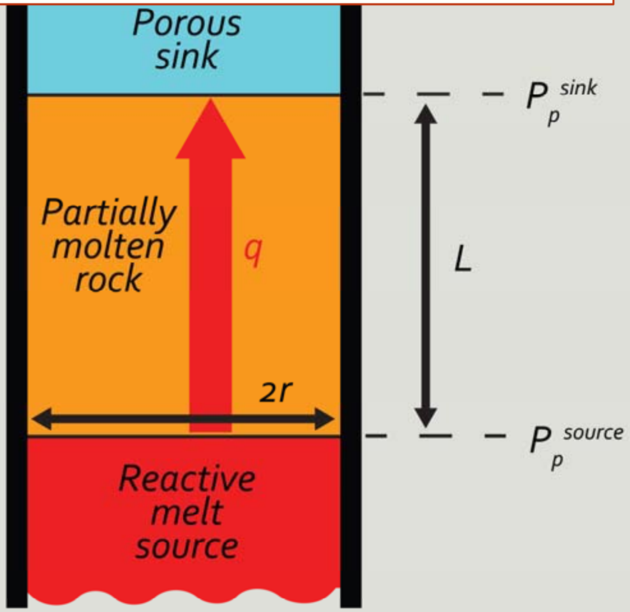
Pec et al. (2016)

Melt flow vs time







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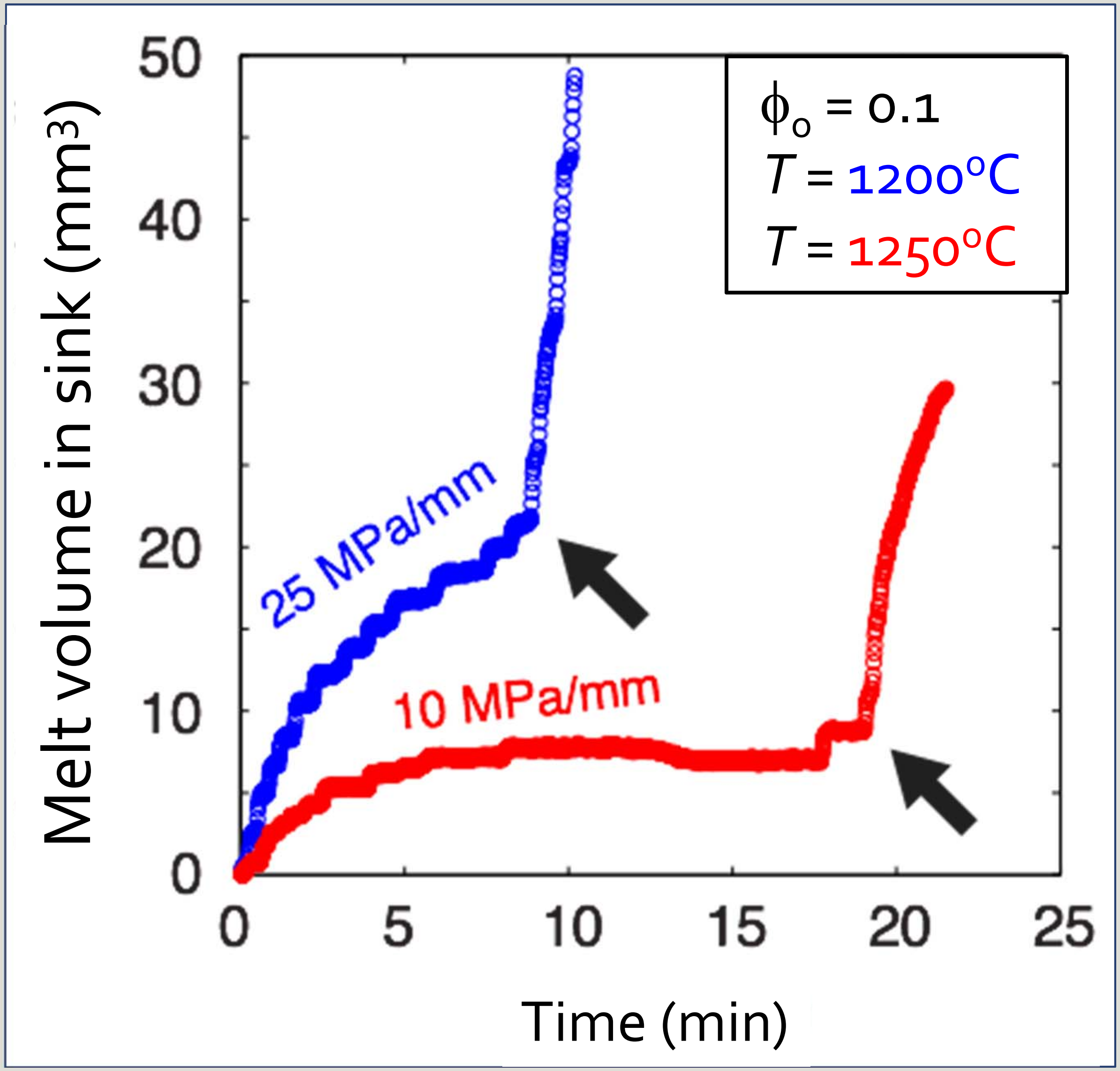
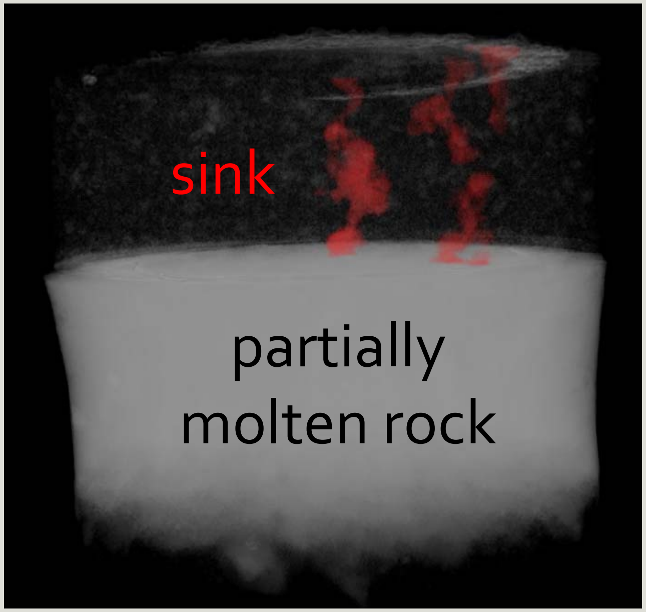
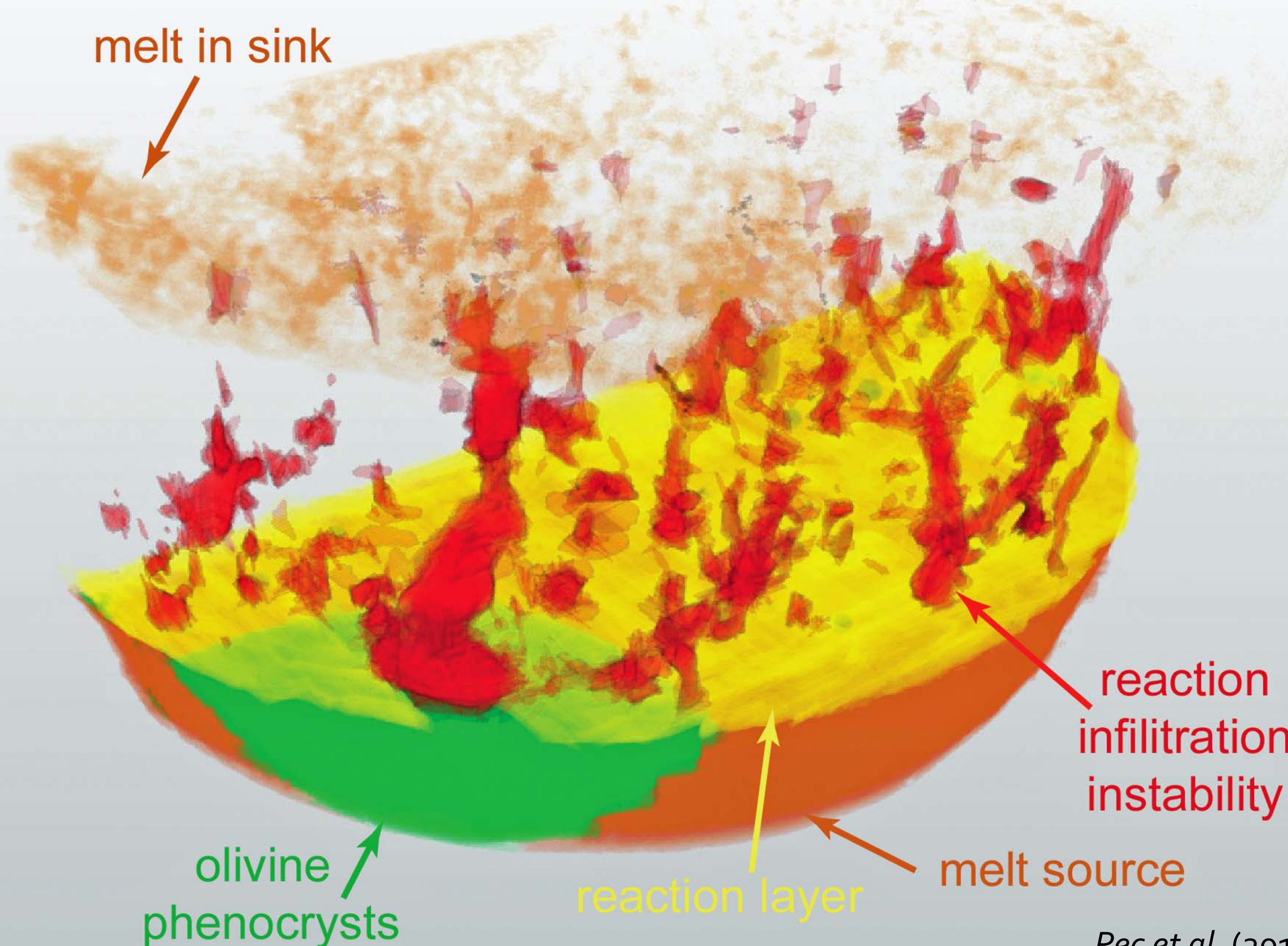




X-ray computed tomography – RRI morphology

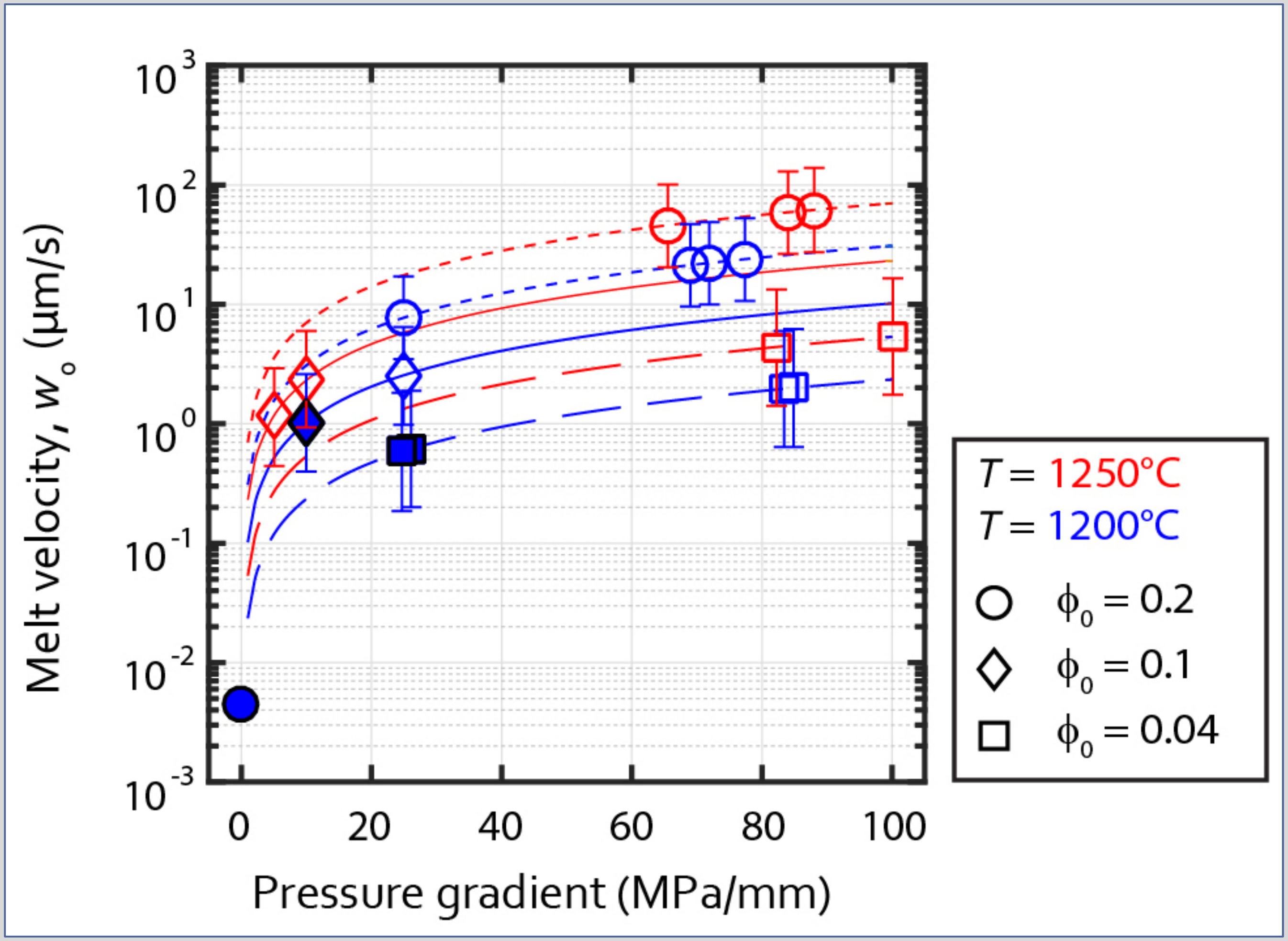


Pec et al. (2015)

Melt velocity

– Stokes settling: 0.5 – 1.0 μm/s

– Pressure gradient: 1 - 10^2 μm/s



$$k = \frac{d^2 \phi^s}{C}$$

$$q = -\frac{k}{\mu} \frac{\partial P_p}{\partial z}$$

$$w_o = \frac{q}{\phi}$$

Pec et al. (2015)

Some conclusions

- Reactive-melt migration results in melt channelization
- Melt-rich channels consist of olivine + melt with no pyroxene
- Melt-rich channels have a crooked finger-like morphology, not tabular form as found in ophiolites
- Initial melt fraction influences channel aspect ratio
- Channelization markedly increases bulk permeability and thus the melt flux
- Interdependencies in RII & porous flow equations render some Da# & Pe# combinations physically unobtainable

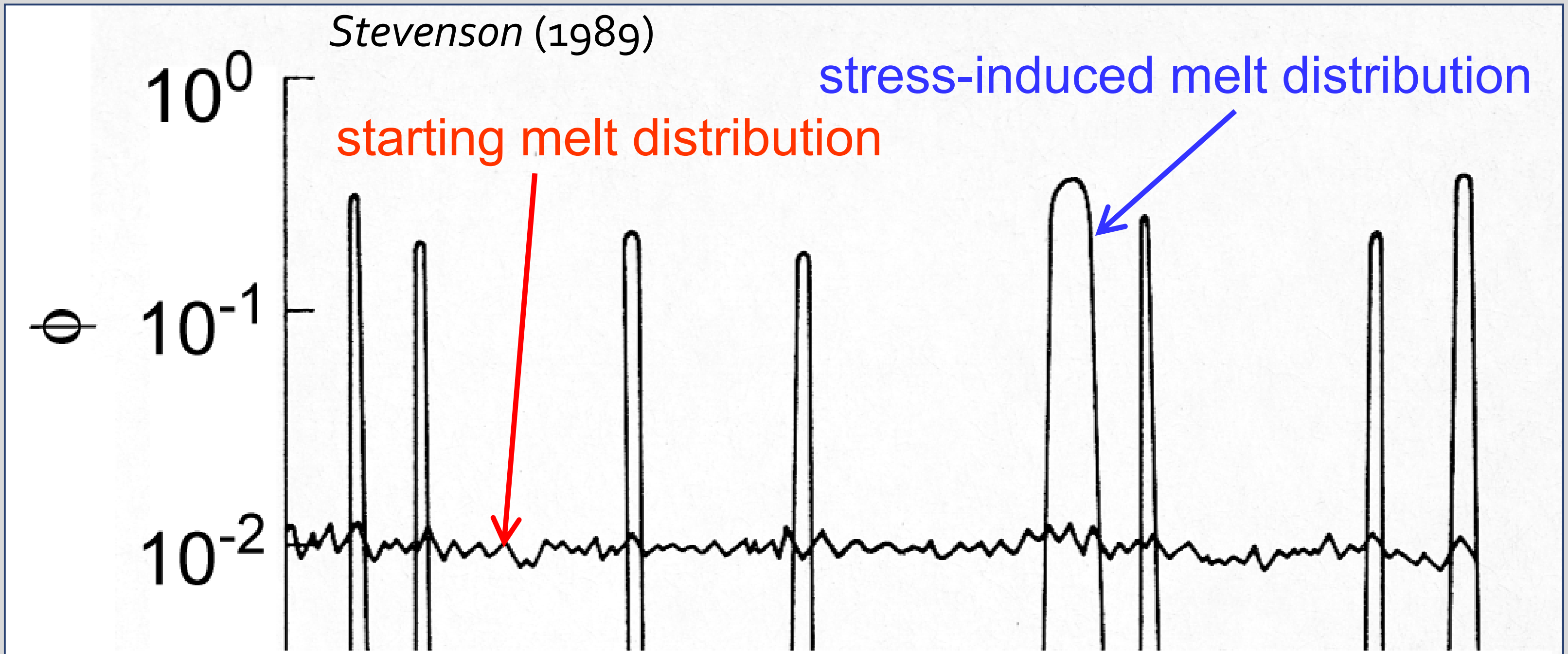
Geophysical aspects of channelization of melt flow – stress-driven melt segregation

Stress-driven melt segregation

- Stevenson (1989) predicted "spontaneous, small-scale melt segregation in deforming rocks" due to dependence of viscosity on melt fraction: $\eta = \eta_o(1 - \alpha'\phi^{1/2}) \rightarrow \eta_o \exp(-\alpha\phi)$
- Spiegelman (2003), based on a linear analysis, predicted that spontaneously developed melt-rich bands oriented at $\theta = 45^o$ to the shear plane will grow fastest
- Katz et al. (2006) predicted a band angle of $\theta = 15^o$ for a porosity-weakening, non-Newtonian, power-law viscosity of the form $\eta = \eta_o \exp[\alpha(\phi-\phi_o)]/\sigma^{1-n}$ if $n = 6$
- Takei and Holtzman (2009) obtained $\theta \approx 25^o$ by introducing anisotropic viscosity combined with porosity-weakening and Newtonian viscosity

Spontaneous stress-induced melt segregation

Channelized flow occurs due to positive feedback between flow and reaction.



Assumption: $\dot{\varepsilon}$ is spatially constant. Recall: $\eta = (\sigma_1 - \sigma_3) / \dot{\varepsilon}$.

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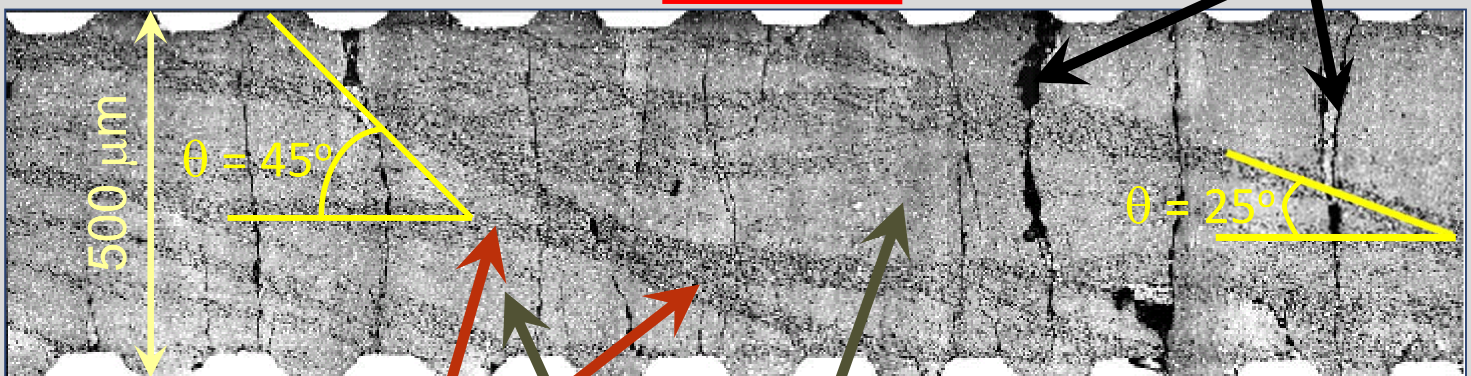
Stress-driven melt segregation

– simple shear

olivine + 4% MORB + 20% chromite

unloading cracks

$\gamma \approx 3$



45° ≠ 25°

serrated tungsten pistons

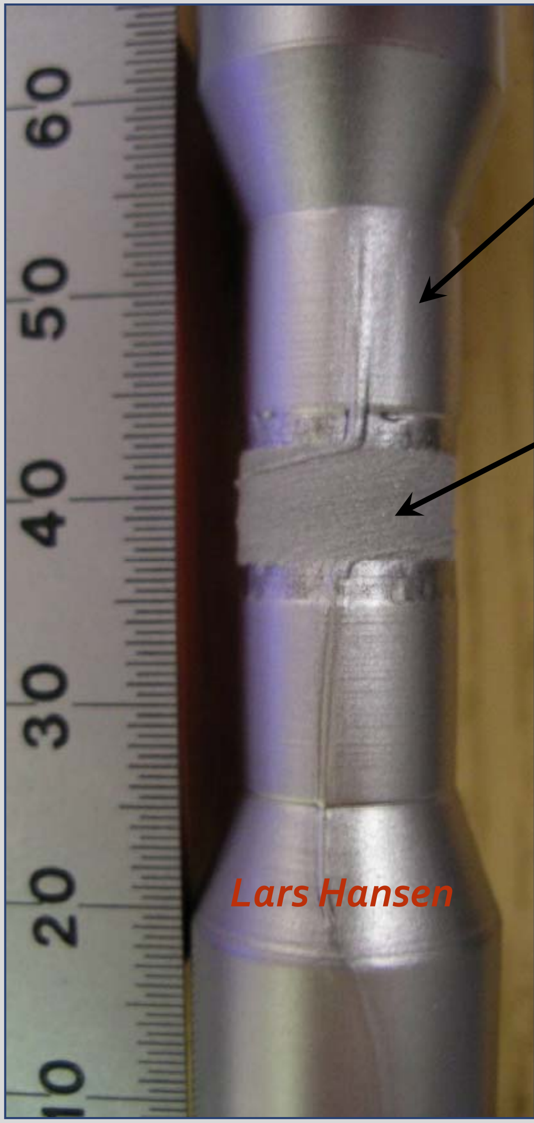
melt-rich bands
$\phi > 0.15$

melt-depleted lenses
$\phi < 0.01$

Holtzman et al. (2003)

Stress-driven melt segregation

– torsional shear



piston

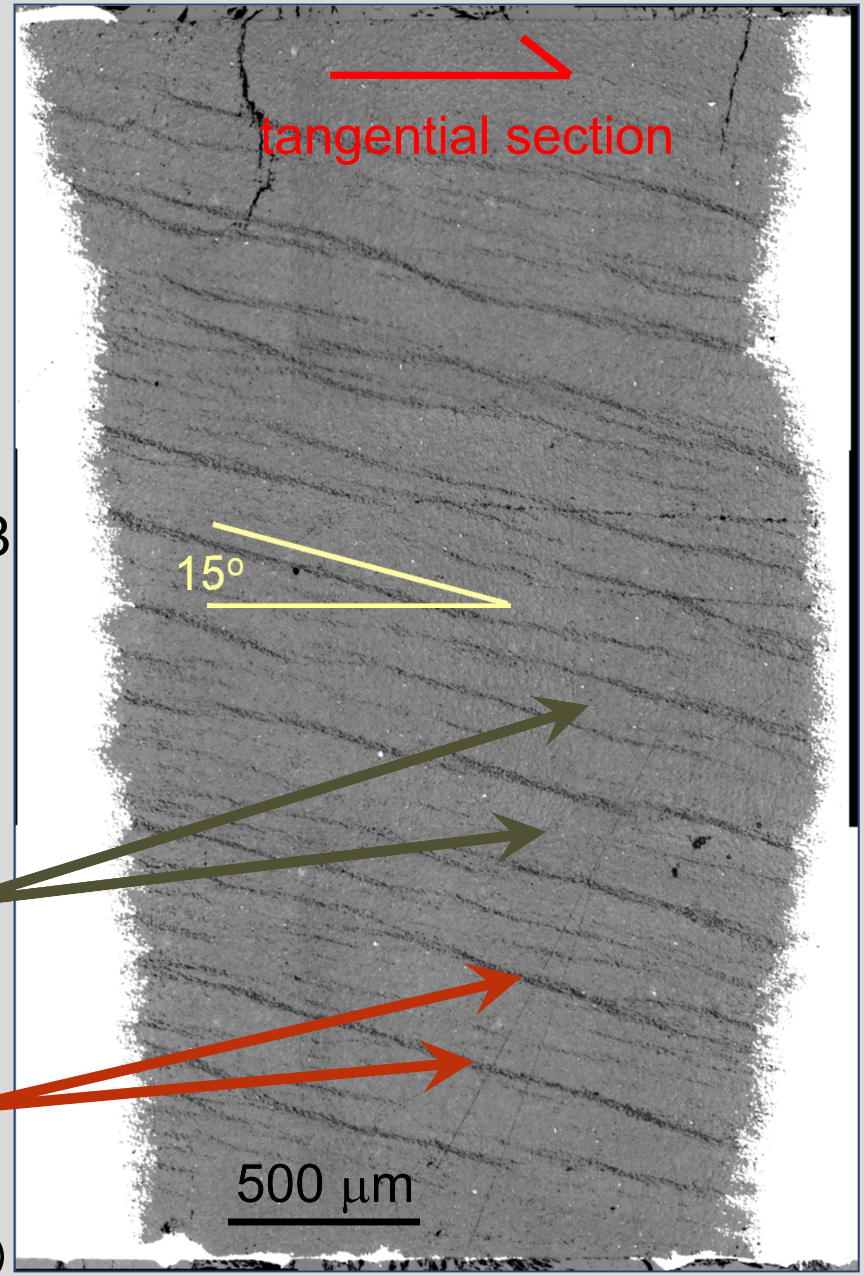
sample of
olivine + 4% MORB
in Fe jacket

melt-depleted
lenses
$\phi < 0.01$

melt-rich bands
$\phi \approx 0.20$

King et al. (2010)

$\gamma \approx 2$



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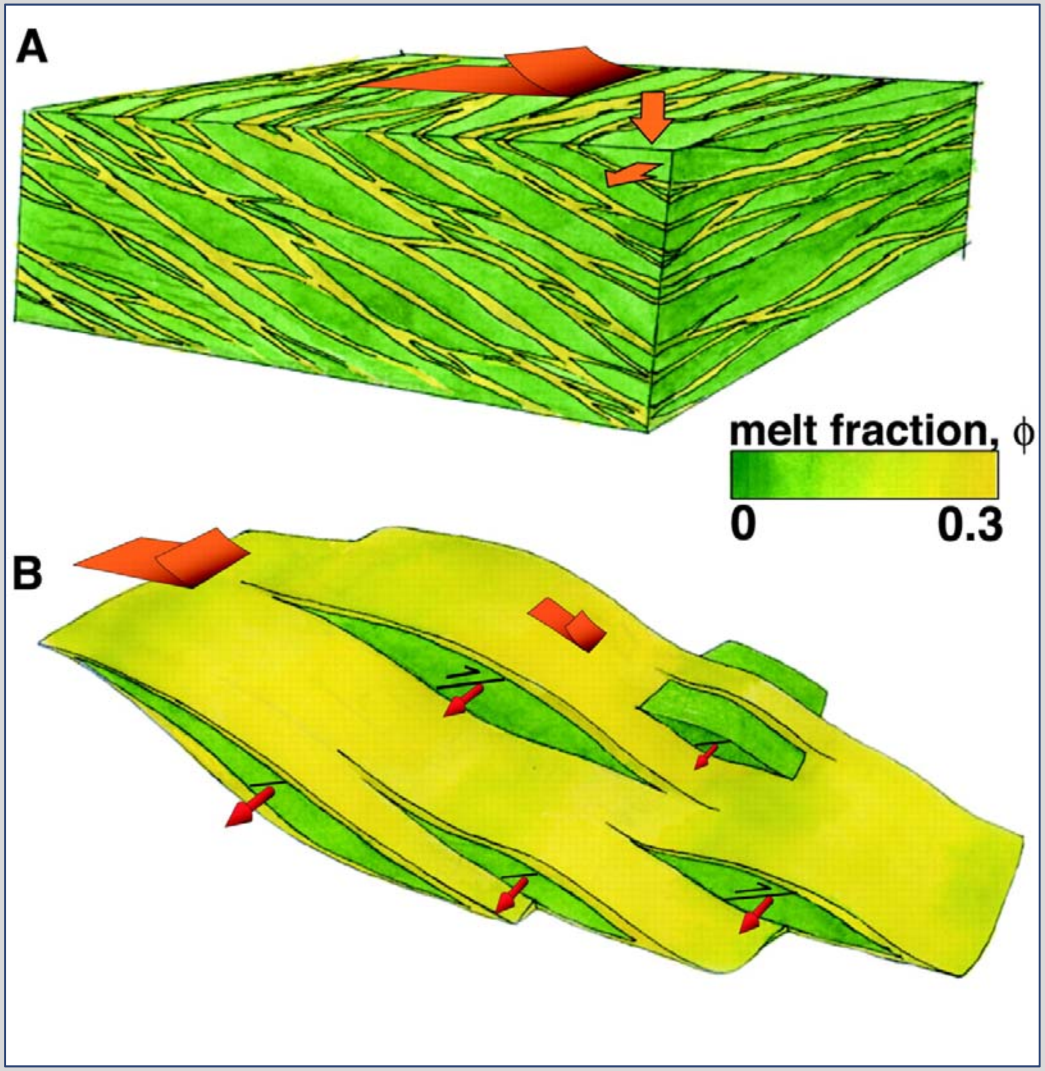

Holtzman et al. (2003)

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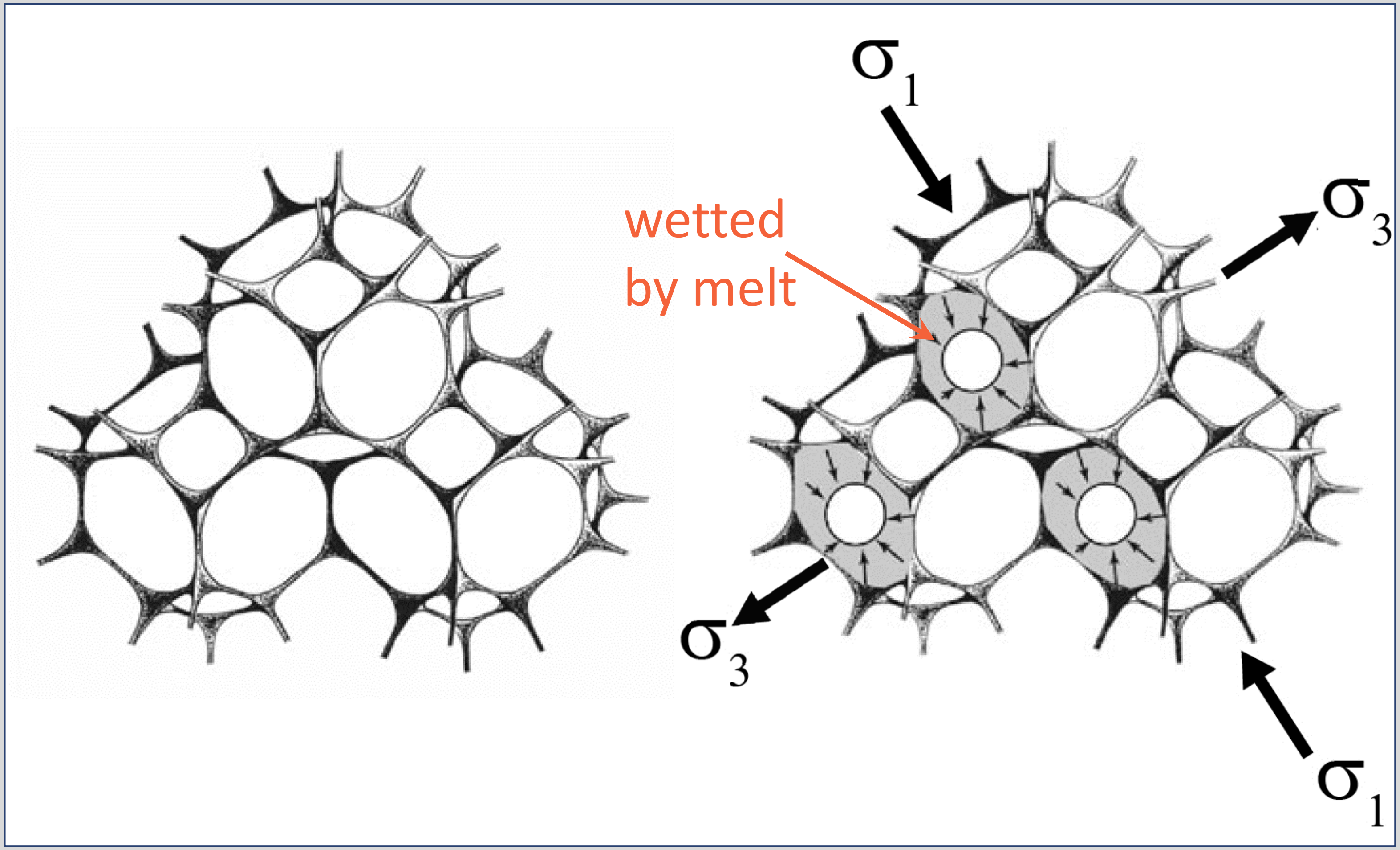
- Takei and Holtzman (2009) obtained $\theta \approx 15$ to 25^o by introducing *anisotropic viscosity* combined with porosity-weakening and Newtonian ($\dot{\varepsilon} \propto \sigma^1$) flow behavior

Stress-induced anisotropy in grain-scale melt distribution produces anisotropy in viscosity



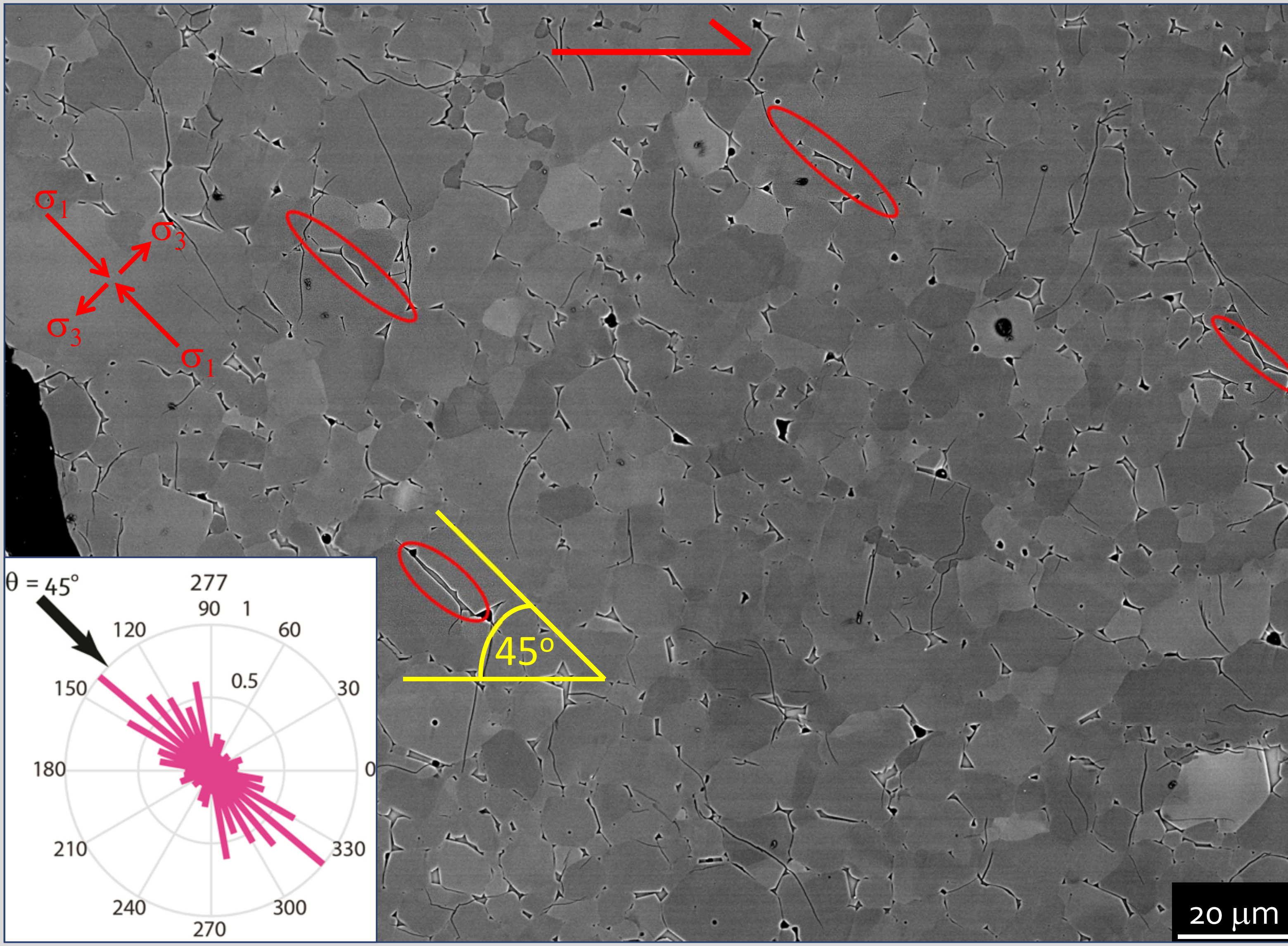
Takei and Holtzman, (2009); *Takei and Katz* (2013)

Melt pocket alignment in simple shear

– without melt-rich bands

– melt pockets align ~45° to shear plane

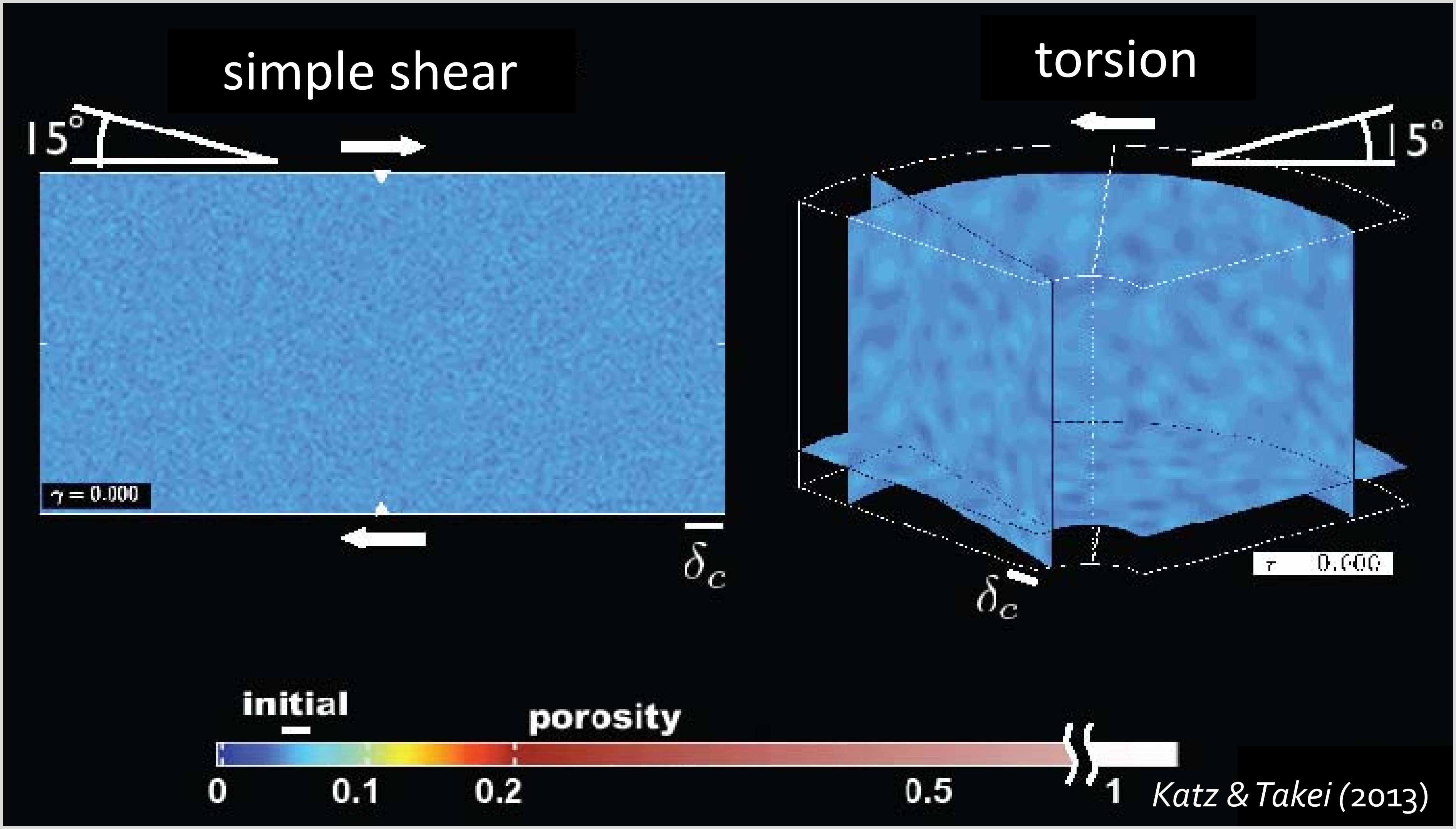
BSE image



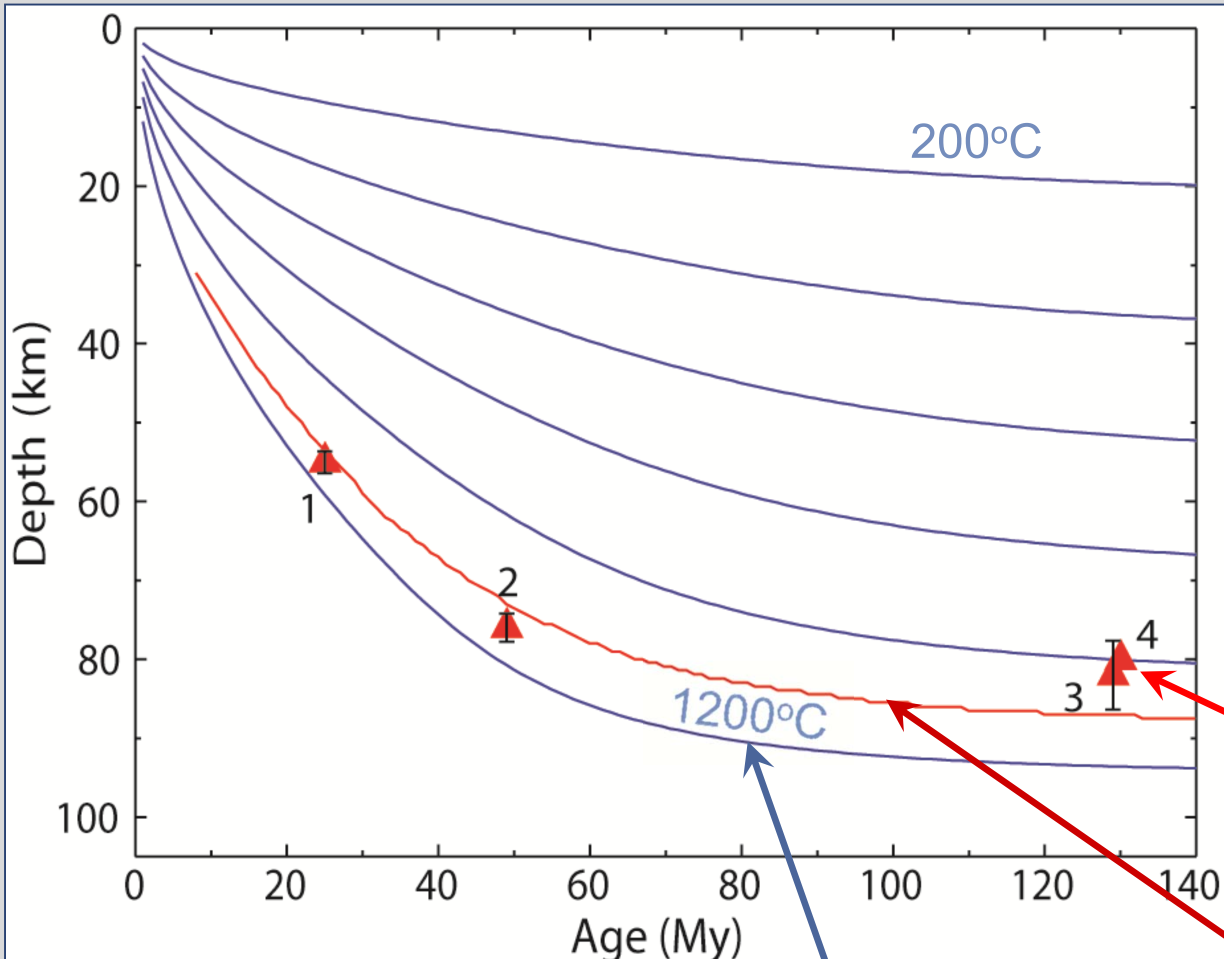
Pec et al. (2016)

Stress-driven melt segregation – perturbations grown into melt-rich bands

low band angle ➜ anisotropic viscosity



"Seismic evidence for sharp lithosphere-asthenosphere boundaries of oceanic plates" *- Pacific and Philippine Sea*



Shear wave velocity is reduced at the lithosphere-astenosphere boundary (LAB) by ~7 to 8%, which would require ~4% of texturally equilibrated melt.

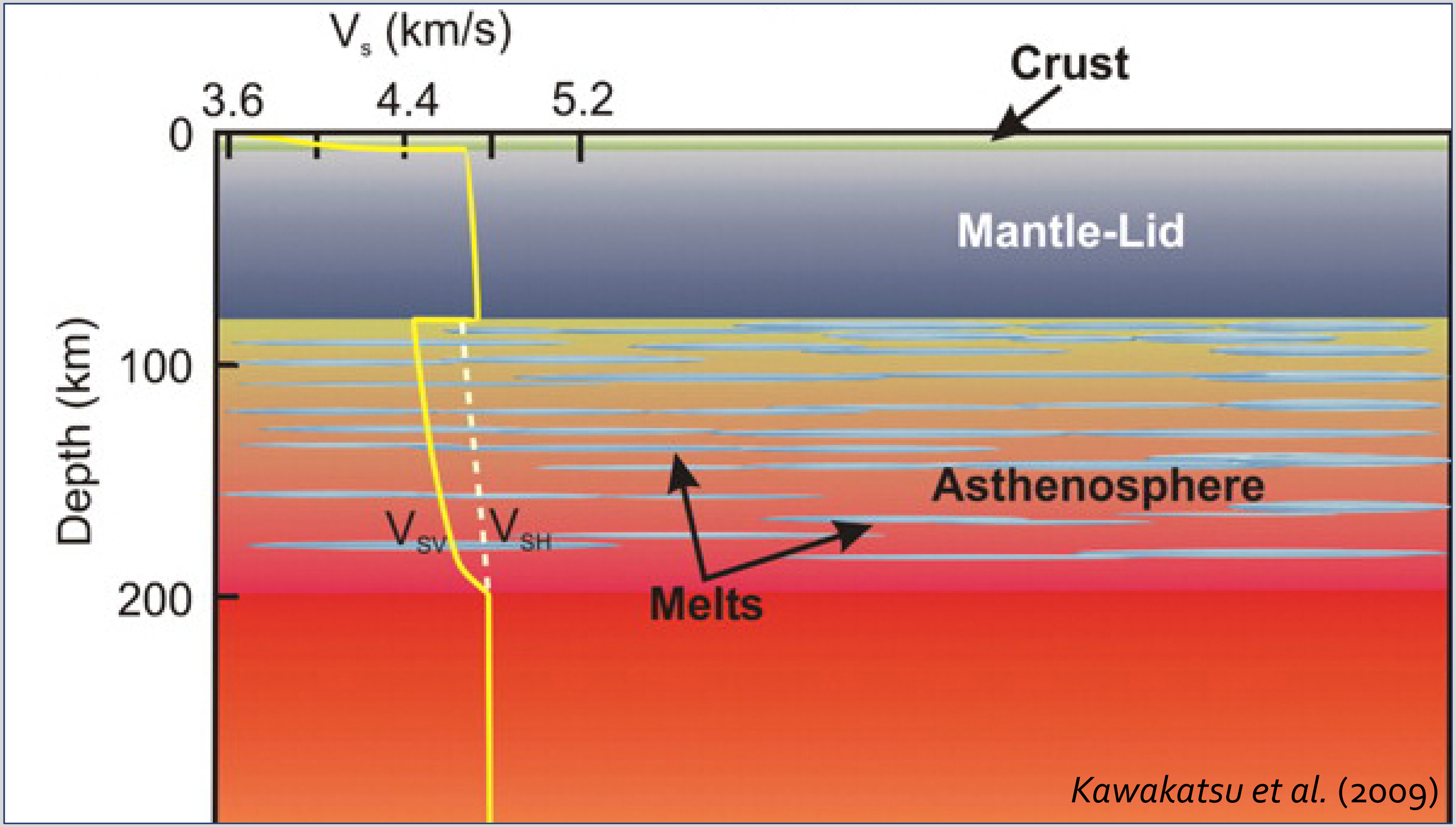
▲ indicates location of jump in shear wave velocity

geotherm for hydrous partial melting

1200°C isotherm cooling plate model

Kawakatsu et al. (2009)

Lithosphere-asthenosphere boundary



Based on petrological constraints, the average amount of melt in LAB is <1%. Velocity drop possible with layered structure composed of melt-rich bands (ϕ_{bands} = 0.25) and melt-depleted lenses ($\phi_{lenses} \approx 0$) with 1% bands.

Some conclusions

- Shear deformation of partially molten rocks results in formation of an anastomosing network of *melt-rich bands*
- Melt-rich bands/sheets have a tabular morphology similar to that found in ophiolites
- Deformation localizes in these melt-rich regions, forming shear zones
- Melt-rich bands increase bulk permeability, channelizing melt flow
- Differential stress causes alignment of melt pockets at the grain scale resulting in *viscous anisotropy* at the sample scale
- Two-phase flow theory incorporating *viscous anisotropy* predicts *formation of melt-rich bands at low angle to the shear plane*
- The challenge – combine reactive-melt infiltration with shear