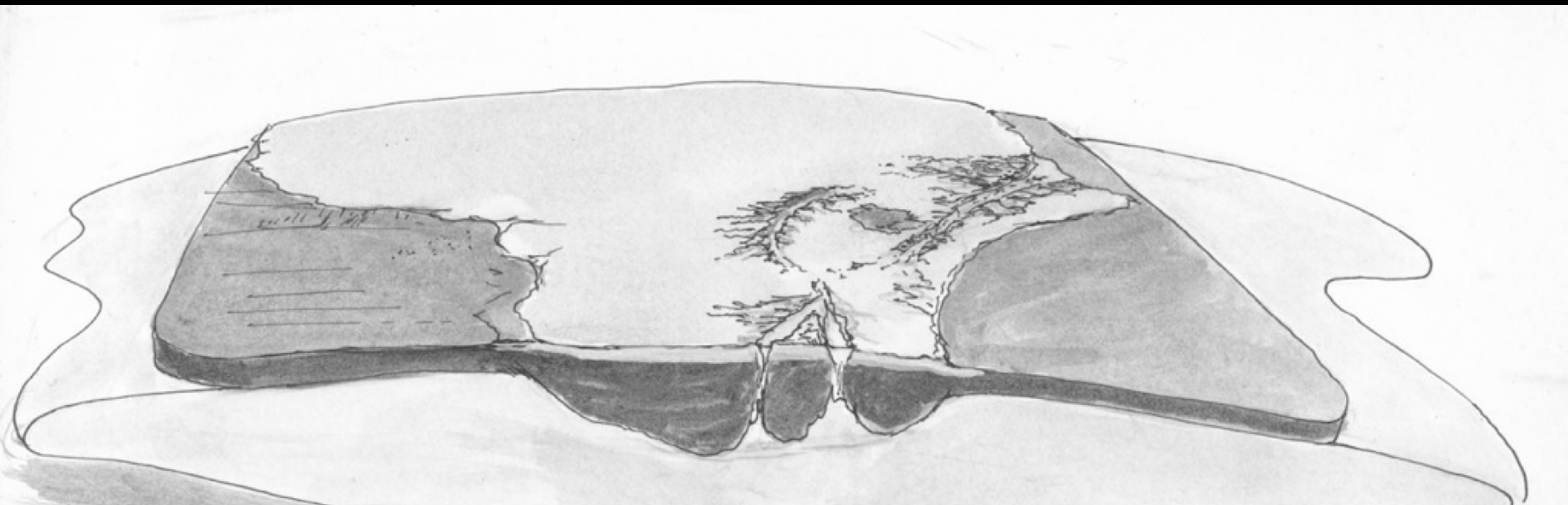
# Some questions on the interactions of deformation and melting in the rifting of a continent

Ben Holtzman,
LDEO, Columbia University, NY



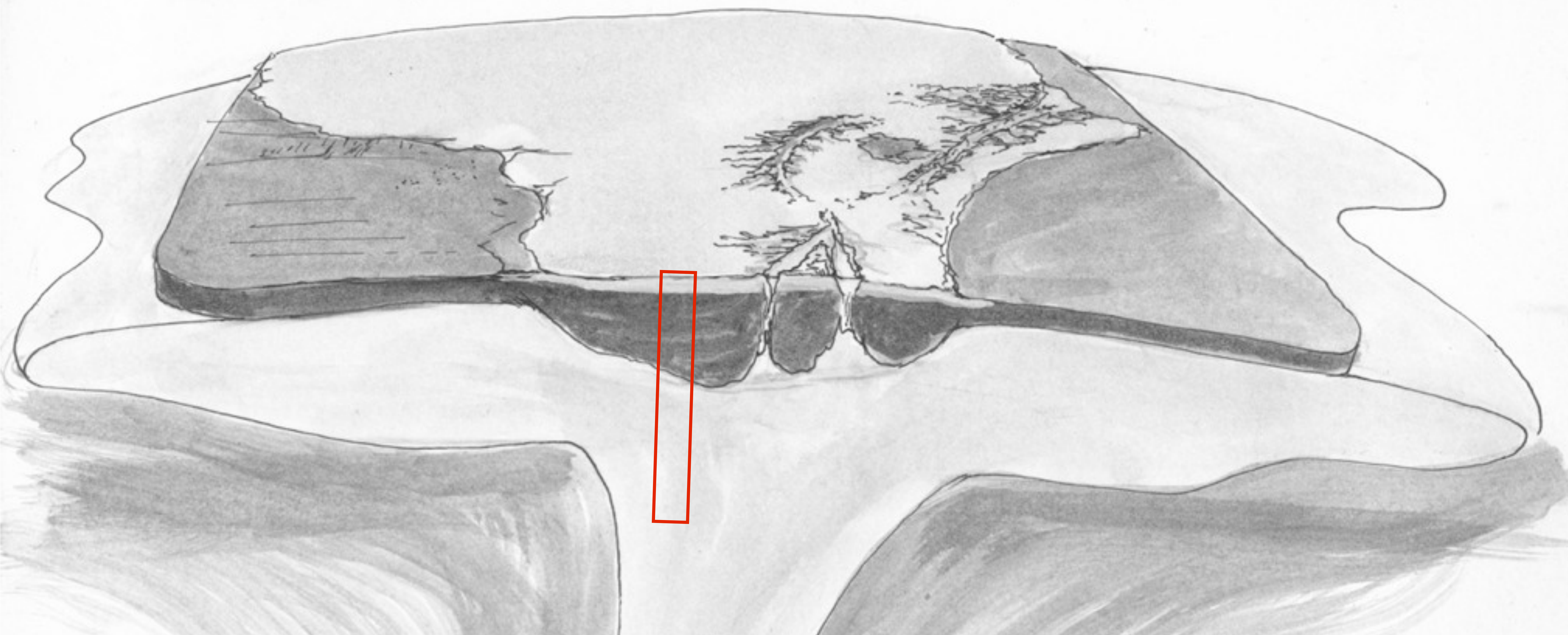
1. ***Intro: who does all the work around here ?***

2. ***Interactions of deformation and melt migration in experiment.***

3. ***Speculation on the Main Ethiopian Rift from below..***

**Geophysicists consider the dynamic uplift (mechanical work) of the African lithosphere due to mantle upwelling...**

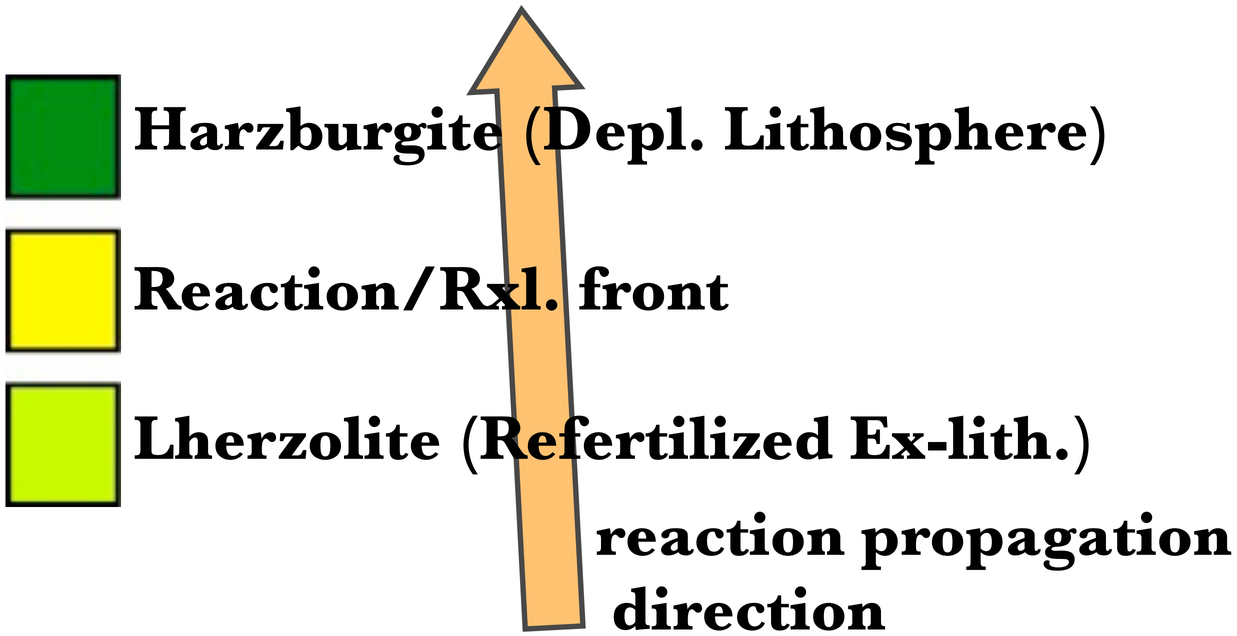
**But, at the rift scale, what about the thermal and chemical energy ?**



**a holy grail of mineral/rock physics:**
**to interpret seismic velocity and attenuation structure in terms of temperature, stress, composition (including melt/water content), structural properties (melt distribution, grain size, etc...).**

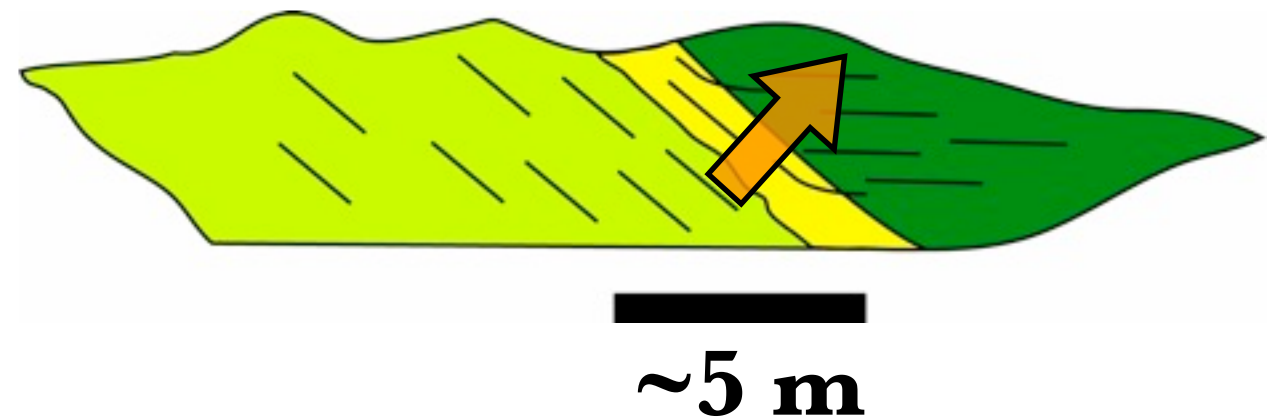
**in this case, we can eventually constrain the degree of thermal/chemical disequilibrium across the LAB...** ***but why?***

# Geologic examples of refertilization fronts:




**Lherz Massif, Pyrenees**

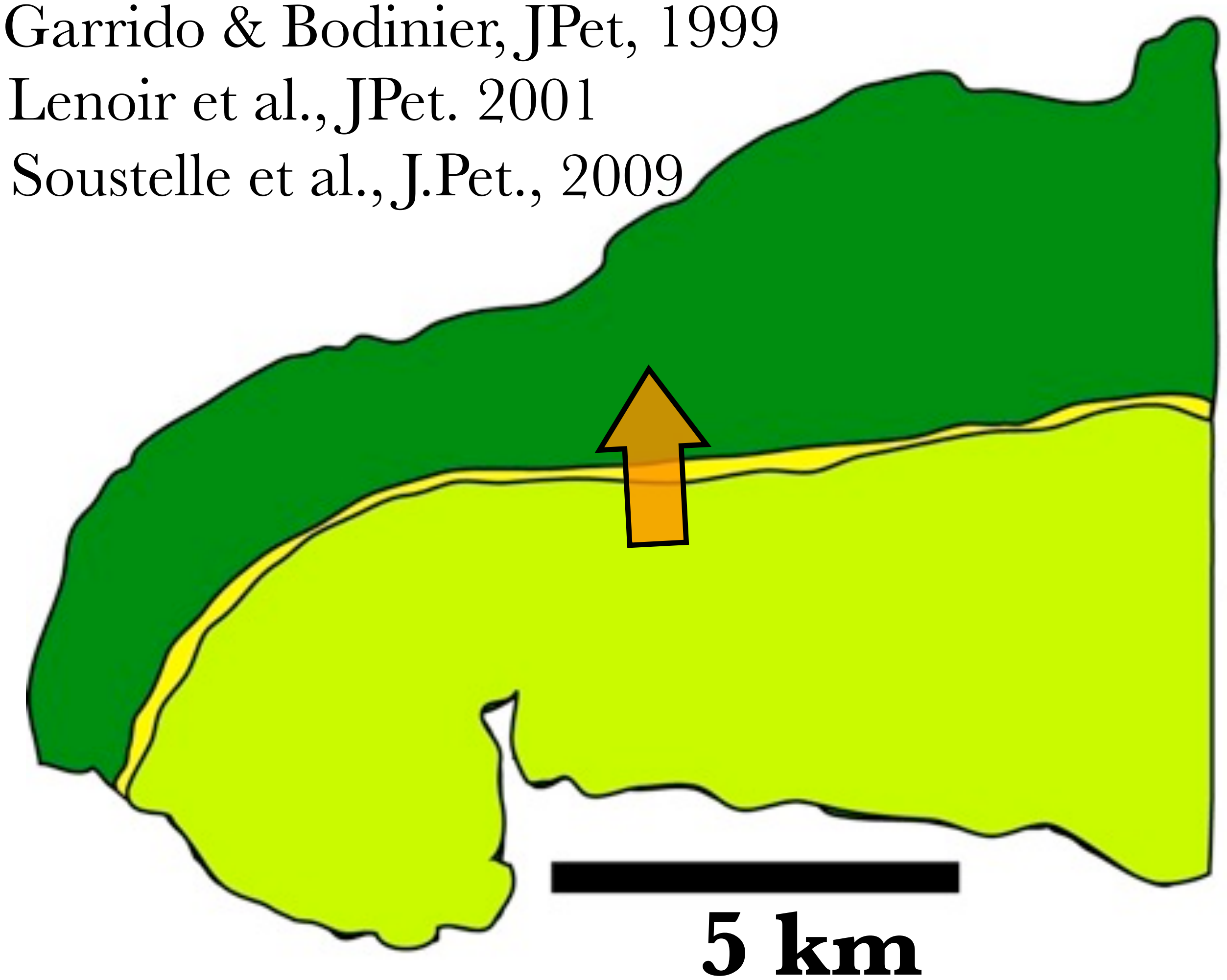
LeRoux et al., EPSL, 2007, 2008




Foliation in Hbz is overprinted by foliation in Lhz, in the reaction front:
coupling between melt flux, reaction & deformation

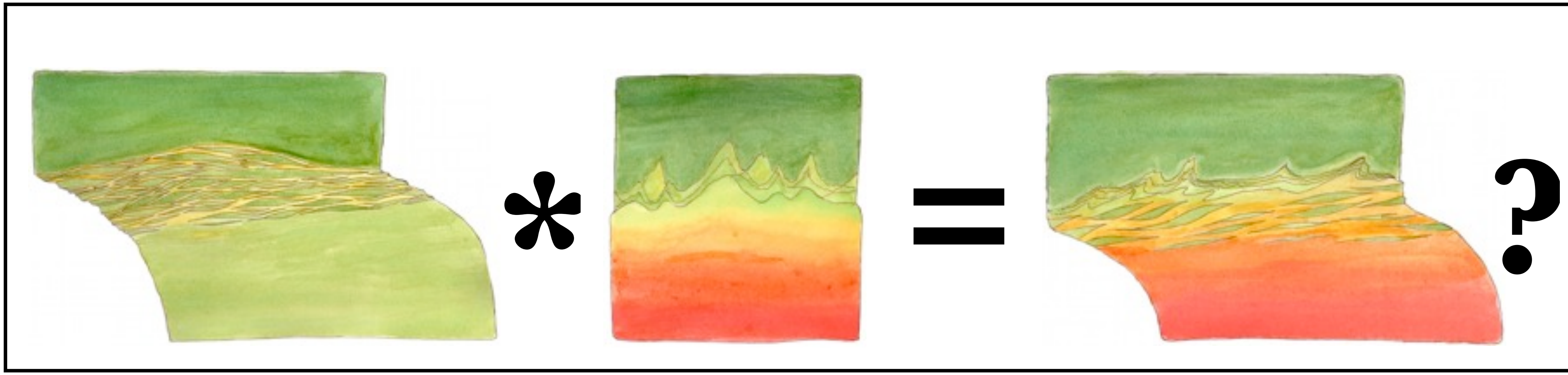
**Ronda Massif, S. Spain**

Garrido & Bodinier, JPet, 1999
Lenoir et al., JPet. 2001
Soustelle et al., J.Pet., 2009

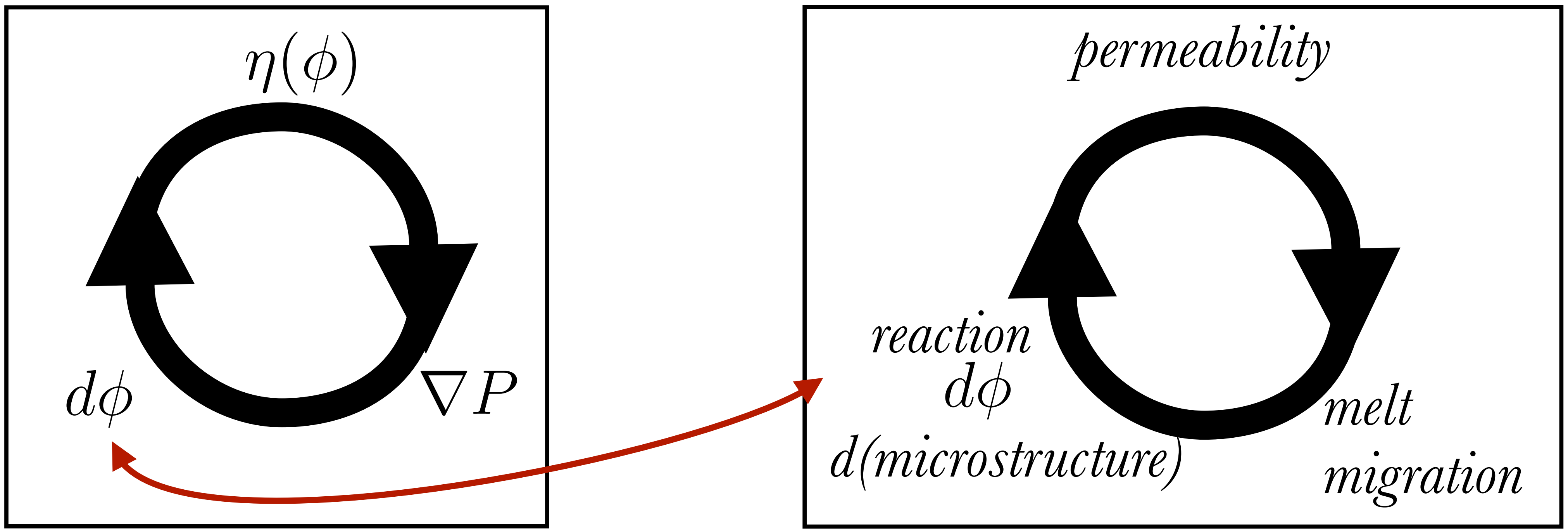



Van der Wal & Bodinier, CMP, 1996

+ Kelemen, Hart & Bernstein, 1998
+ Jagoutz (Beni Boussera)




**Mechanical feedbacks** | **Thermal/chemical feedbacks**




*D. Stevenson, GRL, 1989*

Dissolution==>Reaction Infiltration Instability (e.g. Kelemen et al., 1995, Aharonov, Daines, others.. ),
Crystallizing in TBL: Kelemen et al., 1995

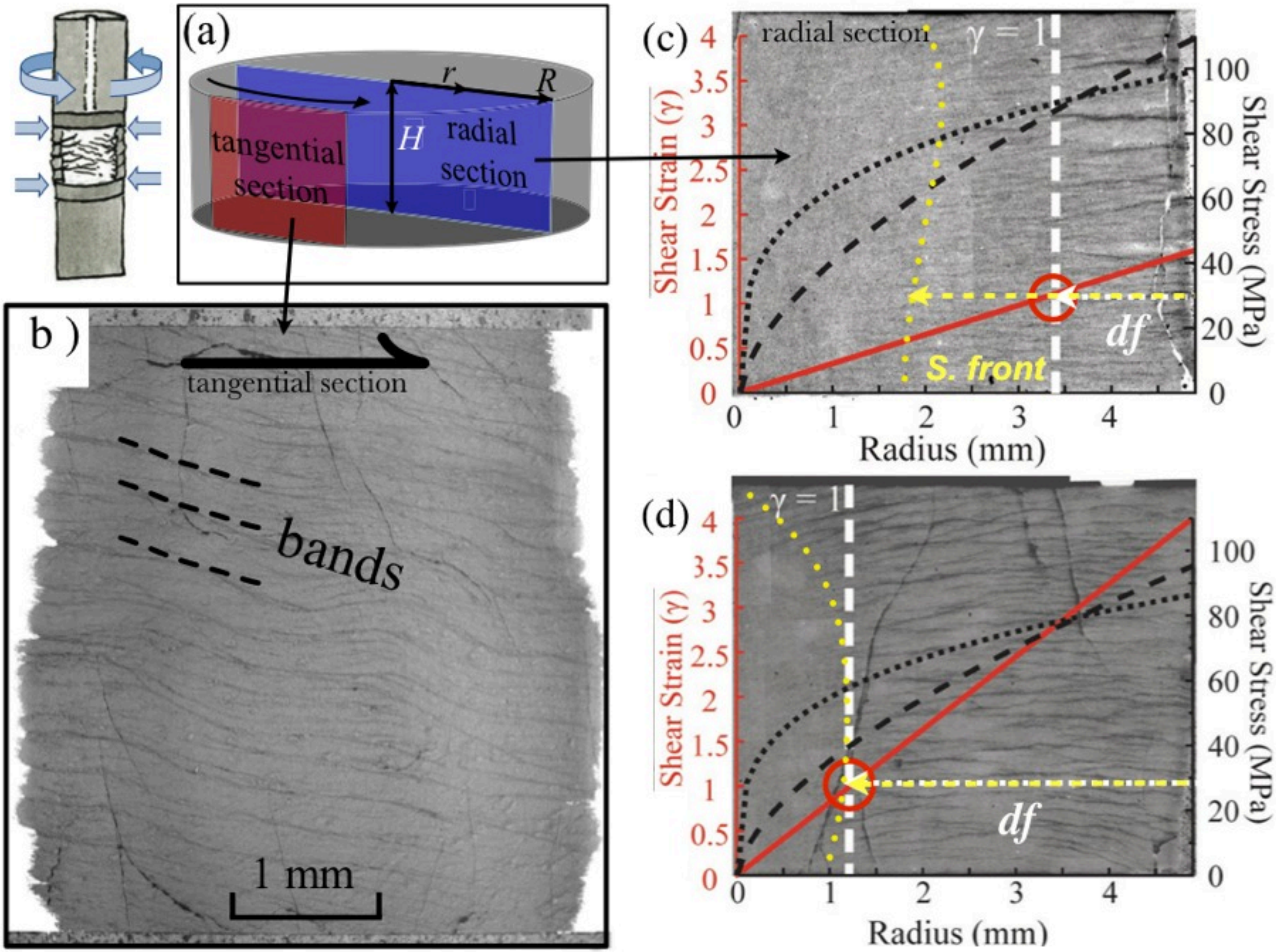
***The rates of these processes depend on the degree of thermal/chemical disequilibrium across the LAB...***

1. *Intro: who does all the work around here ?*

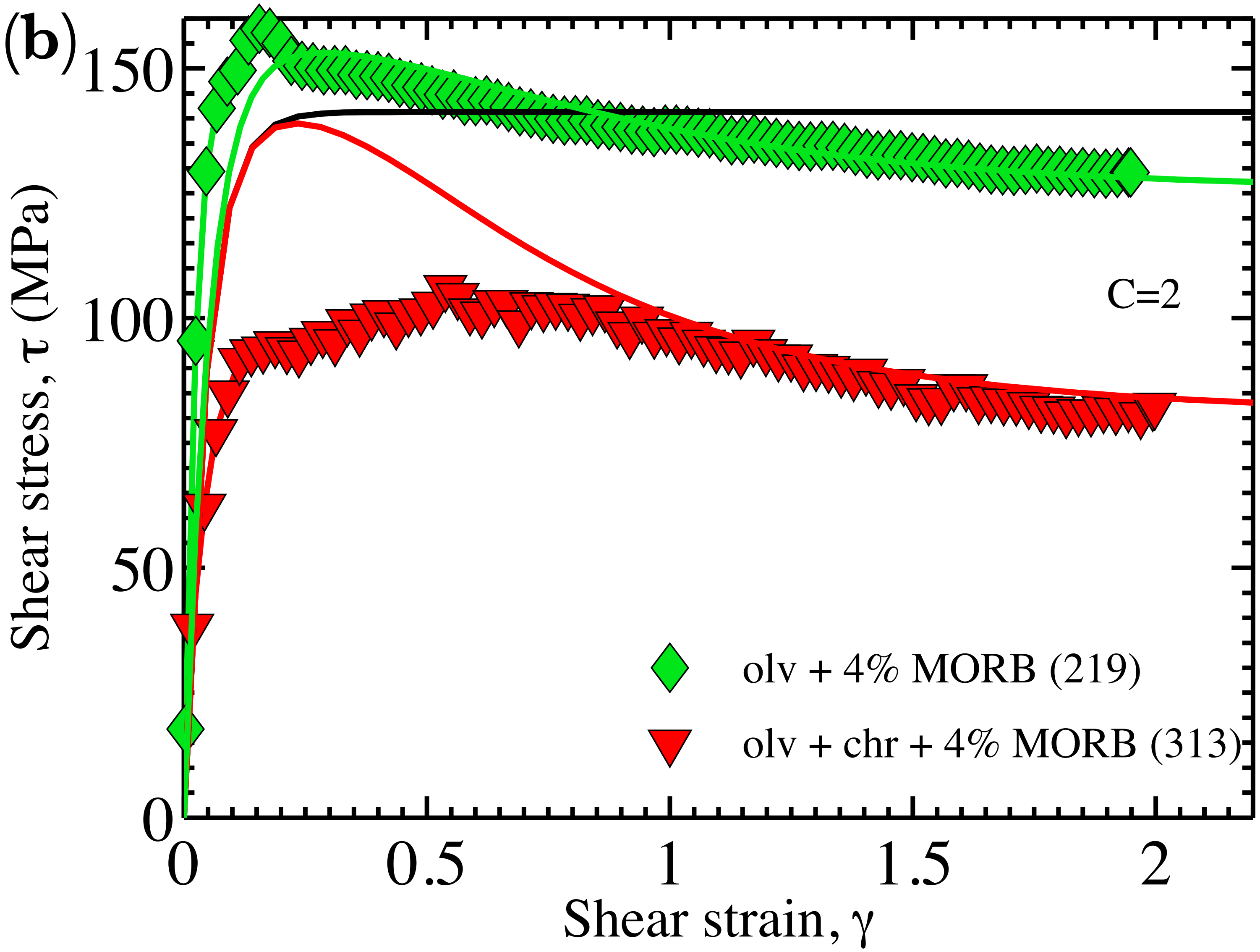
2. *Interactions of deformation and melt migration in experiment.*

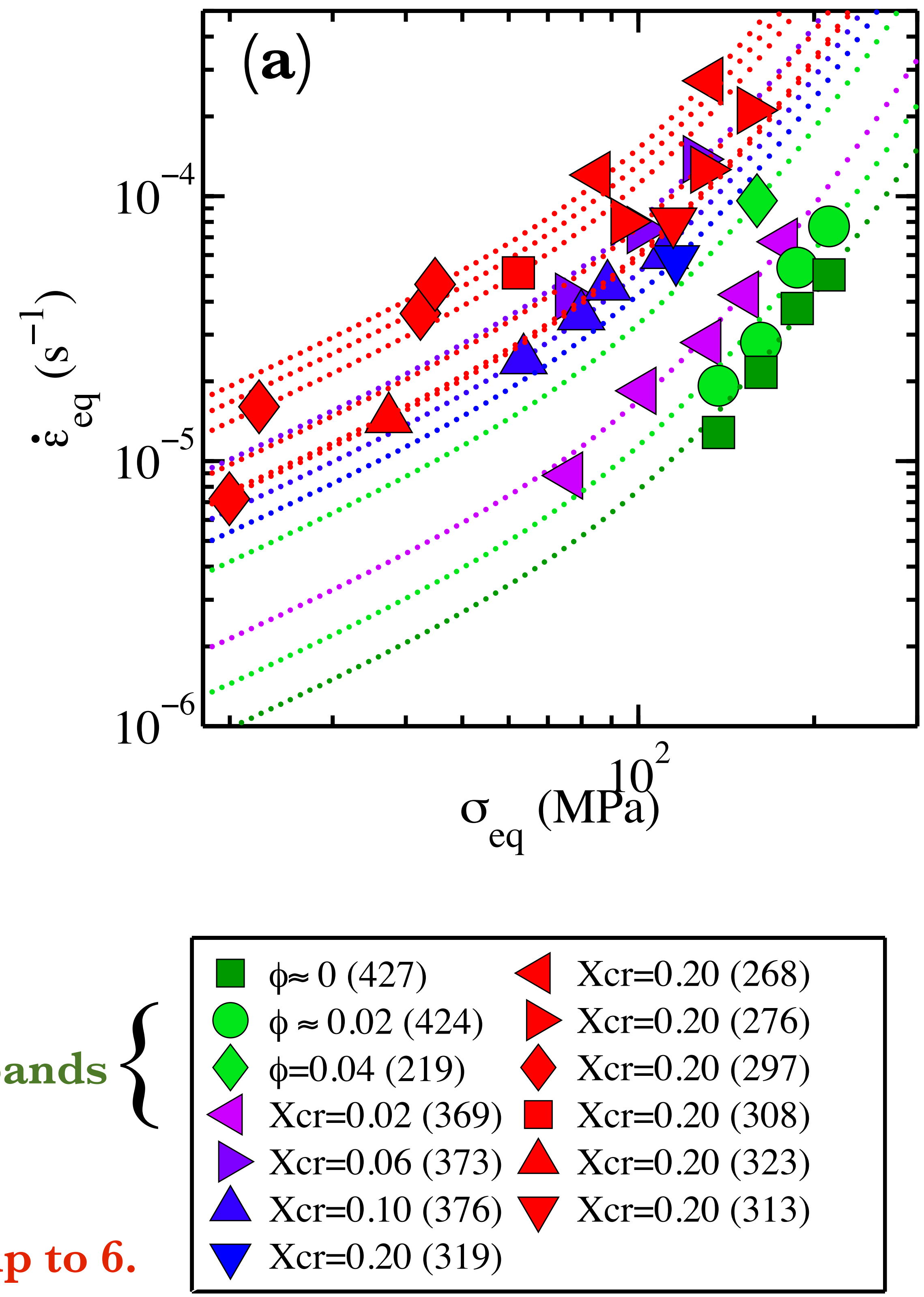
3. *Speculation on the Main Ethiopian Rift from below..*

**Torsion experiments on olivine +/-chromite + MORB, at 300 MPa, 1200 C, at UMN.**
**from Dan King's thesis (2010), e.g. King, Zimmerman & Kohlstedt, JPet 2010**



**Holtzman, King & Kohlstedt, EPSL, in press**




Melt but no bands {

All others form bands,
and are weaker by a factors of up to 6.

# A simple parameterization of stress-driven segregation:

$S$ = state variable describing the degree of segregation

**Evolution equation for S**

$$\begin{cases} \dot{S} = A(S_{max} - S) \\ A(\dot{\varepsilon}_p) = C(\dot{\varepsilon}_p - \dot{\varepsilon}_c) \end{cases}$$

**Constitutive model:**

$$\eta(S)$$

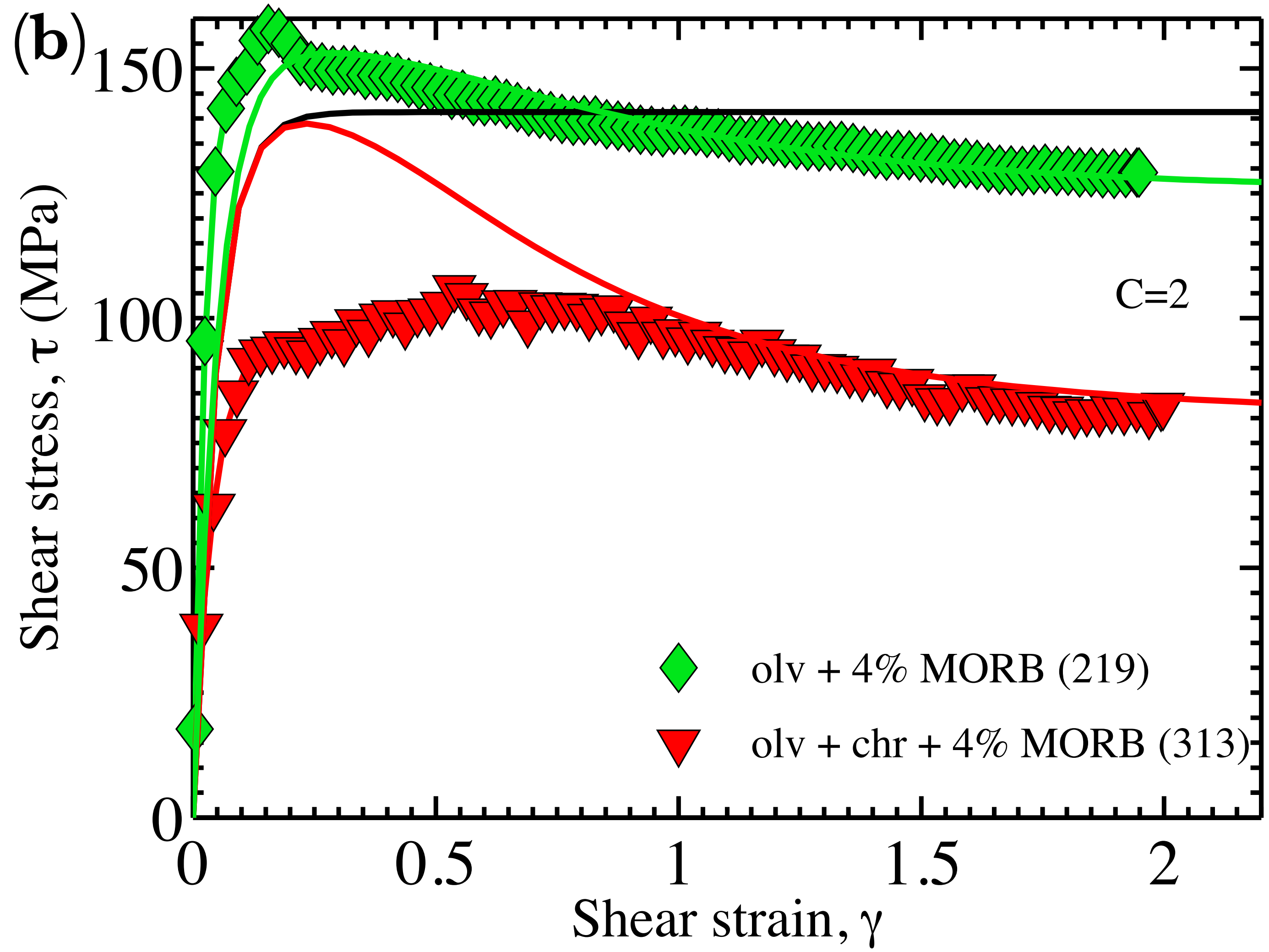
**Mechanical model:**

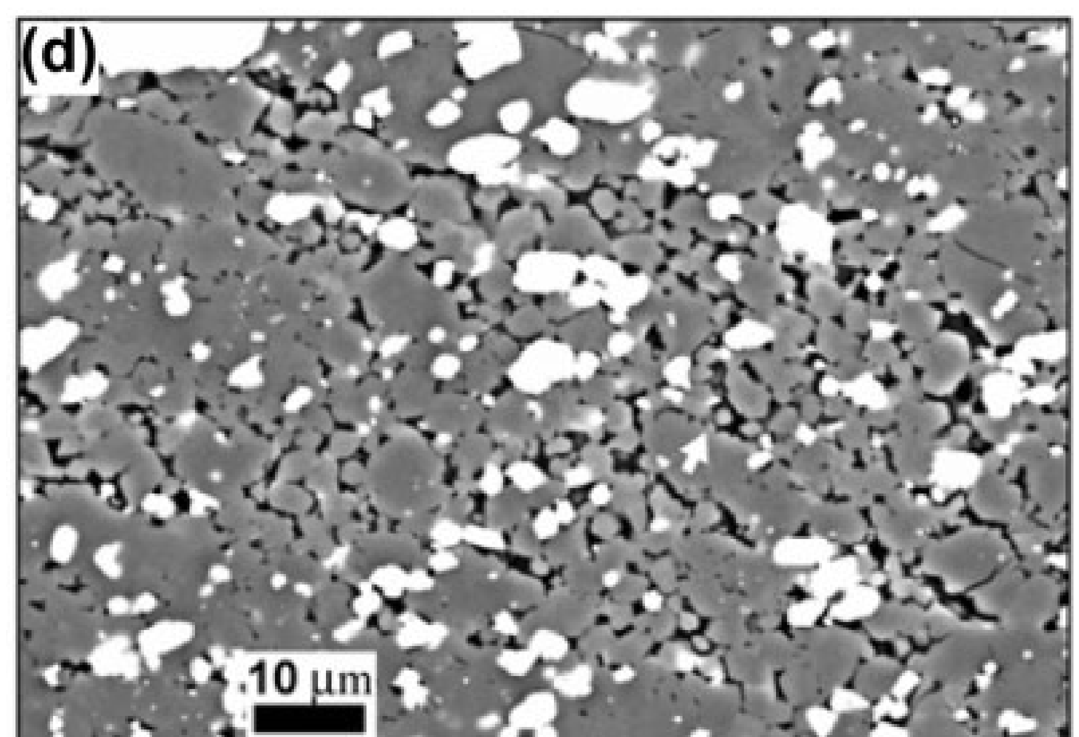
$$\dot{\sigma} = E(\dot{\varepsilon}_l - \dot{\varepsilon}_p)$$

**Permeability:**

$$k(s)$$

**based on Montesi, 2007**



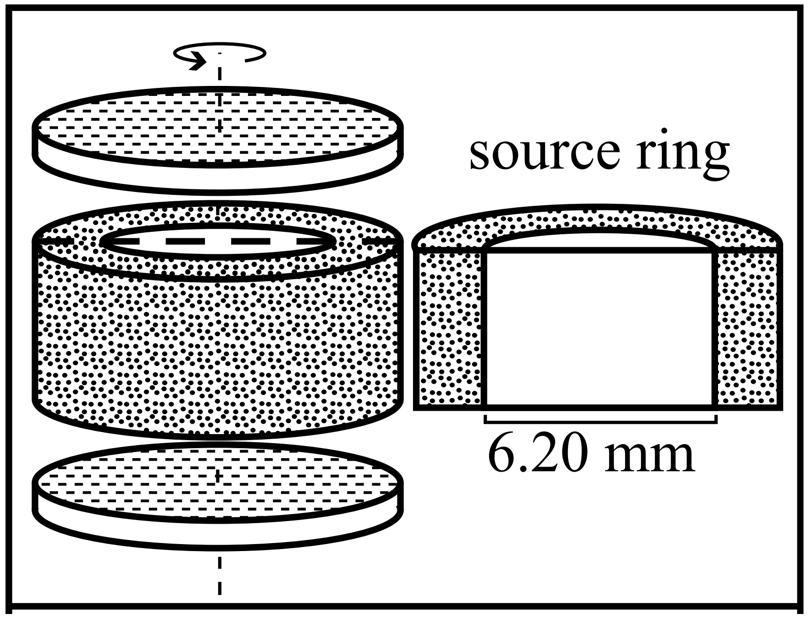



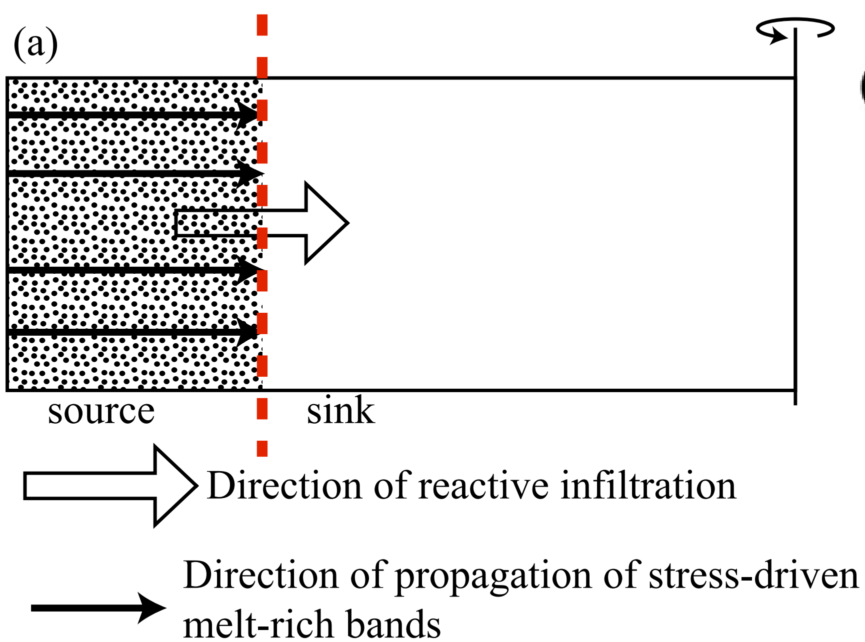

**from Holtzman & Kohlstedt, J. Pet.2007**

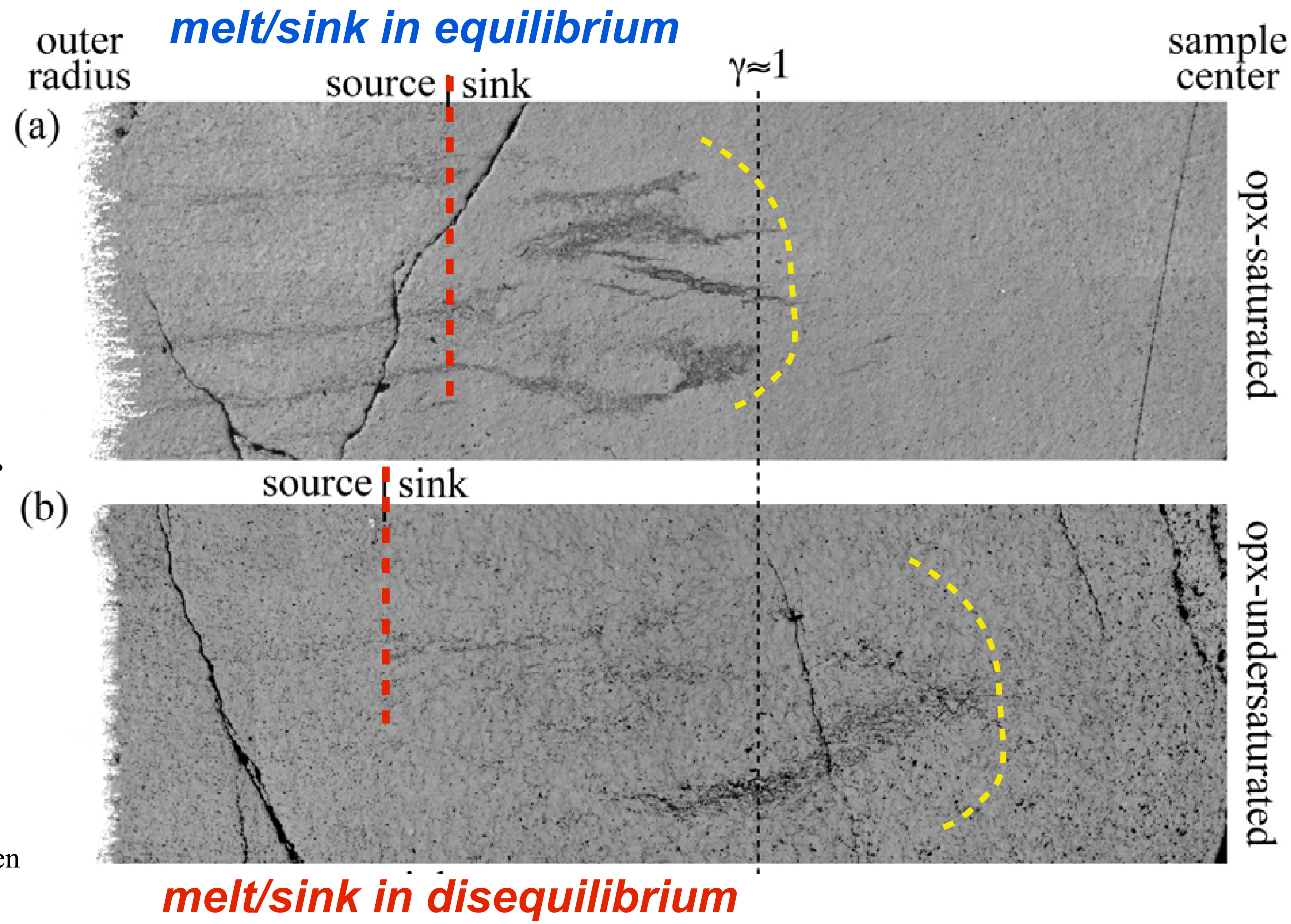
Geochemistry Geophysics Geosystems G3

# An experimental investigation of the interactions between reaction-driven and stress-driven melt segregation: 1. Application to mantle melt extraction

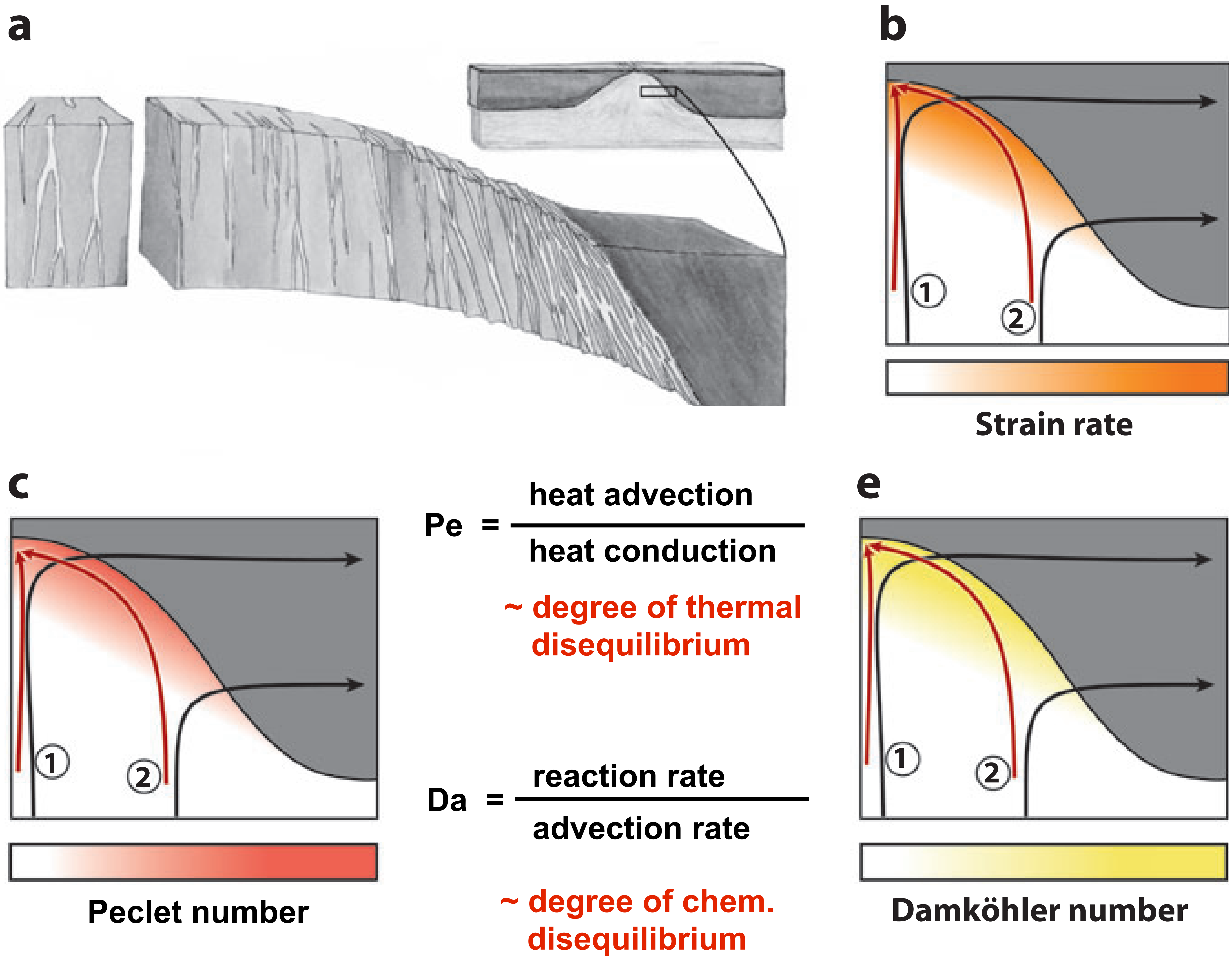
King, D. S. H., B. K. Holtzman, and D. L. Kohlstedt (2011)




control: disequilibrium with no deformation: source sink boundary barely moves, so the difference is related to the coupling of chemical and mechanical processes


a
b
1
2
Strain rate
c
1
2
Peclet number
Pe = heat advection / heat conduction
~ degree of thermal disequilibrium
Da = reaction rate / advection rate
~ degree of chem. disequilibrium
e
1
2
Damköhler number

1. Intro: who does all the work around here ?

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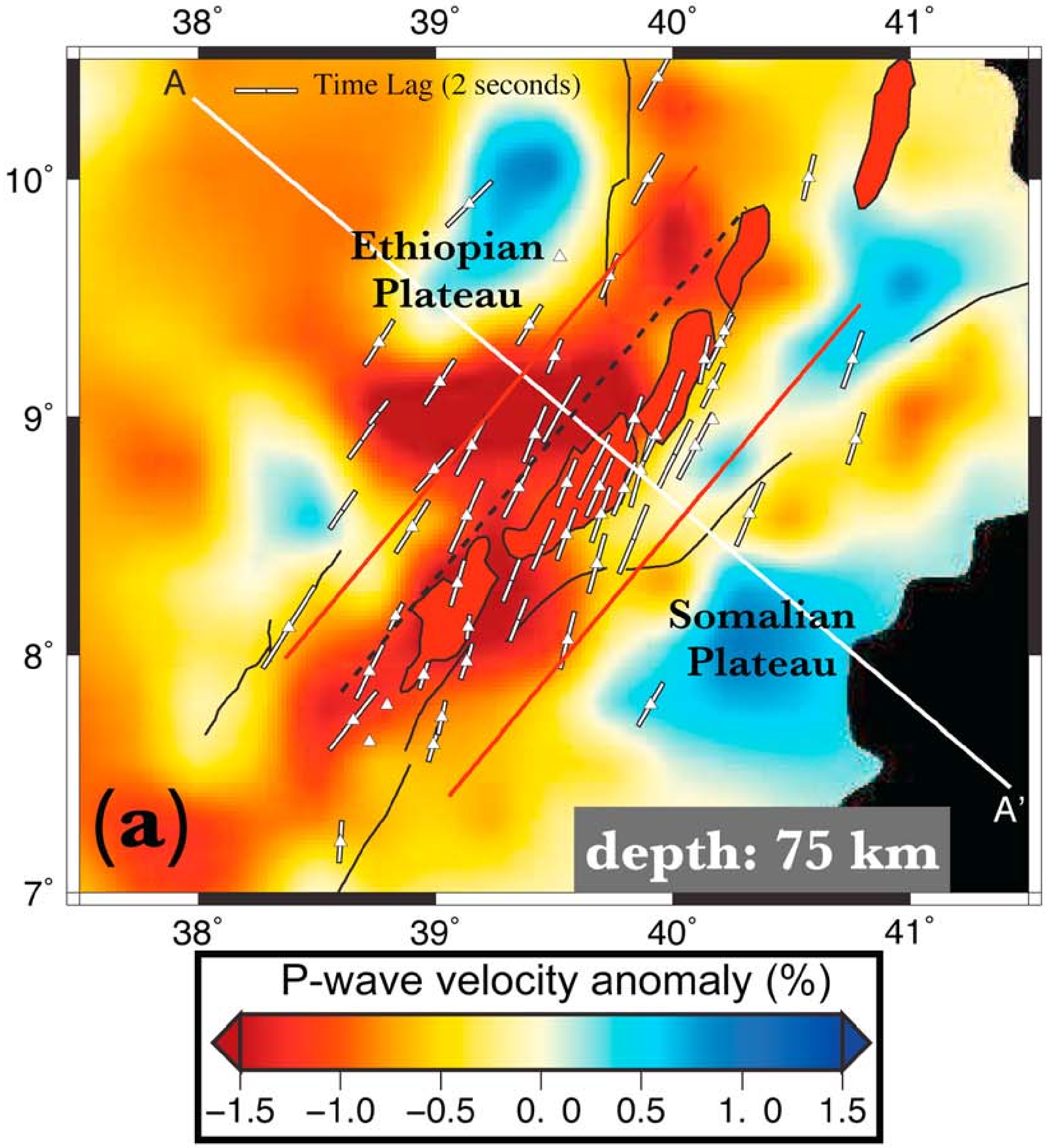
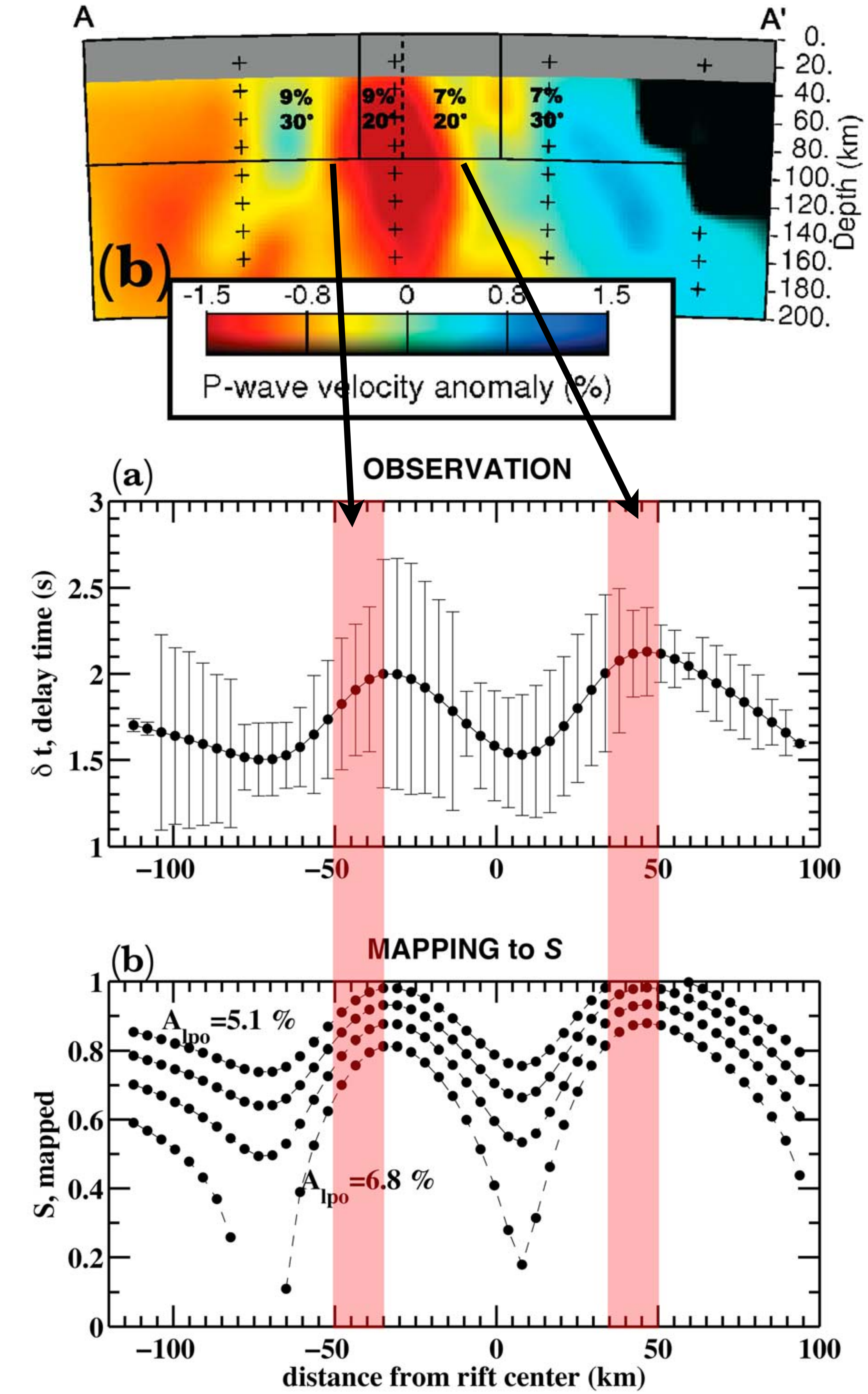
3. Speculation on the Main Ethiopian Rift from below..

# Main Ethiopian Rift:

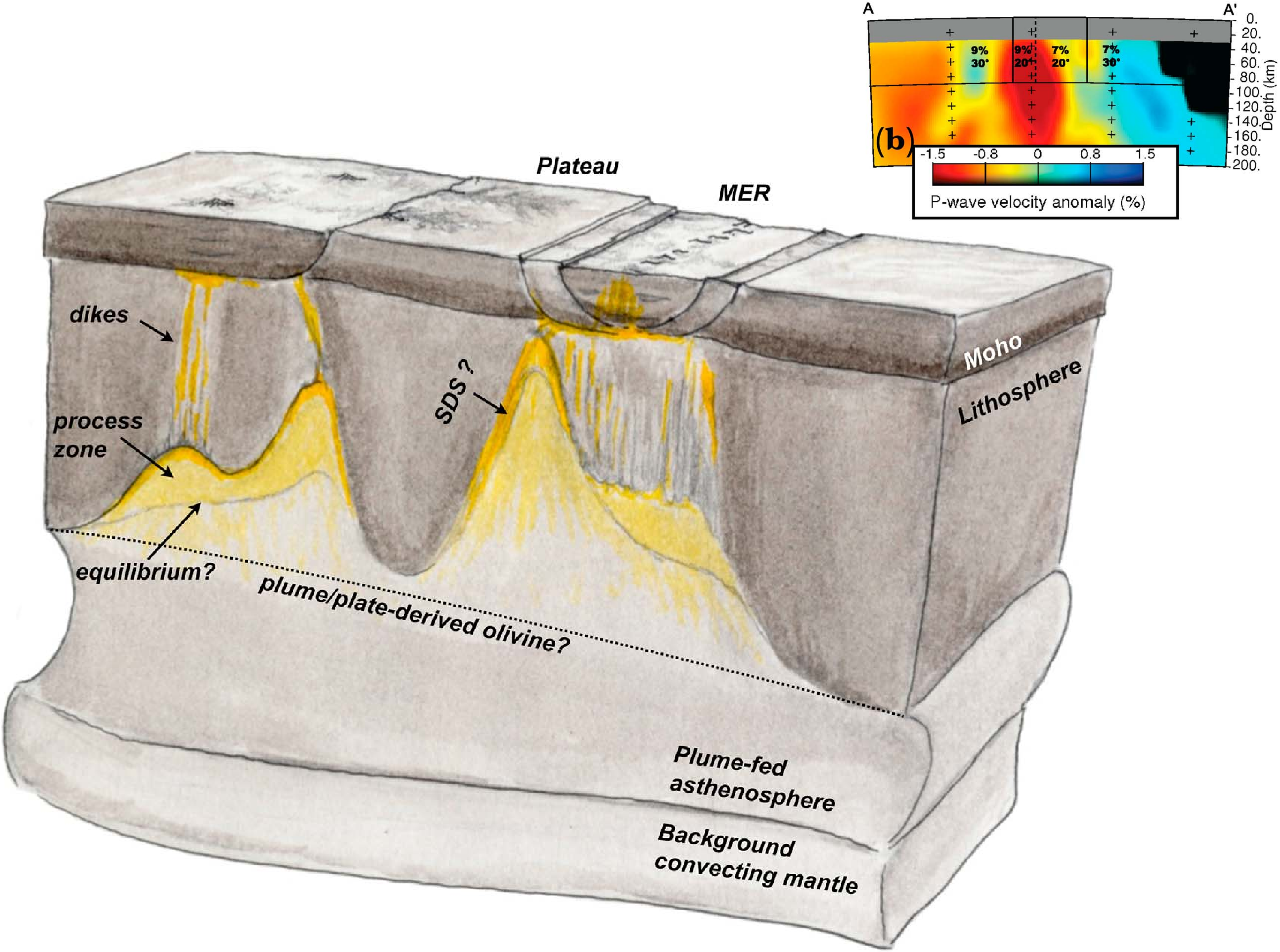
a) 30 Ma of wide surface volcanism, 20 Ma of surface deformation, now focused in rift.

b) Low velocities to shallow depth below the plate. Very low beneath rift. Anisotropy strong beneath rift, peaking at flanks.

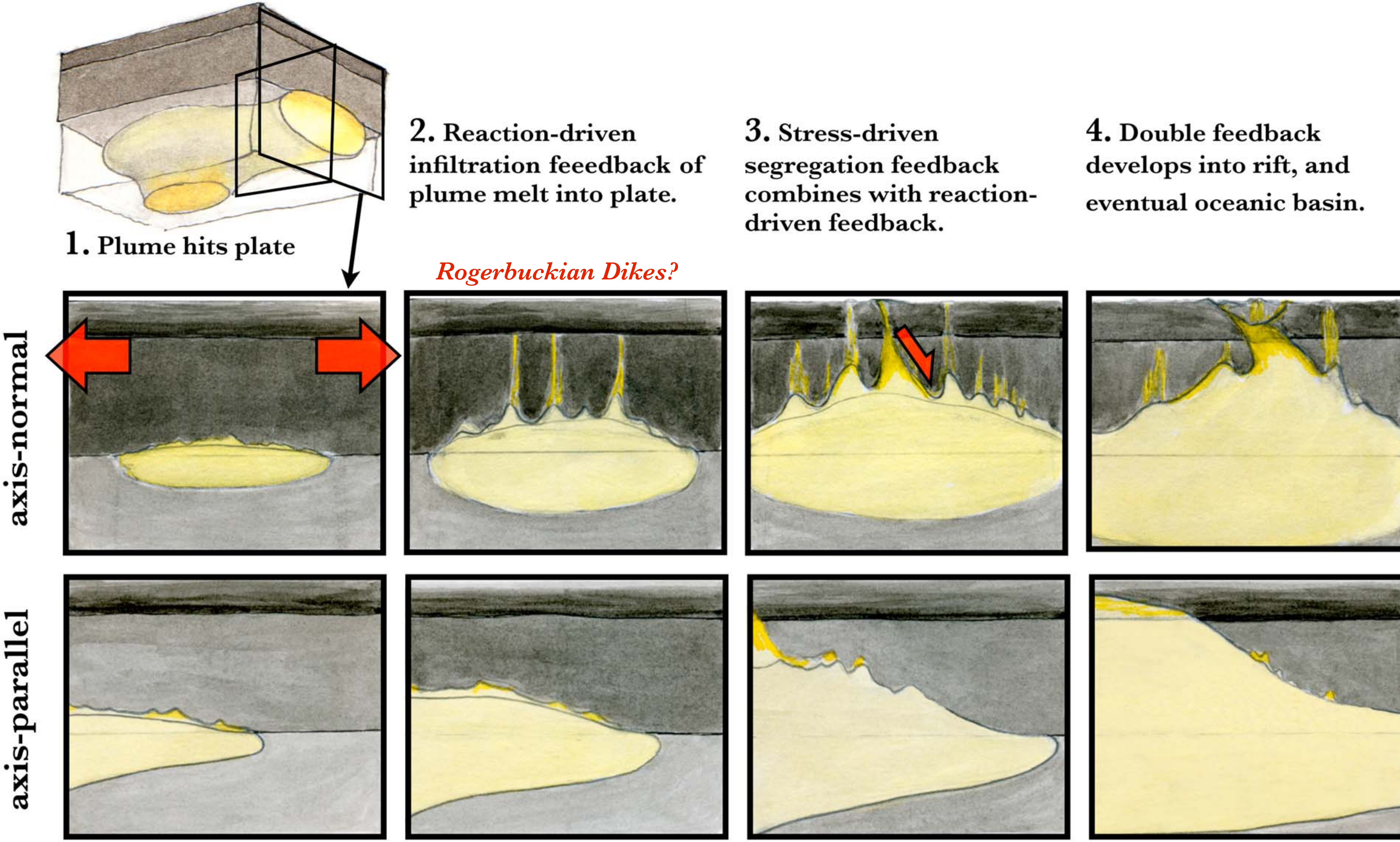



after Bastow et al. 2008; Hammond et al, 2010 in Holtzman & Kendall, G3 2010



A
A'
0.
20.
40.
60.
80.
100.
120.
140.
160.
180.
200.
Depth (km)
9% 30°
9% 20°
7% 20°
7% 30°
(b)
-1.5
-0.8
0
0.8
1.5
P-wave velocity anomaly (%)
Plateau
MER
dikes
process zone
equilibrium?
SDS ?
Moho
Lithosphere
plume/plate-derived olivine?
Plume-fed asthenosphere
Background convecting mantle




dynamic uplift causes stress in the plate!

mainly plume-derived melt...

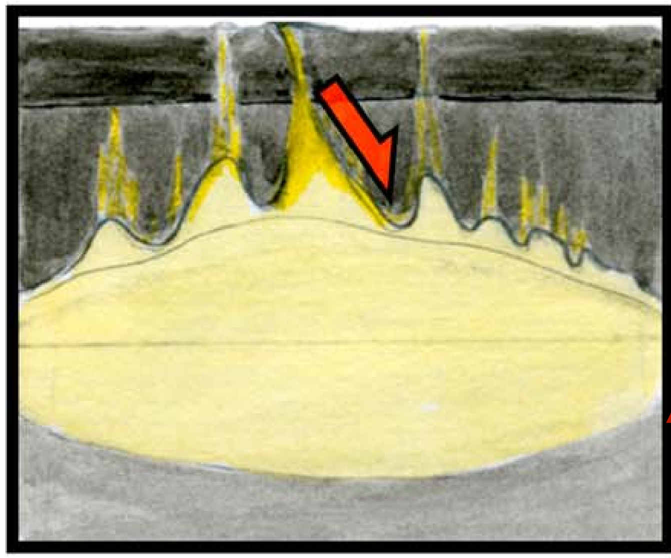
then, when plate starts to deform, pressure release melting begins, strain rates increase, melt segregation occurs?

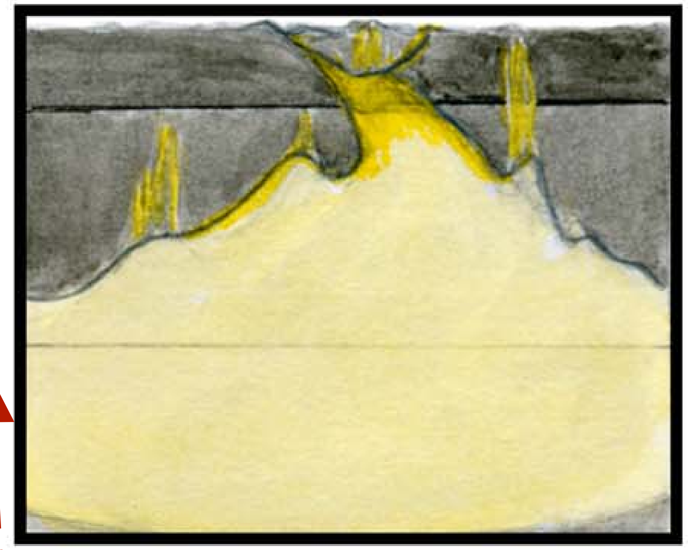
*so when do these deeper processes occur relative to the stages of volcanism and surface deformation ?*

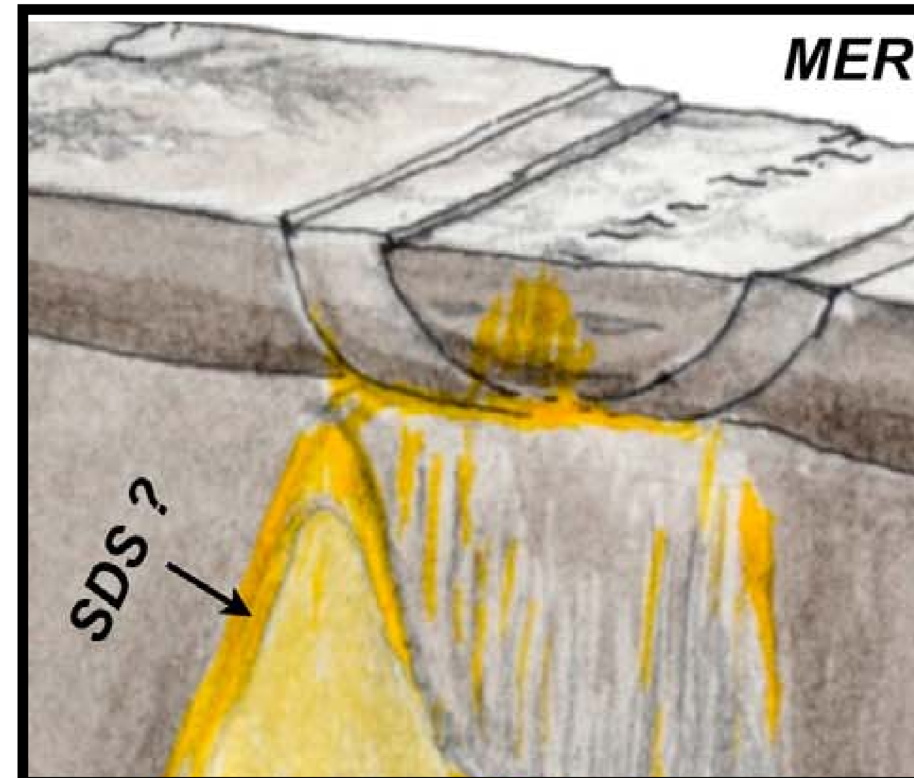
see Schmeling & Wallner, G^3, 2012

**3. Stress-driven segregation feedback combines with reaction-driven feedback.**

**4. Double feedback develops into rift, and eventual oceanic basin.**








*In the MER, does the transition from magmatism at rift edge to rift center correspond to the increase melt production due to the onset of significant decompression melting and thus greater weakening of asthenosphere?*

# Conclusions and further questions:

1. Stress-driven segregation and thermal-chemical corrosion of lithosphere are observed in the geologic record.

2. Mechanical and chemical-mechanical feedbacks in melt segregation and migration are observed in experiments. Parameterizations of the mechanical aspects of melt segregation can now be incorporated into geodynamic-scale models.

3. Constraining the degree of disequilibrium between plume and plate can help us understand the potential for corrosion.

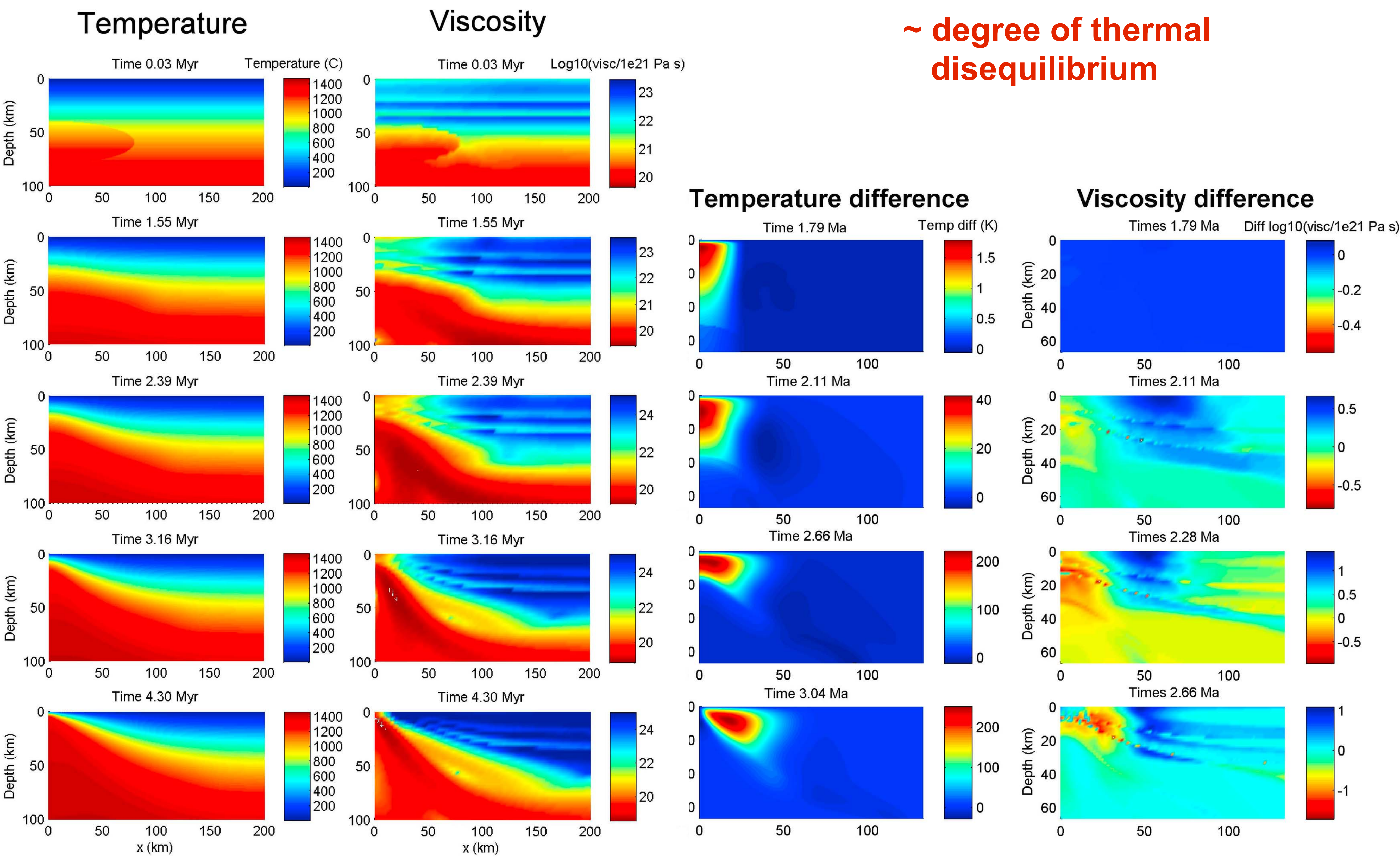
4. In the EAR, does corrosion help explain the degree of plate weakening/velocity reduction while the rift has undergone only a small degree of extension ?

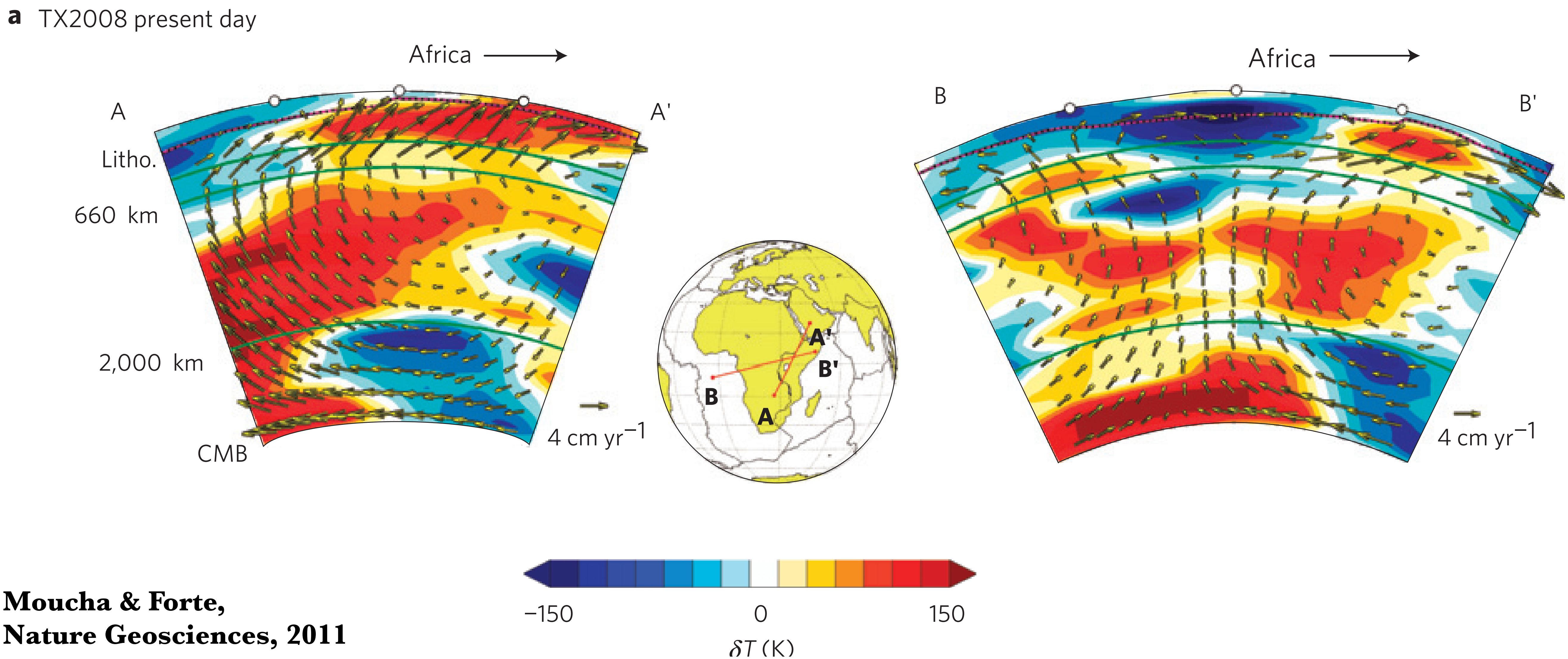
**BASTA**

# Schmeling & Wallner, G^3, 2012

$$Pe = \frac{\text{heat advection}}{\text{heat conduction}}$$

~ degree of thermal disequilibrium

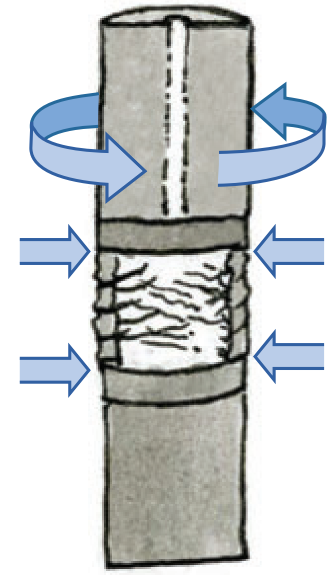


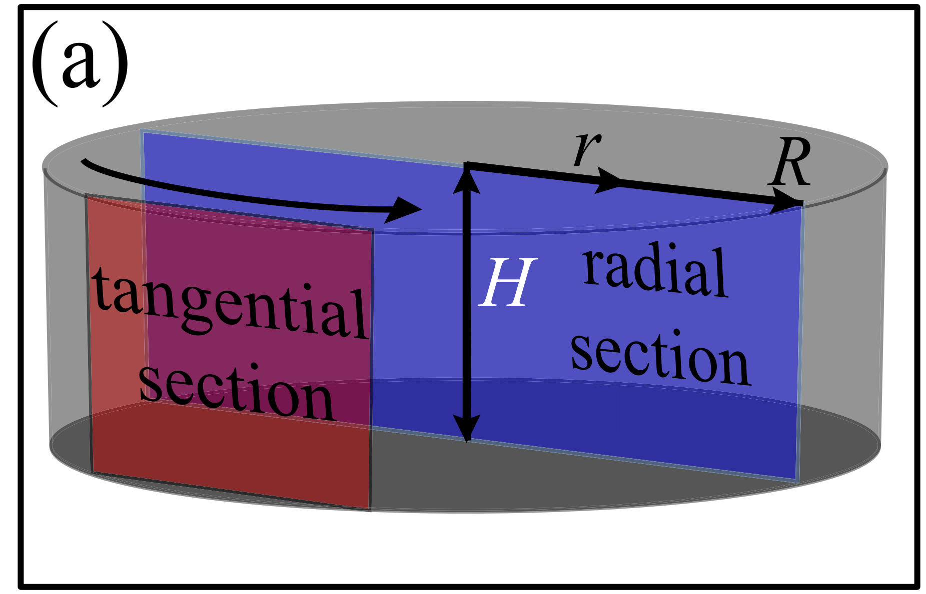



**Moucha & Forte,**
**Nature Geosciences, 2011**

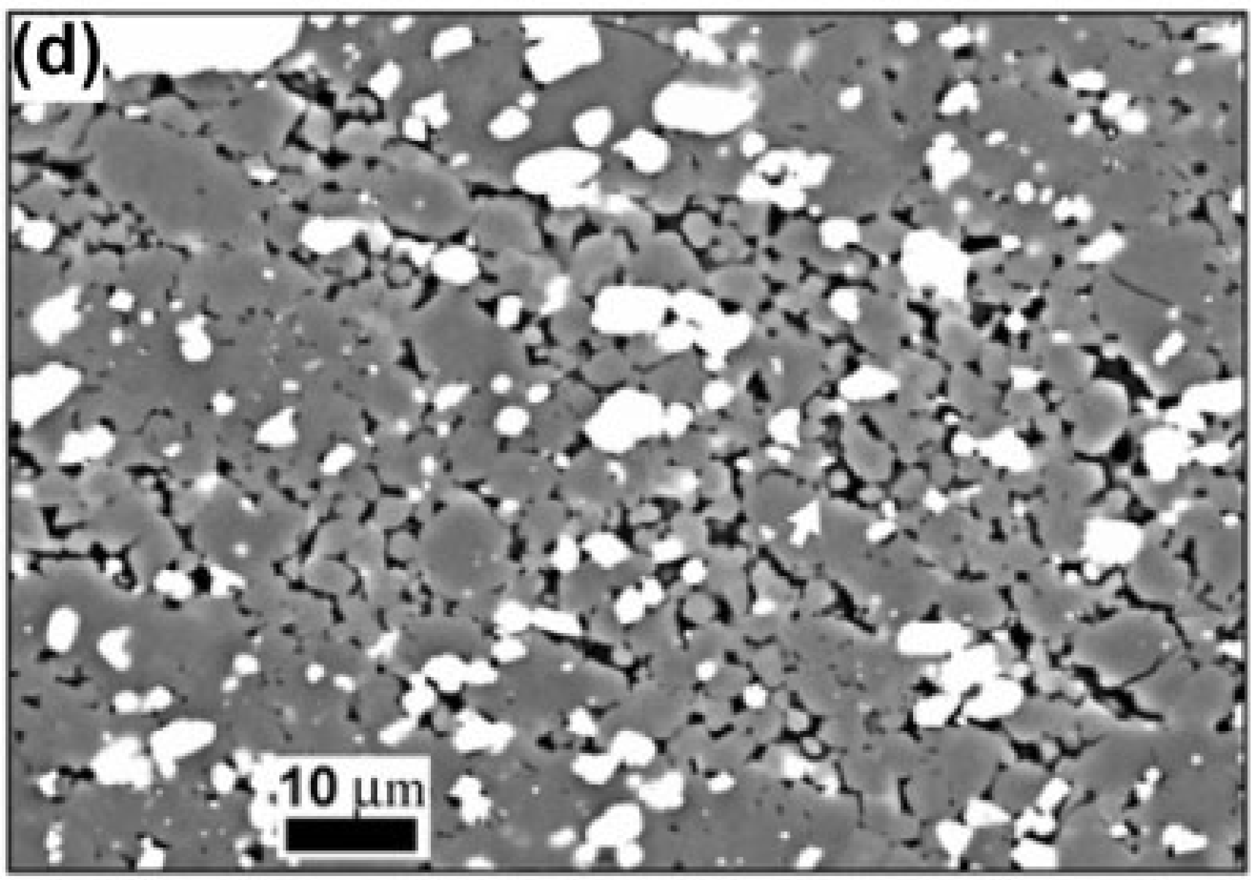
**Torsion experiments on olivine +/-chromite + MORB,**

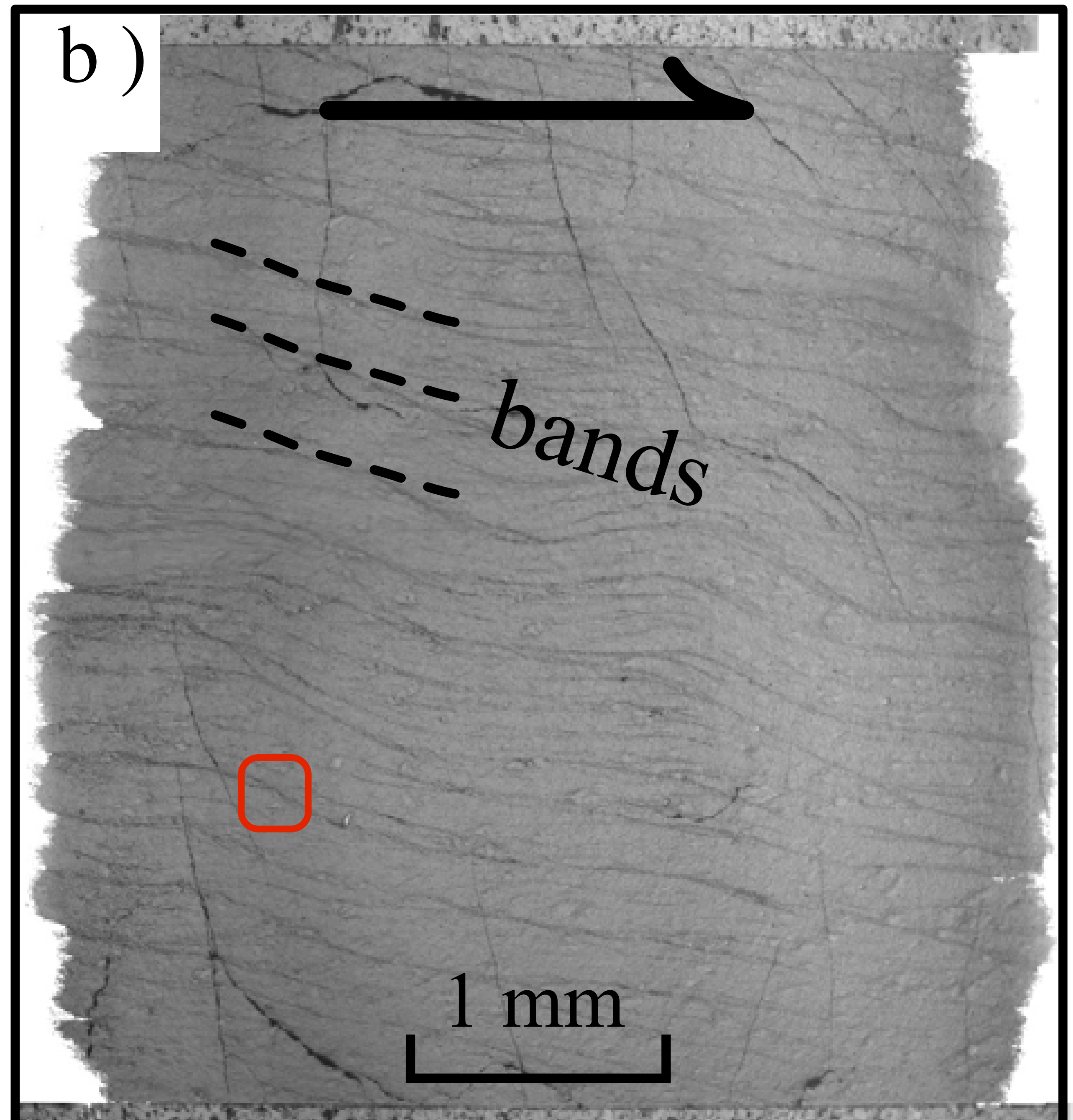
**at 300 MPa, 1200 C,**
**in the Paterson Apparatus at UMN.**
**from Dan King's thesis (2010), e.g.**
**King, Zimmerman & Kohlstedt, JPet 2010**

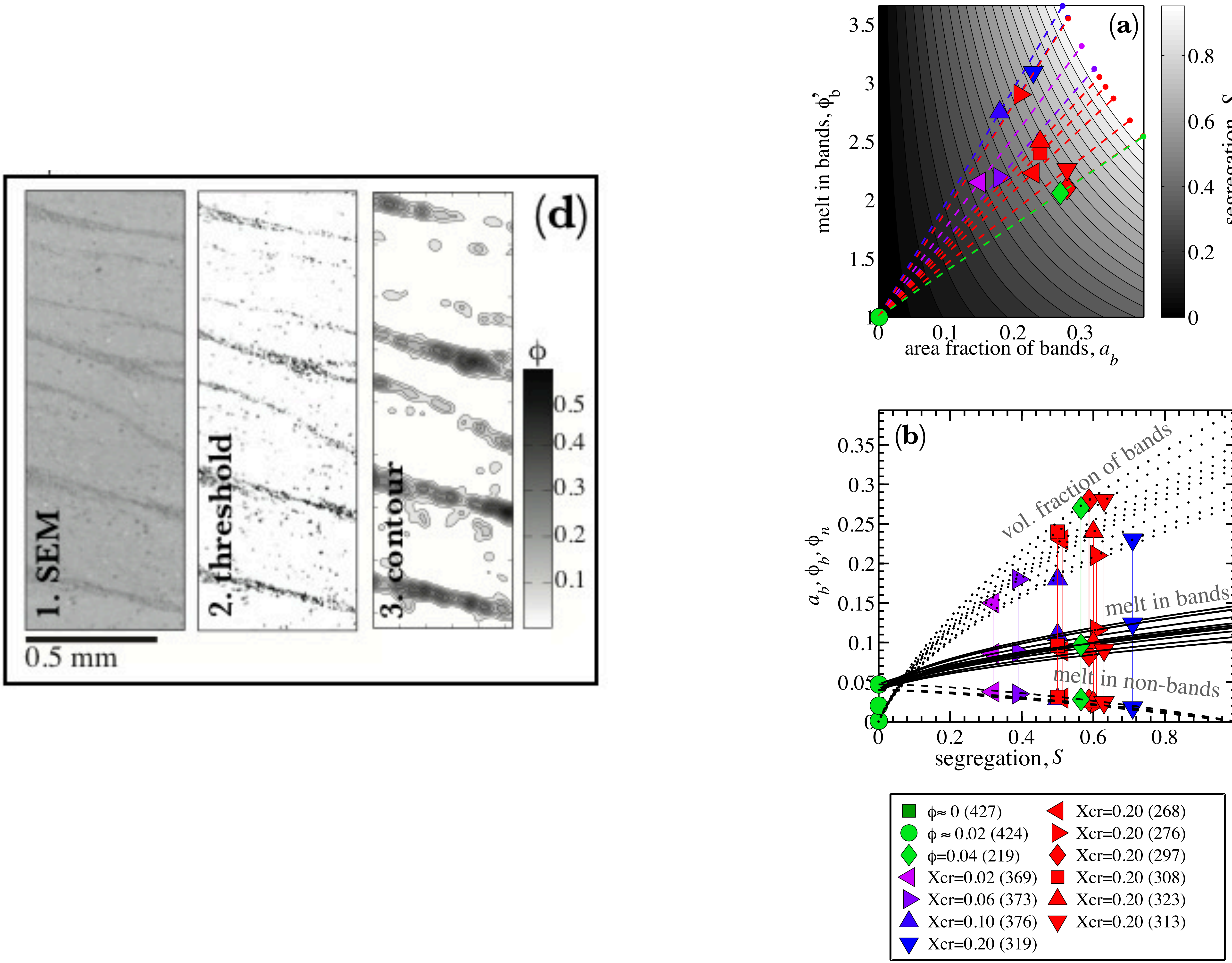


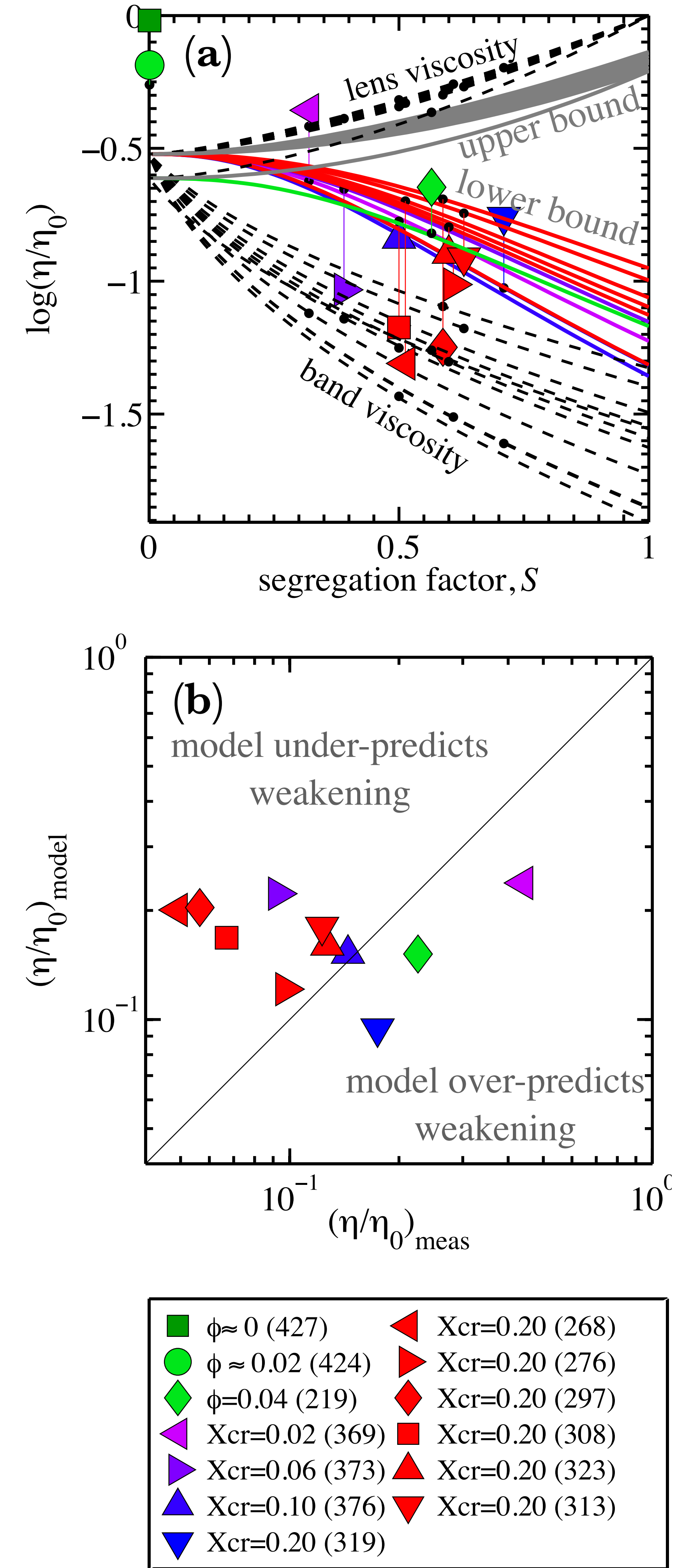



**from Holtzman & Kohlstedt, J. Pet.2007**




(d)
1. SEM
2. threshold
3. contour
φ
0.5
0.4
0.3
0.2
0.1
0.5 mm
(a)
melt in bands, φ'_b
3.5
3
2.5
2
1.5
1
0
0.1
0.2
0.3
area fraction of bands, a_b
segregation, S
0.8
0.6
0.4
0.2
0
(b)
a_b, φ_b, φ_n
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
vol. fraction of bands
melt in bands
melt in non-bands
0.2
0.4
0.6
0.8
1
segregation, S
φ≈ 0 (427)
φ ≈ 0.02 (424)
φ=0.04 (219)
Xcr=0.02 (369)
Xcr=0.06 (373)
Xcr=0.10 (376)
Xcr=0.20 (319)
Xcr=0.20 (268)
Xcr=0.20 (276)
Xcr=0.20 (297)
Xcr=0.20 (308)
Xcr=0.20 (323)
Xcr=0.20 (313)


(a)
lens viscosity
upper bound
lower bound
band viscosity
log(η/η0)
segregation factor, S
0
−0.5
−1
−1.5
0.5
1
(b)
model under-predicts weakening
model over-predicts weakening
(η/η0)model
(η/η0)meas
10^0
10^−1
ϕ≈ 0 (427)
ϕ ≈ 0.02 (424)
ϕ=0.04 (219)
Xcr=0.02 (369)
Xcr=0.06 (373)
Xcr=0.10 (376)
Xcr=0.20 (319)
Xcr=0.20 (268)
Xcr=0.20 (276)
Xcr=0.20 (297)
Xcr=0.20 (308)
Xcr=0.20 (323)
Xcr=0.20 (313)

$$\dot{\varepsilon}_i(\sigma, d, \phi_t, T, P) = A_i \sigma^{n_i} d^{-p_i} \exp((E_i + PV_i)/RT) \exp(\alpha_i \phi_t)$$

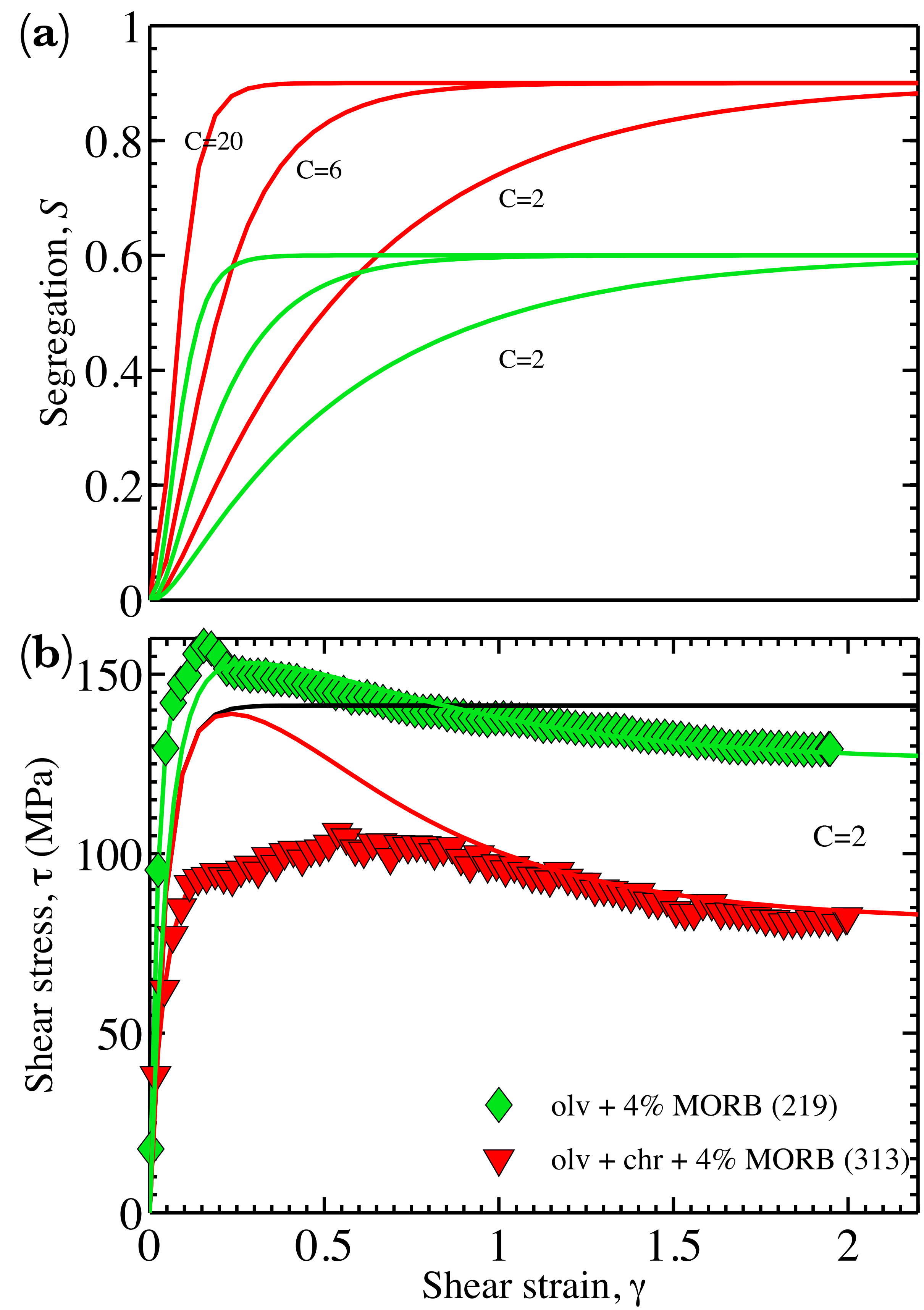
$$\dot{\varepsilon} = \dot{\varepsilon}'_S \left( \sum_i \dot{\varepsilon}_i \right)$$

$$\begin{cases} \dot{S} = A(S_{max} - S) \\ A(\dot{\varepsilon}_p) = C(\dot{\varepsilon}_p - \dot{\varepsilon}_c) \end{cases}$$

$$\begin{aligned} \phi_n &= \phi_t(1 - S)/(1 - a_b) \\ \phi_b &= \phi_t(1 + (\phi_b^* - 1)(S)^c) \end{aligned}$$

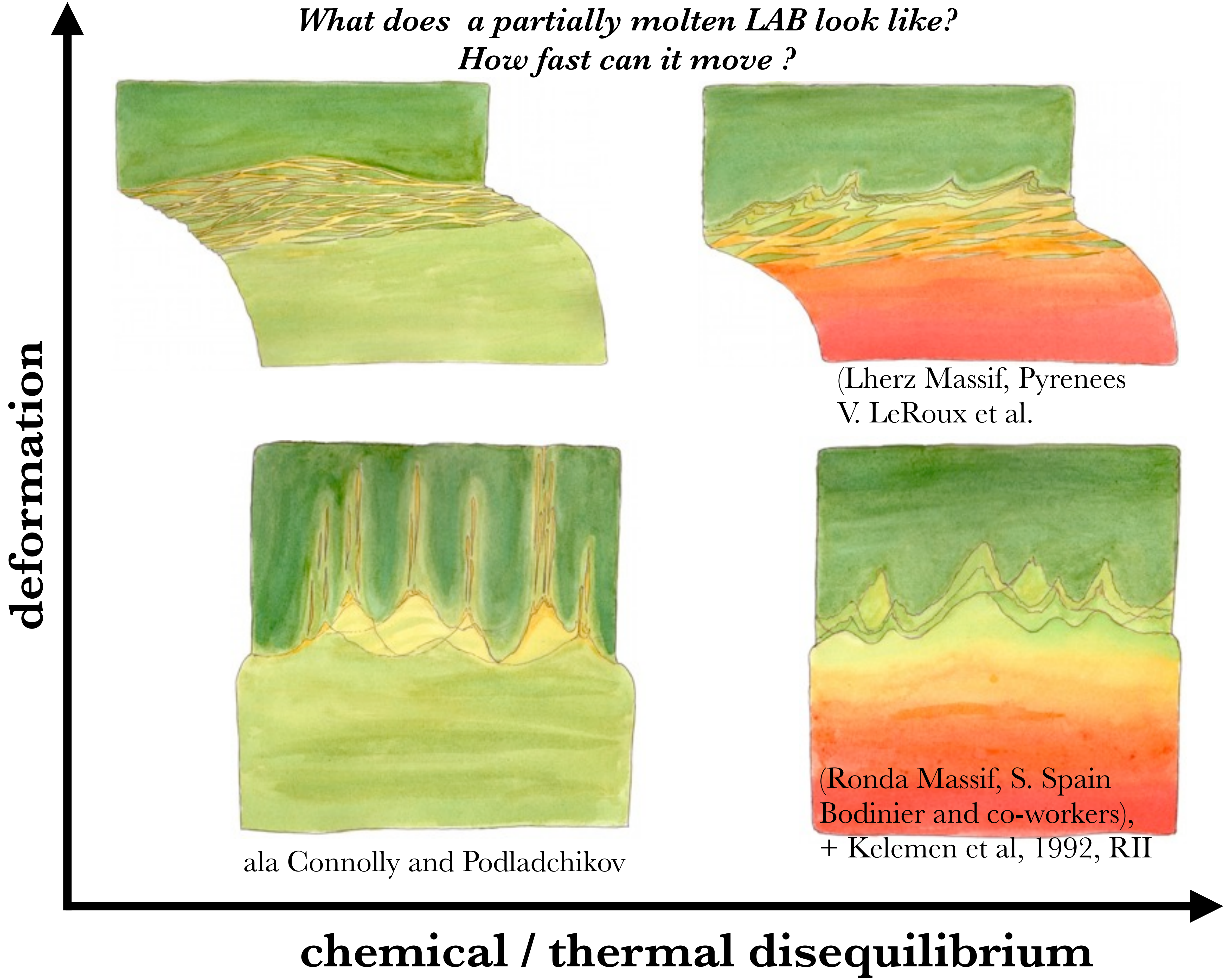
$$\eta_S = \left( \frac{a_b}{\eta_b} + \frac{(1 - a_b)}{\eta_n} \right)^{-1}$$

$$\dot{\sigma} = E(\dot{\varepsilon}_l - \dot{\varepsilon}_p)$$



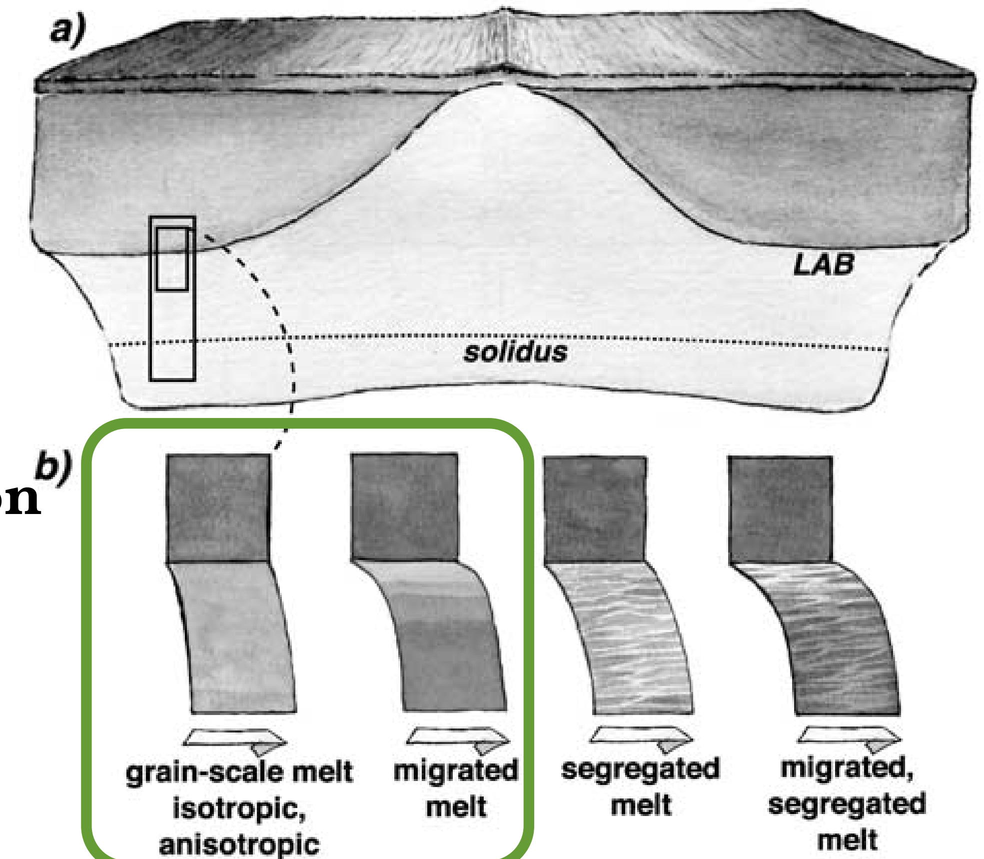
# LAB migration mechanism map:

***What does a partially molten LAB look like?***
***How fast can it move ?***

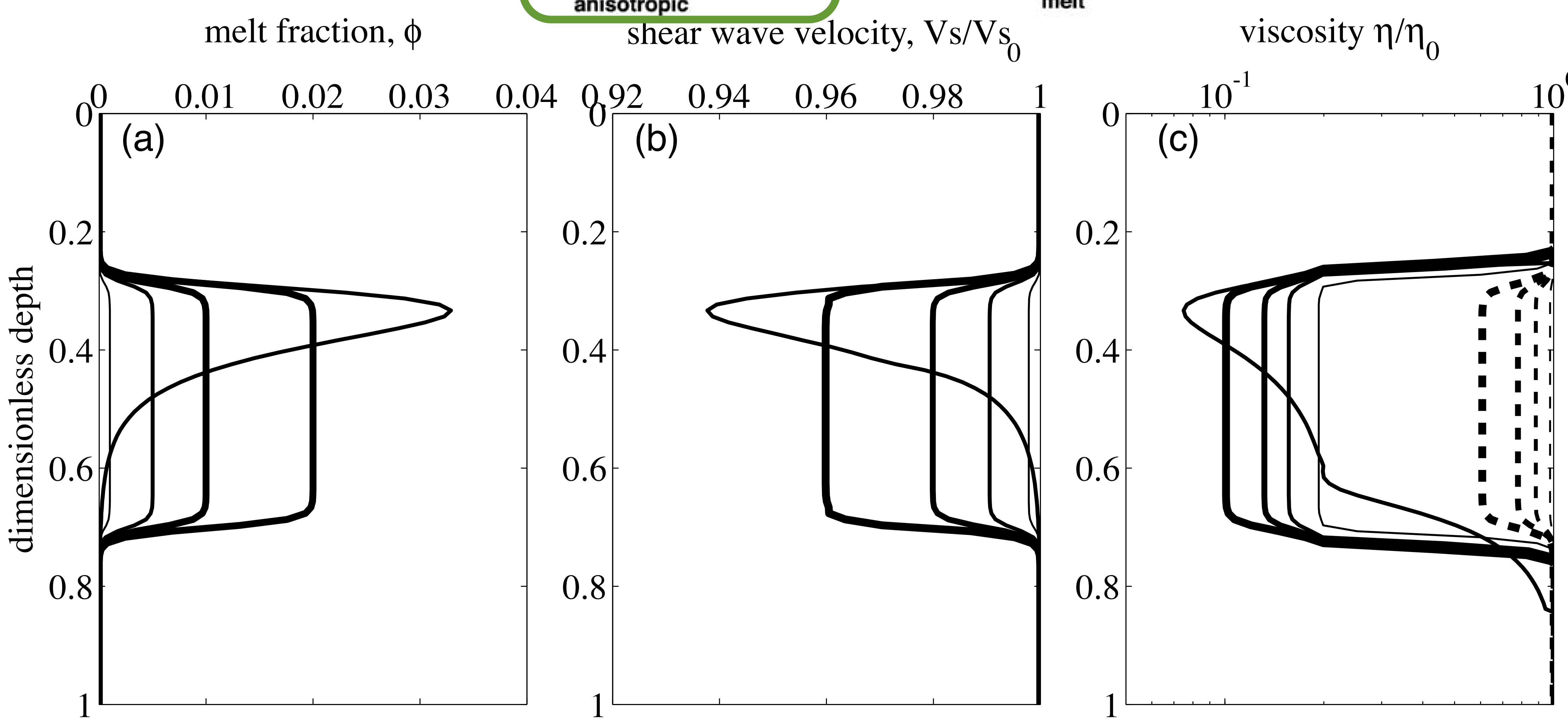


*and what are its consequences?*

**Takei & Holtzman, JGR 2009a**
**isotropic and anisotropic grain scale melt distribution**




**For effects of segregated melt on elastic properties:**
**Kawakatsu et al., 2009**
**Holtzman & Kendall, 2010.**



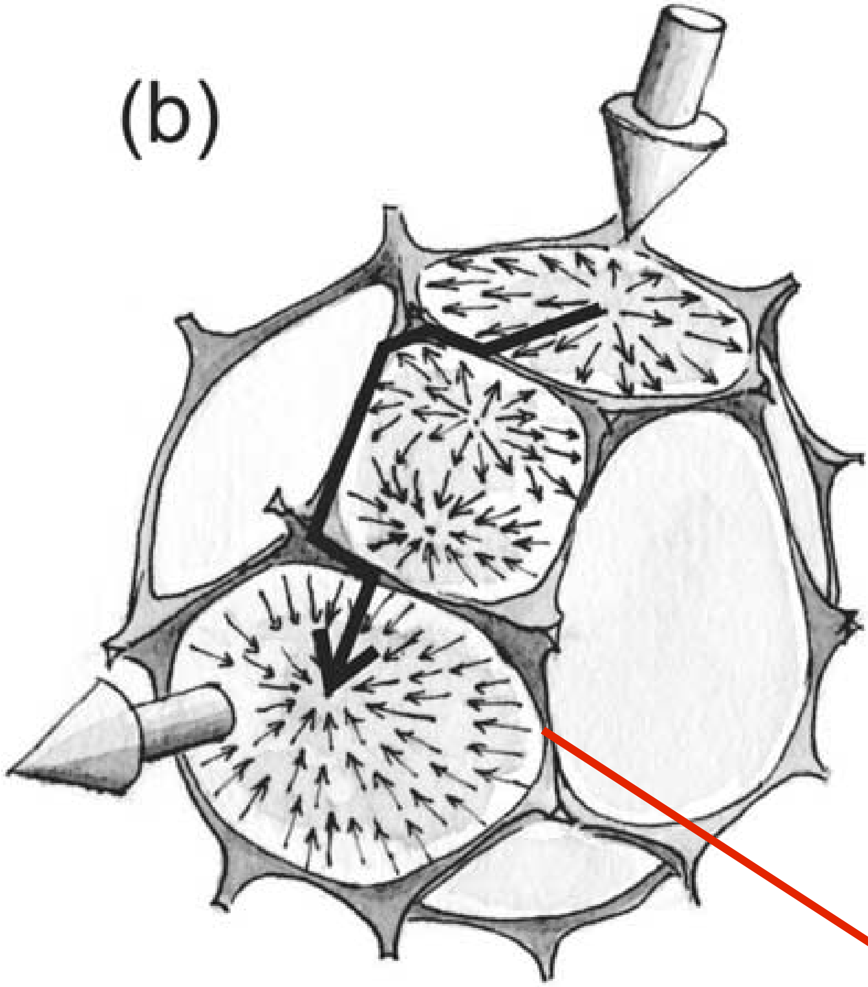
# What is the critical melt fraction, $\phi_c$?

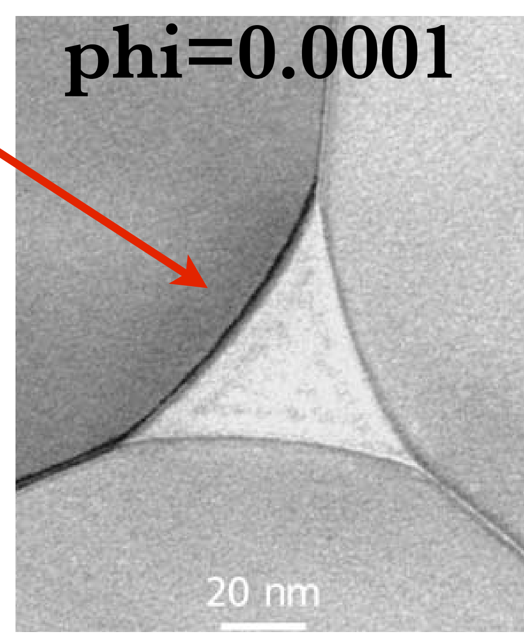
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, B06206, doi:10.1029/2008JB005851, 2009

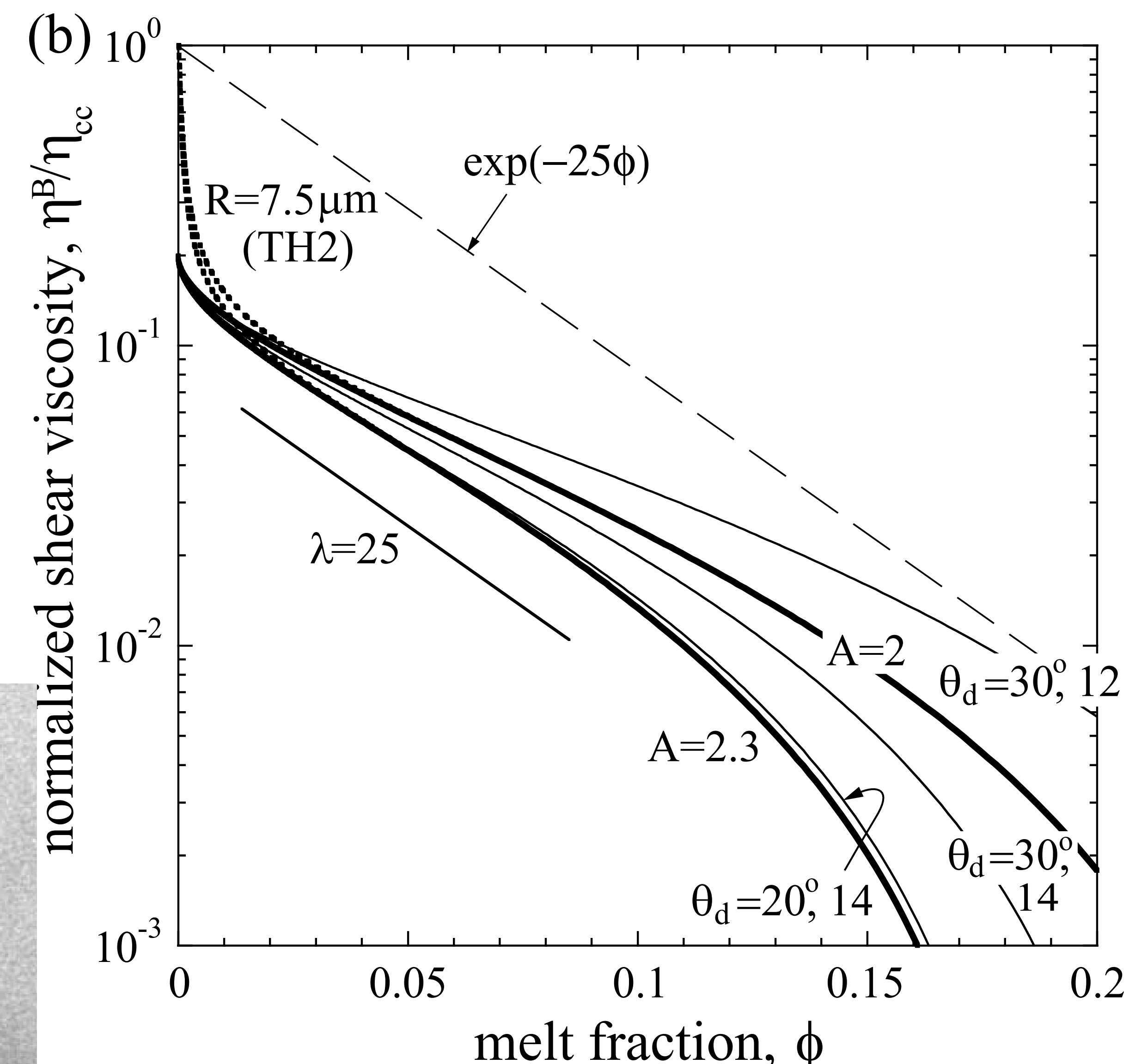
**Viscous constitutive relations of solid-liquid composites in terms of grain boundary contiguity:**
**1. Grain boundary diffusion control model 2. Compositional model for small melt fractions**

Yasuko Takei[1] and Benjamin K. Holtzman[2]

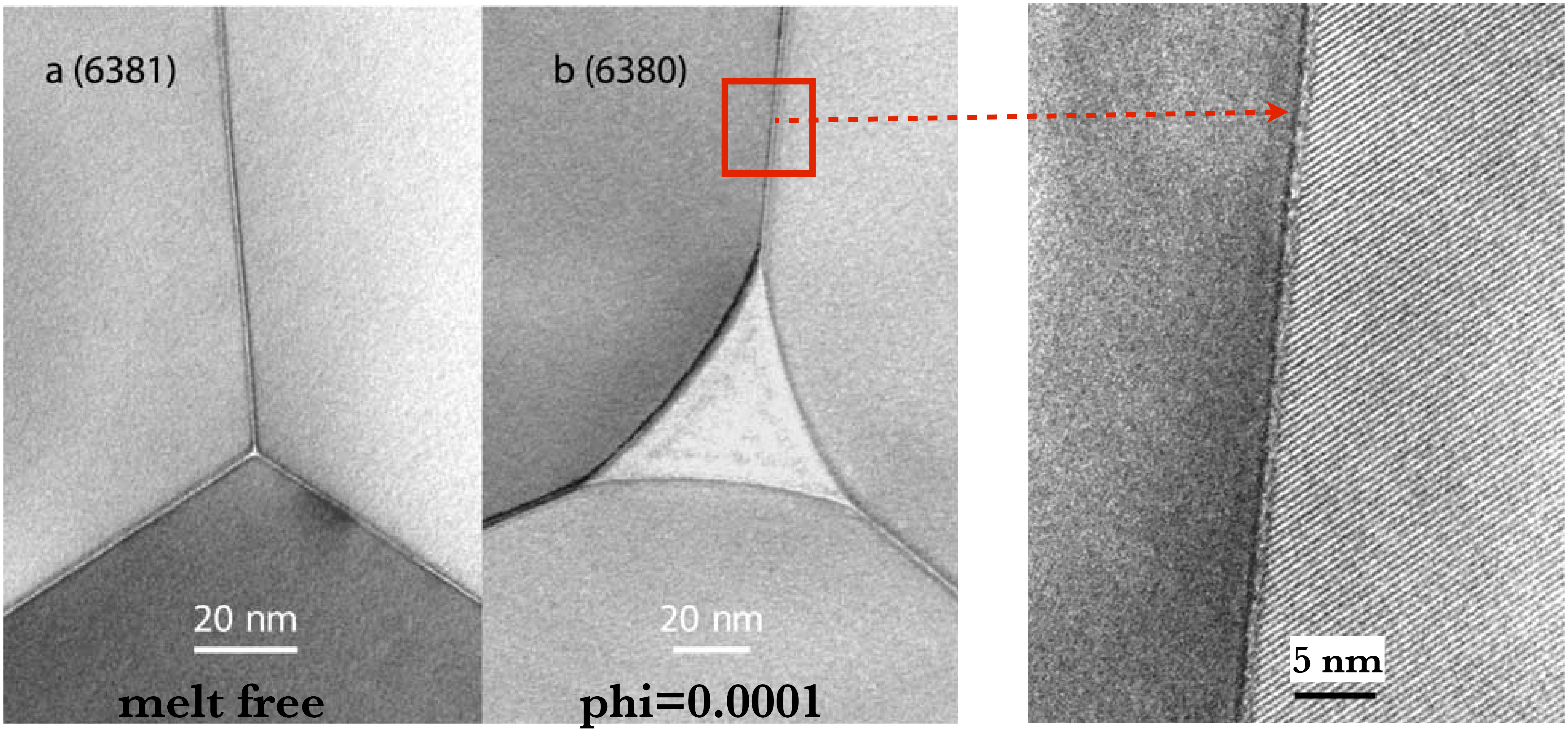
**for natural grain sizes, the critical melt fraction is <<0.1%**



# What does the onset of melting look like ?



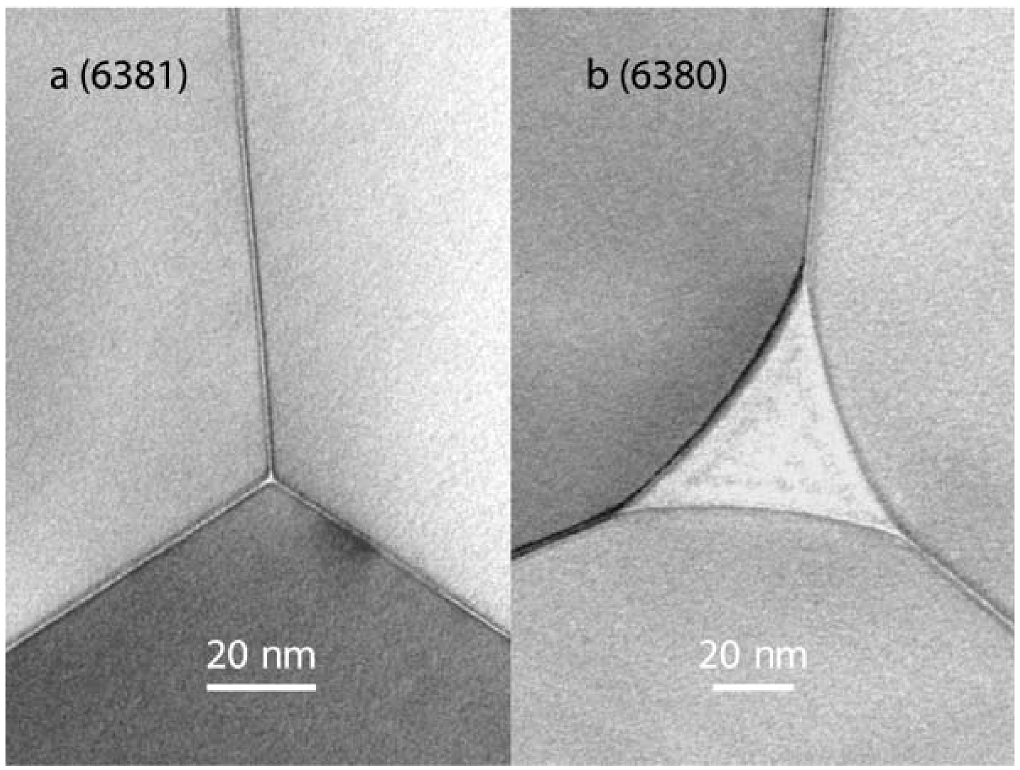

**Shear wave attenuation and dispersion in melt-bearing olivine polycrystals:**
**2. Microstructural interpretation and seismological implications**

Ulrich H. Faul, John D. Fitz Gerald, and Ian Jackson

**Faul et al., JGR 2004**

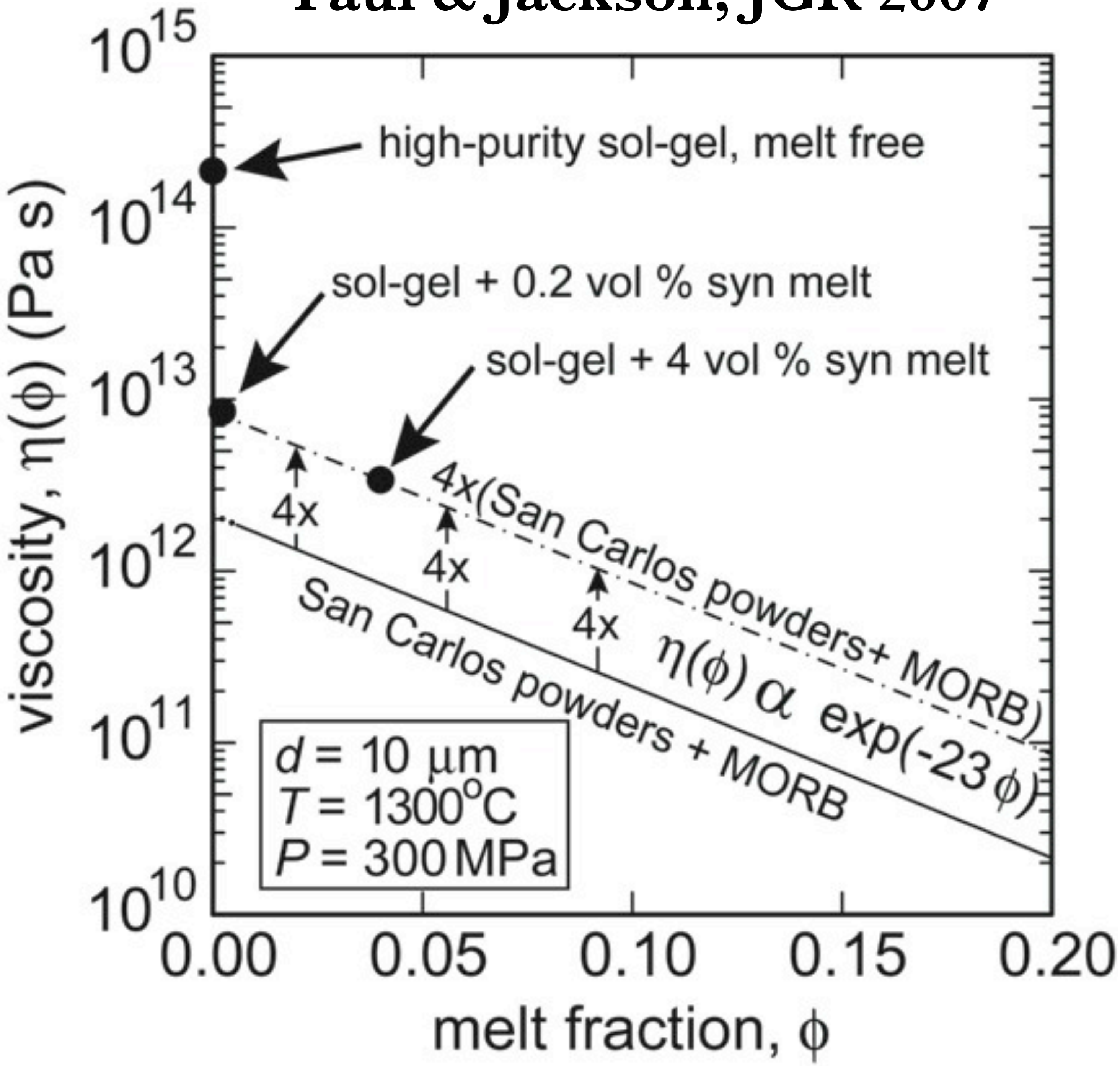
i.e. the "nominally melt free" San Carlos olivine actually, always contains a very small amount of melt... what is that very small amount, and how does it cause so much weakening?

"chemical effects" (i.e. elevated defect concentrations) and "melt effects"




Faul et al., JGR 2004

Faul & Jackson, JGR 2007

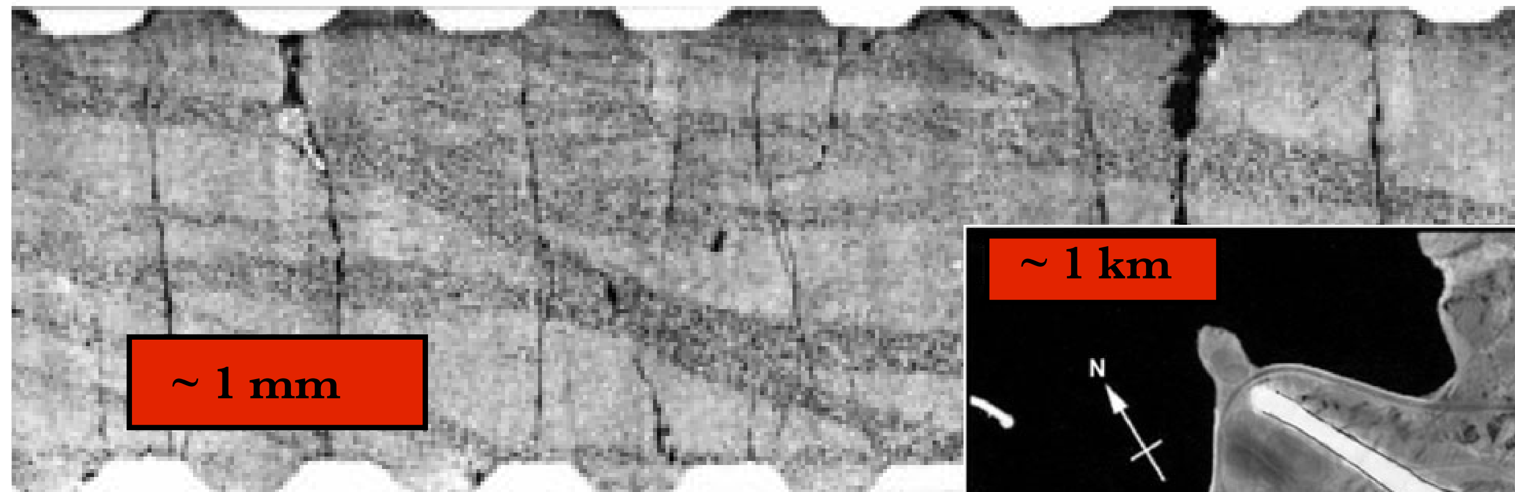


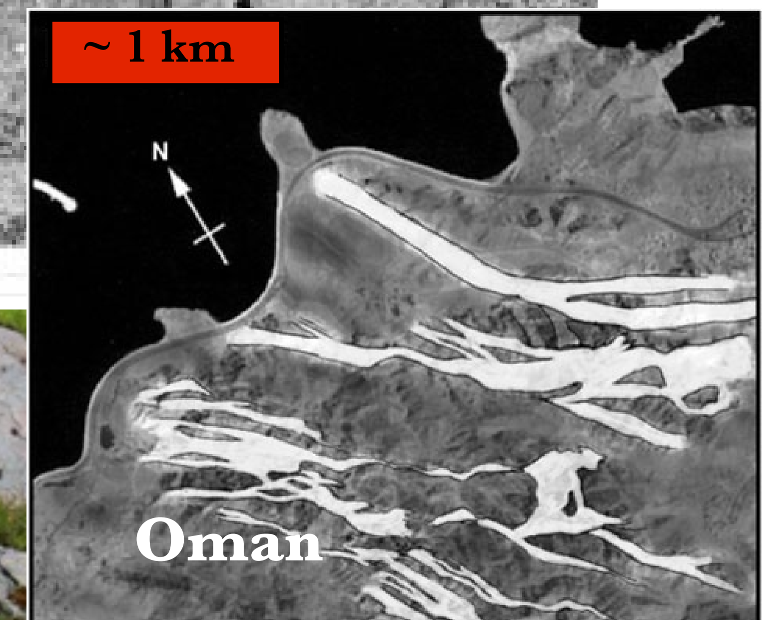
*We need constitutive models that describe meso-scale processes and still capture scaling the kinetics of a given process from lab to earth conditions.*


***grain size***

***meso-scale***

***comp. length***





lower crustal migmatites, SW Ontario, Chris Gerbi, Univ. of Maine

**Compaction length:**

$$\delta_c \approx \sqrt{k\frac{\zeta}{\mu}}$$

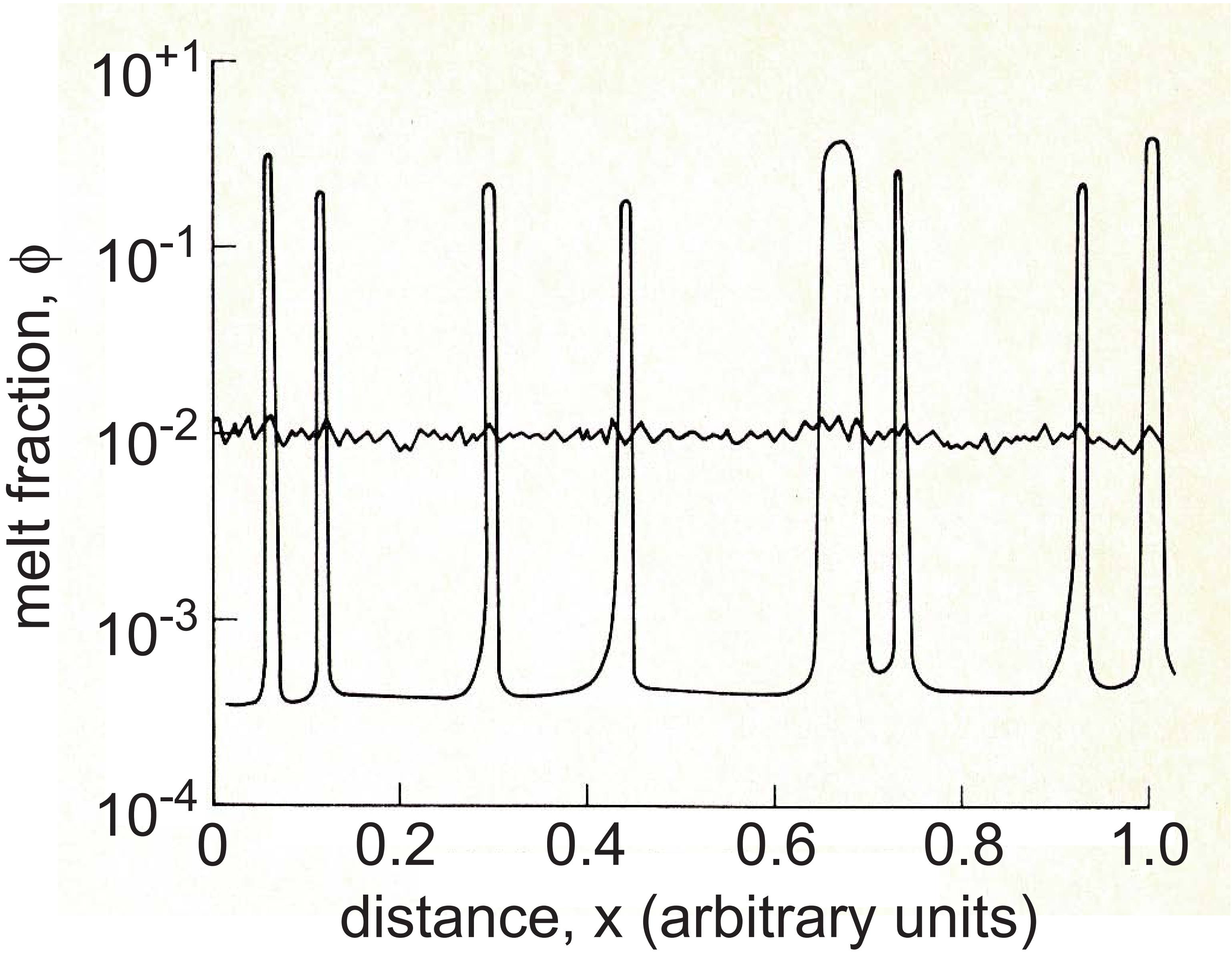
compaction viscosity ($\zeta$)

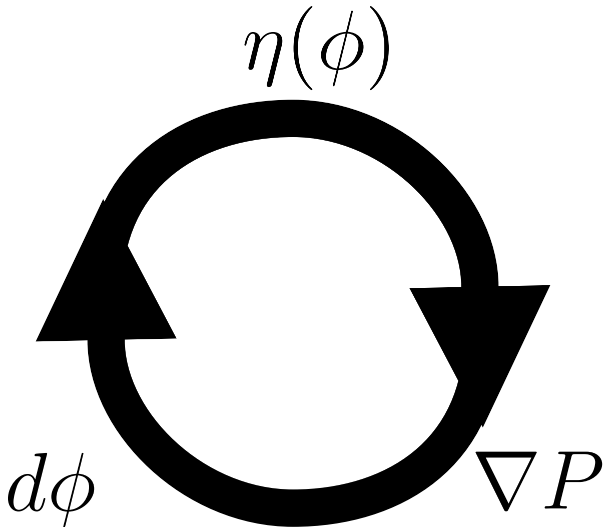
melt viscosity ($\mu$)

permeability ($k$)

# What happens at longer length scales ?

**Stevenson, 1989:**




**Compaction length:**

$$\delta_c \approx \sqrt{k\frac{\zeta}{\mu}}$$

| | |
|---|---|
| $k$ | permeability |
| $\zeta$ | bulk or compaction viscosity |
| $\mu$ | melt viscosity |