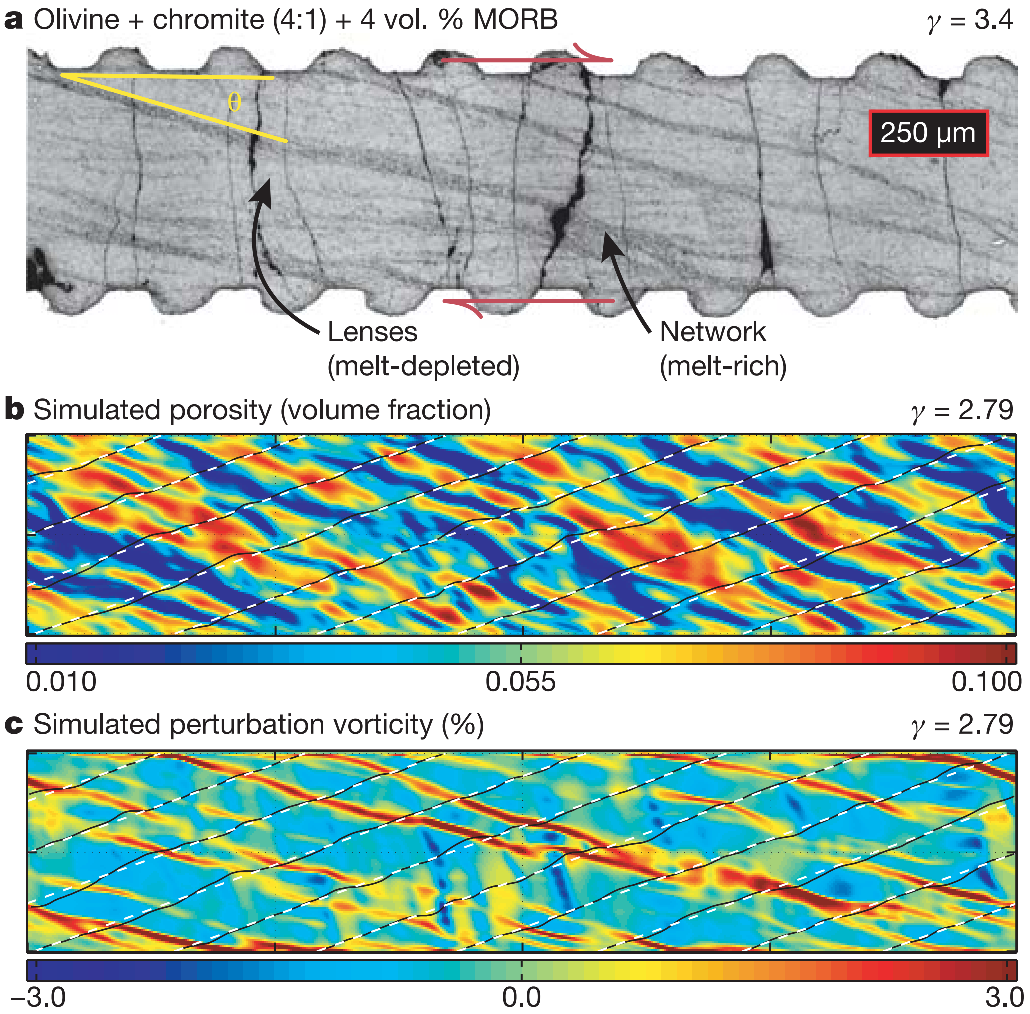
A few thoughts on experimental benchmarks for modeling of stress-driven melt segregation

1. Can magma dynamics theory produce segregation and organization of “melt”?

2. To what level of detail can the theory “reproduce” experimental (and natural) observations? (why and why not?)

3. What is the next level of benchmark that experimentalists can throw at you? (one example: torsion)

1. Can magma dynamics theory produce segregation and organization?



a Olivine + chromite (4:1) + 4 vol. % MORB

b Simulated porosity (volume fraction)

c Simulated perturbation vorticity (%)

yes, and can match first order observation of stable, low angle bands, by using a melt-fraction and strain-rate dependent flow law of the form:

$$\eta(\phi, \dot{\epsilon}) = \eta_0 e^{\alpha(\phi - \phi_0)} \dot{\epsilon}_{II}^{\frac{1-n}{n}}$$

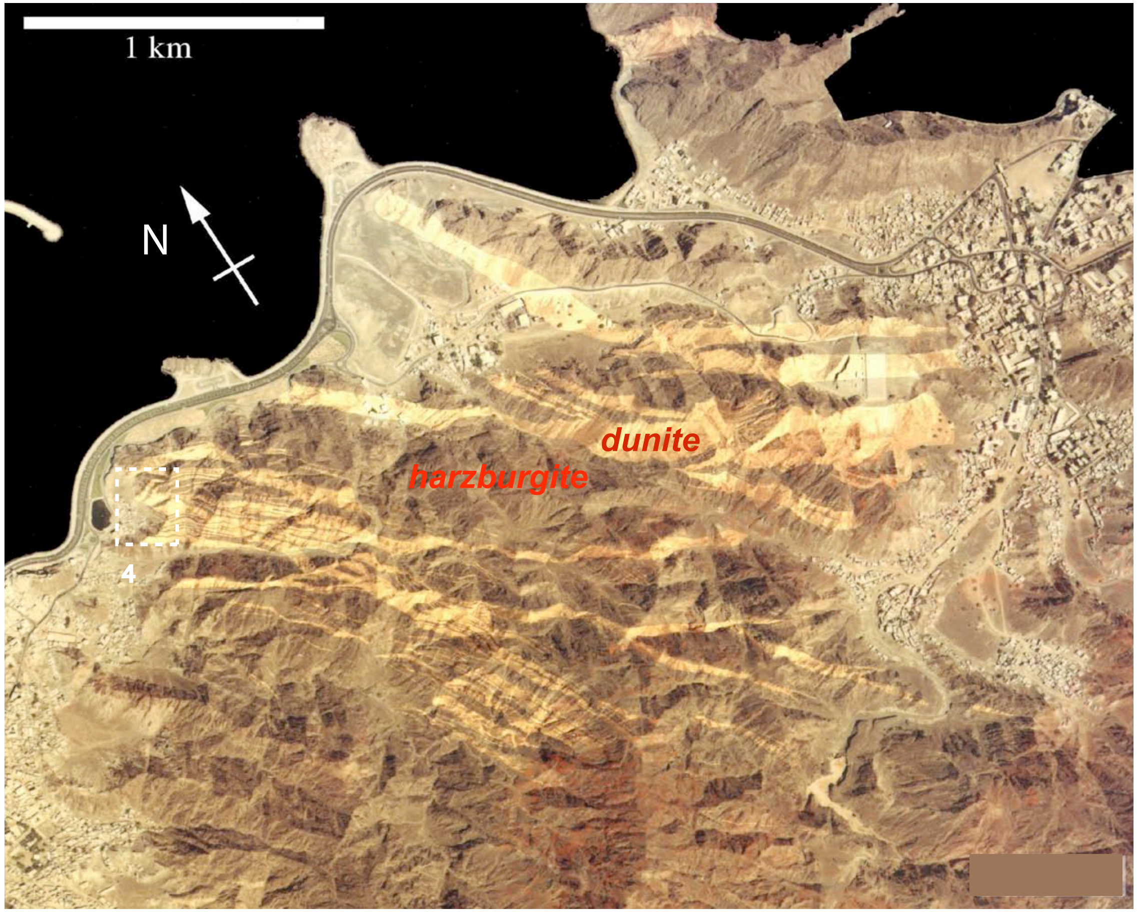
with n>4.

What does this result mean in terms of physical processes?

compaction length

$$\delta_C = \left(k \frac{\eta}{\mu}\right)^{1/2}$$

k = permeability
η = solid viscosity
μ = fluid viscosity



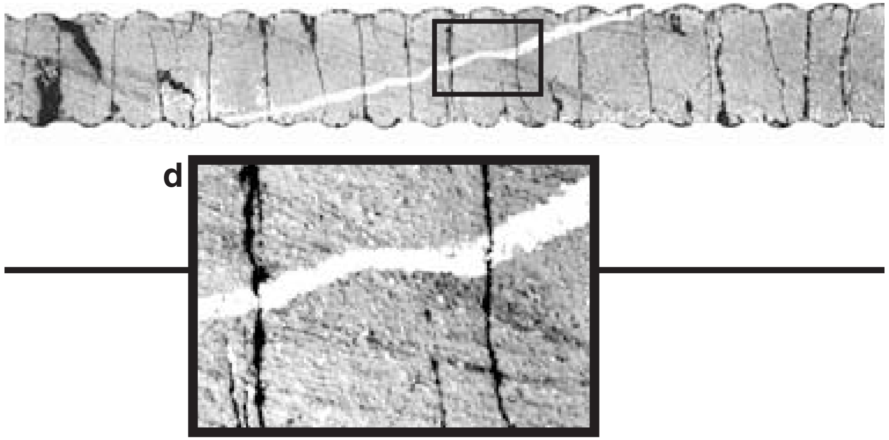
from Braun & Kelemen, G3, November 2002,
Aerial map Muscat-Mutrah region, Oman.

- Dunites are melt conduits, formed by reaction of basalt and pyroxene in harzburgite.

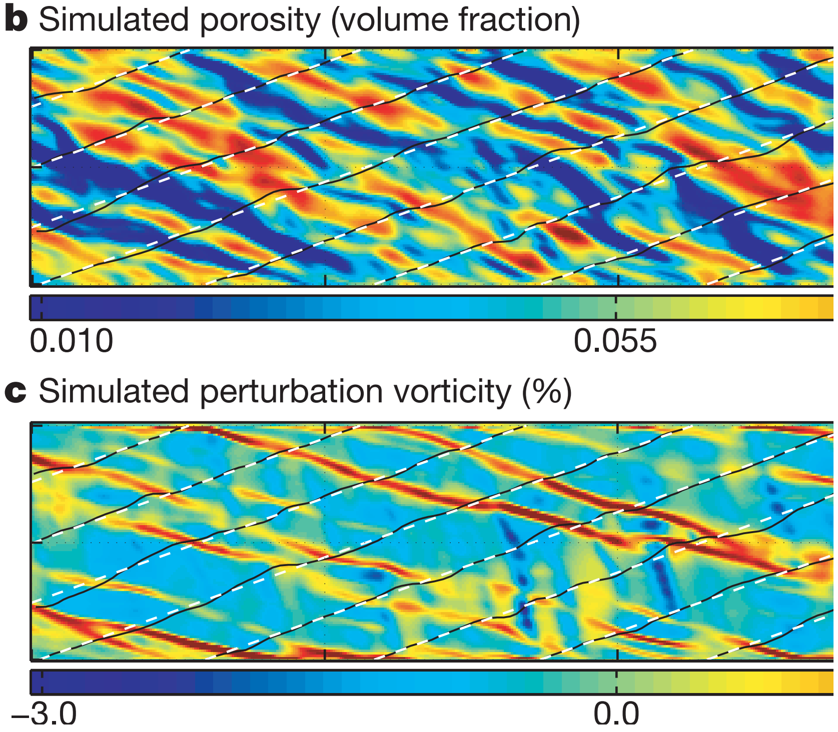
- Basalt is in equilibrium with dunites but not with residual mantle.

2. To what level of detail can the theory “reproduce” experimental (and natural) observations? (why (not)?)

EXPERIMENT



THEORY


b Simulated porosity (volume fraction)

c Simulated perturbation vorticity (%)

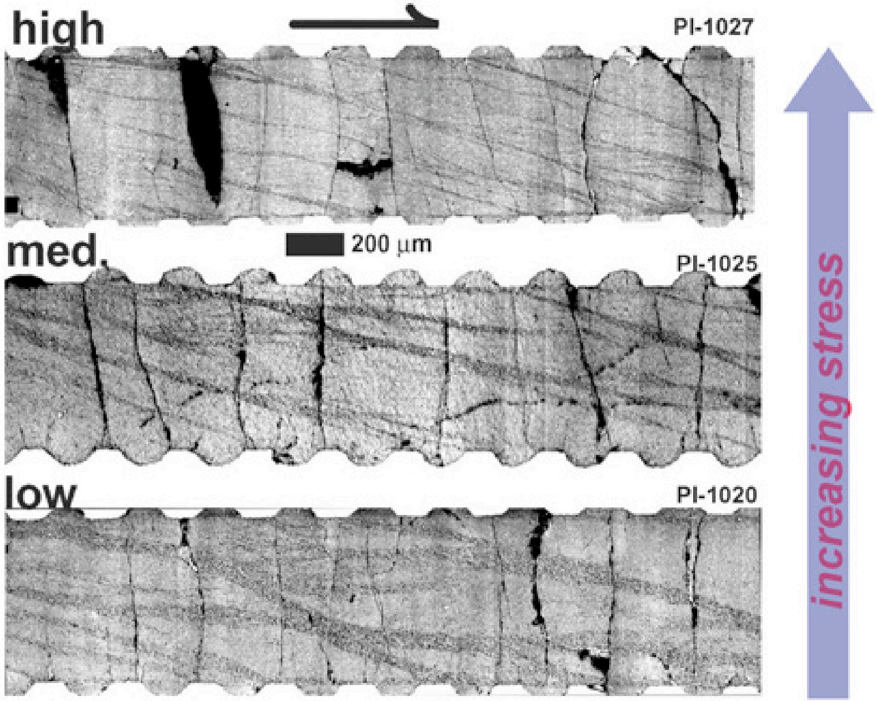
porosity and vorticity fields do not correspond spatially as closely in model as the appear to in experiments.

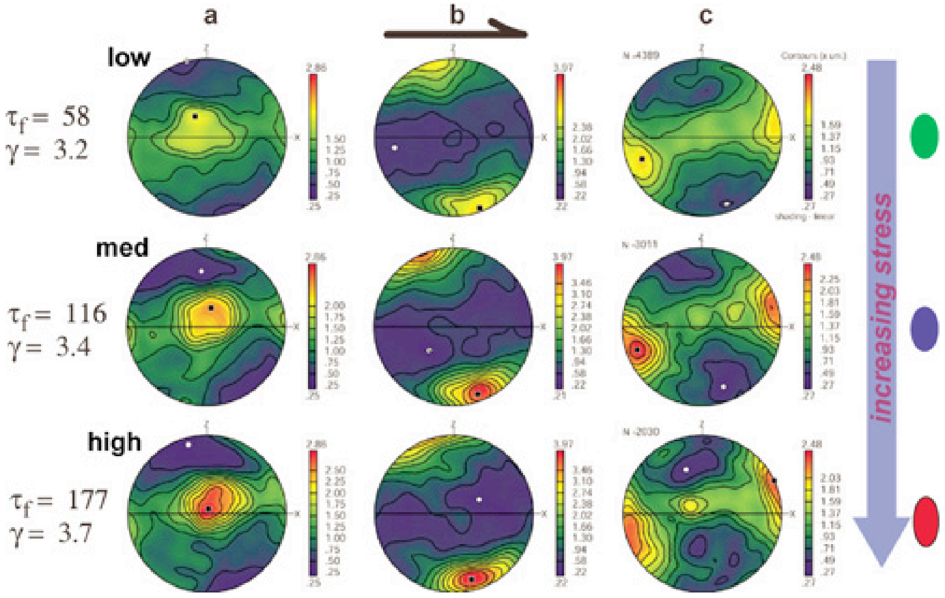
why not?

a rheology problem: can the effects of melt fraction and stress really be decoupled?

$$\eta(\phi, \dot{\epsilon}) = \eta_0 \mathrm{e}^{\alpha(\phi - \phi_0)} \dot{\epsilon}_{\mathrm{II}}^{\frac{1-n}{n}}$$

if so, what does “n” mean in partially molten rocks?





A list of unexplained observations:

1. relationship between stress and characteristic length scales of the melt- rich networks

2. the effect of strain partitioning between melt-depleted lenses and networks on olivine fabrics

3. the “anastomosing” structure of the networks: smoothly connected bands

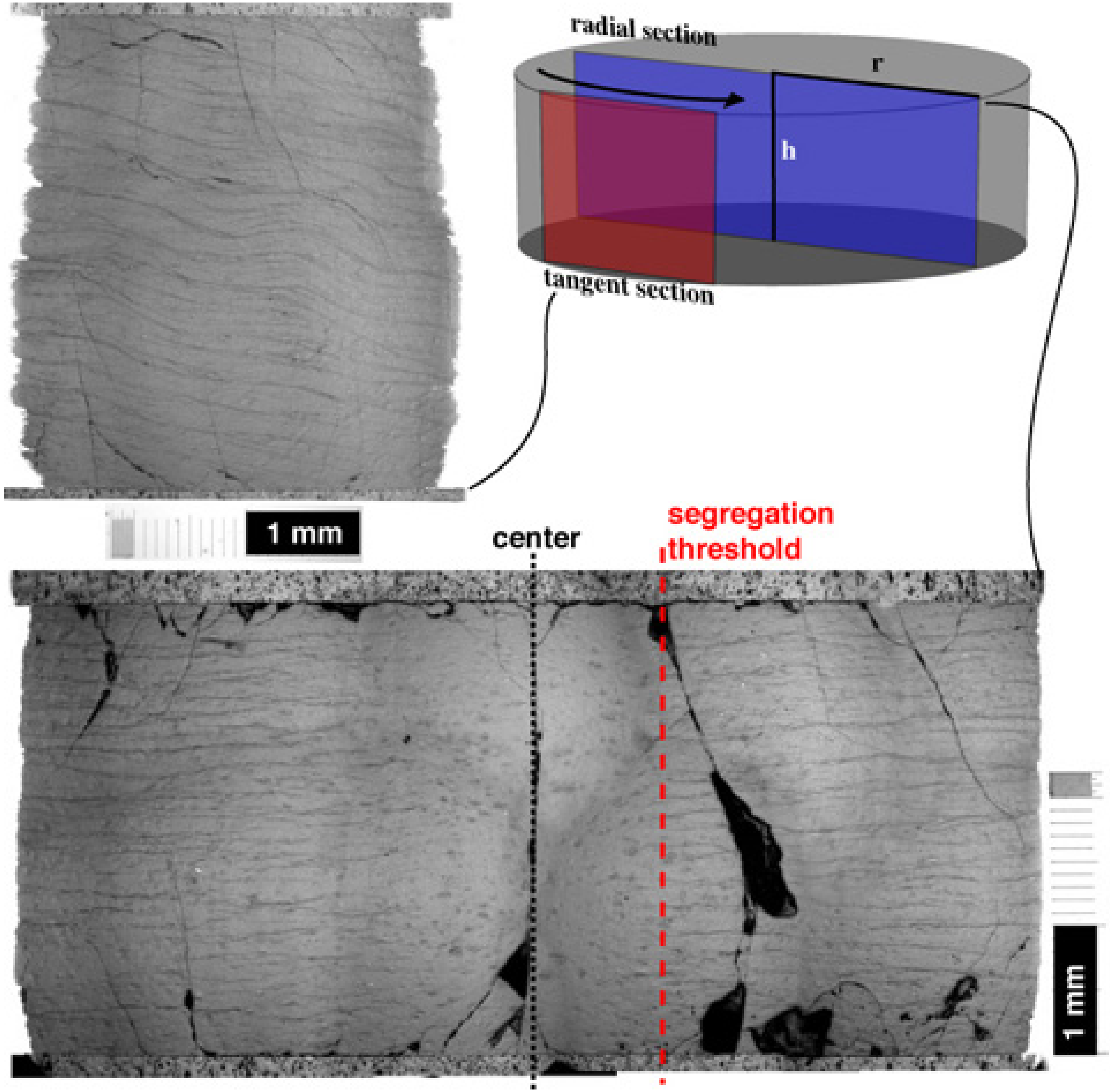
A list of open questions:

1. what are the differences between natural and experimental conditions? how do we incorporate the effects of grain size and surface tension into these theories?

2. rapid rheological changes? i.e. diffusion/ dislocation creep to nearly granular flow over short distances...

3. multi-scale problems- numerical (high res.!) vs. analytical (effective flow laws...)

3. What is the next level of benchmark that experimentalists can throw at you? (one example: torsion)

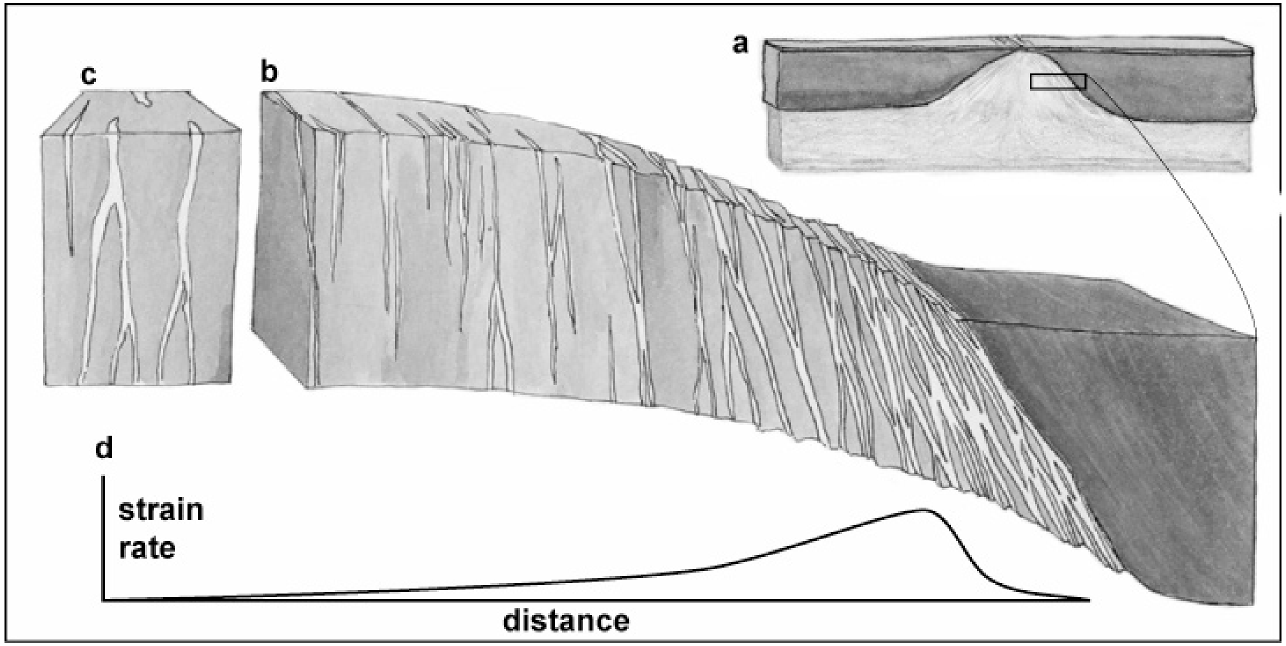


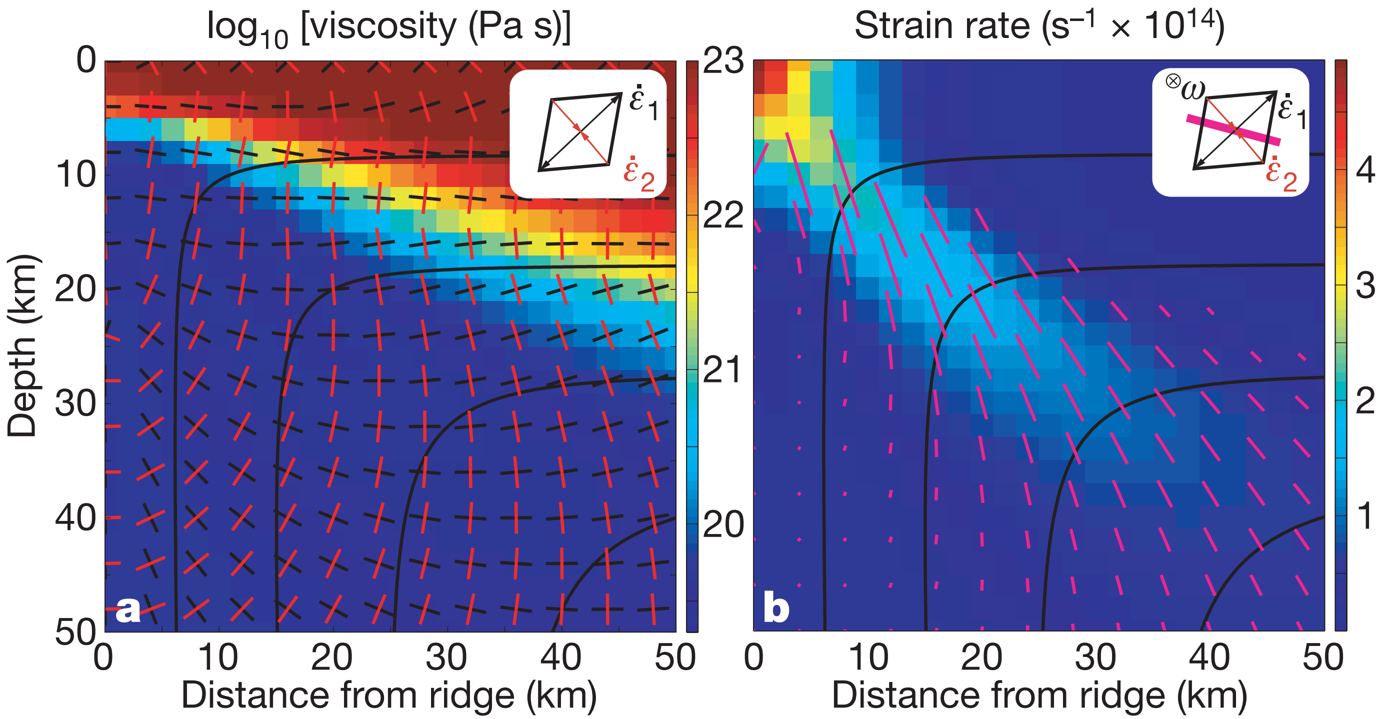
the existence of a segregation threshold will provide a great benchmark:

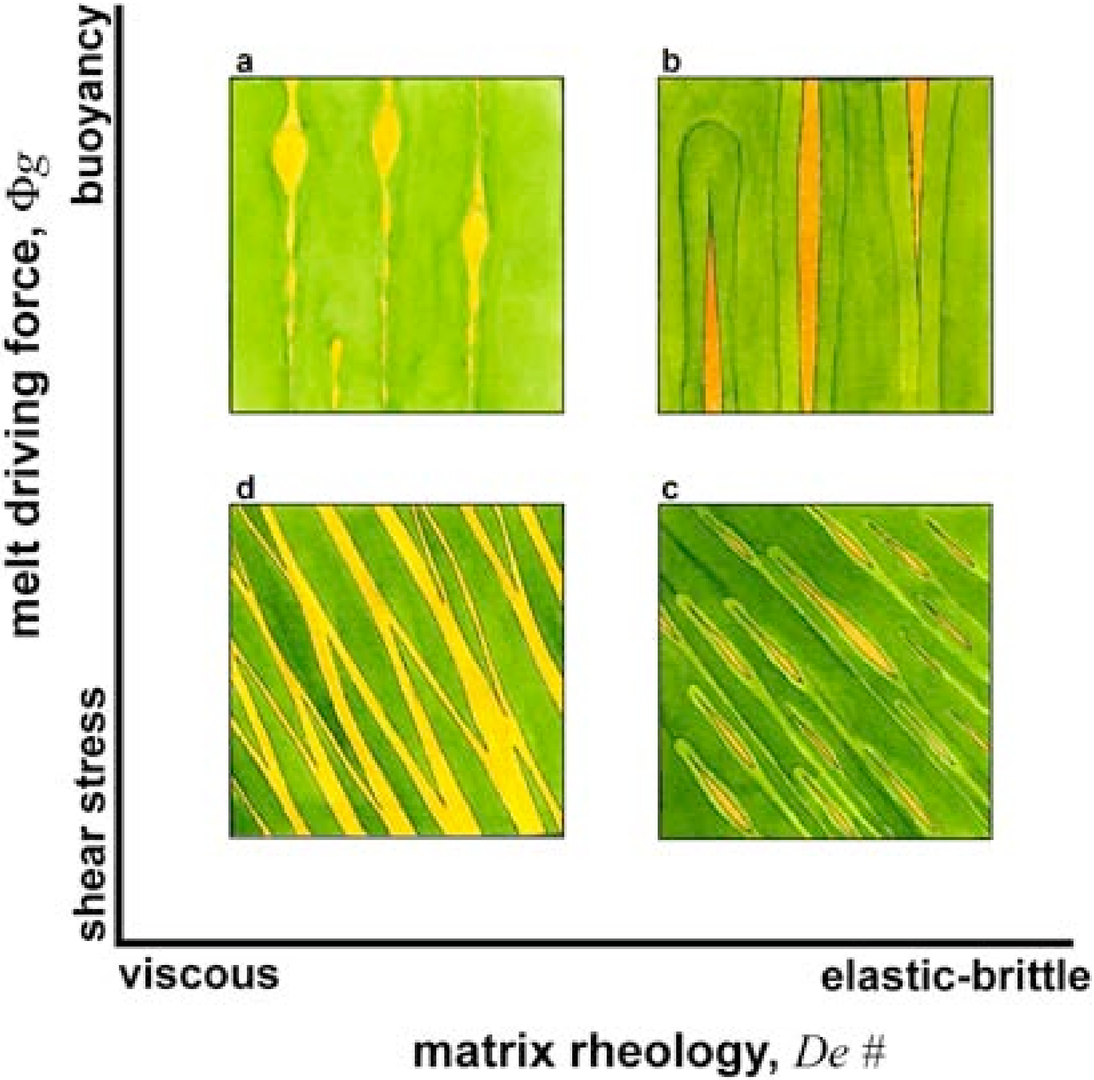
why does it exist?

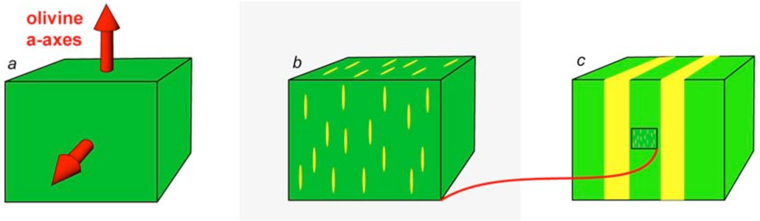
how does it migrate (or not) as functions of stress and time?

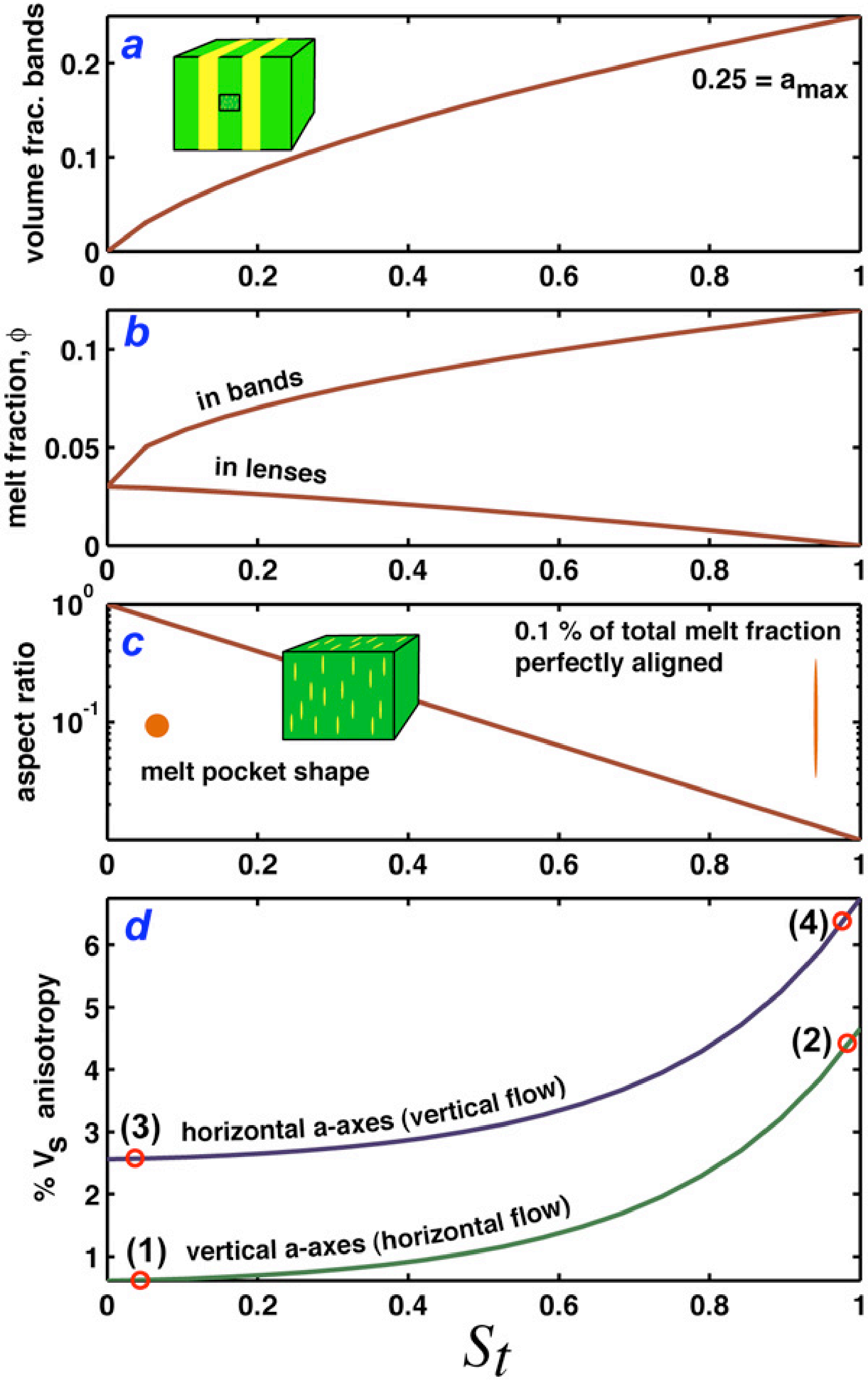
EXTRA SLIDES

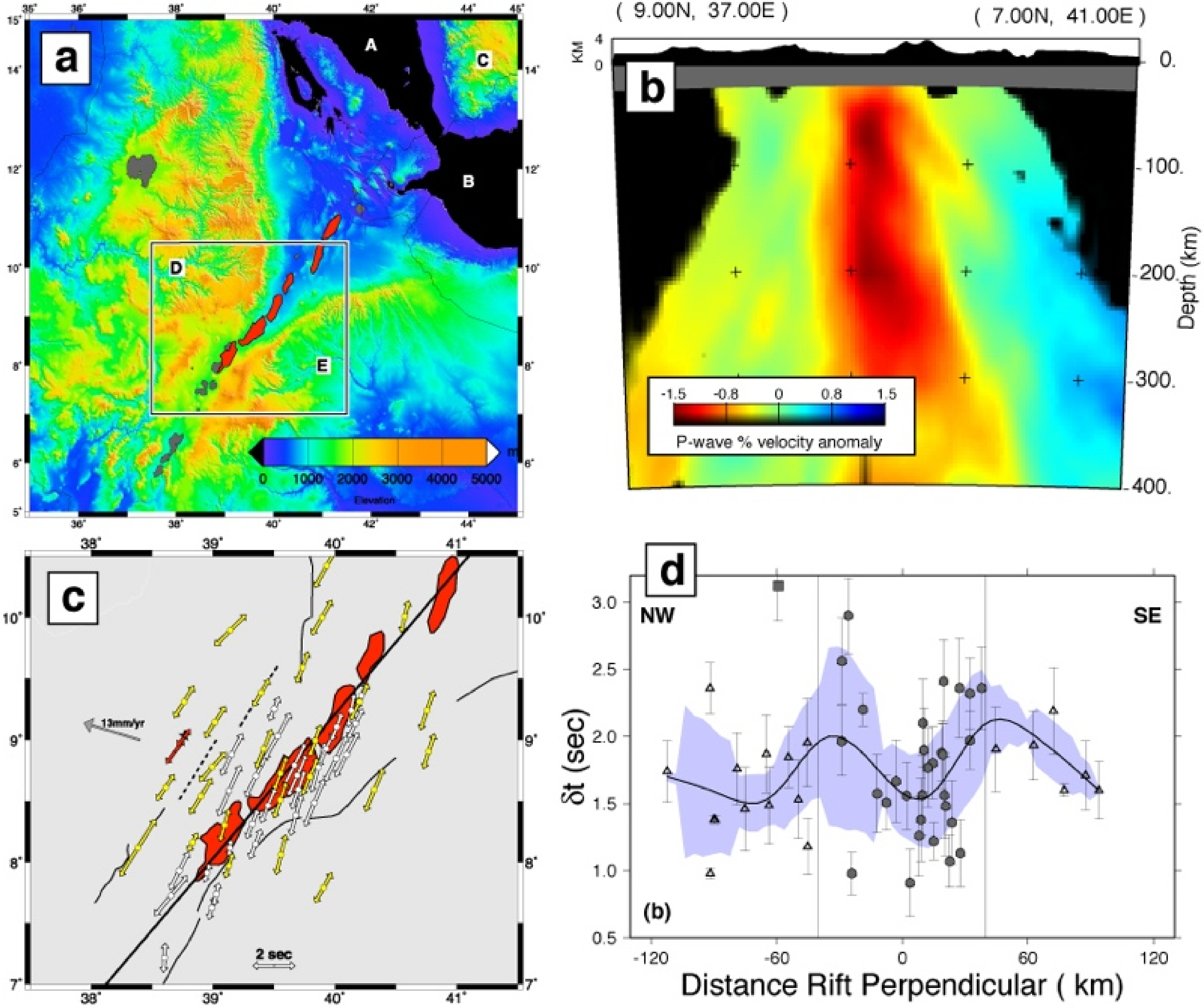

a
b
c
d
strain rate
distance

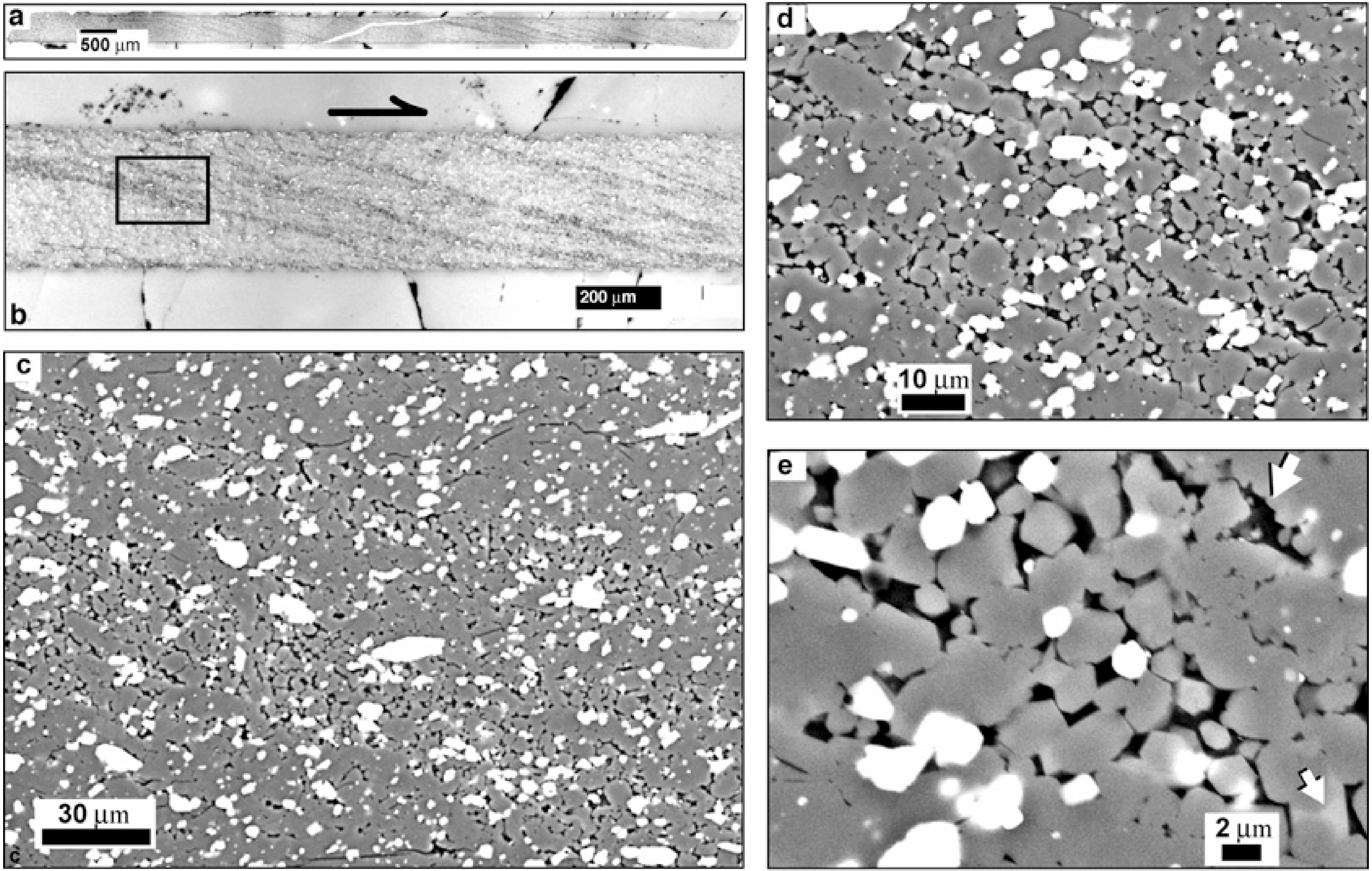

$\log_{10}$ [viscosity (Pa s)]
Strain rate ($s^{-1} \times 10^{14}$)
Depth (km)
0
10
20
30
40
50
Distance from ridge (km)
0
10
20
30
40
50
23
22
21
20
$\dot{\varepsilon}_1$
$\dot{\varepsilon}_2$
$\otimes \omega$
4
3
2
1
a
b


buoyancy
melt driving force, Φg
shear stress
a
b
d
c
viscous
elastic-brittle
matrix rheology, *De* #

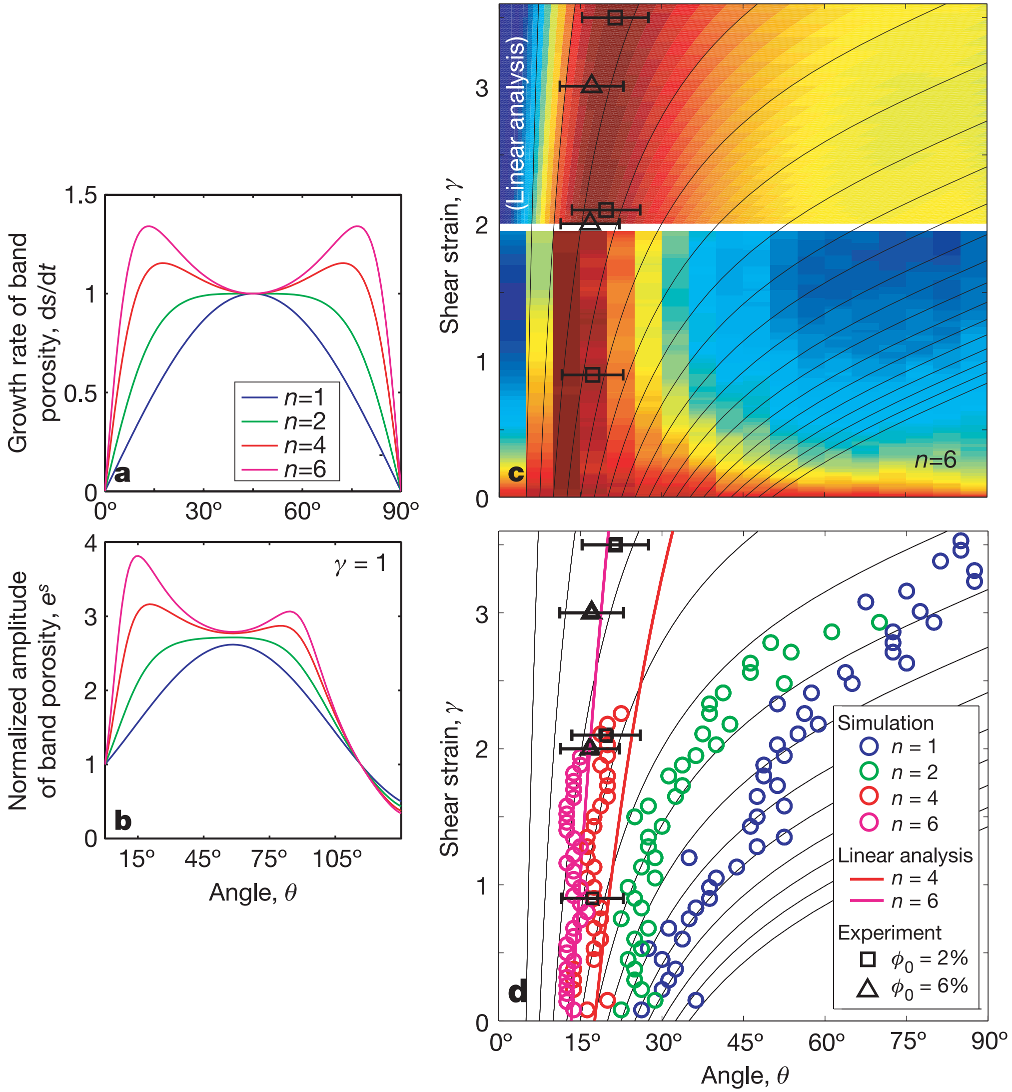

olivine
a-axes
a
b
c


a
volume frac. bands
0.25 = a_{max}
0
0.1
0.2
b
melt fraction, ϕ
in bands
in lenses
0
0.05
0.1
c
aspect ratio
10^0
10^{-1}
0.1 % of total melt fraction
perfectly aligned
melt pocket shape
d
% V_S anisotropy
(1)
(2)
(3)
(4)
horizontal a-axes (vertical flow)
vertical a-axes (horizontal flow)
1
2
3
4
5
6
0
0.2
0.4
0.6
0.8
1
S_t

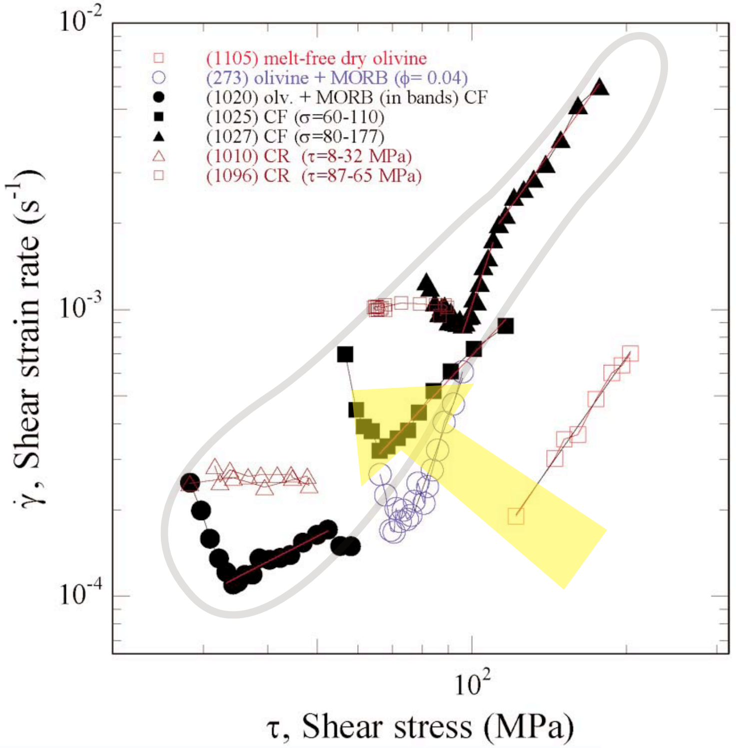

a
A
B
C
D
E
35°
36°
38°
40°
42°
44°
45°
15°
14°
12°
10°
8°
6°
5°
0
1000
2000
3000
4000
5000
m
Elevation
b
(9.00N, 37.00E)
(7.00N, 41.00E)
KM
4
0
0.
100.
200.
300.
400.
Depth (km)
-1.5
-0.8
0
0.8
1.5
P-wave % velocity anomaly
c
38°
39°
40°
41°
10°
9°
8°
7°
13mm/yr
2 sec
d
δt (sec)
NW
SE
(b)
3.0
2.5
2.0
1.5
1.0
0.5
-120
-60
0
60
120
Distance Rift Perpendicular (km)

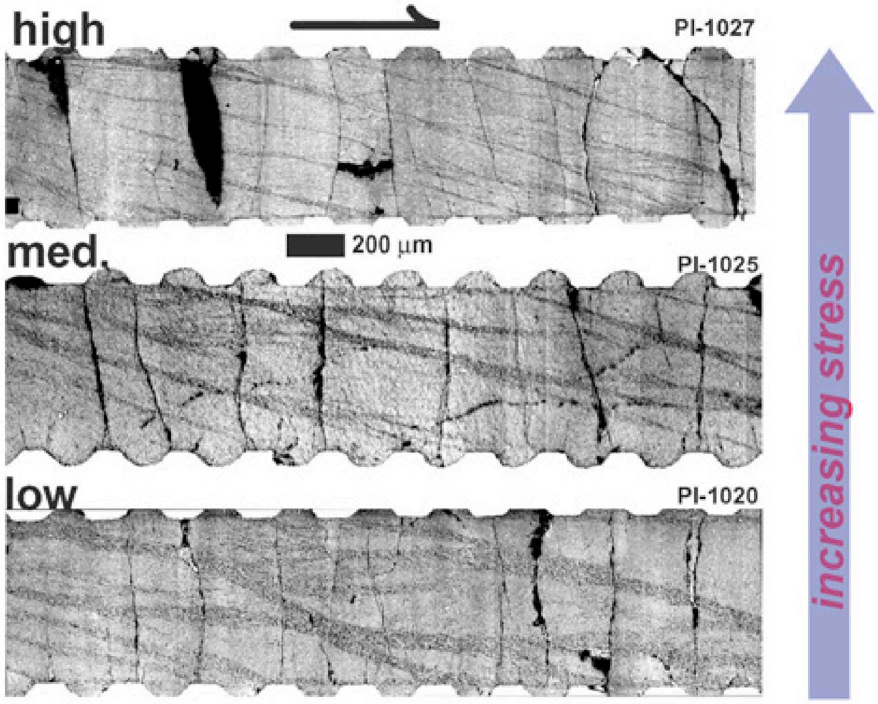

a
500 µm
b
200 µm
c
30 µm
d
10 µm
e
2 µm

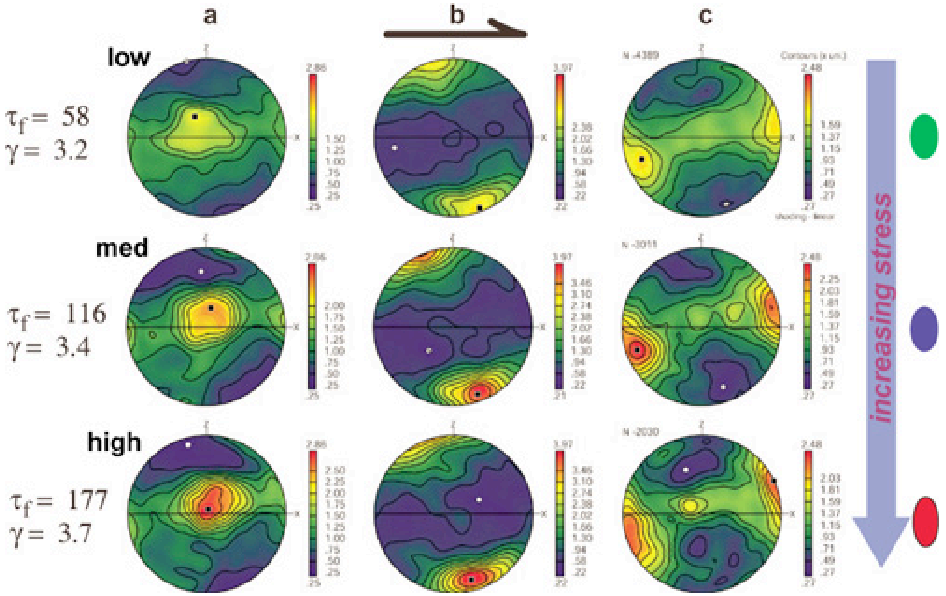
$$\eta(\phi, \dot{\epsilon}) = \eta_0 e^{\alpha(\phi - \phi_0)} \dot{\epsilon}_{\mathrm{II}}^{\frac{1-n}{n}}$$



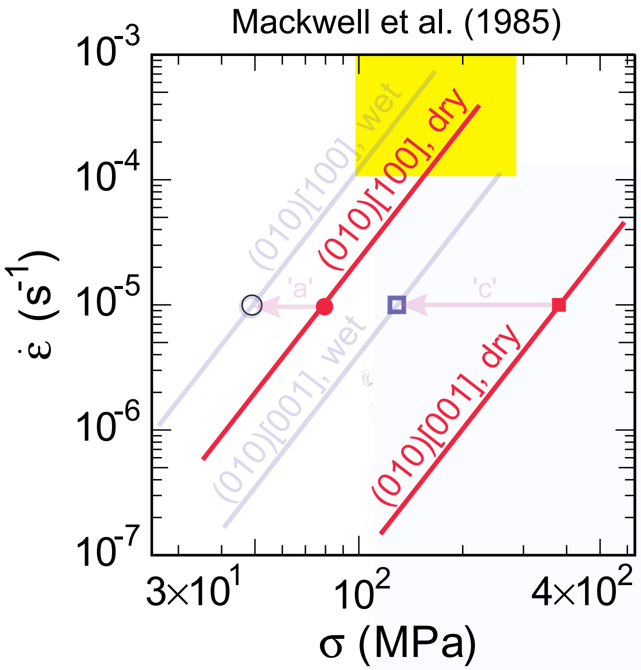
olivine + MORB (+chr)...
(300 MPa, 1250 C)



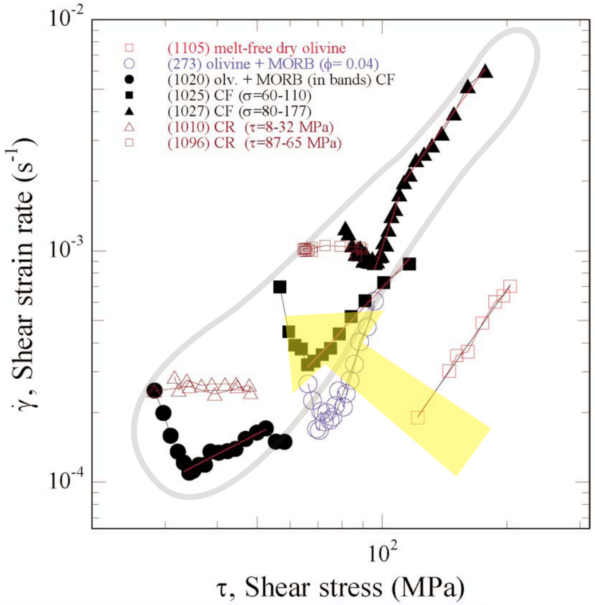


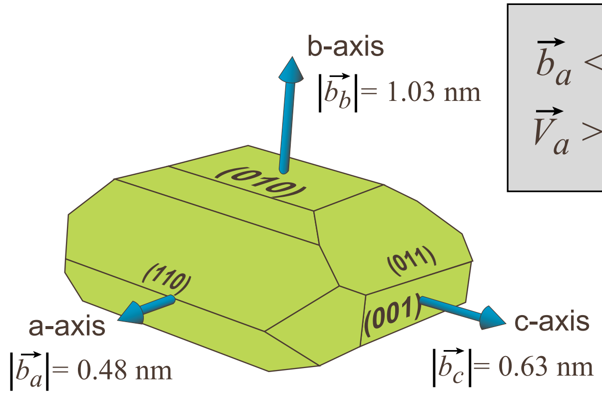


single crystal data (300 MPa, 1250 C)



olivine + MORB (+chr)... (300 MPa, 1250 C)





$$\vec{b}_a < \vec{b}_c < \vec{b}_b$$

$$\vec{V}_a > \vec{V}_c > \vec{V}_b$$