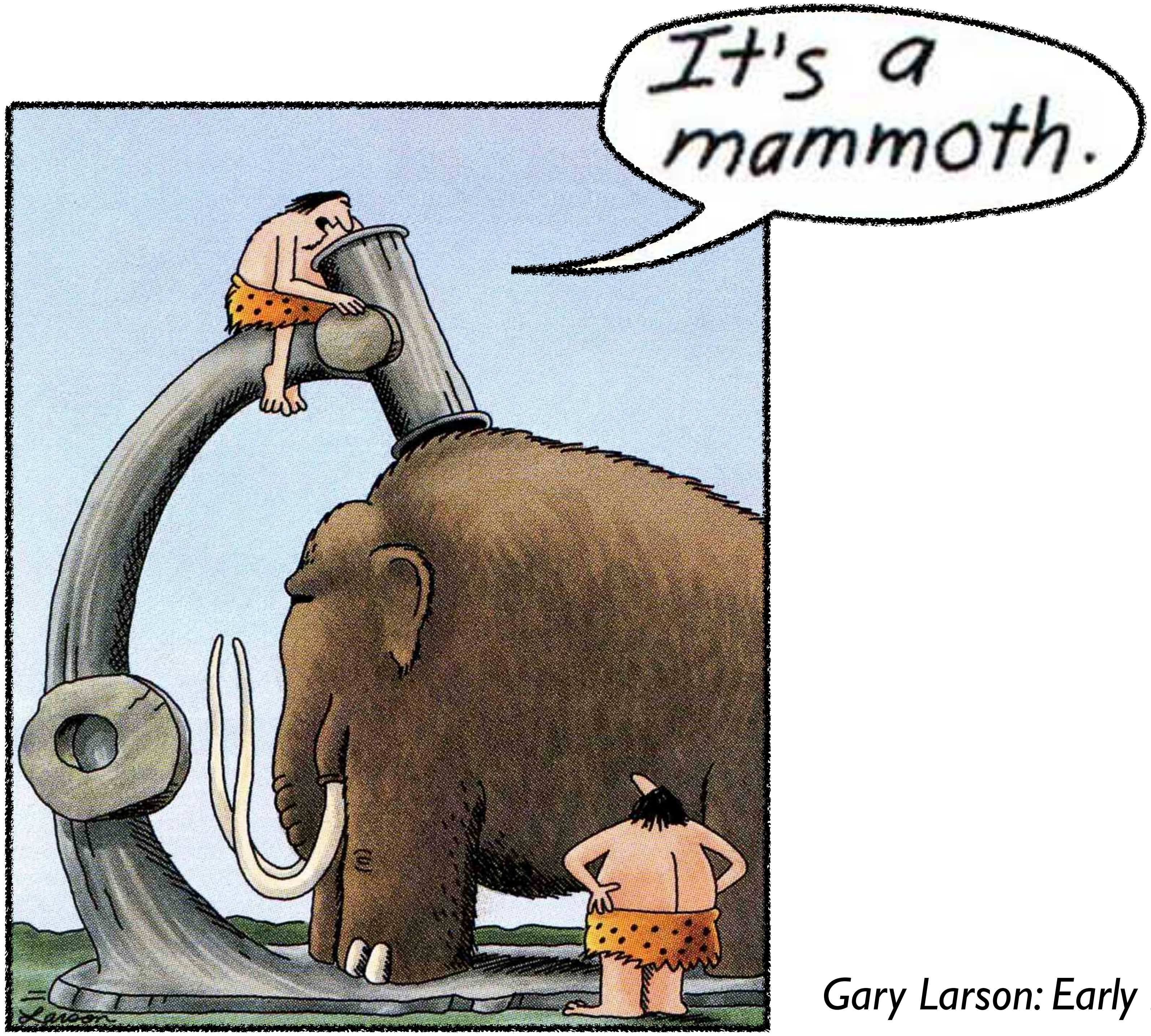
Deformation of the lithosphere and what microstructures can tell you about it

Renée Heilbronner

Basel University
Tromsø University

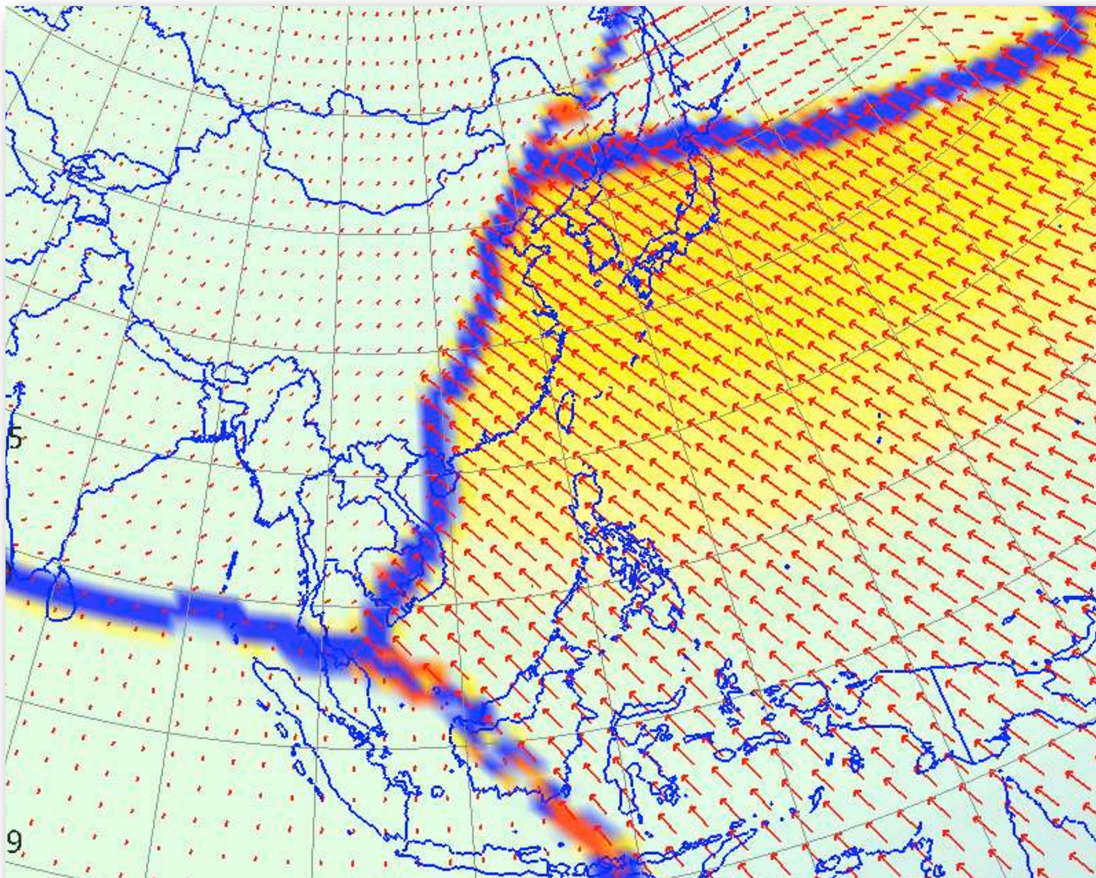
Stefan Müller medal lecture

mammoth and lithosphere

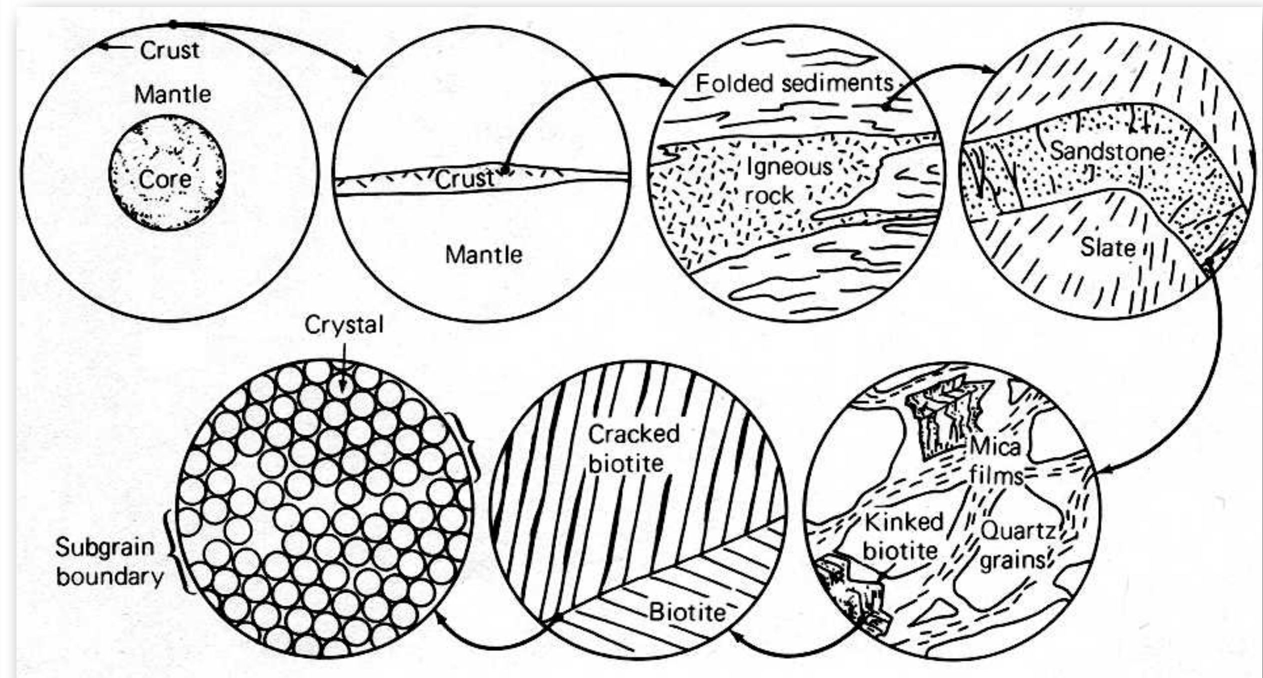


Gary Larson: Early microscopy

deformation ↔ weakening



www.unavco.org



Win Means: Stress and Strain (1976)

Our vision of the mechanisms of lithosphere dynamics and mantle-lithosphere interactions becomes less and less blurred. Yet, many key questions remain open due to the (principally) insufficient observational and experimental constraints.

Evgueni Burov (Stephan Mueller Medal Lecture 2015)

the eye of the needle

how to observe by watching ...

what we see in an image

microstructure is...
2D section of 3D body ?
deformed geometry ?
particles ?
patterns ?

quantified

applies to...
statistics
mechanics (rheology)
geology
geophysics

learning from stereology

A.E.O.J. Delesse

Achille Ernest Oscar Joseph Delesse (1817–1881)

$$V_V = A_A$$

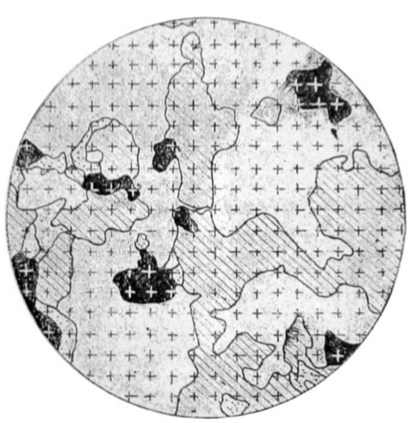
A.K. Rosiwal

August Karl Rosiwal (1860–1923)

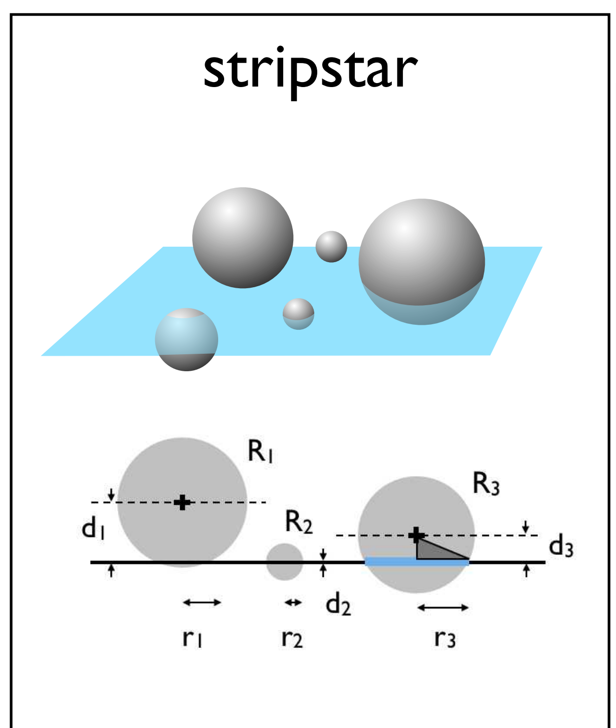
$$V_V = A_A = L_L$$

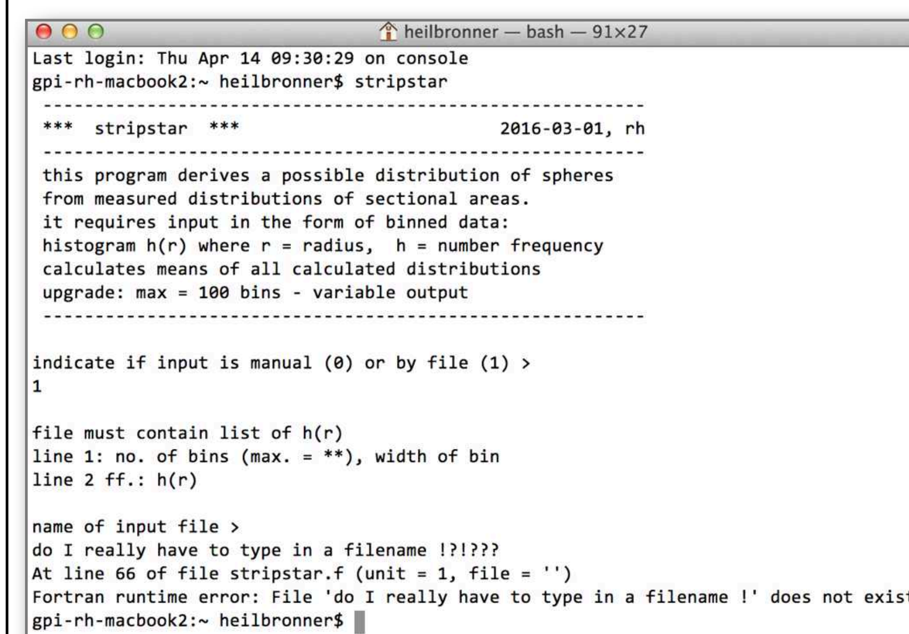
Andrei Aleksandrovich Glagolev (1894 –1969)

$$V_V = A_A = L_L = P_P$$

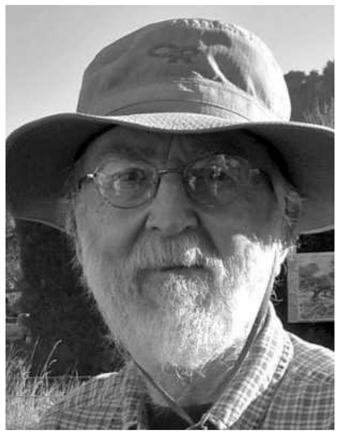


Glagolev and Goldmann (1934)

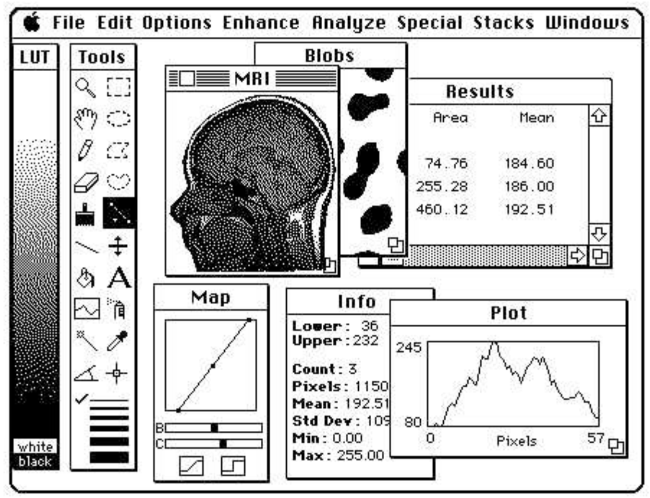




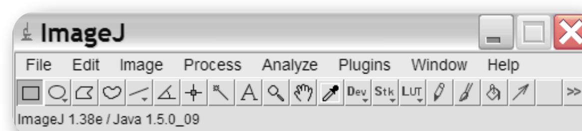
getting into digital image analysis



Wayne Rasband

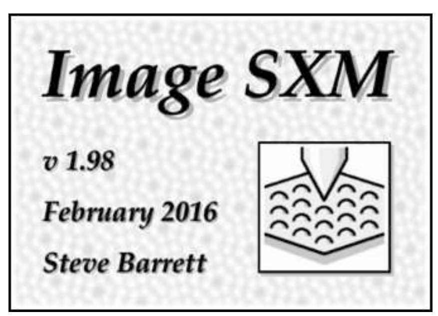


1987 NIH Image (Pascal)
1997 Image J (Java)
2007 → Fiji ('Fiji is just ImageJ')

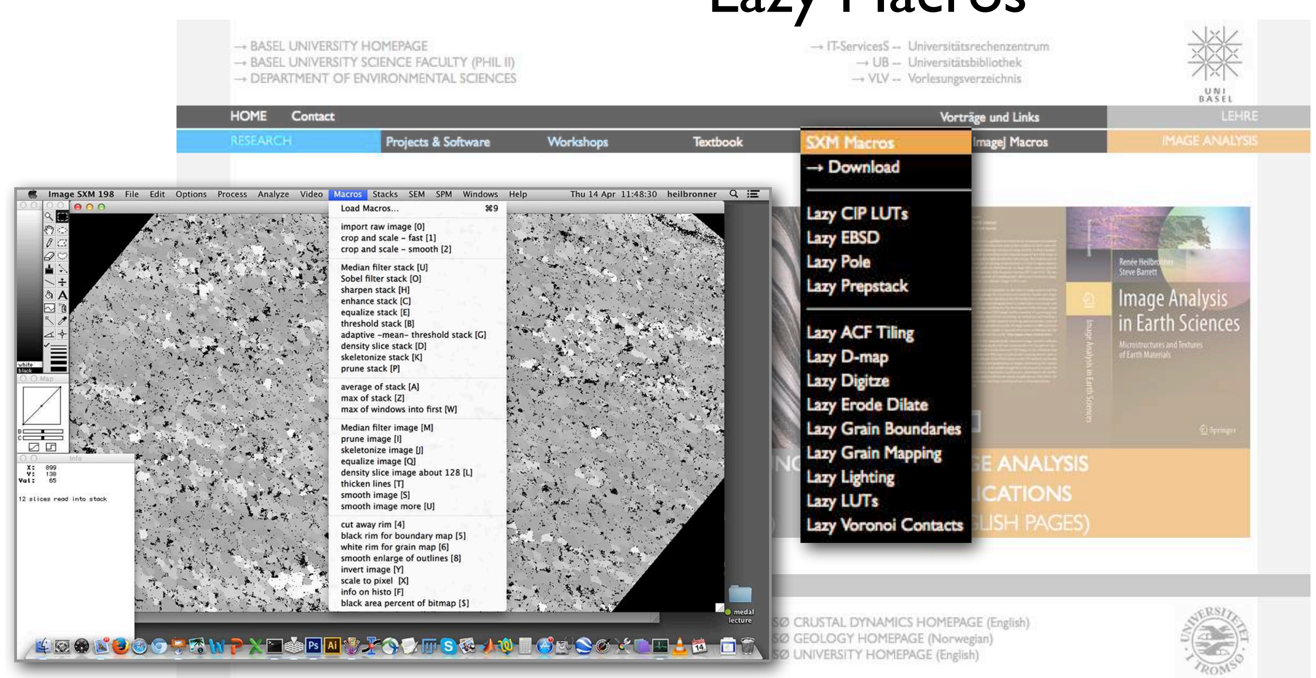


Steve Barrett

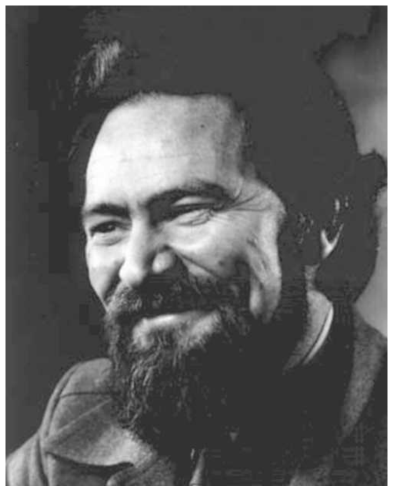
1993 Image SXM (Pascal)



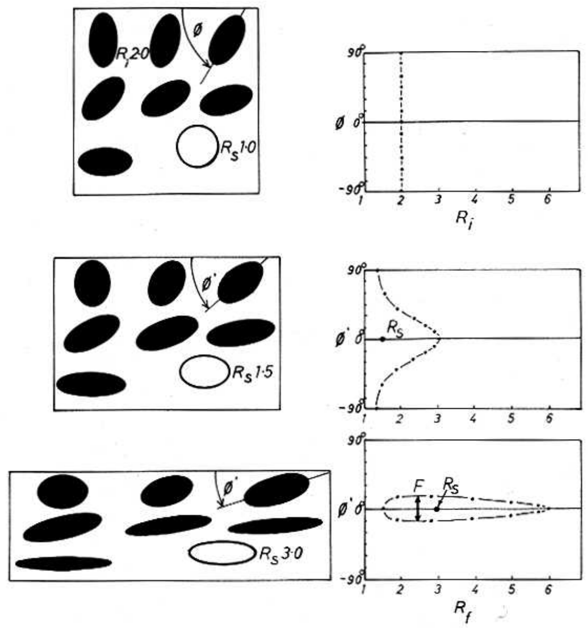
Lazy Macros



shape and strain of particles

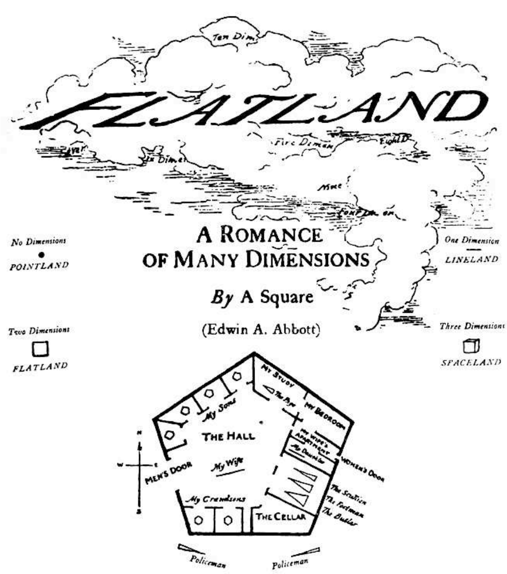


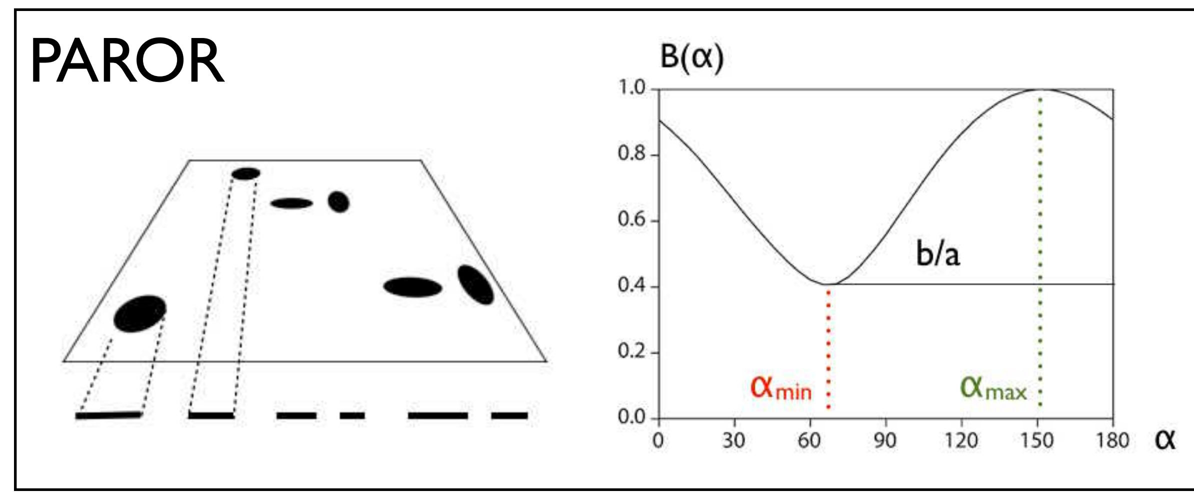
John G. Ramsay

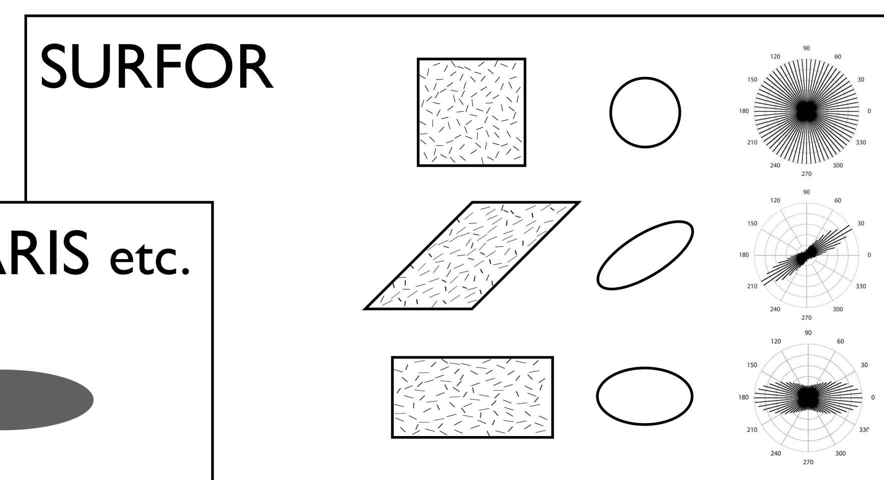


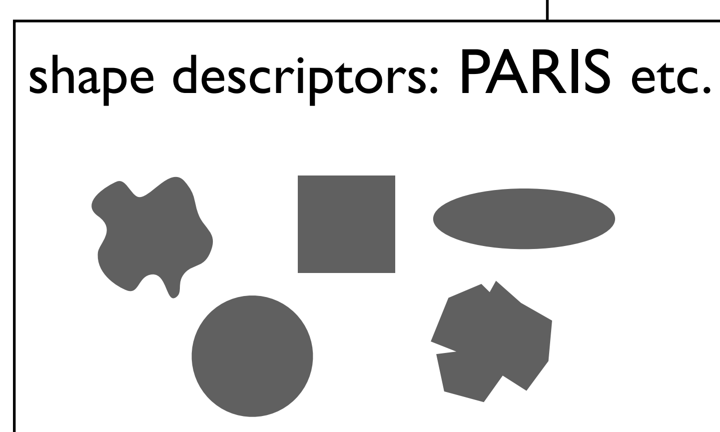
R_f - φ method

Edwin A. Abbott





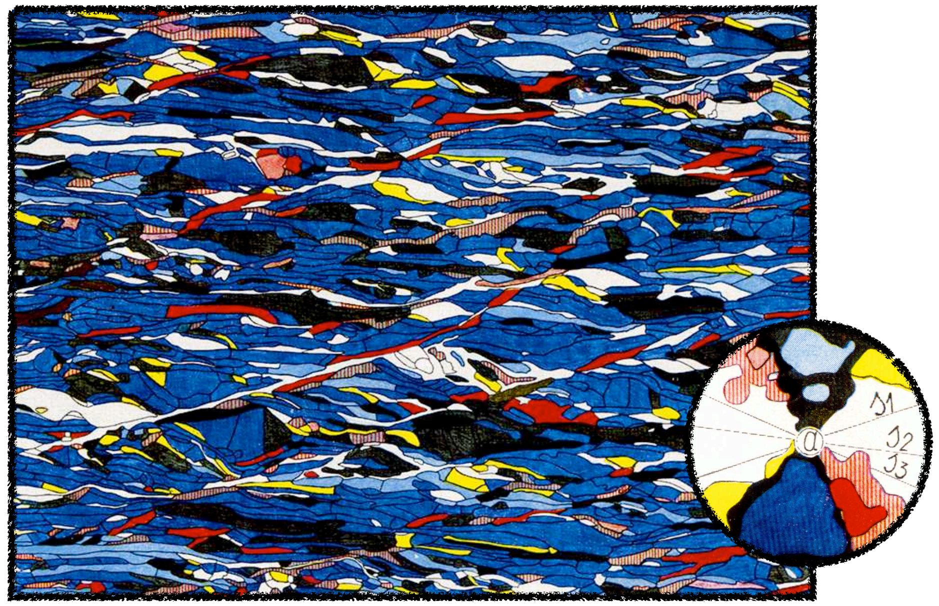


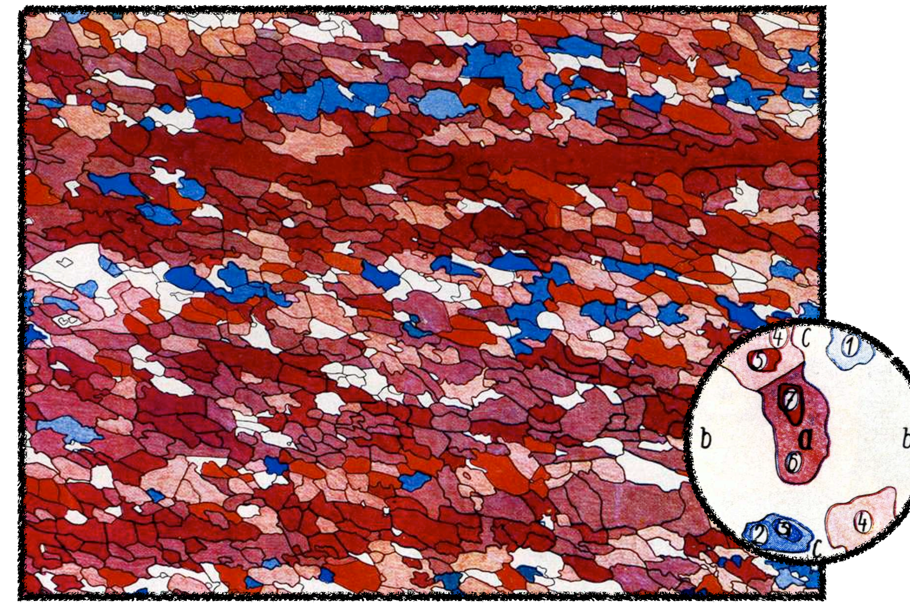


orientation imaging

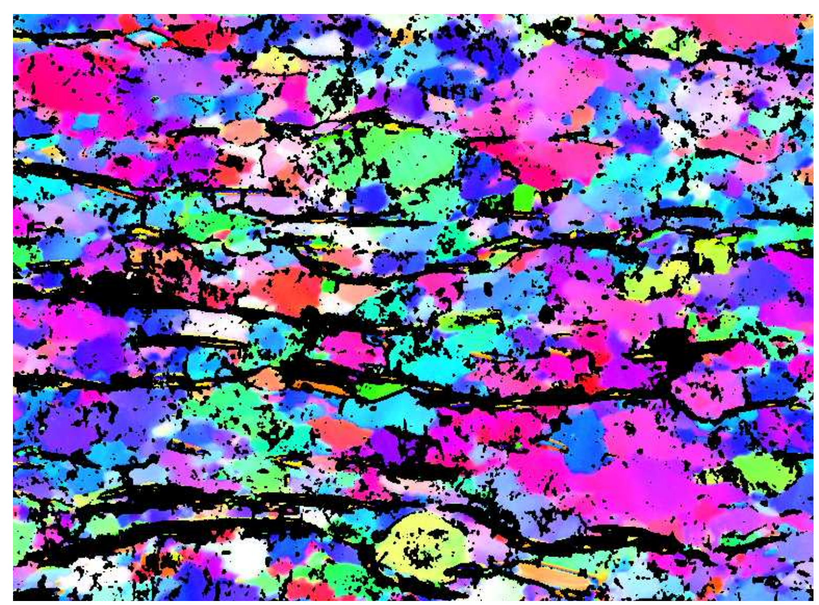
Bruno Sander

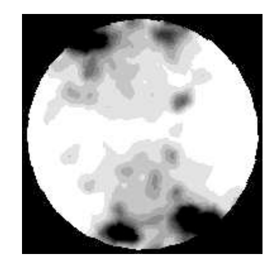
AVA (Achsenverteilungsanalyse)

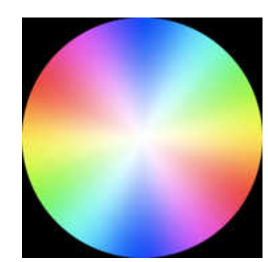


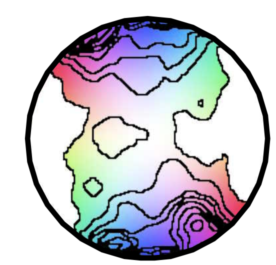


CIP (computer-integrated polarization microscopy)

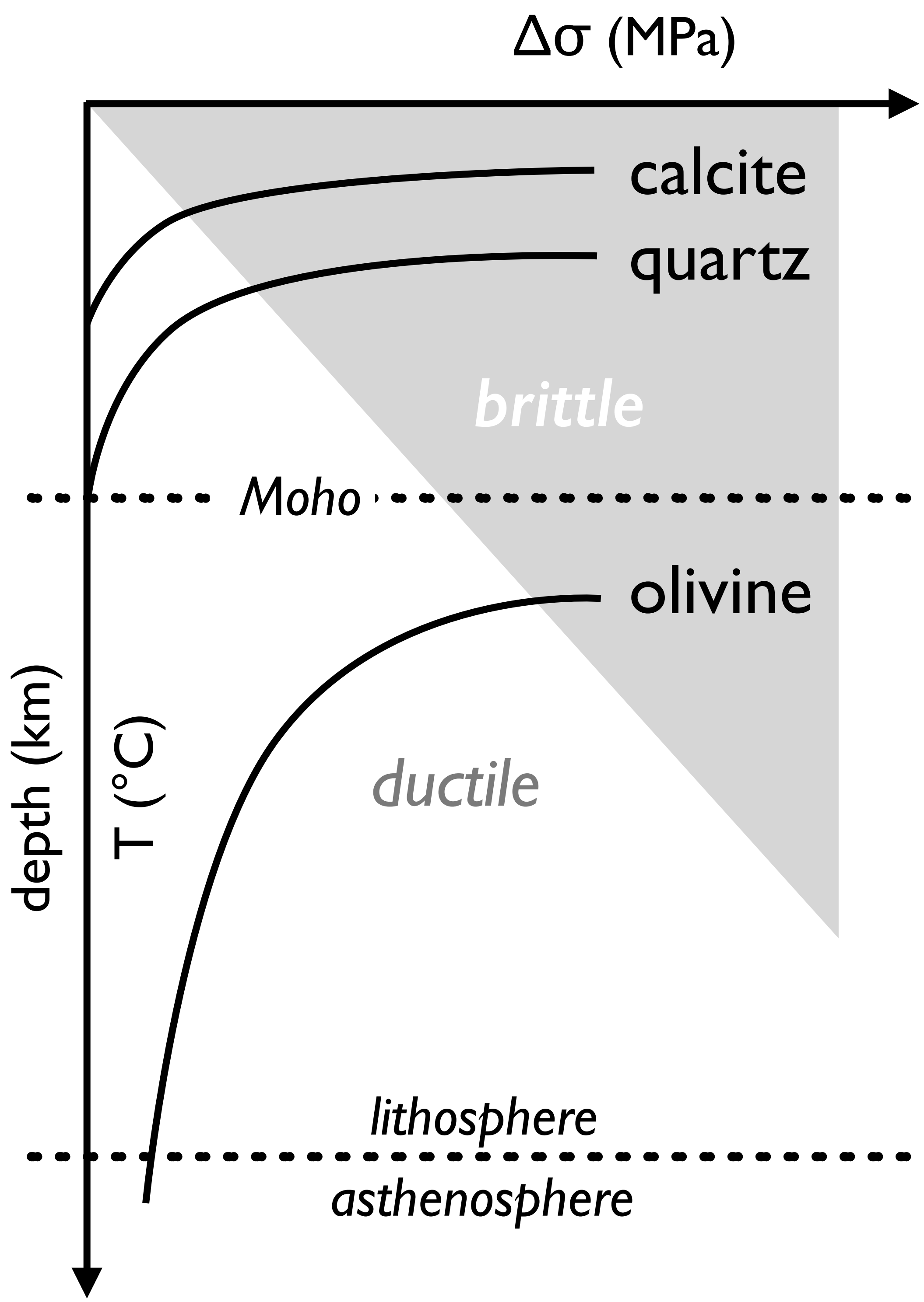








lithosphere deformation in the lab

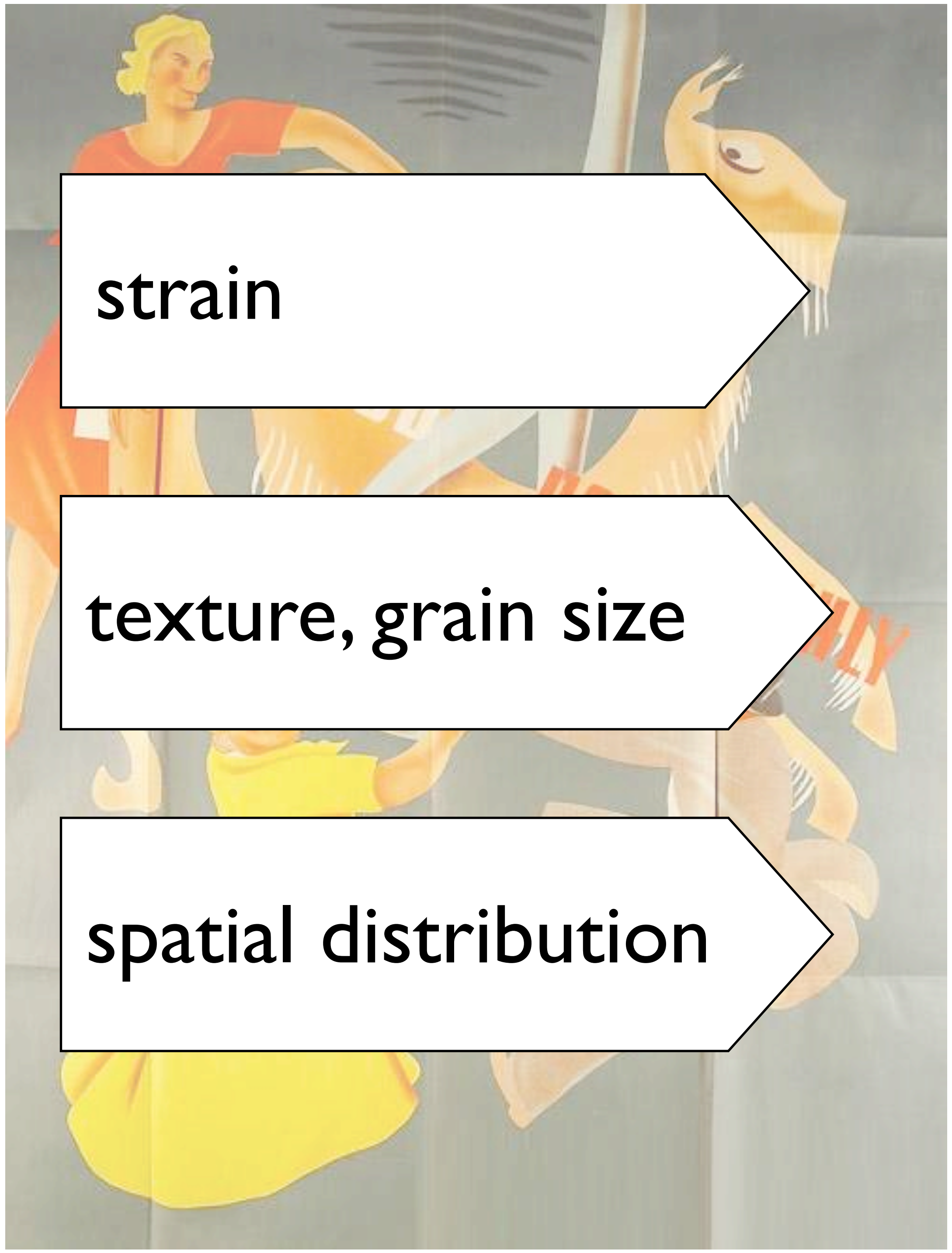


1 Carrara marble
triaxial gas apparatus
Texas A&M University
$\gamma < 3$

2 Black Hills Quartzite
solid medium apparatus
Brown University
$\gamma < 8$

3 Olivine-Orthopyroxene
torsion apparatus
University of Minnesota
$\gamma < 30$

motivation

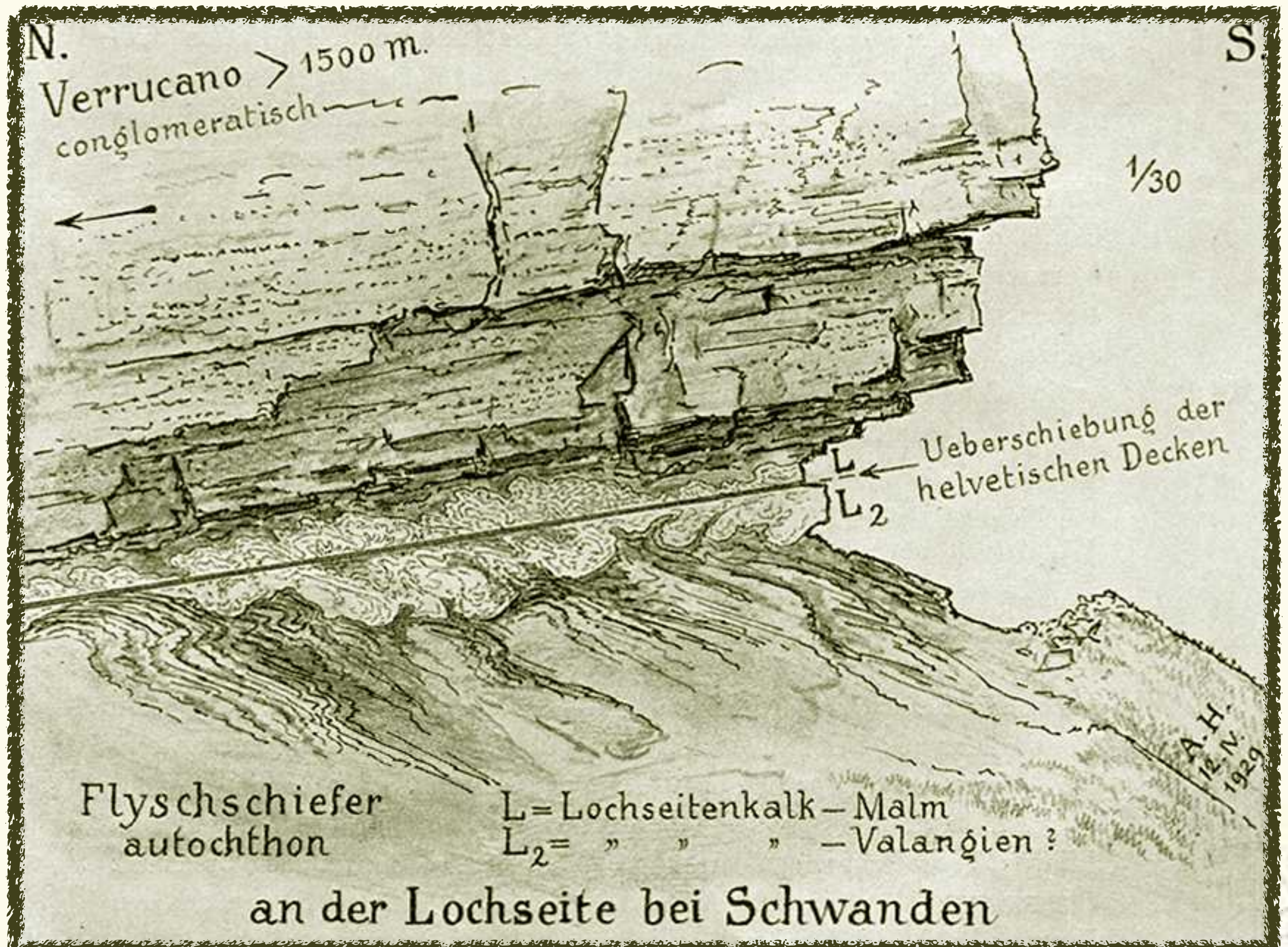


1 Carrara — strain → deformation mechanism

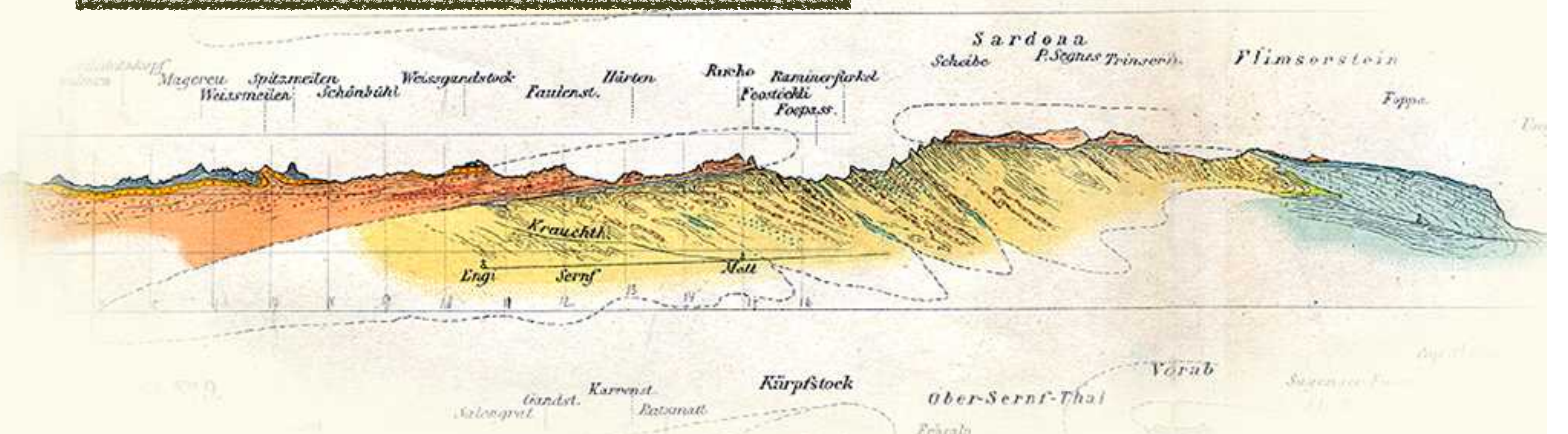
2 BHQ — texture, grain size → regime, flow stress

3 Ol-Opx — spatial distribution → deformation mechanisms?

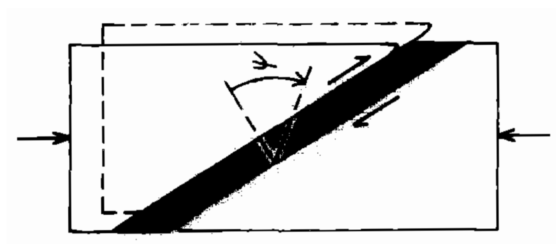
kilometers of displacement



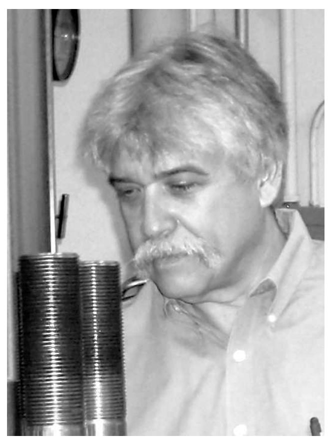
Alber Heim (1929)



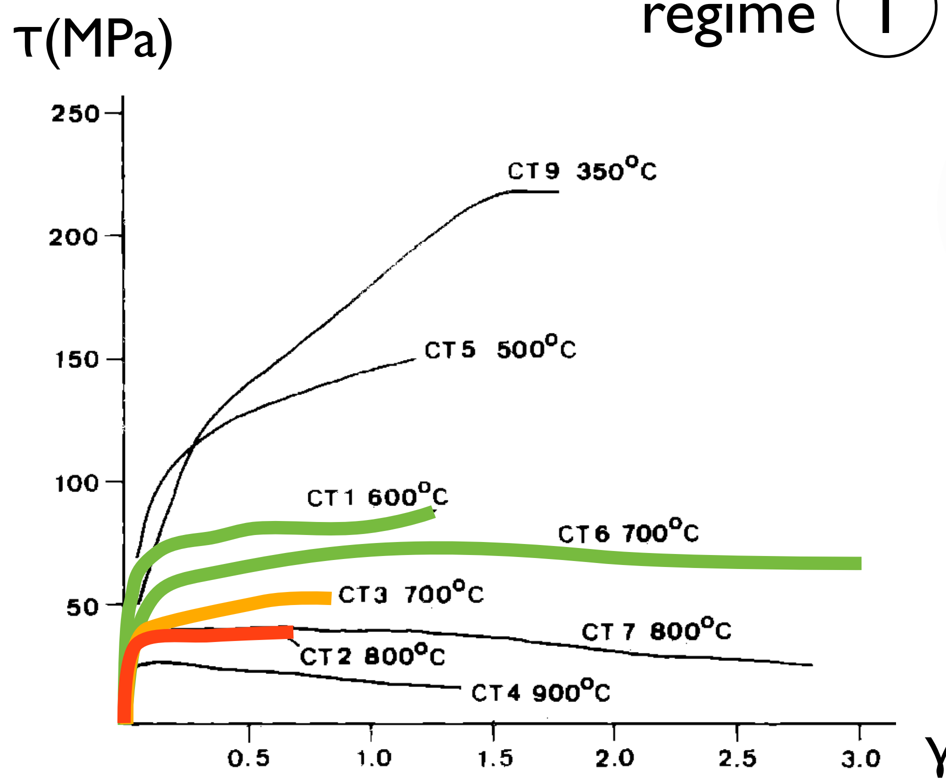
from twinning to superplasticity



Stefan Schmid

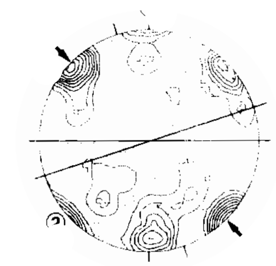


Steve Bauer



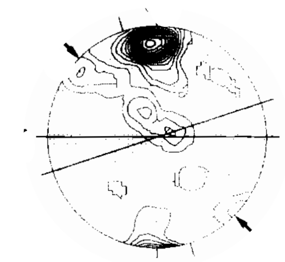
Schmid, Panozzo & Bauer (1987)

regime 1 dislocation glide



CT6

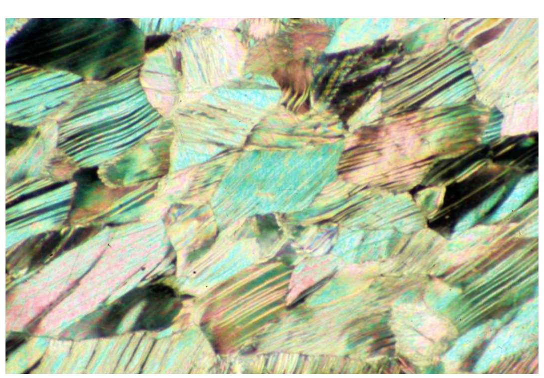
regime 2 dislocation creep



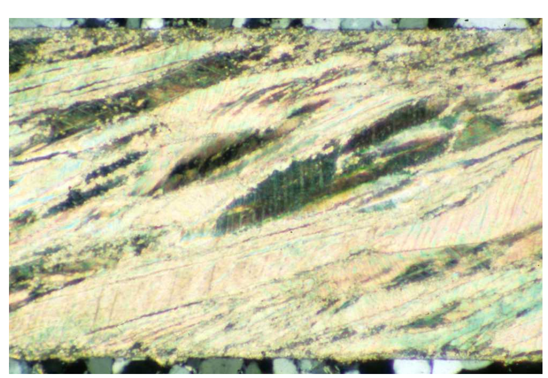
CT7

regime 1 → regime 2

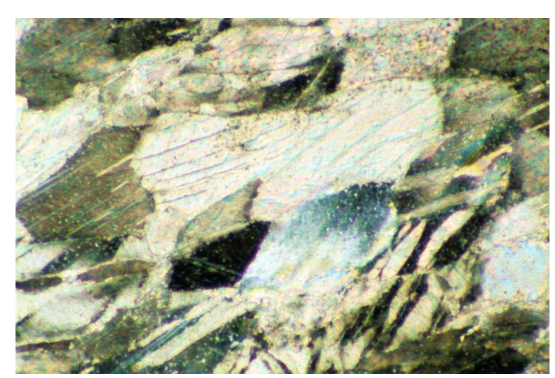
CT1 600°C



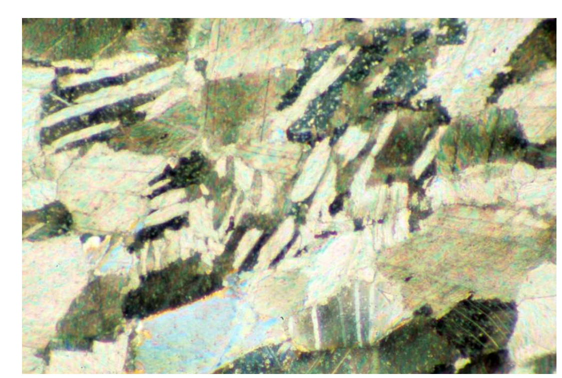
CT6 600°C



CT3 700°C



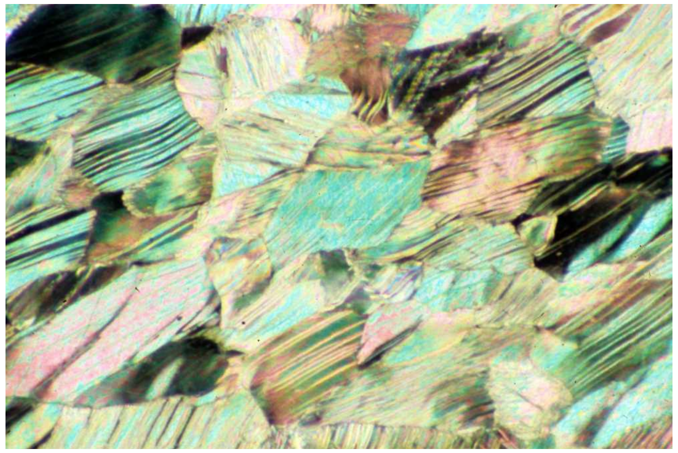
CT2 800°C



500 μm

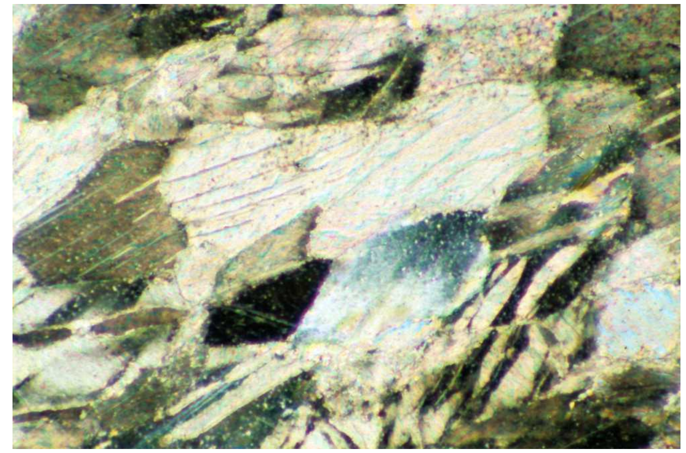
twinning → *dynamic recrystallization*

displacement in - shear strain out?

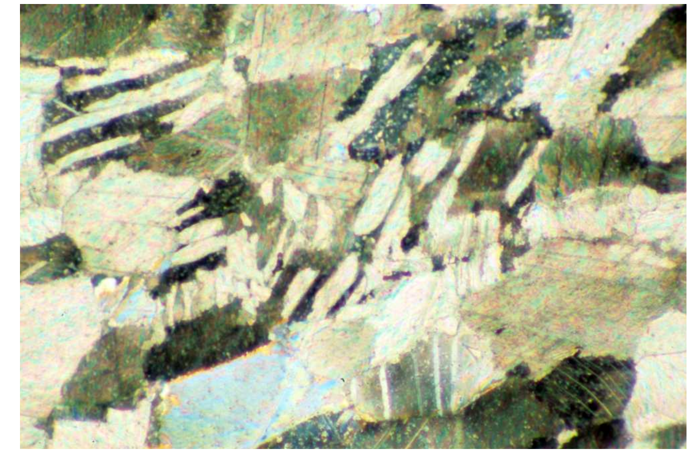


CT1 600°C

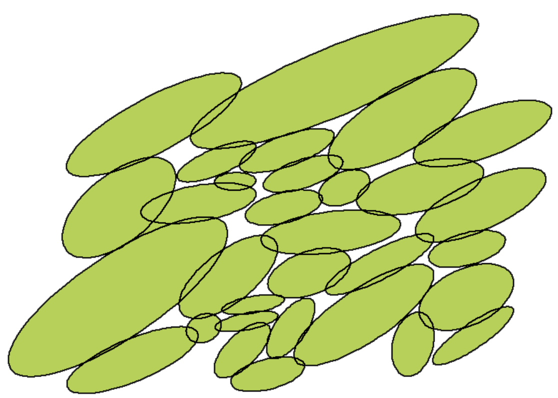
500 µm

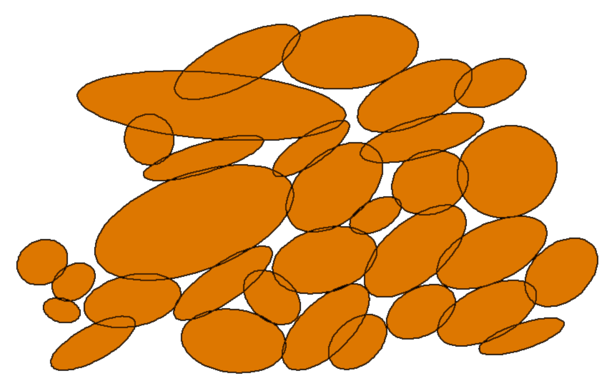


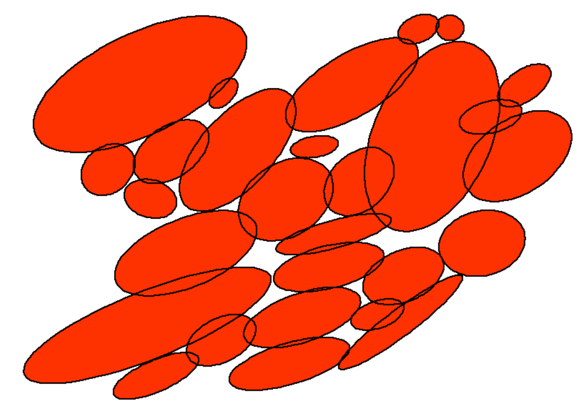
CT3 700°C

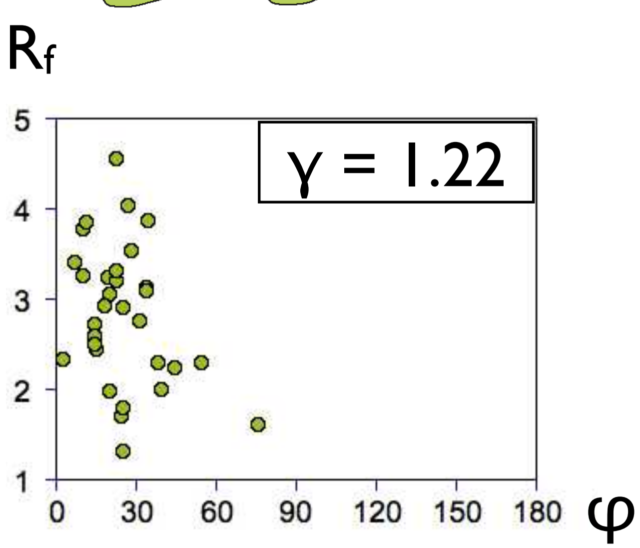


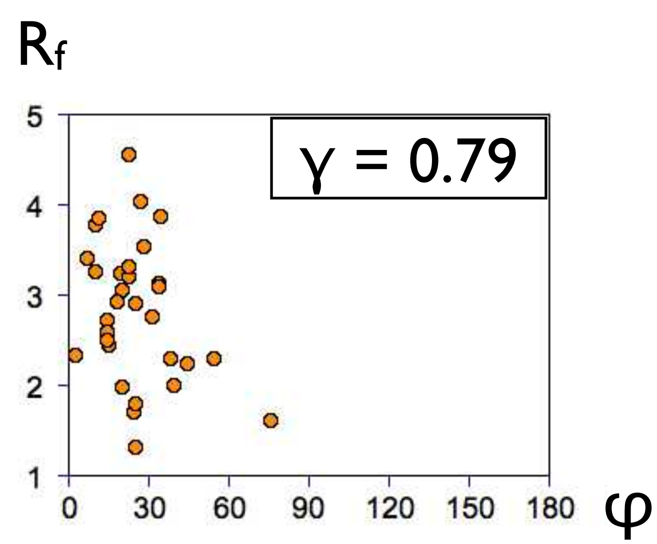
CT2 800°C

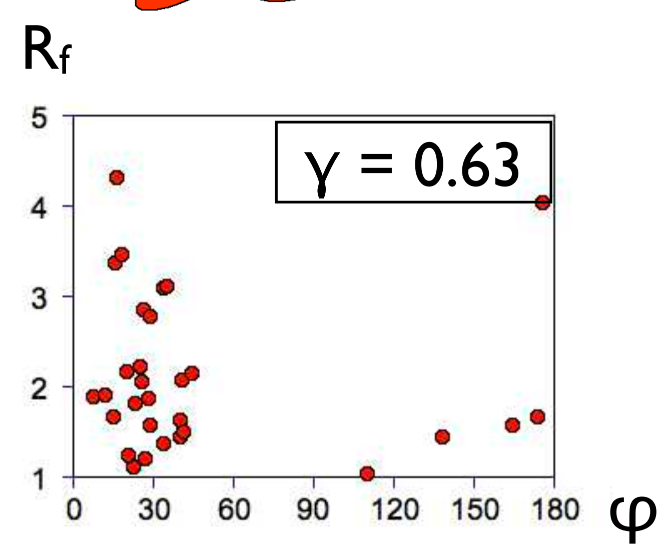




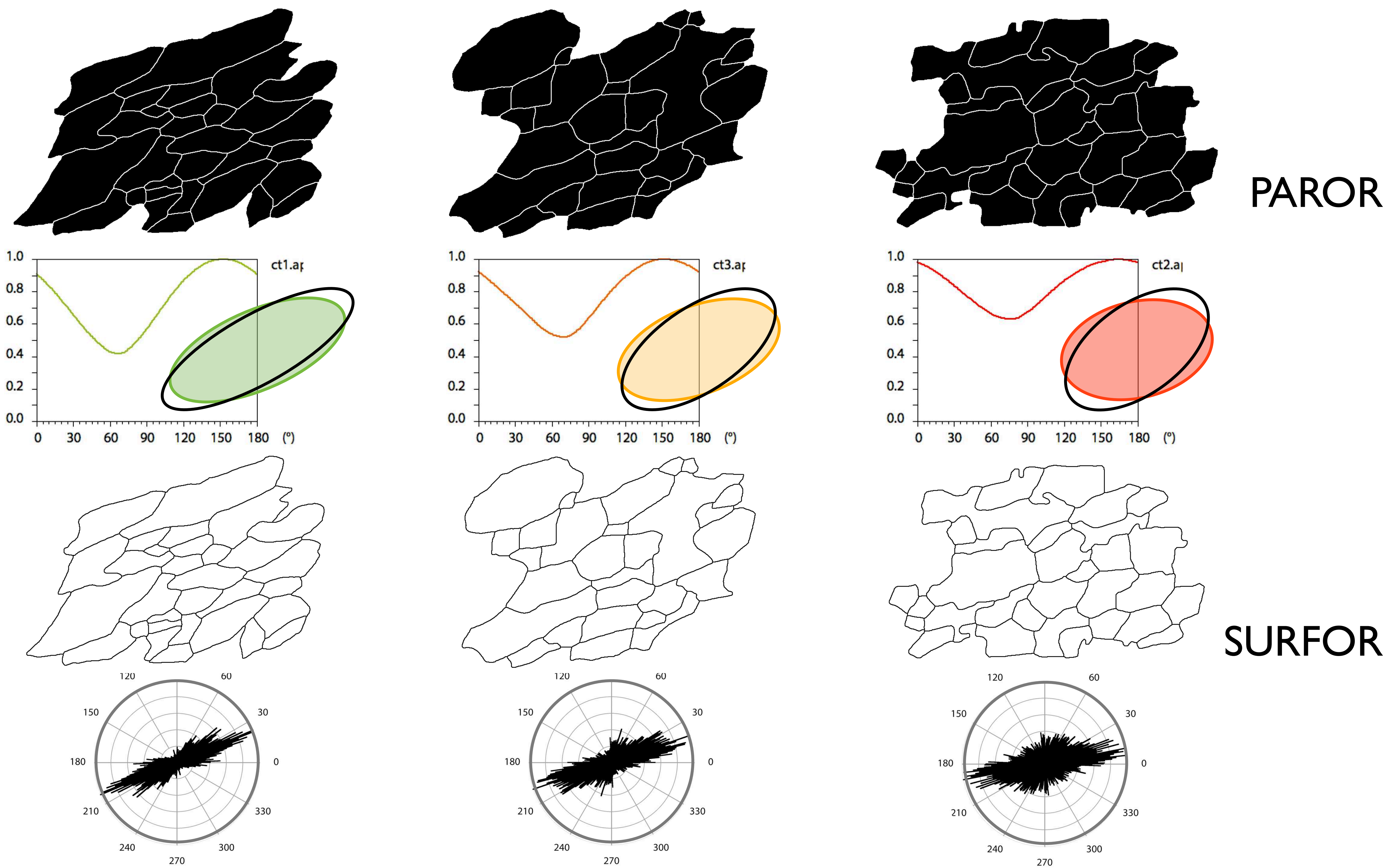




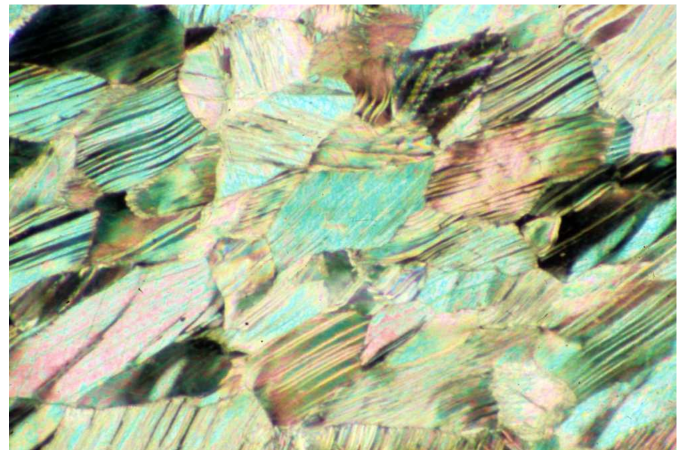




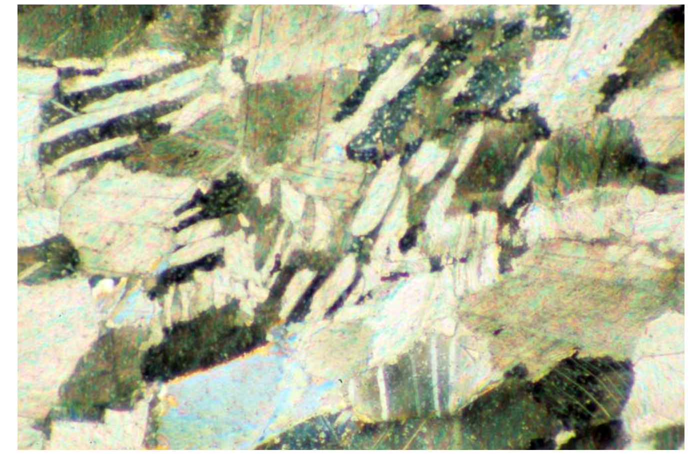
particles and surfaces



describing 'shape'

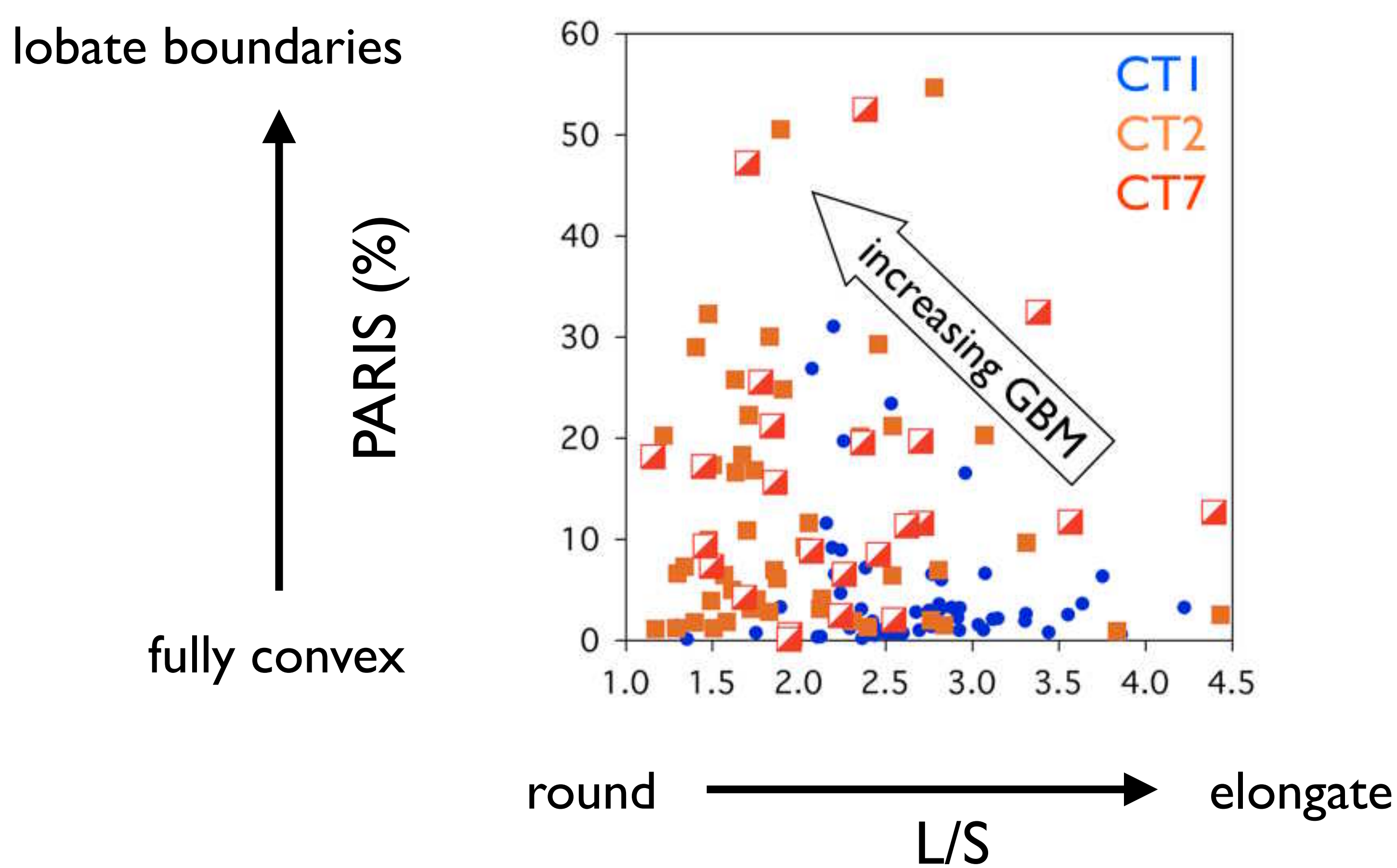


CT1 600°C



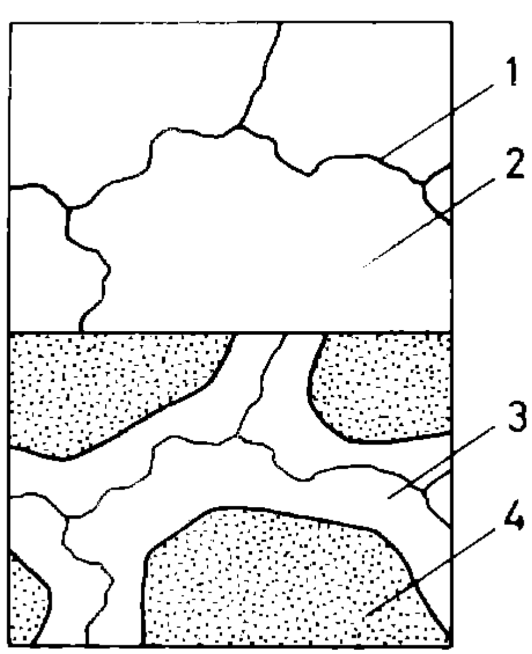
CT2 800°C

500 μm



what do we learn ?

- every grain boundary is a strain marker
- one mineralogical phase implies one rheology
- grain boundary sliding implies straight boundaries
- texture and microstructure go together

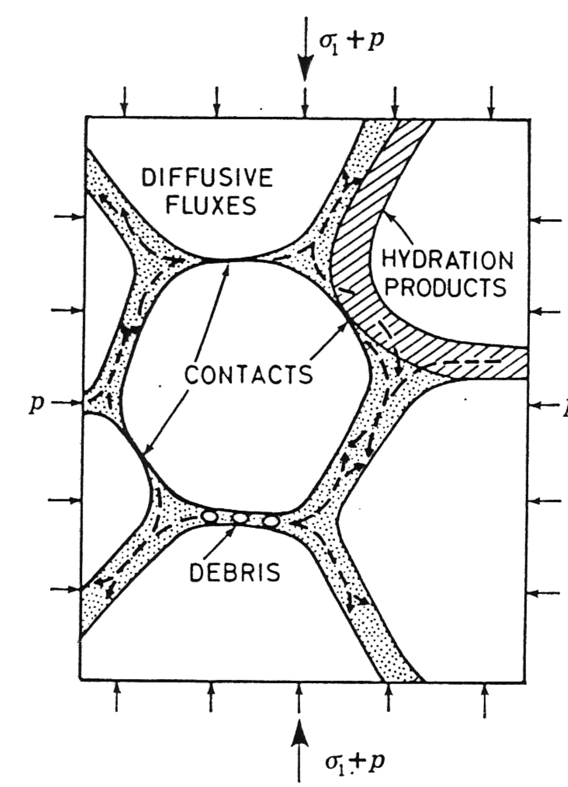


1 visually defined grain boundary

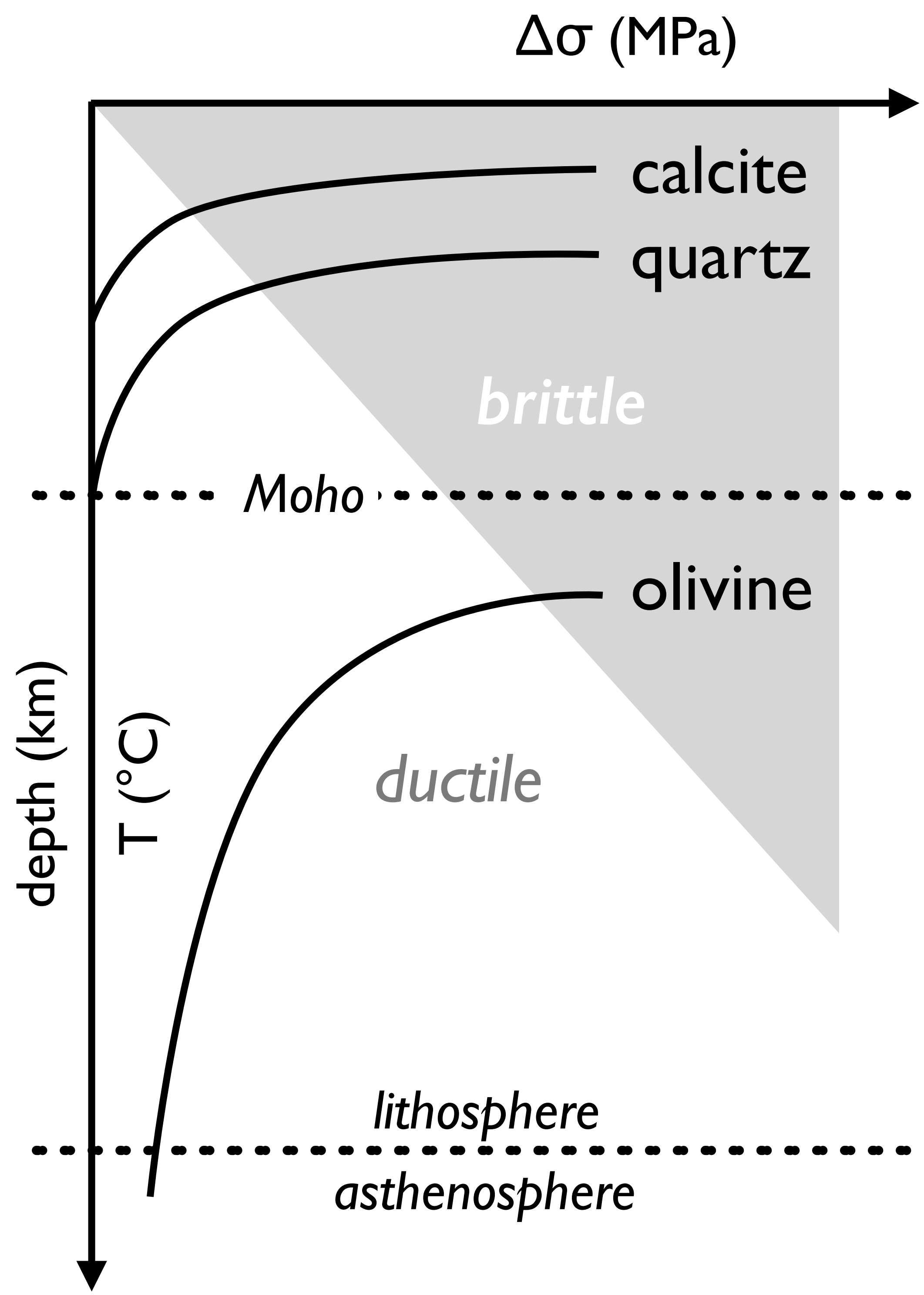
2 visually defined grain

3 mechanically defined grain boundary region

4 mechanically defined core of grain



lithosphere deformation in the lab



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triaxial gas apparatus
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$\gamma < 3$

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solid medium apparatus
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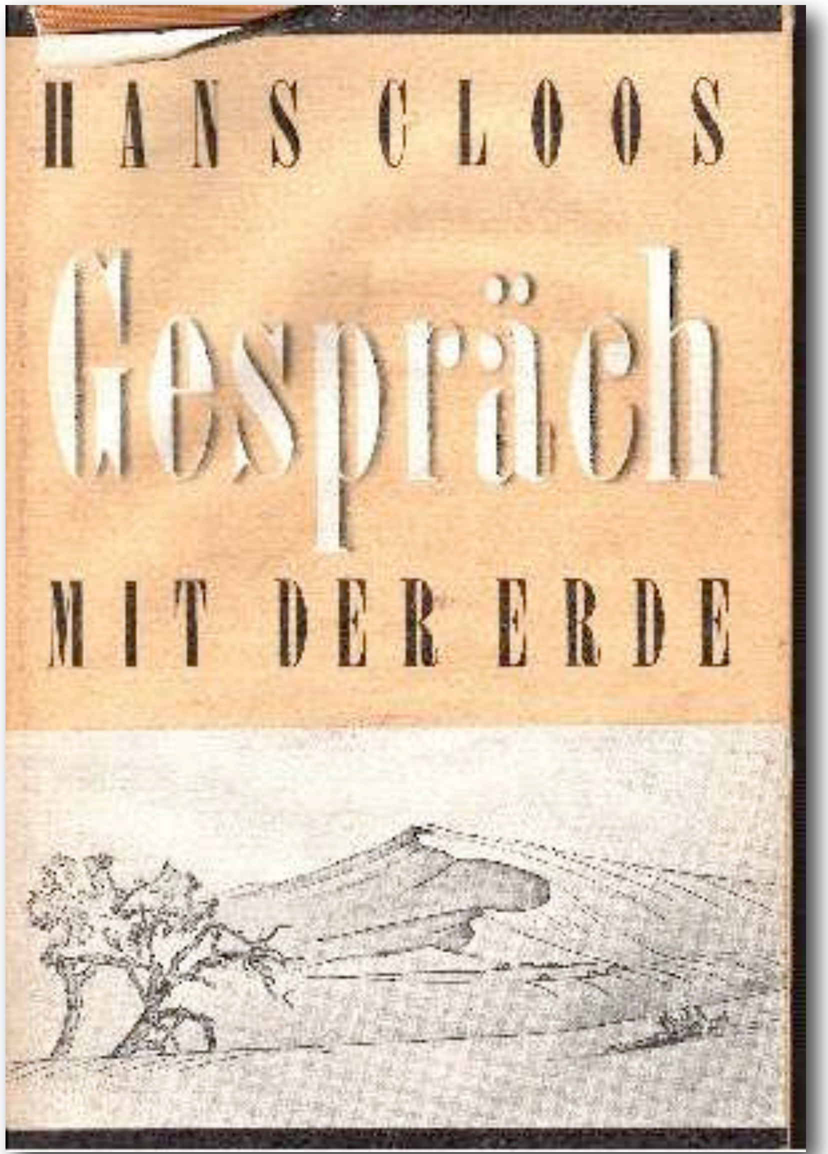
$\gamma < 8$

3 Olivine-Orthopyroxene
torsion apparatus
University of Minnesota
$\gamma < 30$

"... der freche Gassenjunge ..."



Quartz

"....the cheeky street urchin"

- regime 1, 2, 3 (lab) versus
- bulging - sgr - gbm (field)

The eastern Tonale fault zone: a 'natural laboratory' for crystal plastic deformation of quartz over a temperature range from 250 to 700 °C

Michael Stipp*, Holger Stünitz, Renée Heilbronner, Stefan M. Schmid

Department of Earth Sciences, Basel University, Bernoullistrasse 32, 4056 Basel, Switzerland

Received 30 November 2000; received in revised form 24 January 2002; accepted 26 February 2002

- quartz piezometer

The recrystallized grain size piezometer for quartz

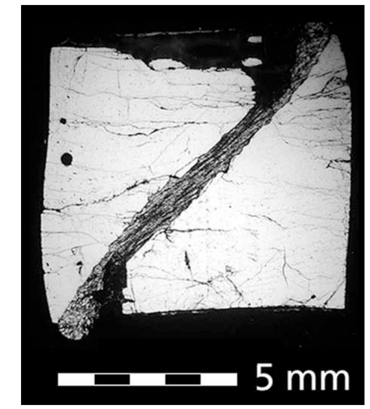
Michael Stipp and Jan Tullis
Department of Geological Sciences, Brown University, Providence, Rhode Island, USA

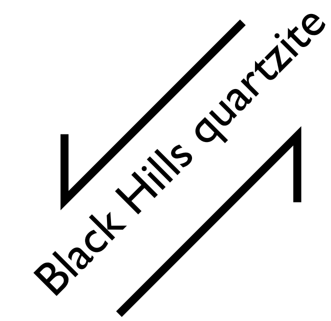
Received 18 August 2003; revised 24 September 2003; accepted 30 September 2003; published 4 November 2003.

BHQ - texture and grain size

Jan Tullis and ...

her Grigg's apparatus



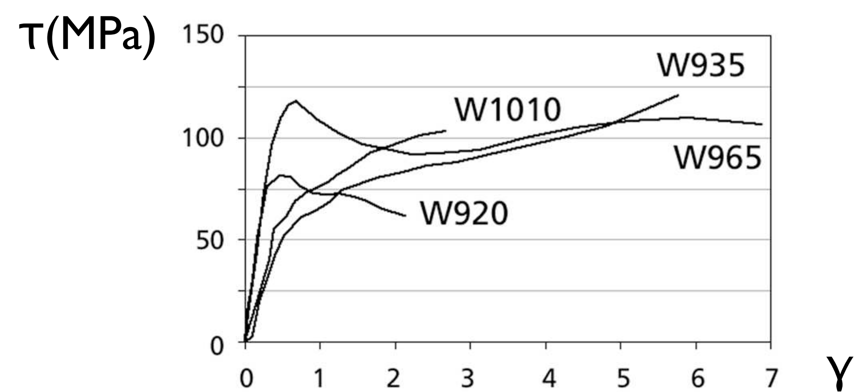


Dislocation creep regime 3

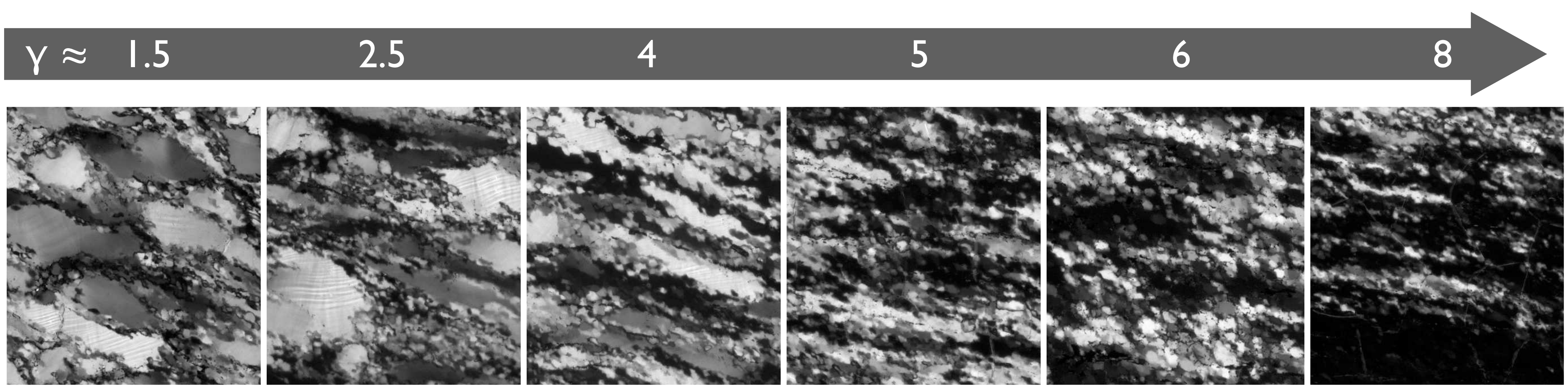
p_c = 1.5 GPa T = 850 - 915°C

$\dot{\gamma}$ = 1-2 · 10^{-5} s^{-1}

up to γ ~ 7 !!!!

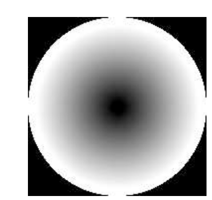


Heilbronner & Tullis (2006)



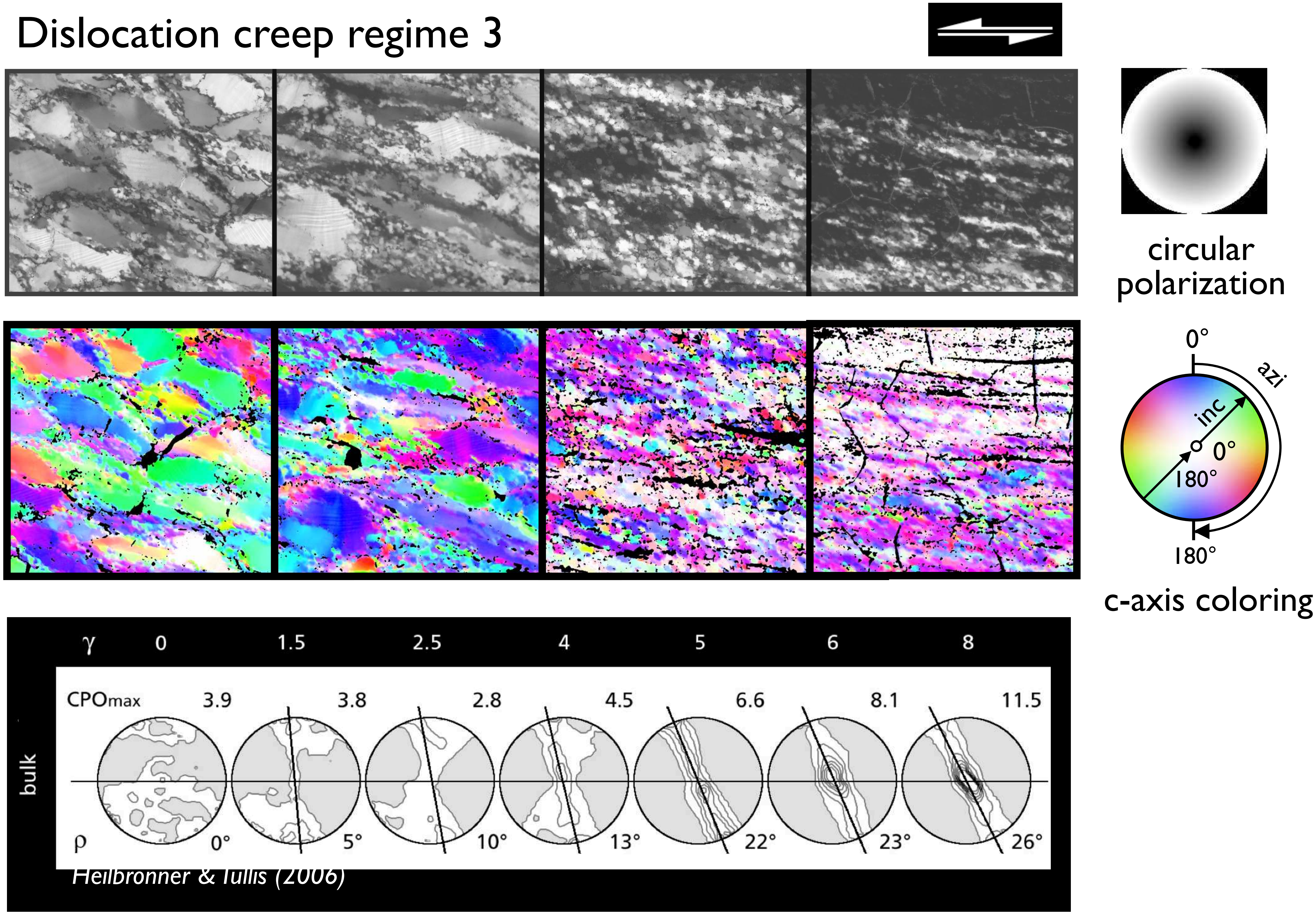
Black Hills Quartzite (circular polarization)

regime 3

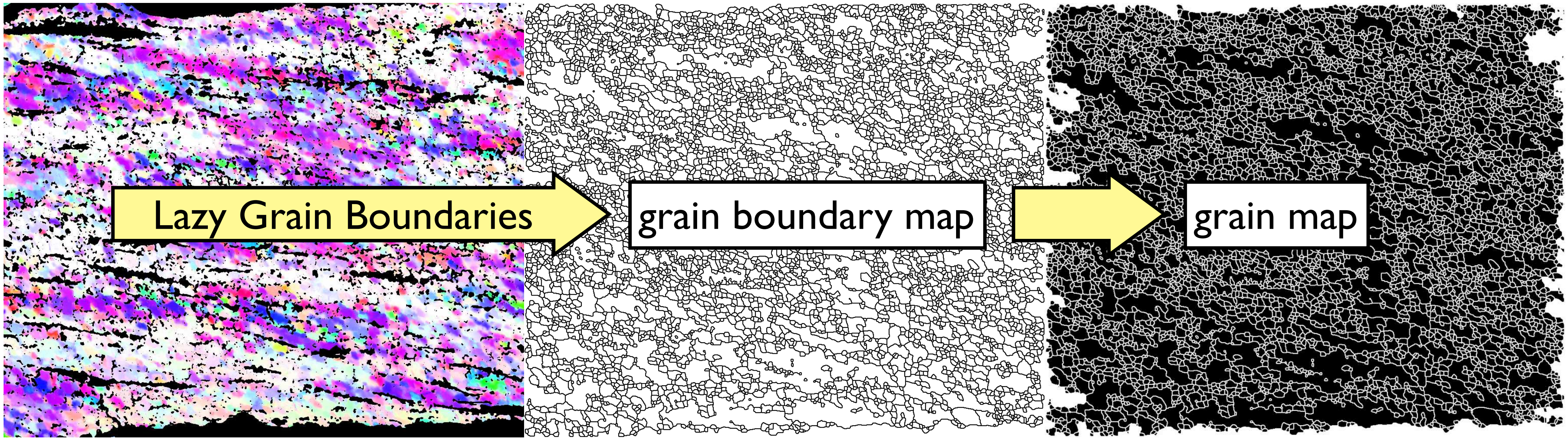


circular polarization

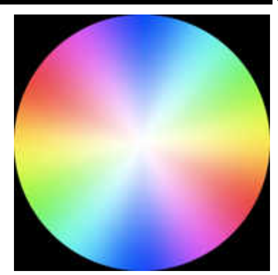
do the CIP - get the texture



from texture to grain size

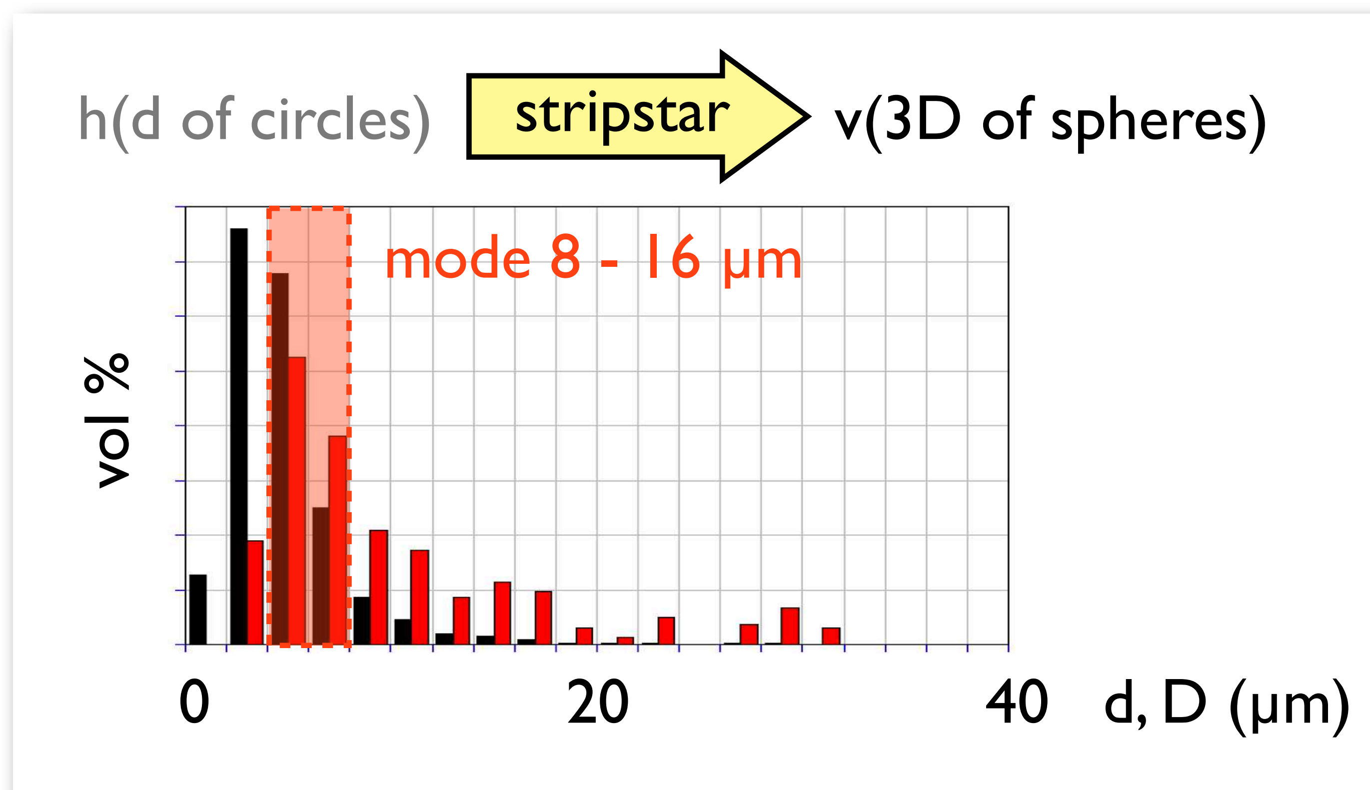


w935 COI



w 935 grain boundary map

w 935 grain map



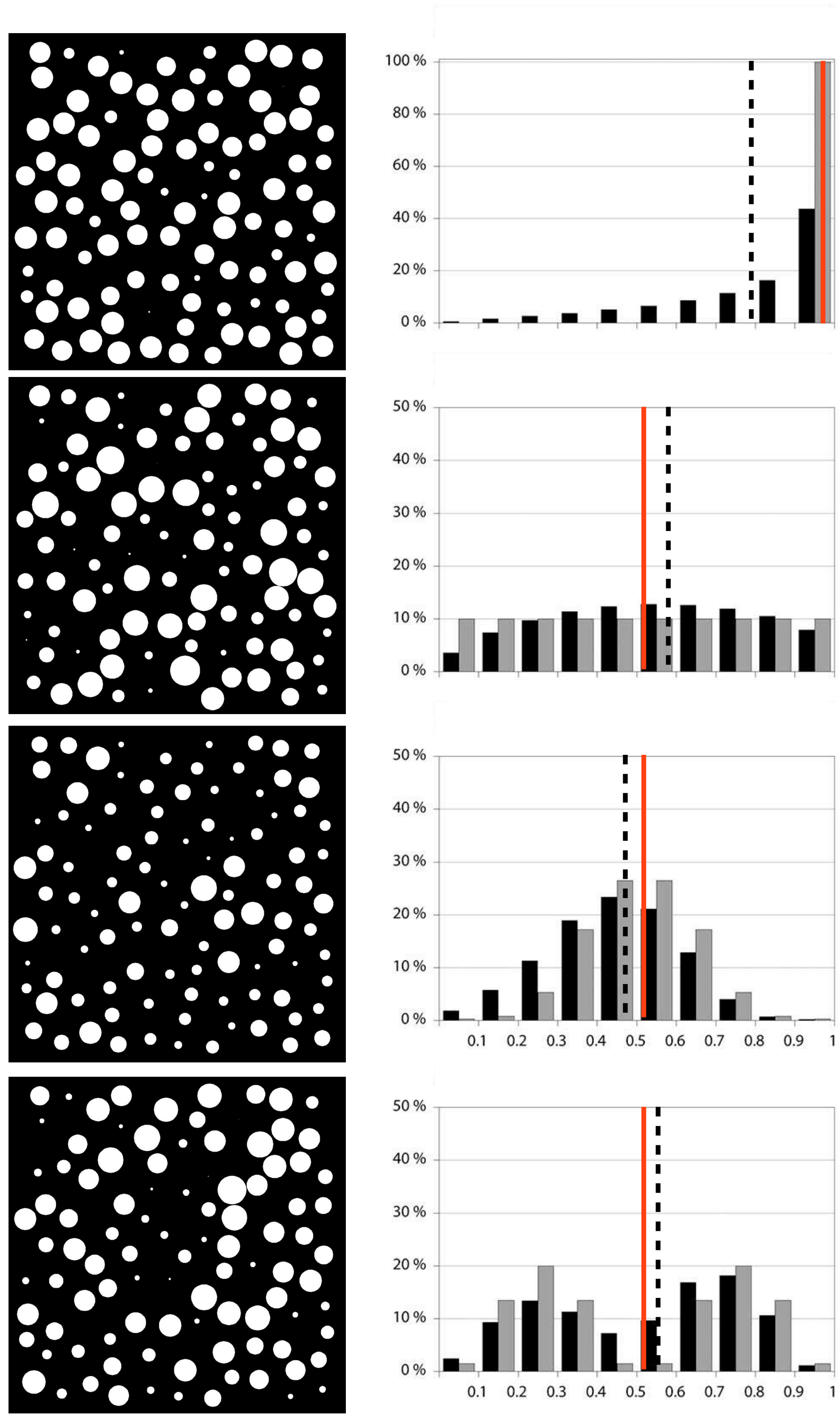
why stripstar ?

monodisperse

uniform
(random)

Gaussian
(normal)

bimodal



here:

$$\frac{\text{mean of } h(D)}{\text{mean of } h(d)} = 1.3$$

3D spheres

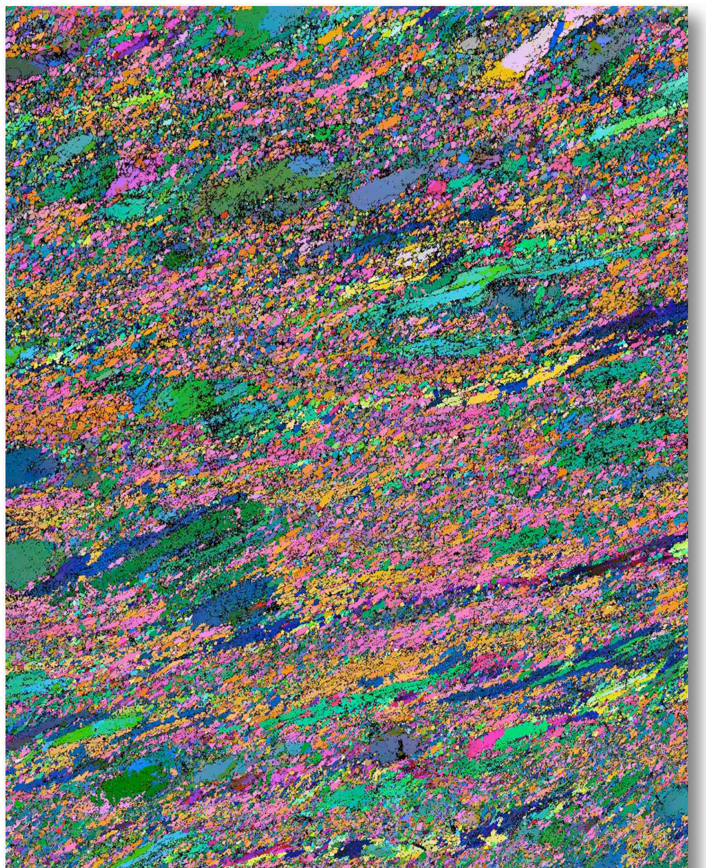
3D means of h(D)

2D sections

2D means of h(d)

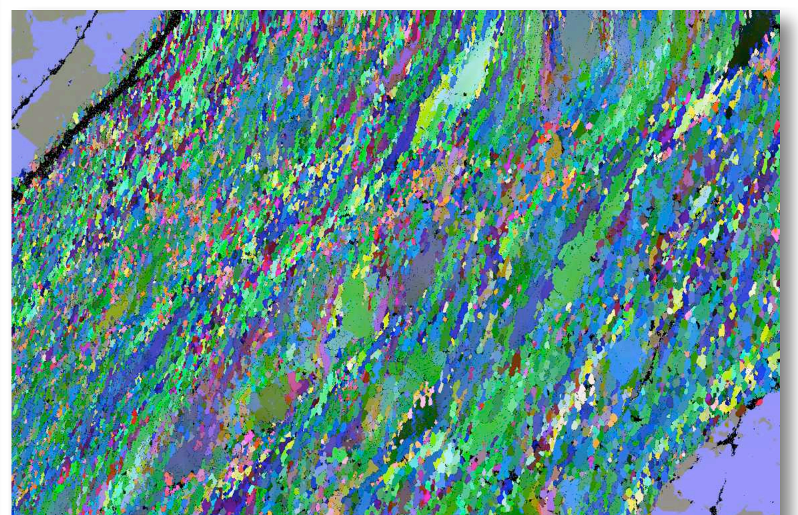
regime 3 ... 2 ... 1 - go EBSD !

100 µm



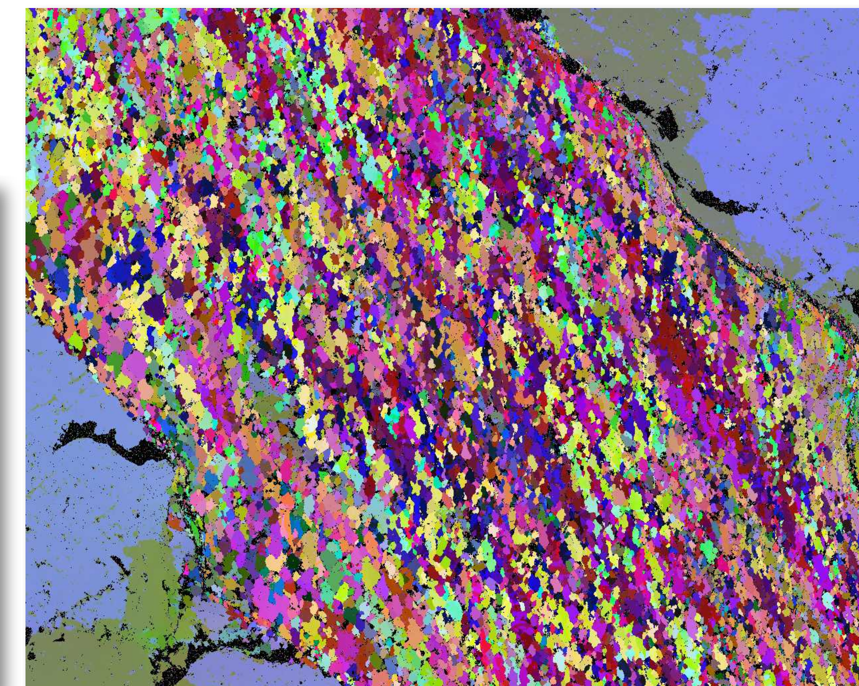
regime 1 (w1092)

100 µm



regime 2 (w946)

100 µm

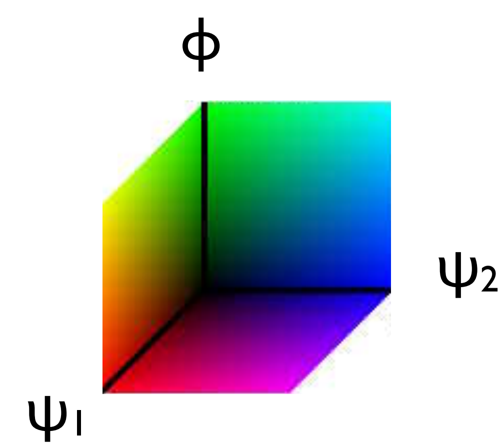


regime 3 (w935)

The effect of static annealing on microstructures and crystallographic preferred orientations of quartzites experimentally deformed in axial compression and shear

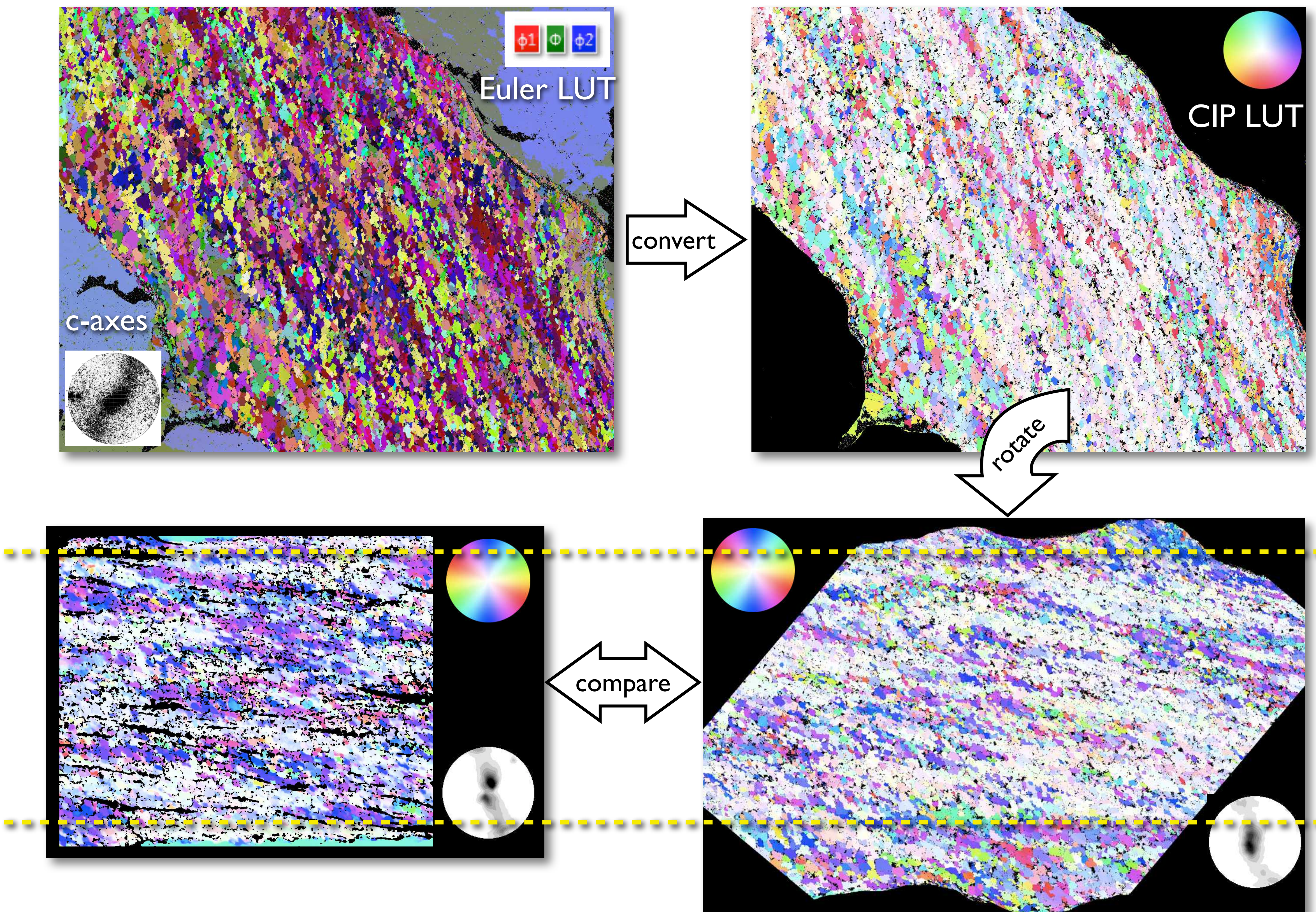
RENÉE HEILBRONNER[1] & JAN TULLIS[2]

could not do grain size for regime 1 and 2



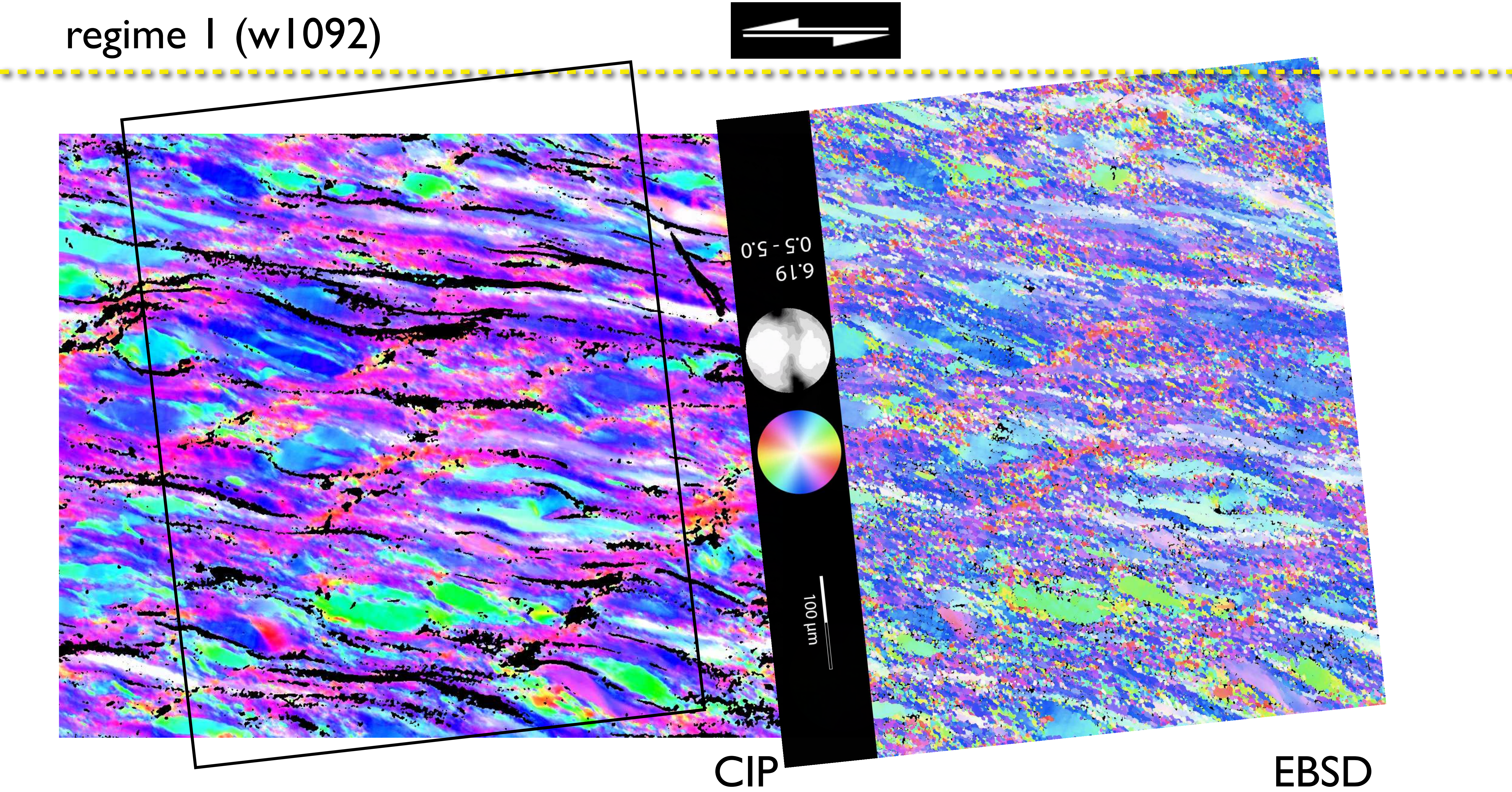
Euler coloring

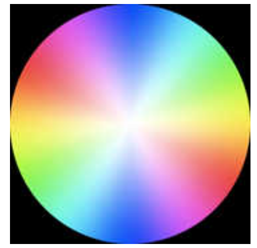
put the CIP glasses on



comparing CIP and EBSD

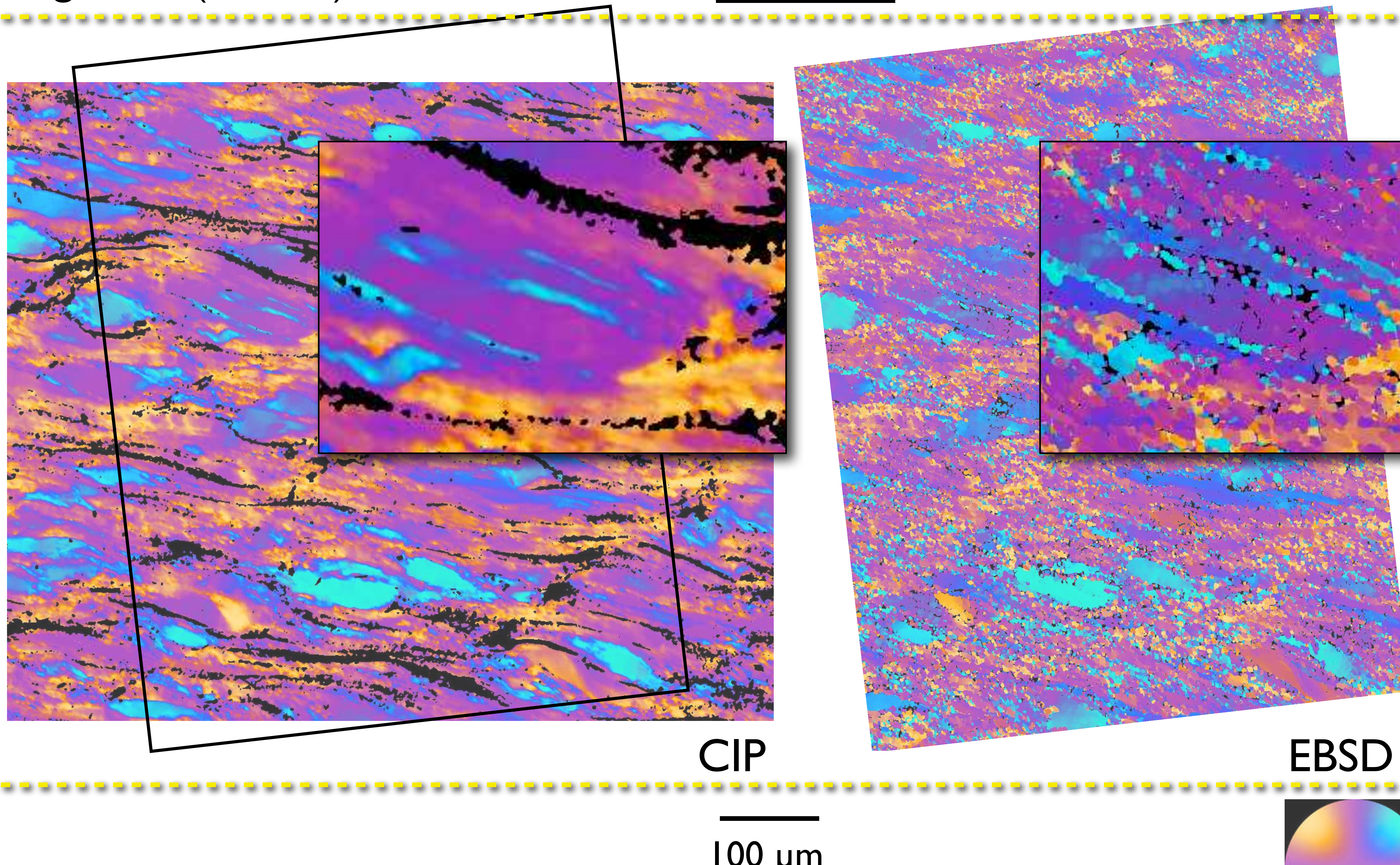
regime 1 (w1092)



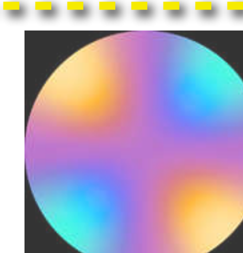


optical microscopy in the SEM

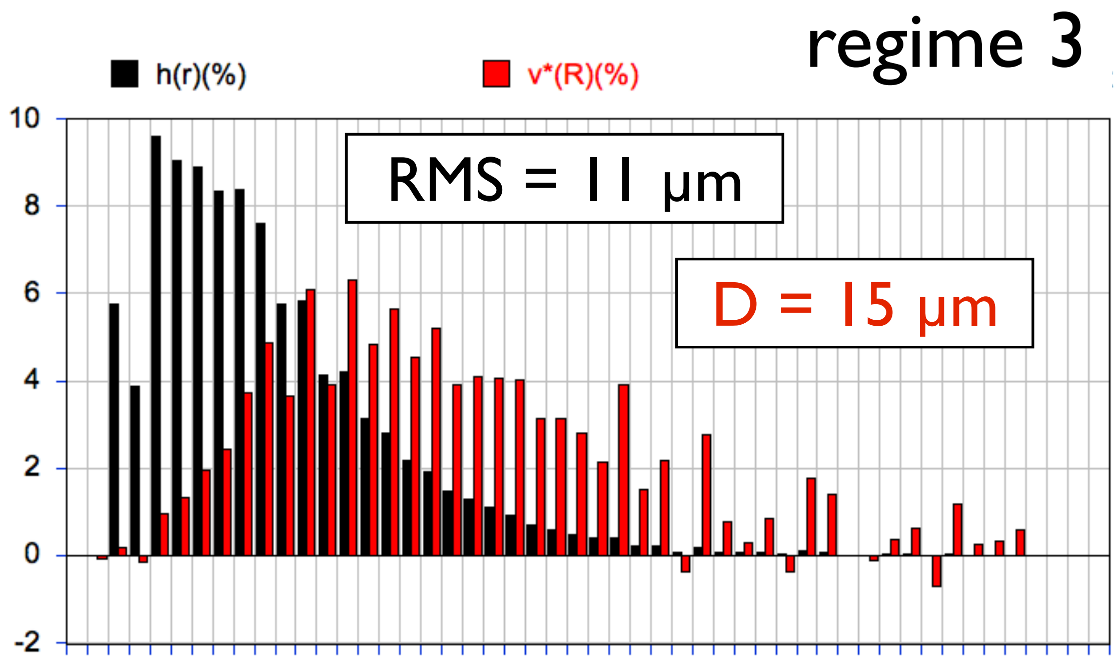
regime 1 (w1092)

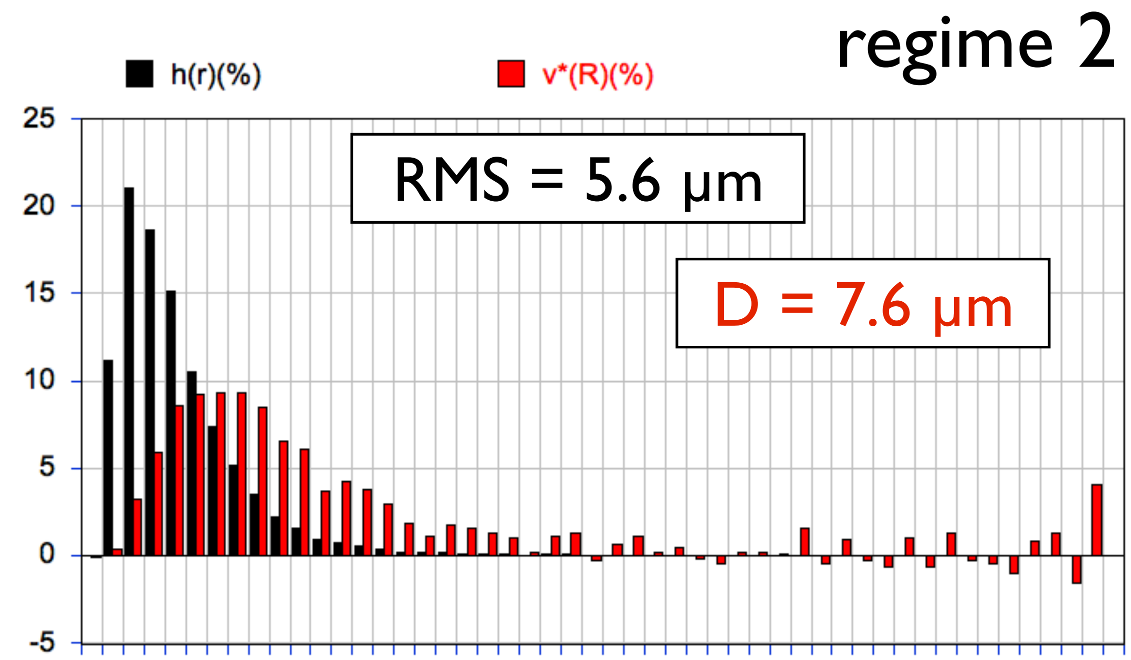


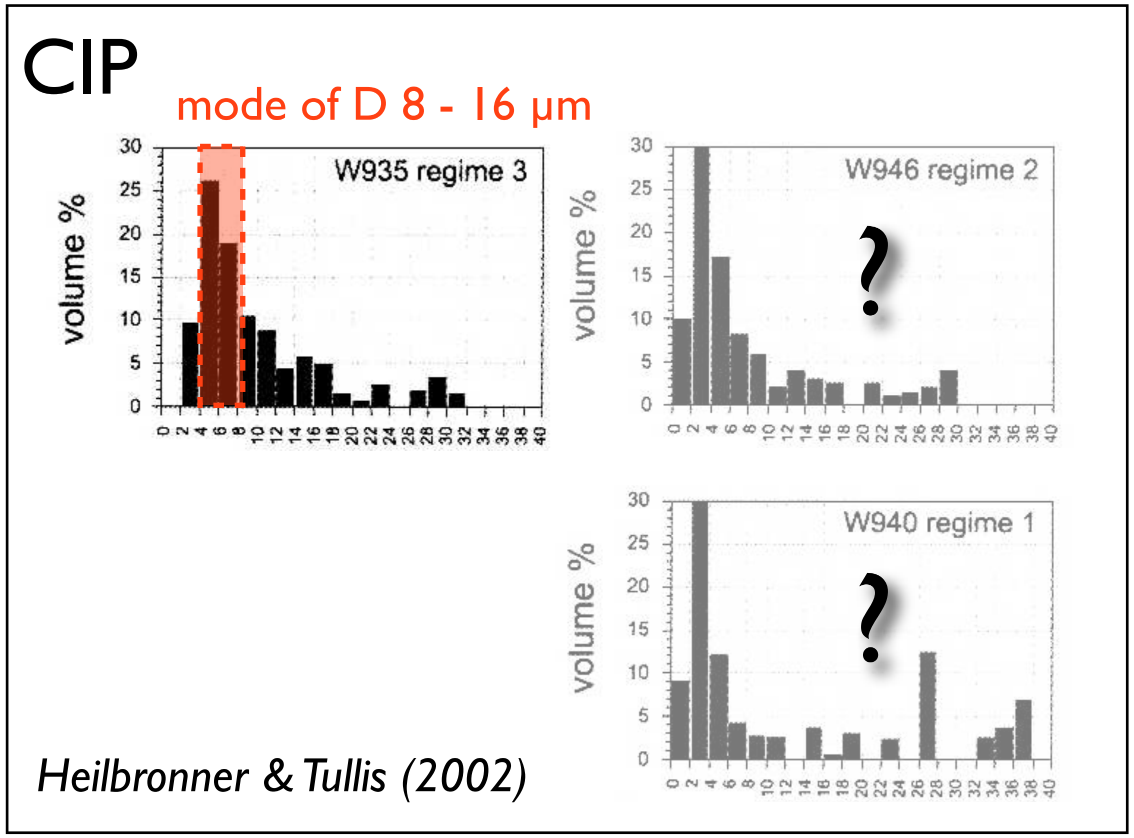
positive CLUT

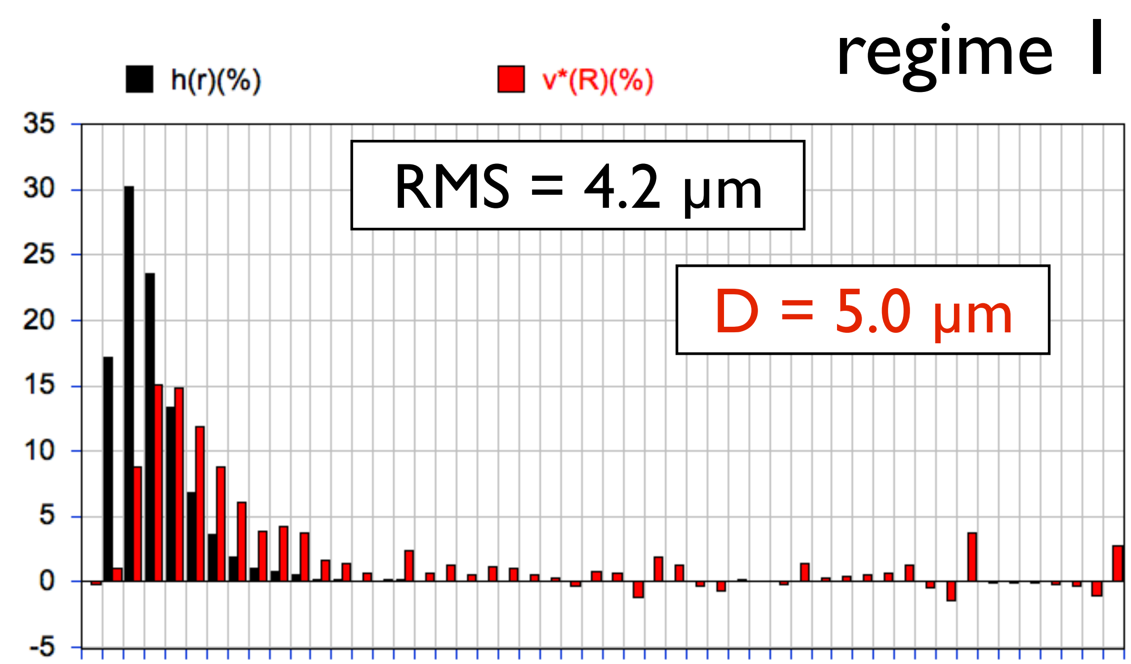


do the stripstar again !

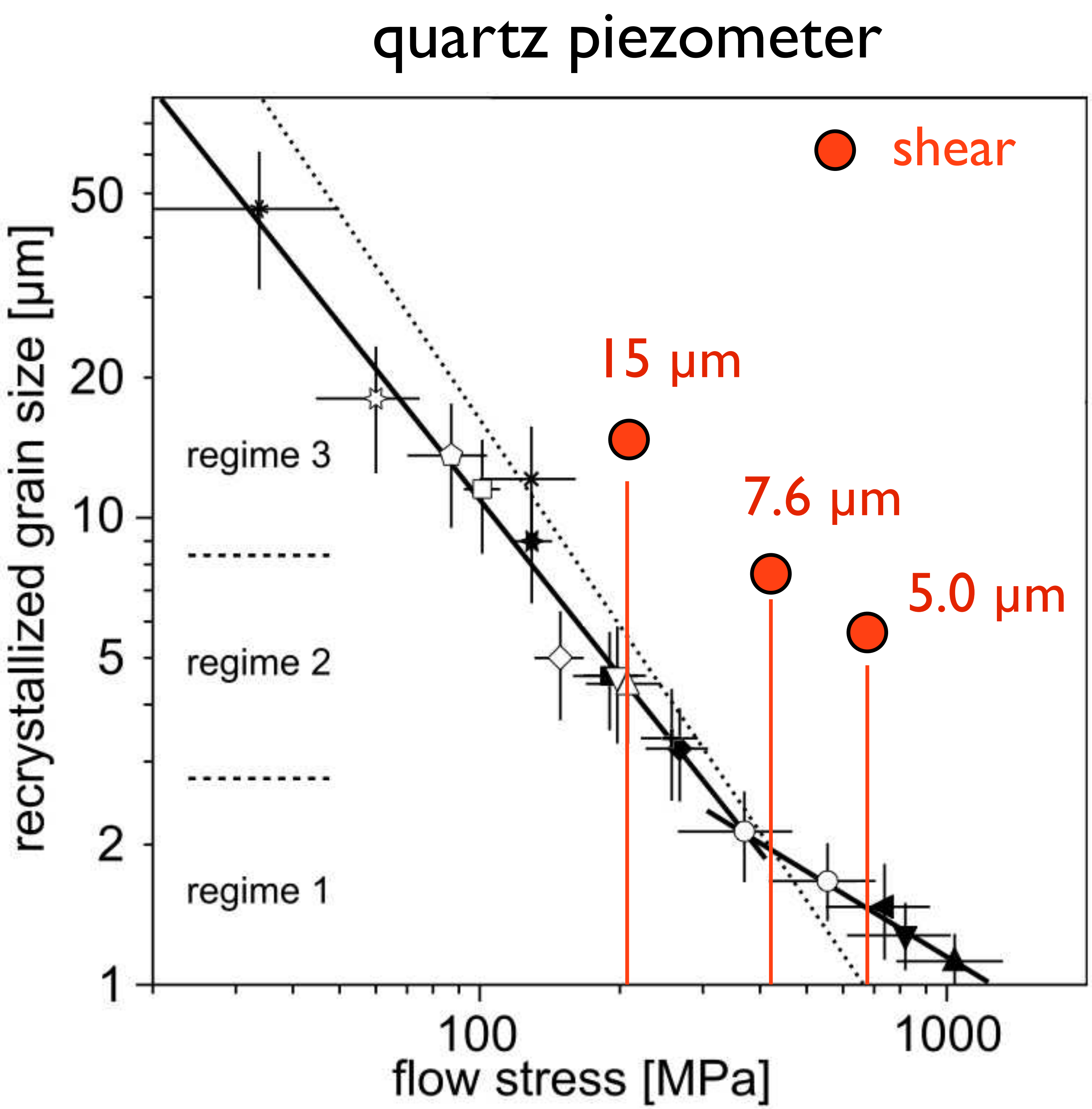








...hmmm...



CIP grain boundaries

RMS of 2D sections

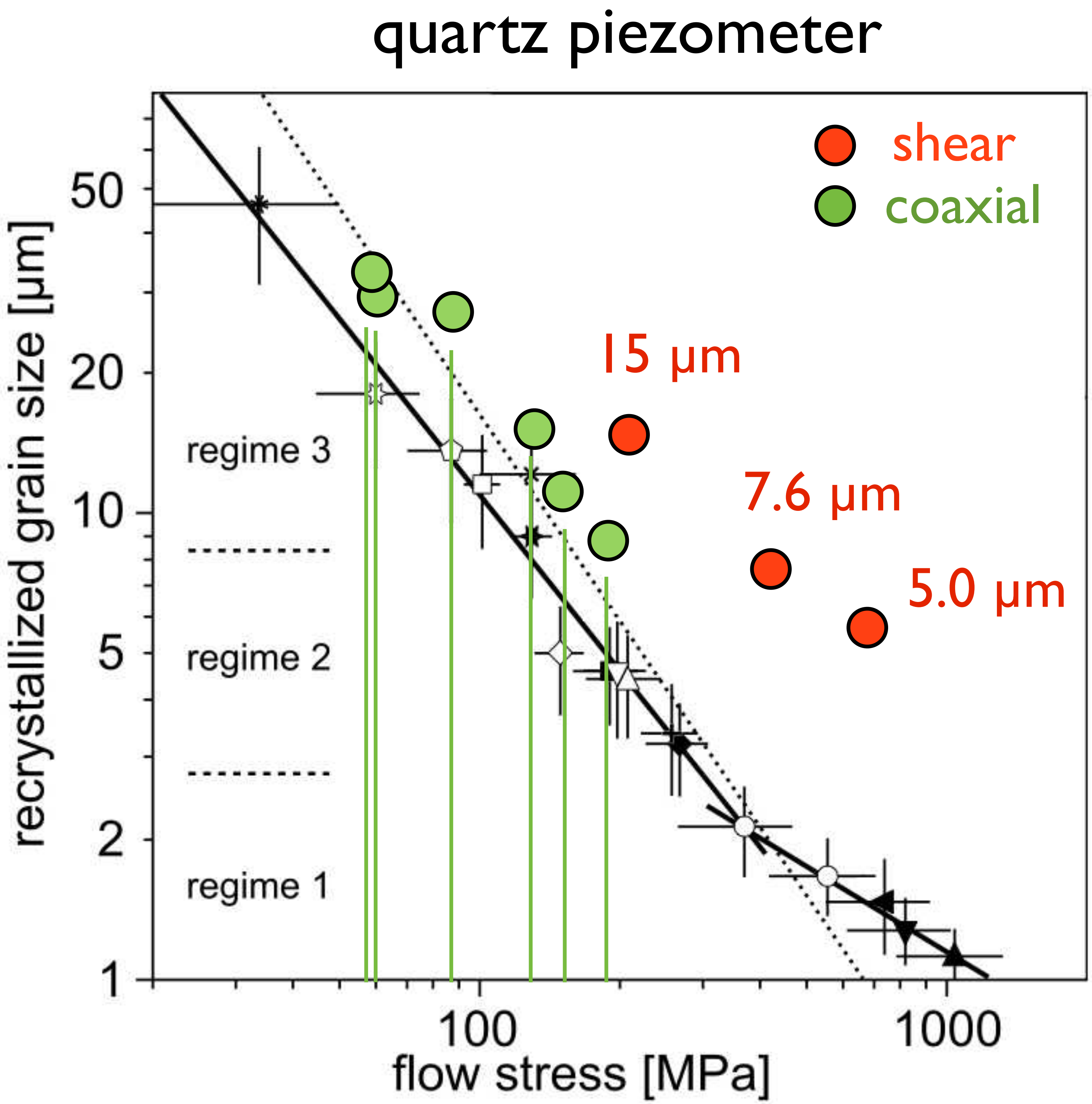
Stipp & Tullis (2003)
original data

EBSD grain boundaries

mode of 3D grains

Heilbronner & Tullis (2002, 2006)
re-measured

re-measure piezometer in EBSD



CIP grain boundaries

RMS of 2D sections

Stipp & Tullis (2003)
original data

EBSD grain boundaries

mode of 3D grains

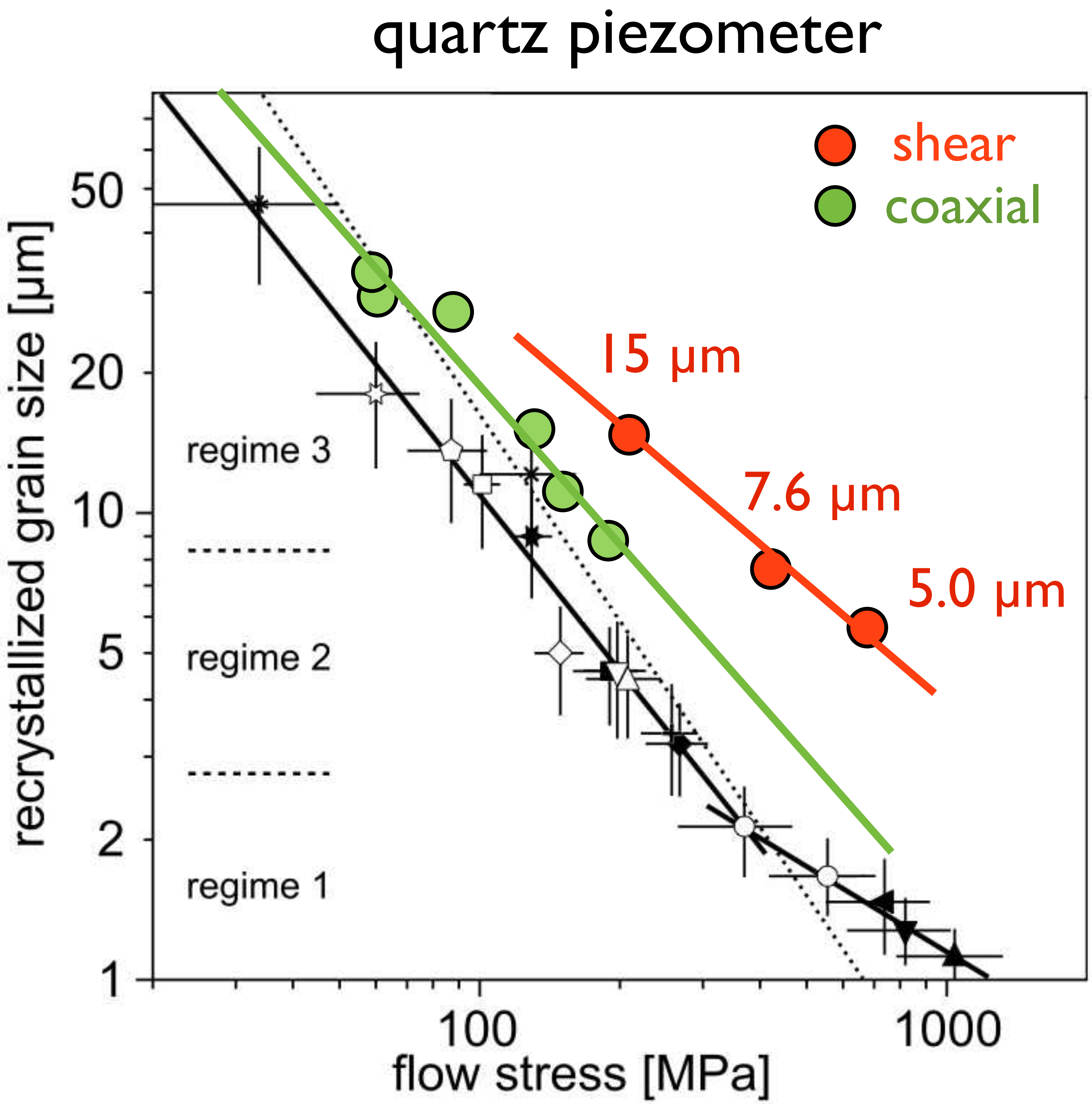
Heilbronner & Tullis (2002, 2006)
re-measured

EBSD grain boundaries

mode of 3D grains

Stipp & Tullis (2003)
original data re-measured by Prior

difference ≠ measuring artefact



CIP grain boundaries

RMS of 2D sections

published piezometer

$d(\mu m) = 3631\ \Delta\sigma^{-1.26}$

EBSD grain boundaries

mode of 3D grains

shear

$D(\mu m) = 1473\ \Delta\sigma^{-0.86}$

EBSD grain boundaries

mode of 3D grains

coaxial (piezo samples)

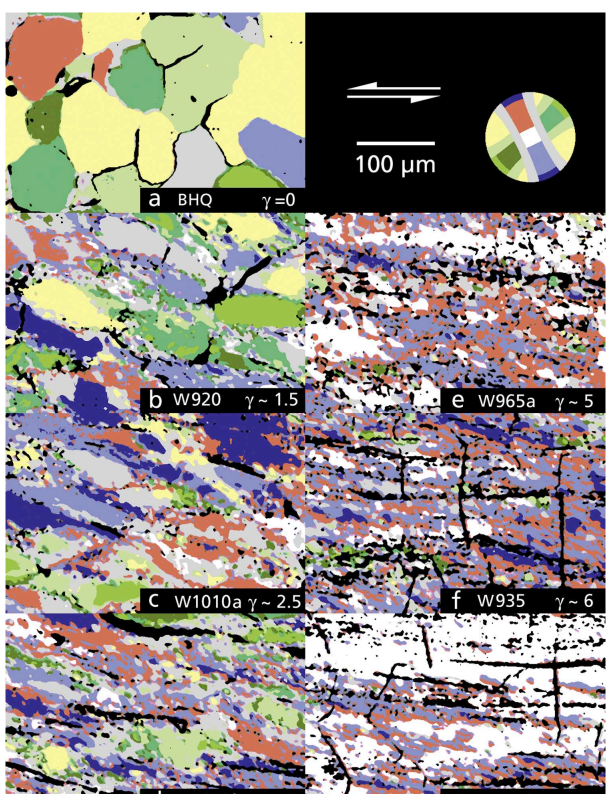
$D(\mu m) = 3325\ \Delta\sigma^{-1.13}$

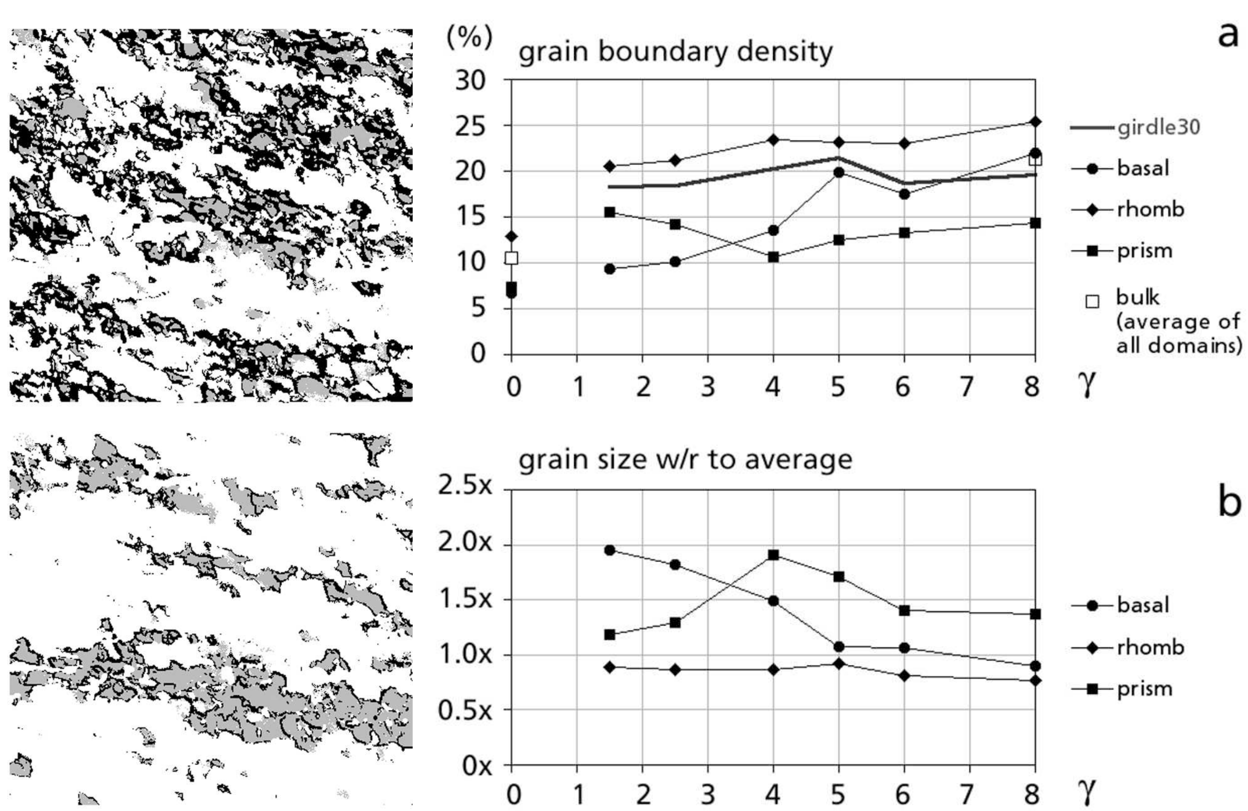
check the grain size in the Y domain

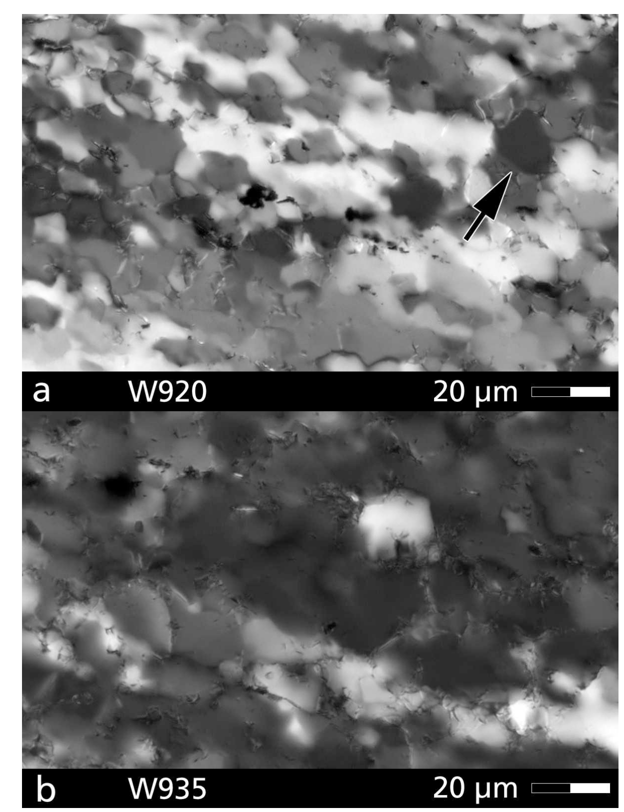
Evolution of c axis pole figures and grain size during dynamic recrystallization: Results from experimentally sheared quartzite

Renée Heilbronner[1] and Jan Tullis[2]

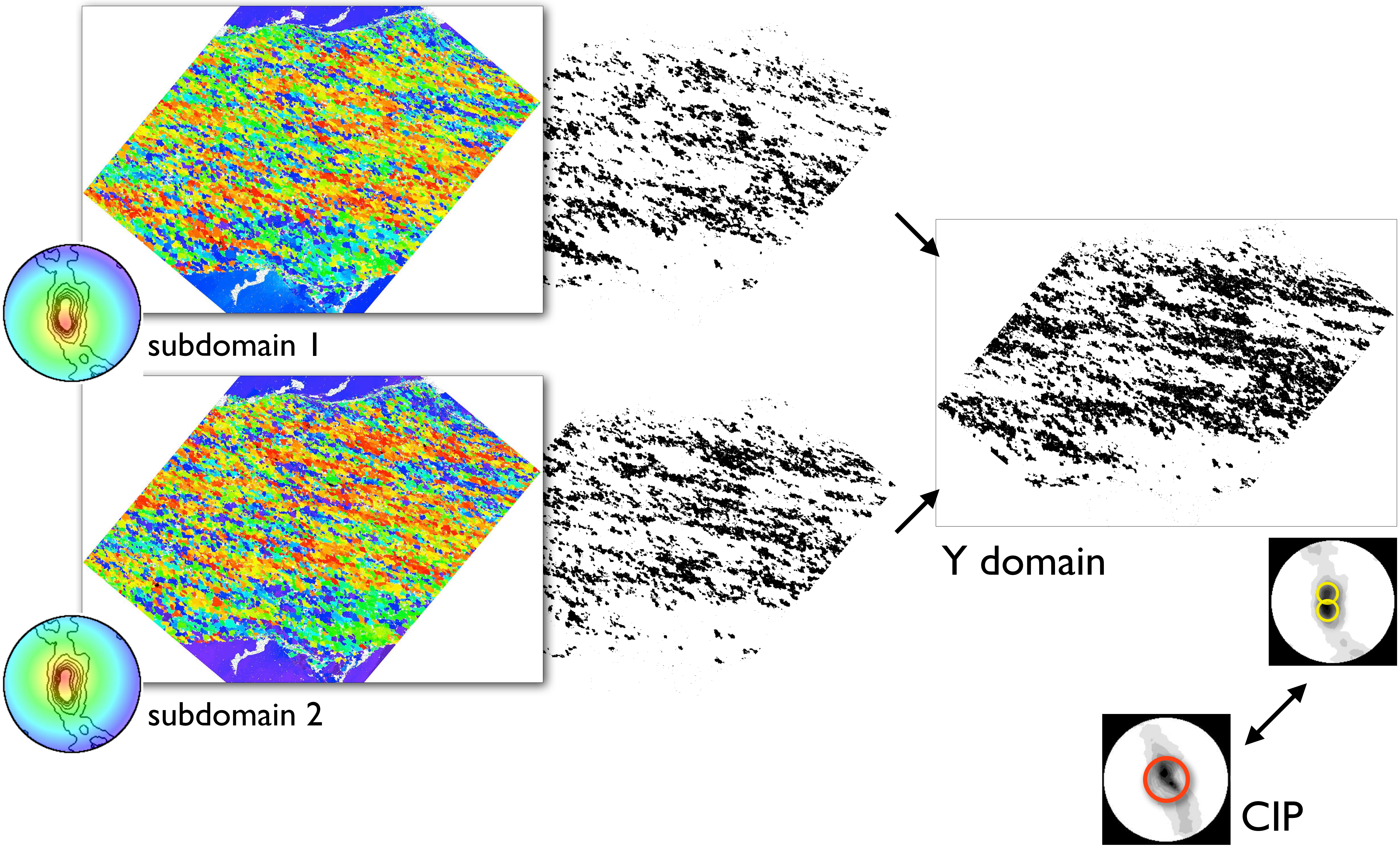
"...the recrystallized grain size of the rhomb domain is approx. 12 µm and that of the prism domain is approx. 19 µm, corresponding to shear stresses of 93 and 64 MPa..."



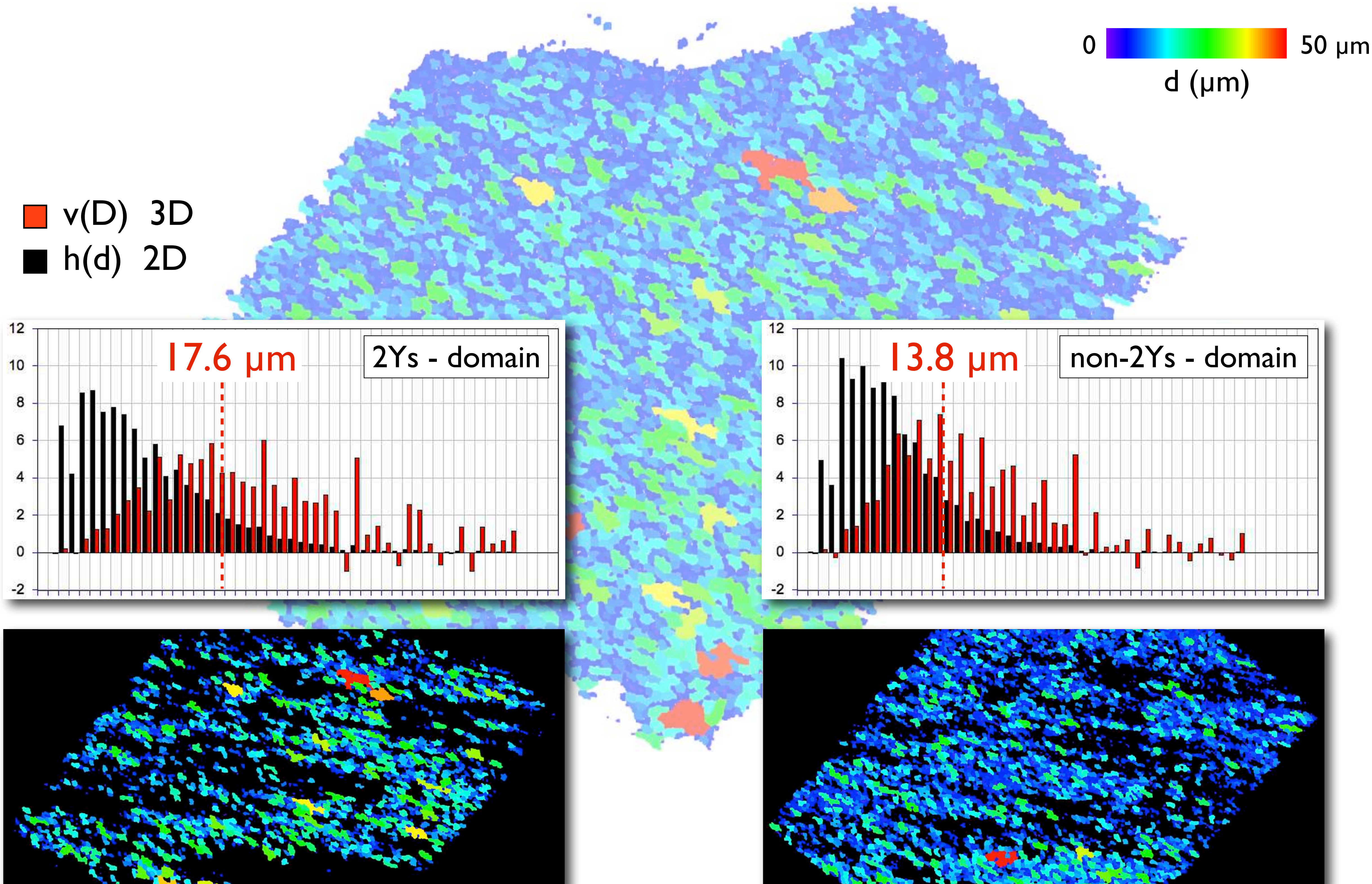




Y domain = 2 subdomains



we actually got it right !



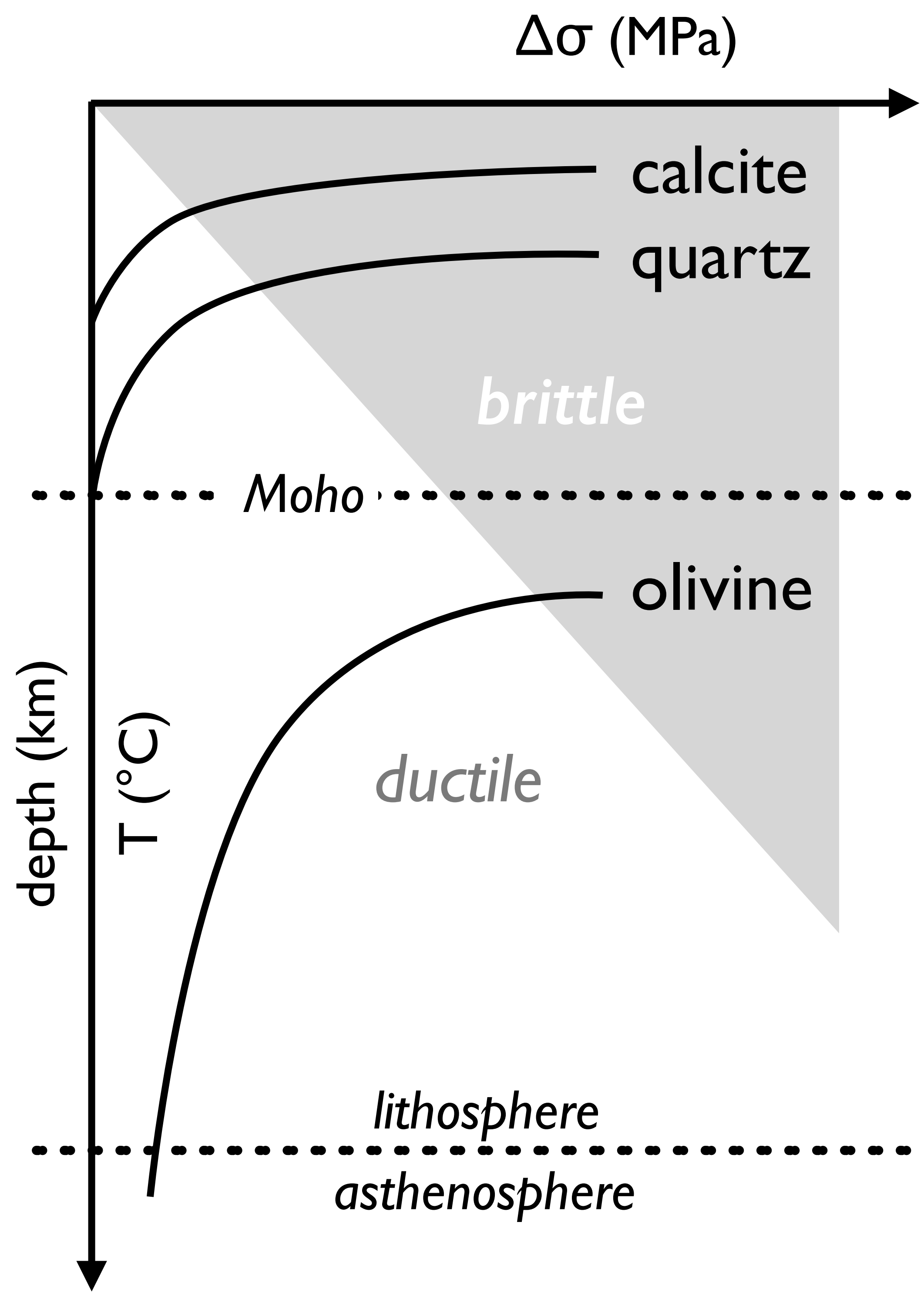
$\Rightarrow \tau = 86$ MPa

$\Rightarrow \tau = 114$ MPa

what do we learn ?

- orientation images "... says more than a thousand pole figures"
- EBSD grains ≈ optical grains (CIP grains)
- 3D grain size distributions are not what we see in 2D
- shear piezometer ≠ coaxial piezometer
- recrystallized grain size depends on CPO
- one mineralogical phase ≠ one rheology

lithosphere deformation in the lab



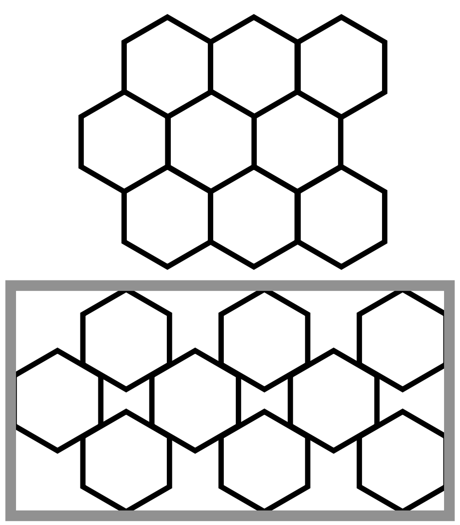
1 Carrara marble
triaxial gas apparatus
Texas A&M University
$\gamma < 3$

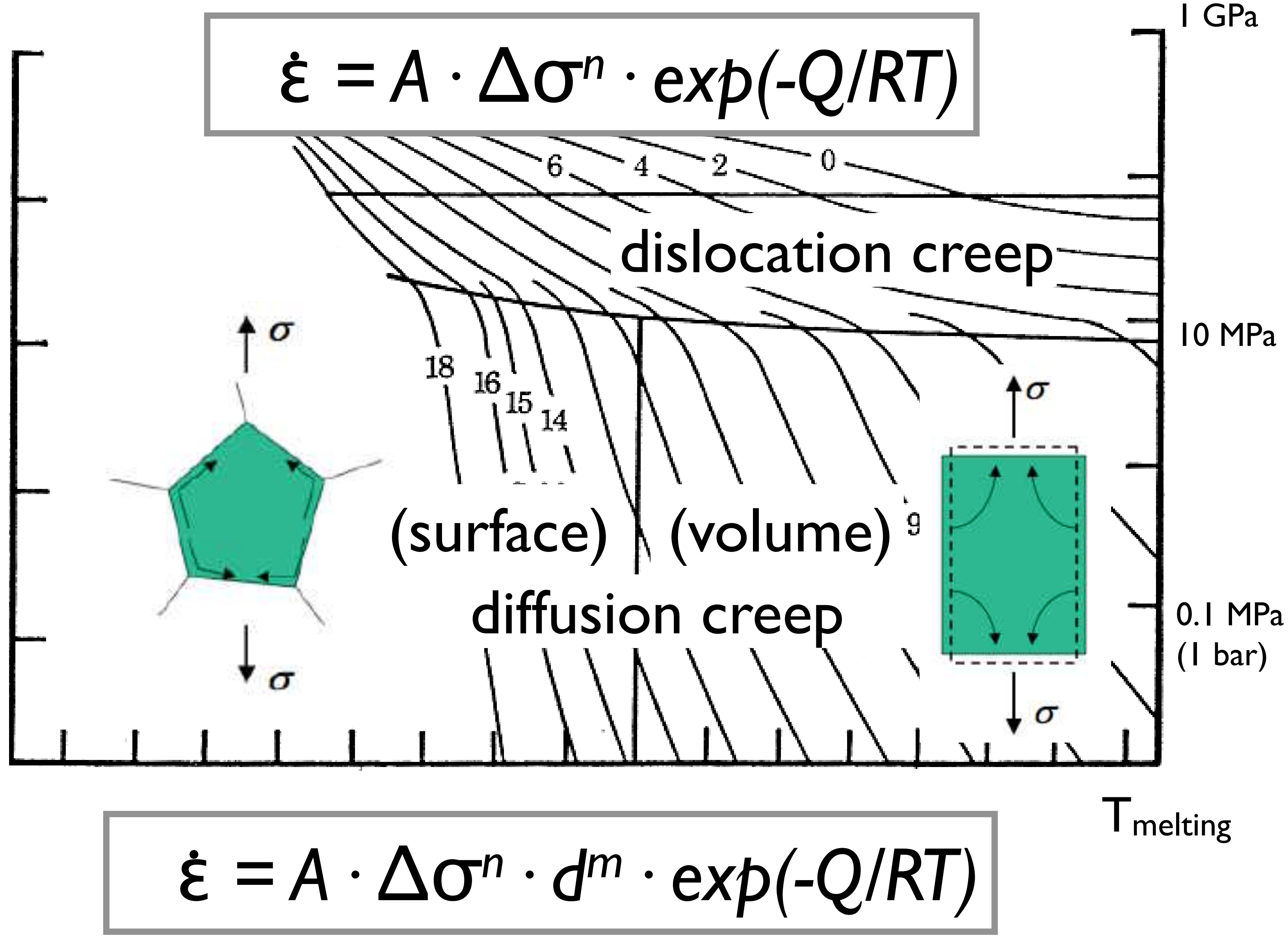
2 Black Hills Quartzite
solid medium apparatus
Brown University
$\gamma < 8$

3 Olivine-Orthopyroxene
torsion apparatus
University of Minnesota
$\gamma < 30$

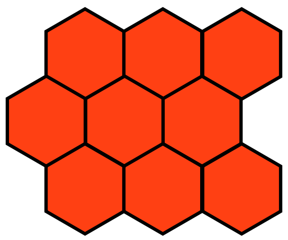
getting weak in the knees

from dislocation creep to diffusion creep

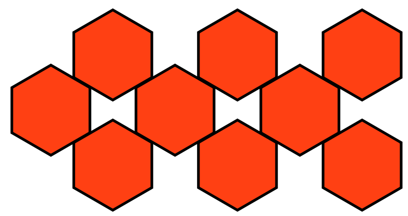




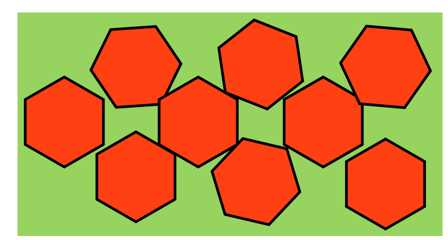
how diffuse is diffusion creep?



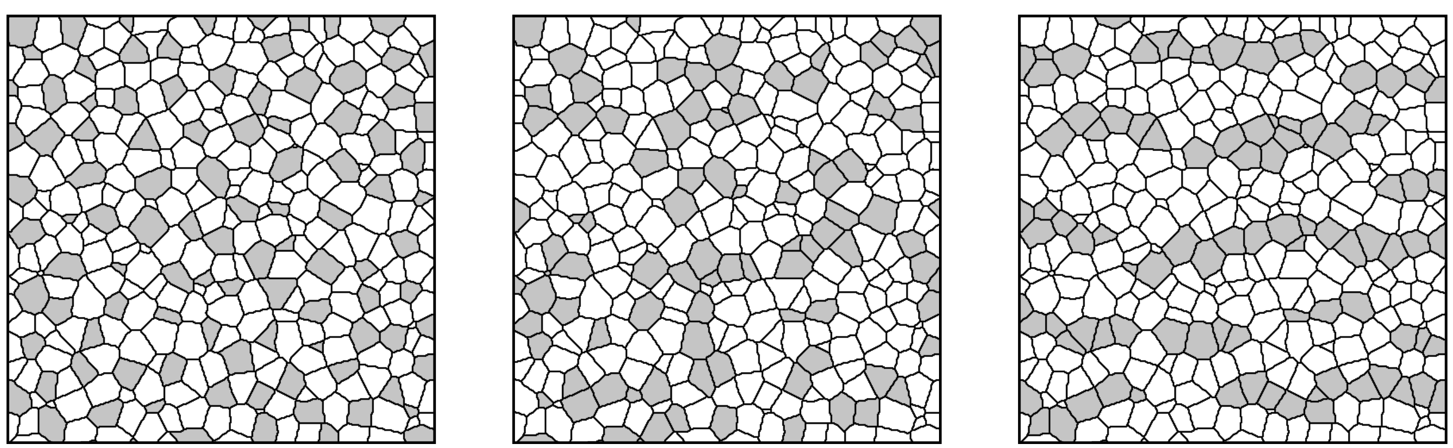
diffusion creep



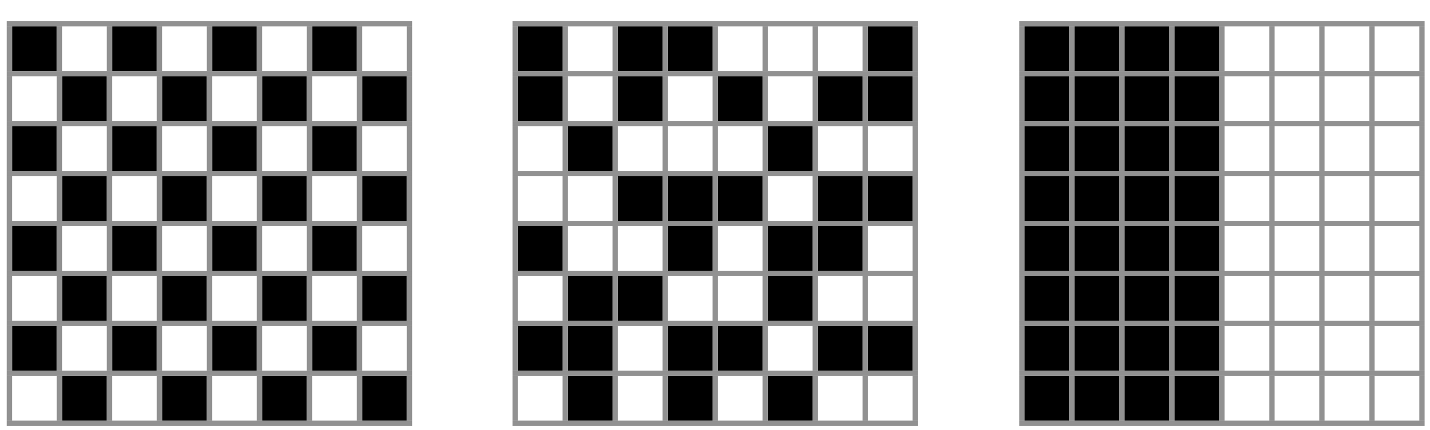
grain boundary sliding

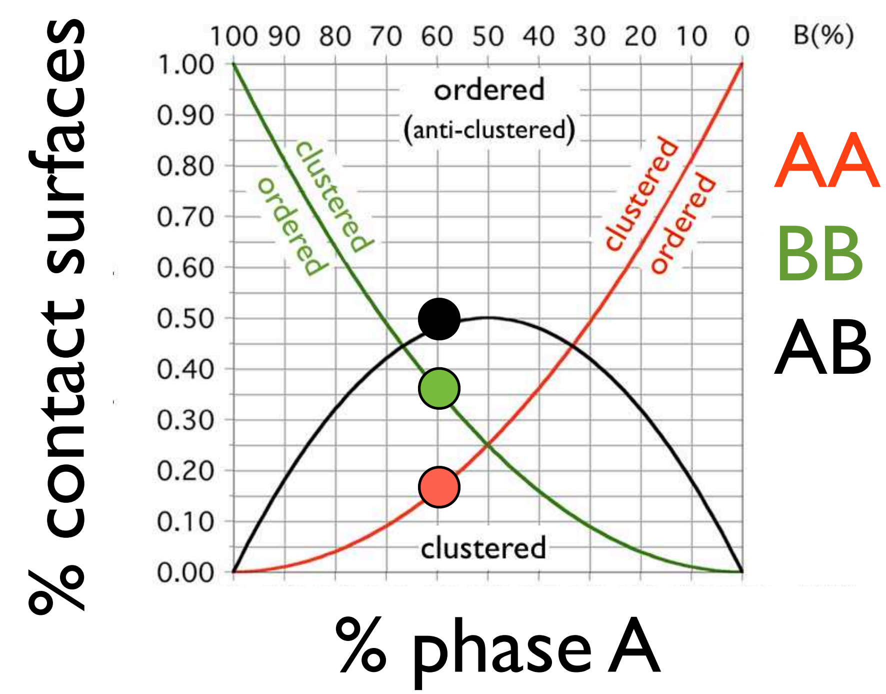


granular flow



ordered random clustered

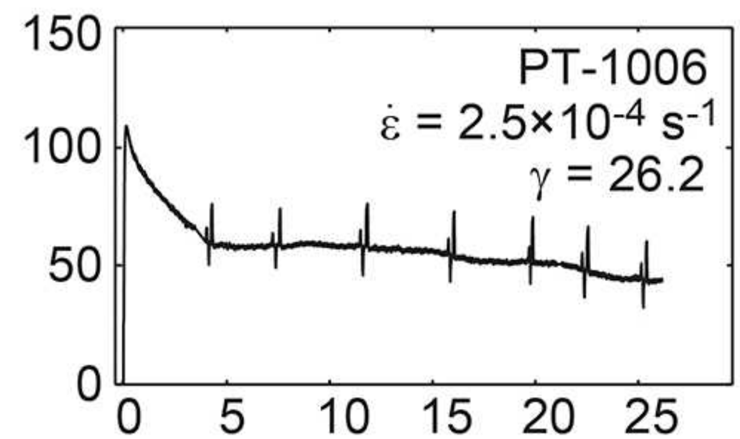




going to high strains

Gas medium High pressure Torsion apparatus (UMN)

powder mixture
70% iron-rich olivine
30% orthopyroxene
hotpressed @1200°C



Miki Tasaka

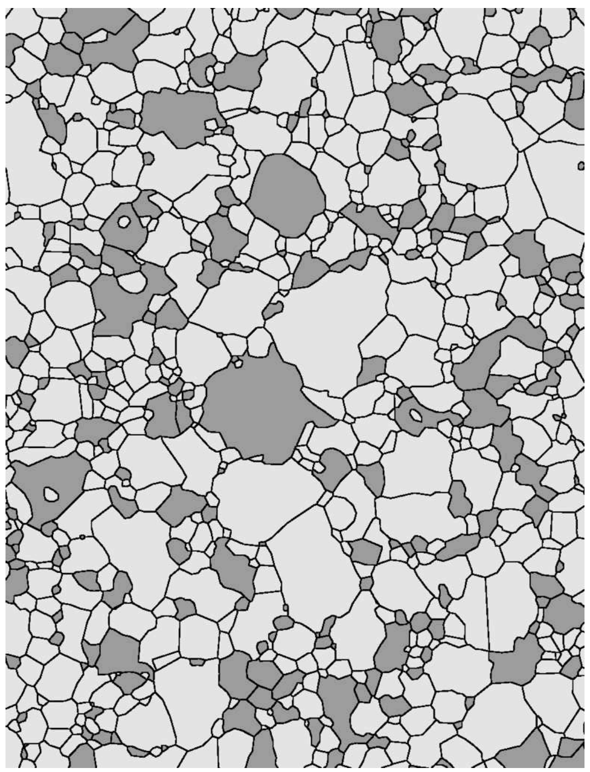
Mark Zimmerman

David Kohlstedt

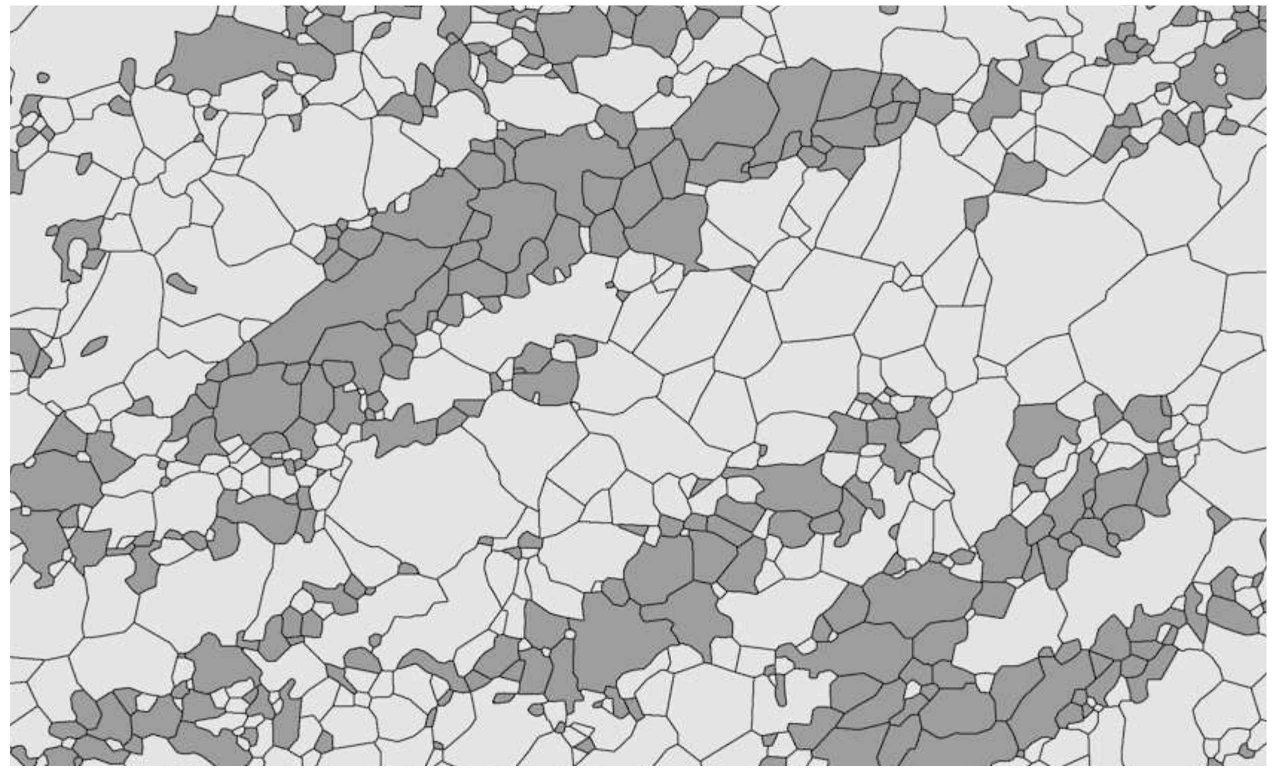
$p_c = 300$ MPa
$T = 1200°C$
$\dot{\gamma} = 2.6 \cdot 10^{-5}$ to $6.8 \cdot 10^{-4}\ s^{-1}$
$\tau = 35$ to 226 MPa
up to $\gamma \sim 26$

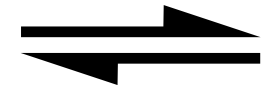
diffusion creep ≠ random

undeformed

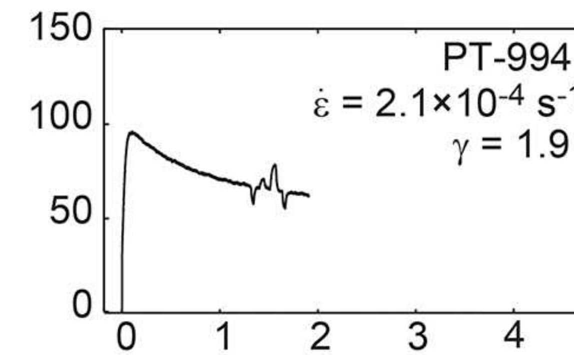


sheared (γ = 1.9)

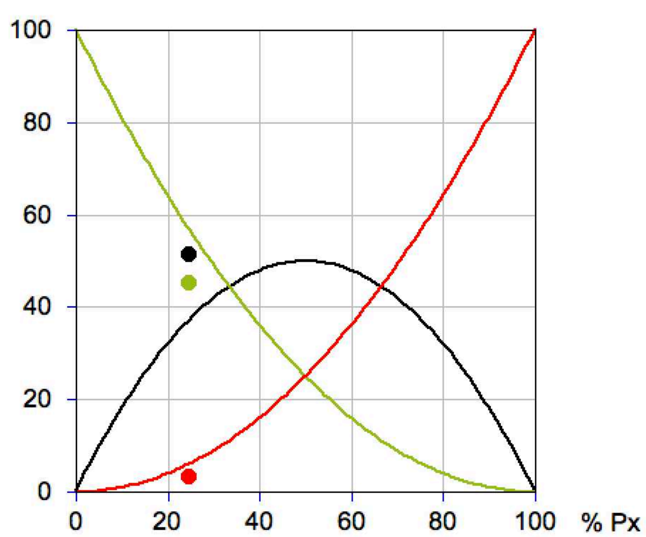


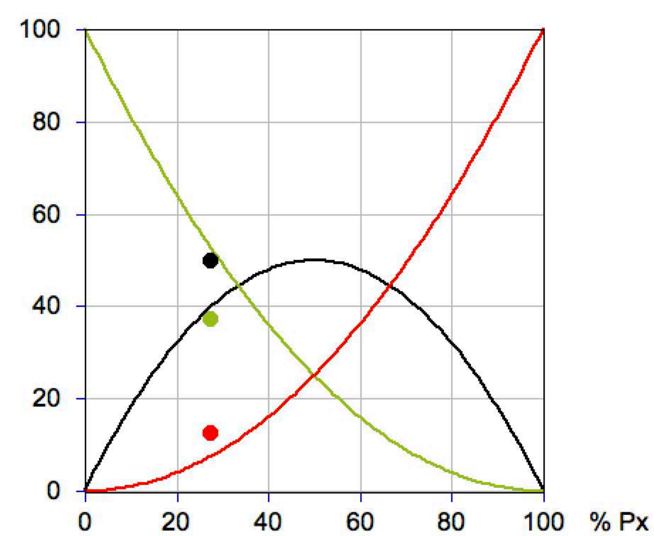


50 µm

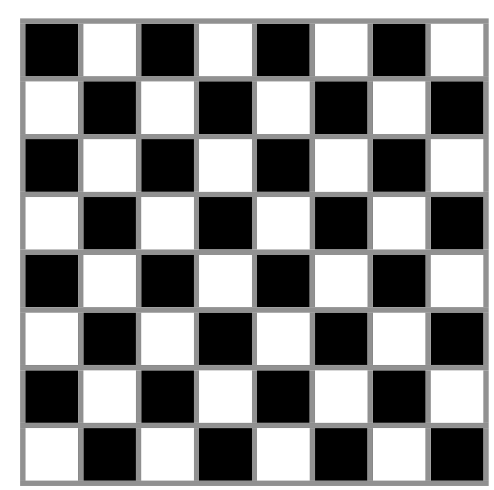


Tasaka et al. (in prep)





=



!

what do we learn

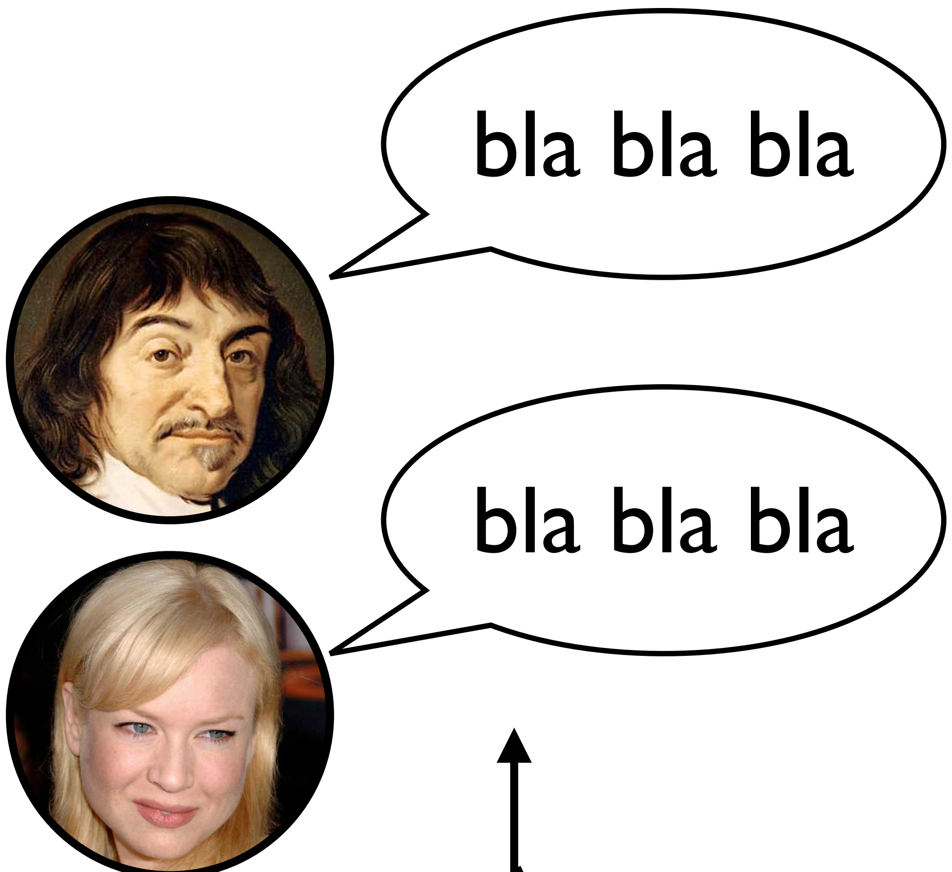
- random does not 'look random'
- diffusion process does not always create random distribution
- starting material is not randomly mixed

so what do microstructures tell us ?

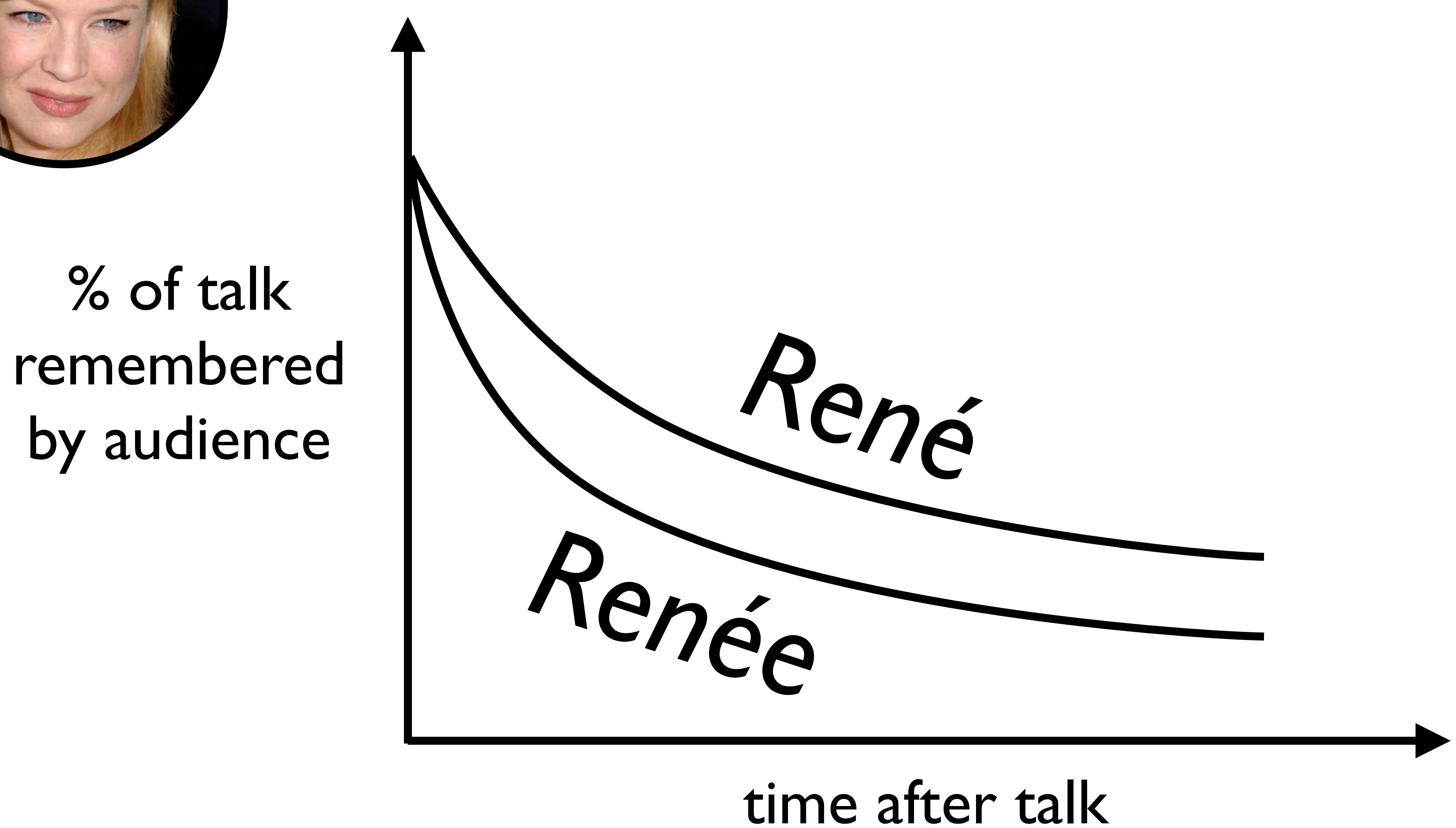
more than you want
not what you expected
confusing stories

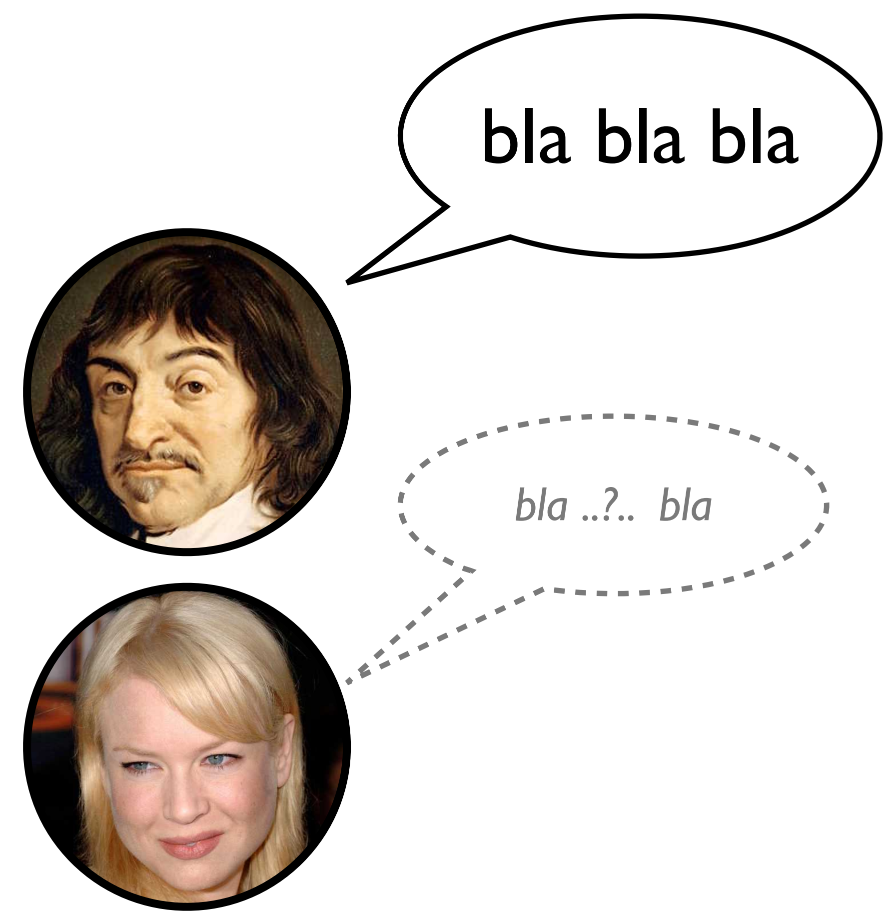
Slow Food® ... for thought

"Finally..."

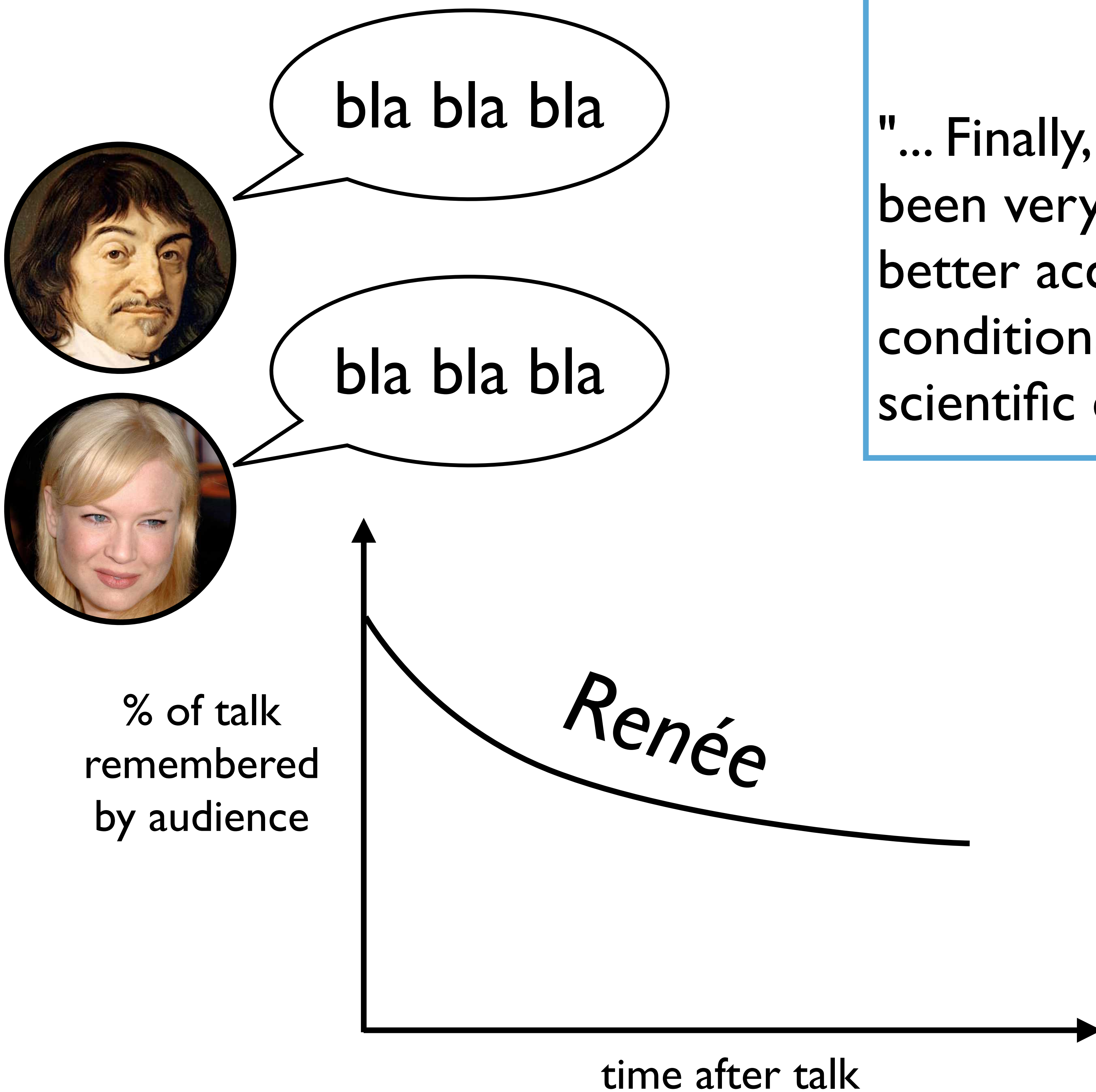


"... Finally, Heilbronner has also been very involved in creating better acceptance and working conditions of women in the scientific community."





"Finally..."



"... Finally, Heilbronner has also been very involved in creating better acceptance and working conditions of women in the scientific community."


Betti Richter
Rüdiger Kilian
Sina Marti
Renée Heilbronner
FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION
UNI BASEL
UNIVERSITY OF TROMSØ
ATM
ETH Zürich
ONCE UPON A TIME IN THE WEST