

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

Renée Heilbronner

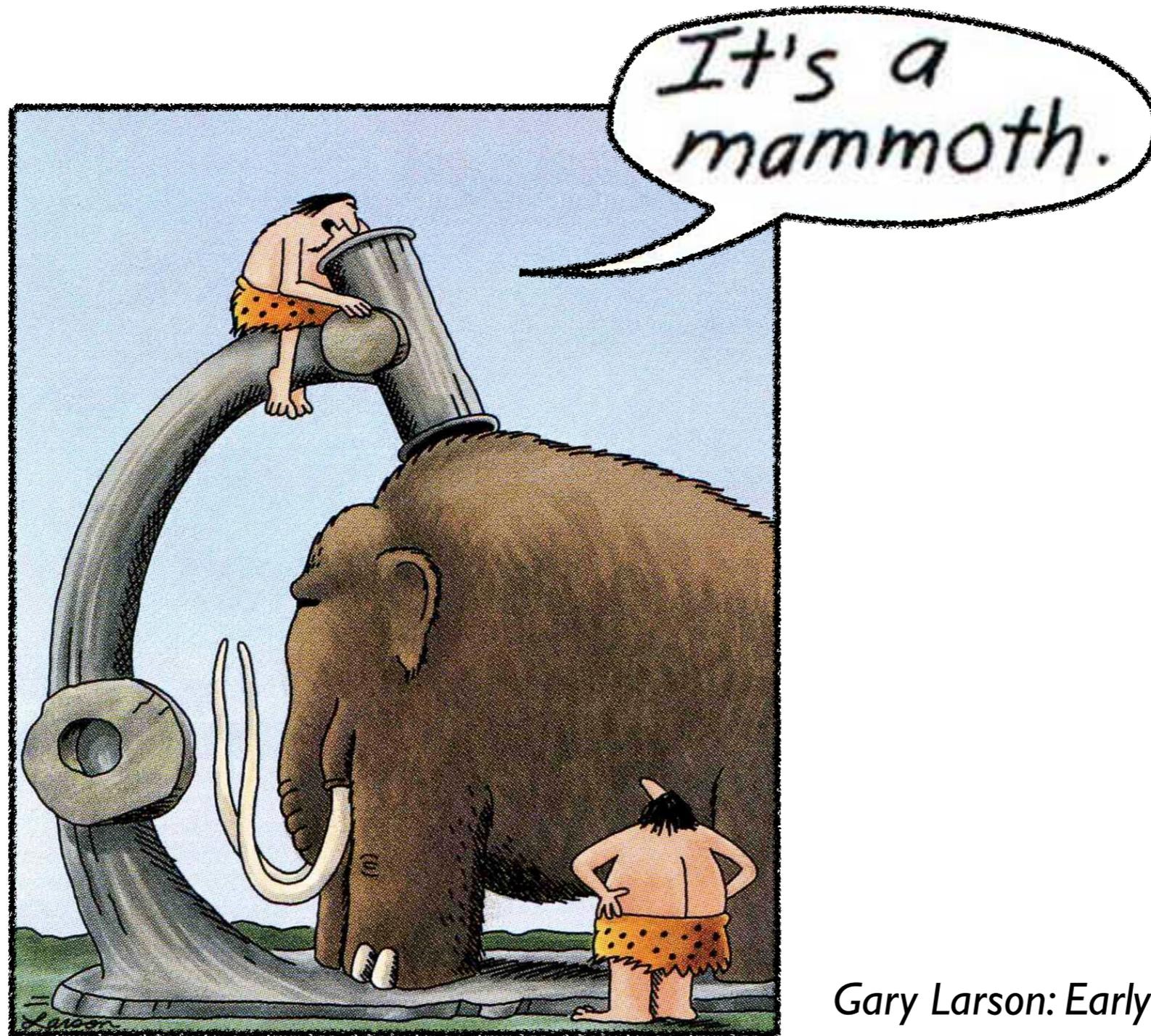


Basel University
Tromsø University



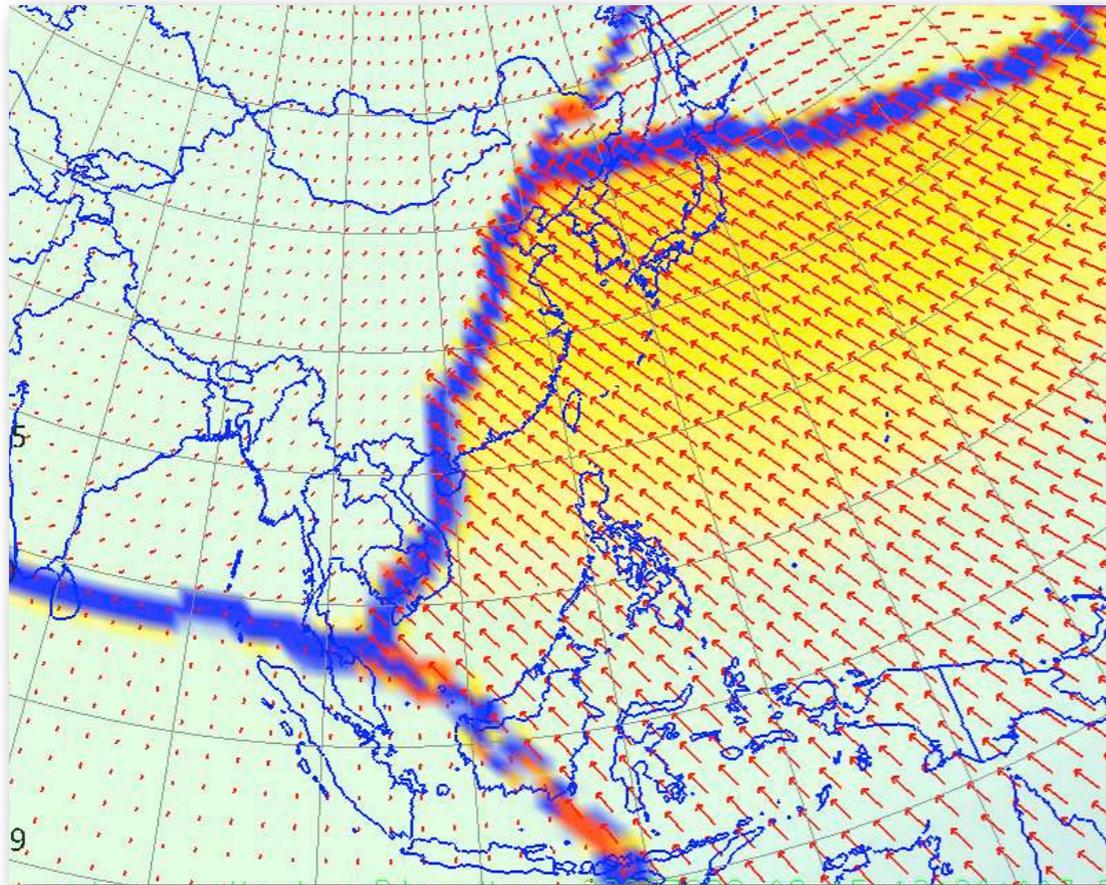
Stefan Müller medal lecture

mammoth and lithosphere

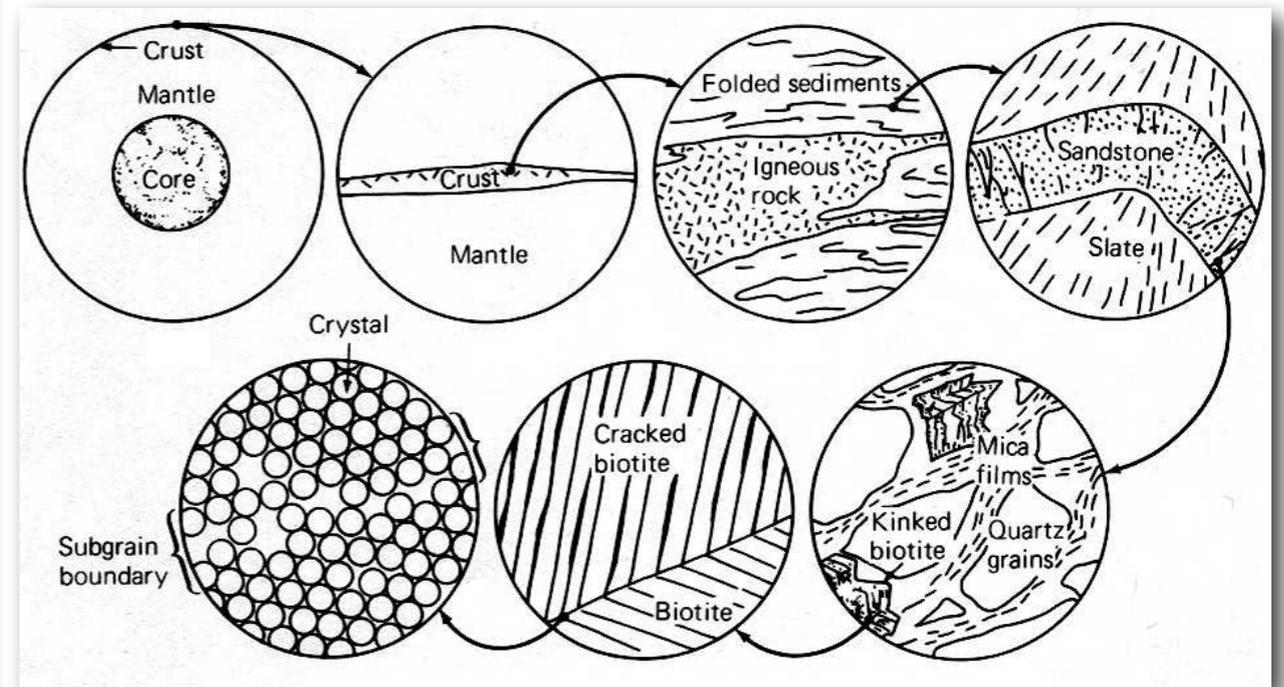


Gary Larson: Early microscopy

deformation \leftrightarrow weakening



www.unavco.org

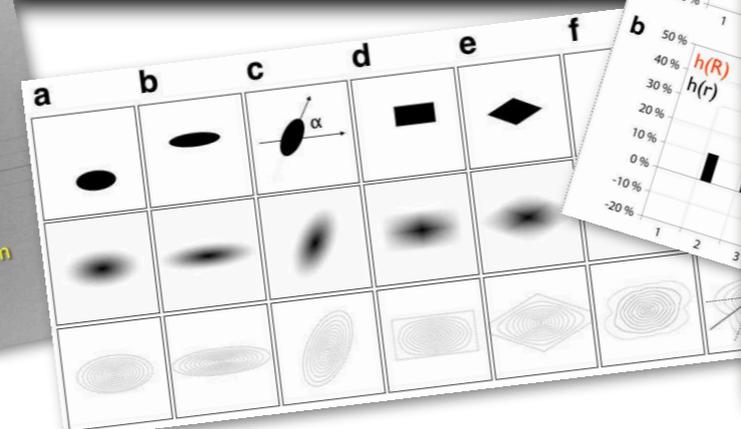


Win Means: Stress and Strain (1976)

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)

how to observe by watching ...



Renée Heilbronner - Steve Barrett
Image Analysis in Earth Sciences
 Microstructures and Textures of Earth Materials

Image Analysis in Earth Sciences is a graduate level textbook for researchers and students interested in the quantitative microstructure and texture analysis of earth materials. Methods of analysis and applications are introduced using carefully worked examples. The input images are typically derived from earth materials acquired at a wide range of scales through digital photography, light and electron microscopy. The book focuses on image acquisition, pre- and post-processing, on the extraction of objects (segmentation), the analysis of volumes and grain size distributions, on shape fabric analysis (particle and surface fabrics) and the analysis of the frequency domain (FFT and ACF). The last chapters are dedicated to the analysis of crystallographic fabrics and orientation imaging. Throughout the book the free software Image SXM is used.

Renée Heilbronner has many years of experience in the field of image analysis and has developed several software packages for microstructure analysis of grain size, shape and strain determinations. She has also developed the CIP method for crystallographic texture determination and orientation imaging based on polarization microscopy and digital image processing. She has contributed to the development of the freeware image analysis software (Image SXM, former NIH Image), and is a member of a growing group of international image analysis experts who are setting up workshops and building a network for microstructure and texture research involving mathematicians, material scientists and geologists. As an experienced teacher of image analysis at different levels ranging from general introductory courses to specialized texture workshops, she has taught at various universities all over the world. <http://pages.unibas.ch/earth/micro>

Steve Barrett is the author of the internationally renowned image analysis software Image SXM. He has been developing the software continuously over the past two decades, from its origins as a spin-off from the freeware NIH Image, to the extensions that allow it to handle images from over fifty types of optical and scanning microscopes. A customized version of this software (Ovin-GIP) based on the CIP method can handle the calculation, display, analysis and manipulation of images representing the crystallographic orientation of grains in rock samples imaged by polarizing microscopes. He has published widely in the field of manoscience and has also collaborated with medics to create microscopy image analysis software for medical applications (MIASMA). He has over twenty years experience teaching to undergraduates and postgraduates. <http://www.liv.ac.uk/~sdb>

Earth Sciences
 ISBN 978-3-642-10342-1

 Springer

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)

$$V_V = A_A$$

August Karl Rosiwal (1860–1923)

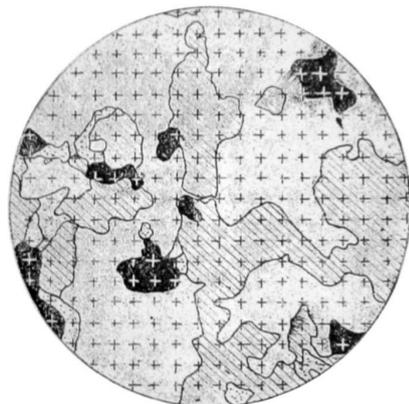
$$V_V = A_A = L_L$$



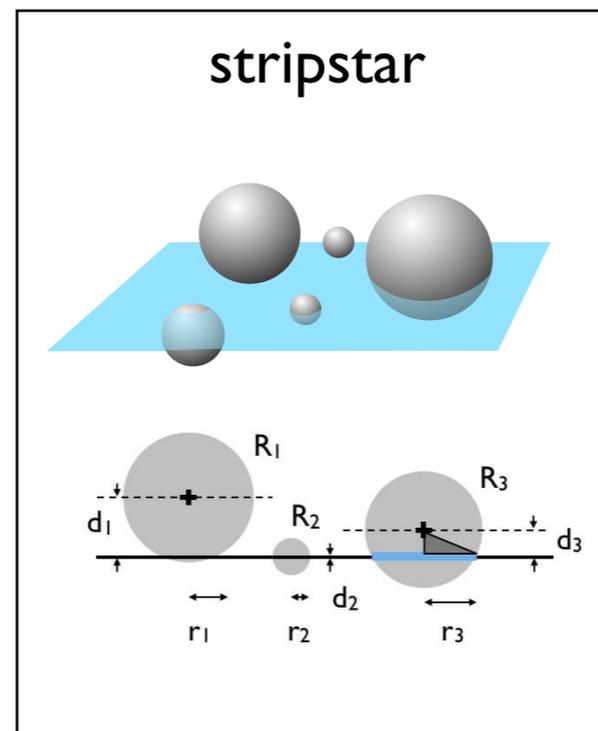
A.K. Rosiwal

Andrei Aleksandrovich Glagolev (1894 –1969)

$$V_V = A_A = L_L = P_P$$



Glagolev and Goldmann (1934)



```
heilbronner — bash — 91x27
Last login: Thu Apr 14 09:30:29 on console
gpi-rh-macbook2:~ heilbronner$ stripstar
-----
*** stripstar ***                               2016-03-01, rh
-----
this program derives a possible distribution of spheres
from measured distributions of sectional areas.
it requires input in the form of binned data:
histogram h(r) where r = radius, h = number frequency
calculates means of all calculated distributions
upgrade: max = 100 bins - variable output
-----

indicate if input is manual (0) or by file (1) >
1

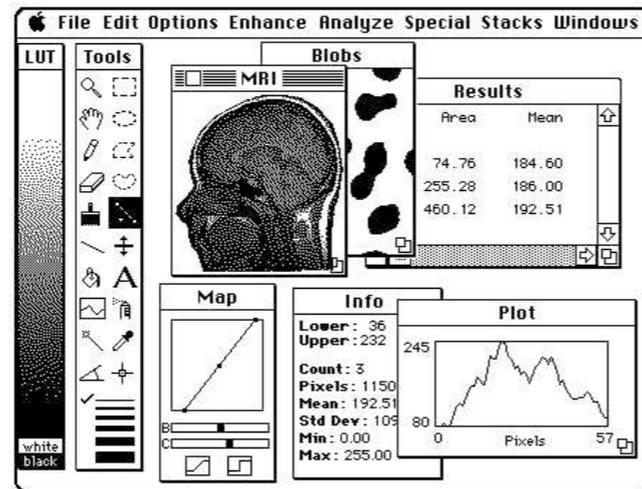
file must contain list of h(r)
line 1: no. of bins (max. = **), width of bin
line 2 ff.: h(r)

name of input file >
do I really have to type in a filename !!!!!
At line 66 of file stripstar.f (unit = 1, file = '')
Fortran runtime error: File 'do I really have to type in a filename !' does not exist
gpi-rh-macbook2:~ heilbronner$
```

getting into digital image analysis



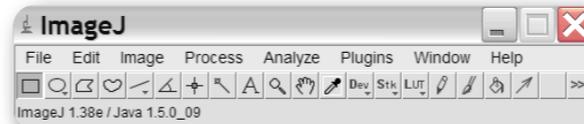
Wayne Rasband



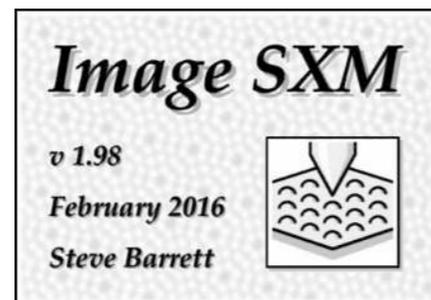
1987 NIH Image (Pascal)

1997 Image J (Java)

2007 → Fiji ('Fiji is just ImageJ')



Steve Barrett



1993 Image SXM (Pascal)

Lazy Macros

→ BASEL UNIVERSITY HOMEPAGE
→ BASEL UNIVERSITY SCIENCE FACULTY (PHIL II)
→ DEPARTMENT OF ENVIRONMENTAL SCIENCES

→ IT-Services – Universitätsrechenzentrum
→ UB – Universitätsbibliothek
→ VL – Vorlesungsverzeichnis

UNIVERSITÄT BASEL

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RESEARCH Projects & Software Workshops Textbook

Vorträge und Links

SXM Macros ImageJ Macros IMAGE ANALYSIS

→ Download

- Lazy CIP LUTs
- Lazy EBSD
- Lazy Pole
- Lazy Prepstack
- Lazy ACF Tiling
- Lazy D-map
- Lazy Digitize
- Lazy Erode Dilate
- Lazy Grain Boundaries
- Lazy Grain Mapping
- Lazy Lighting
- Lazy LUTs
- Lazy Voronoi Contacts

Image Analysis in Earth Sciences

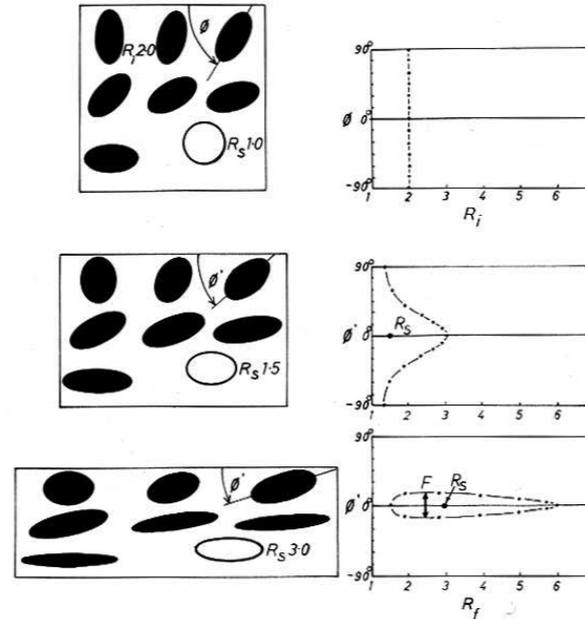
CRUSTAL DYNAMICS HOMEPAGE (English)
GEOLOGY HOMEPAGE (Norwegian)
UNIVERSITY HOMEPAGE (English)

UNIVERSITÄT TROMSØ

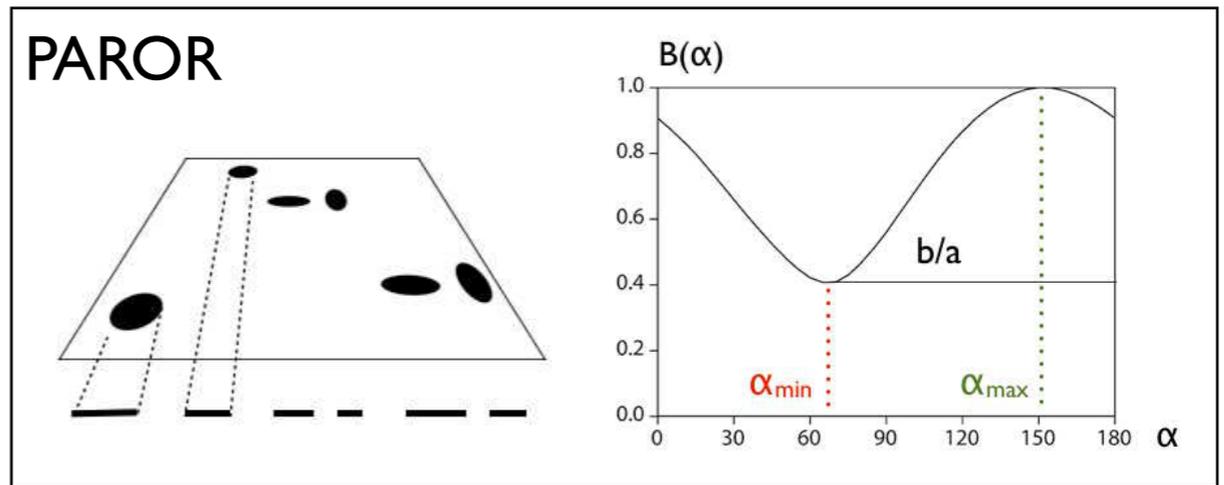
shape and strain of particles



John G. Ramsay



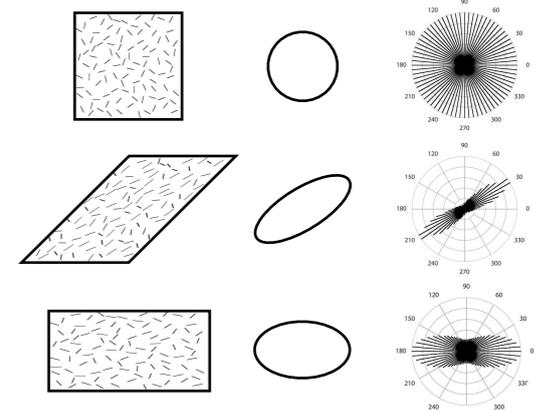
$R_f - \varphi$ method



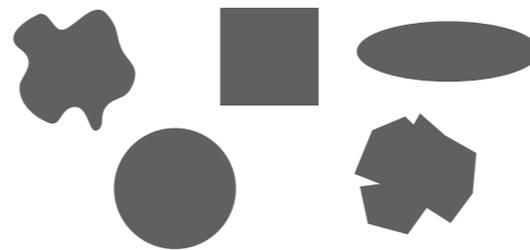
Edwin A. Abbott



SURFOR



shape descriptors: PARIS etc.

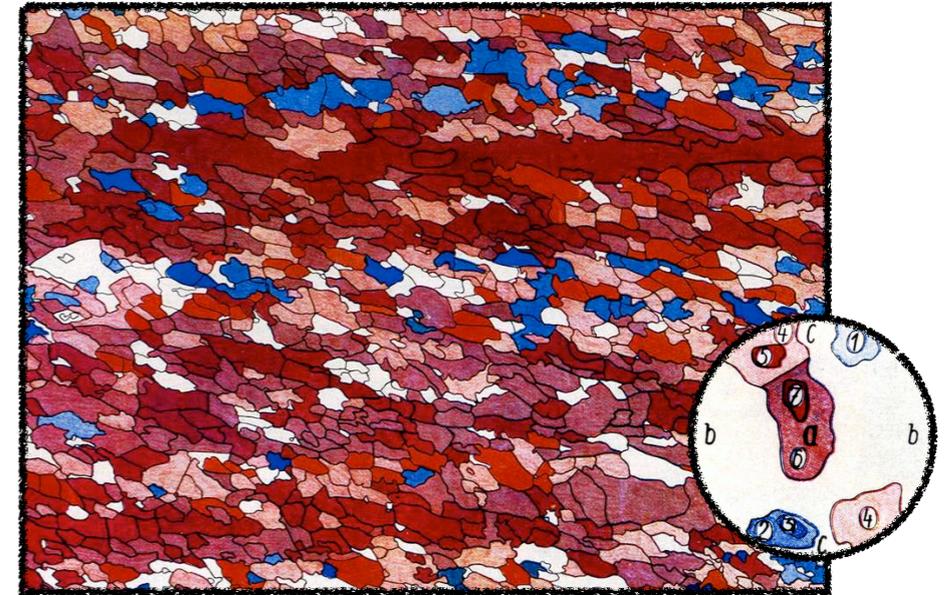


orientation imaging

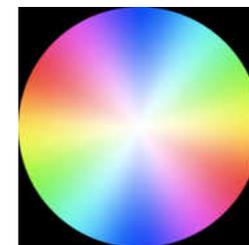
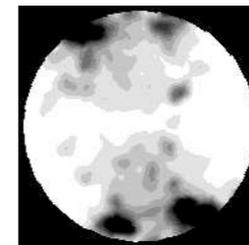
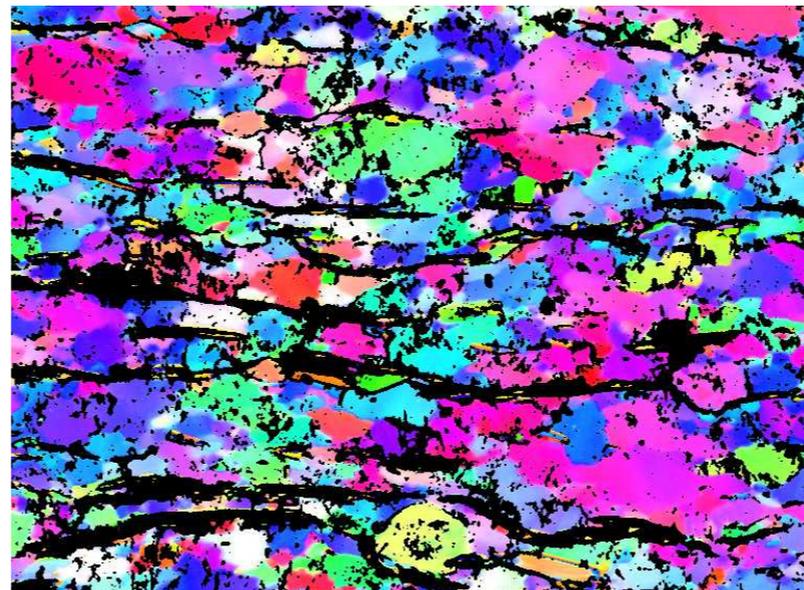
AVA (Achsenverteilungsanalyse)



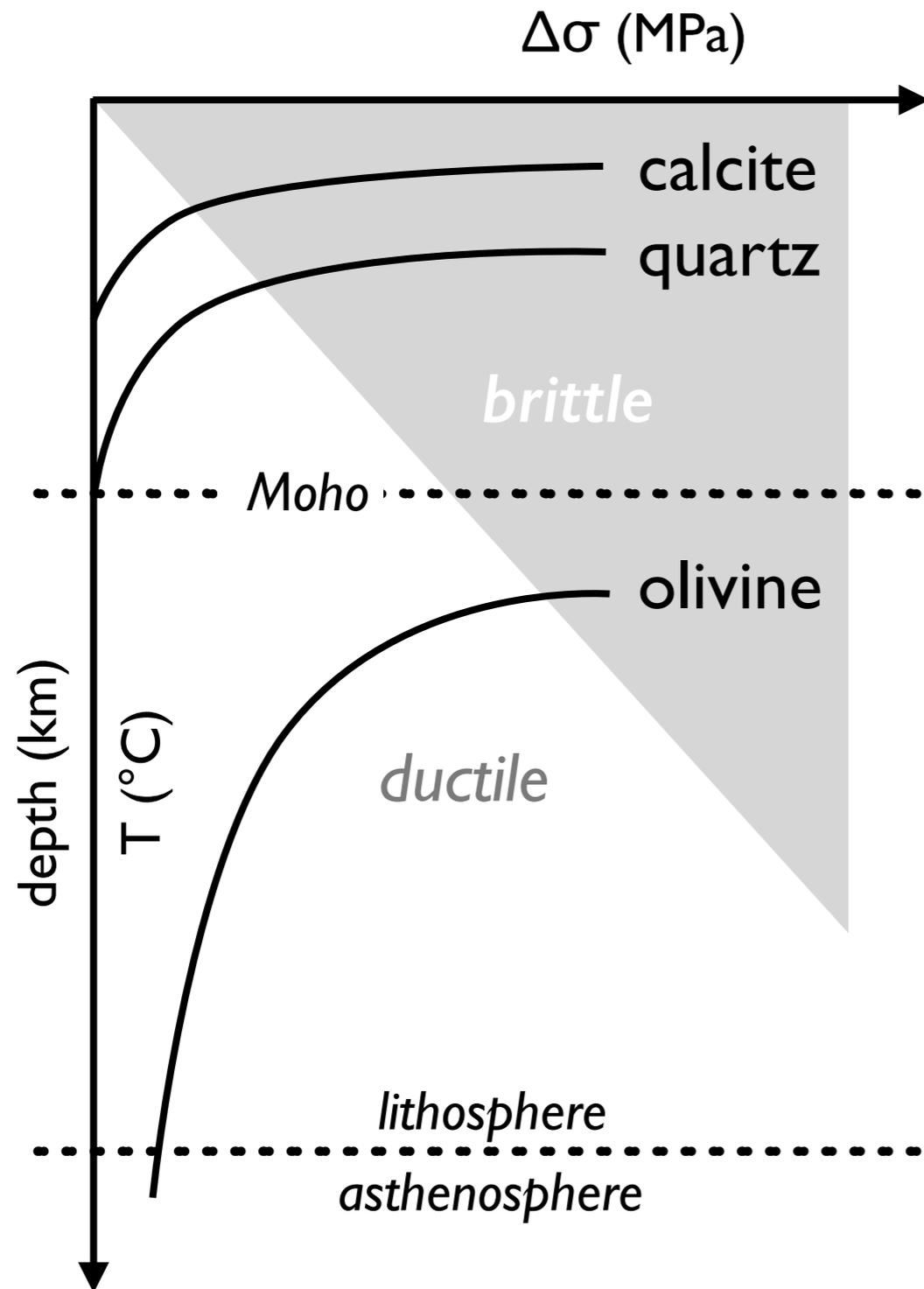
Bruno Sander



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

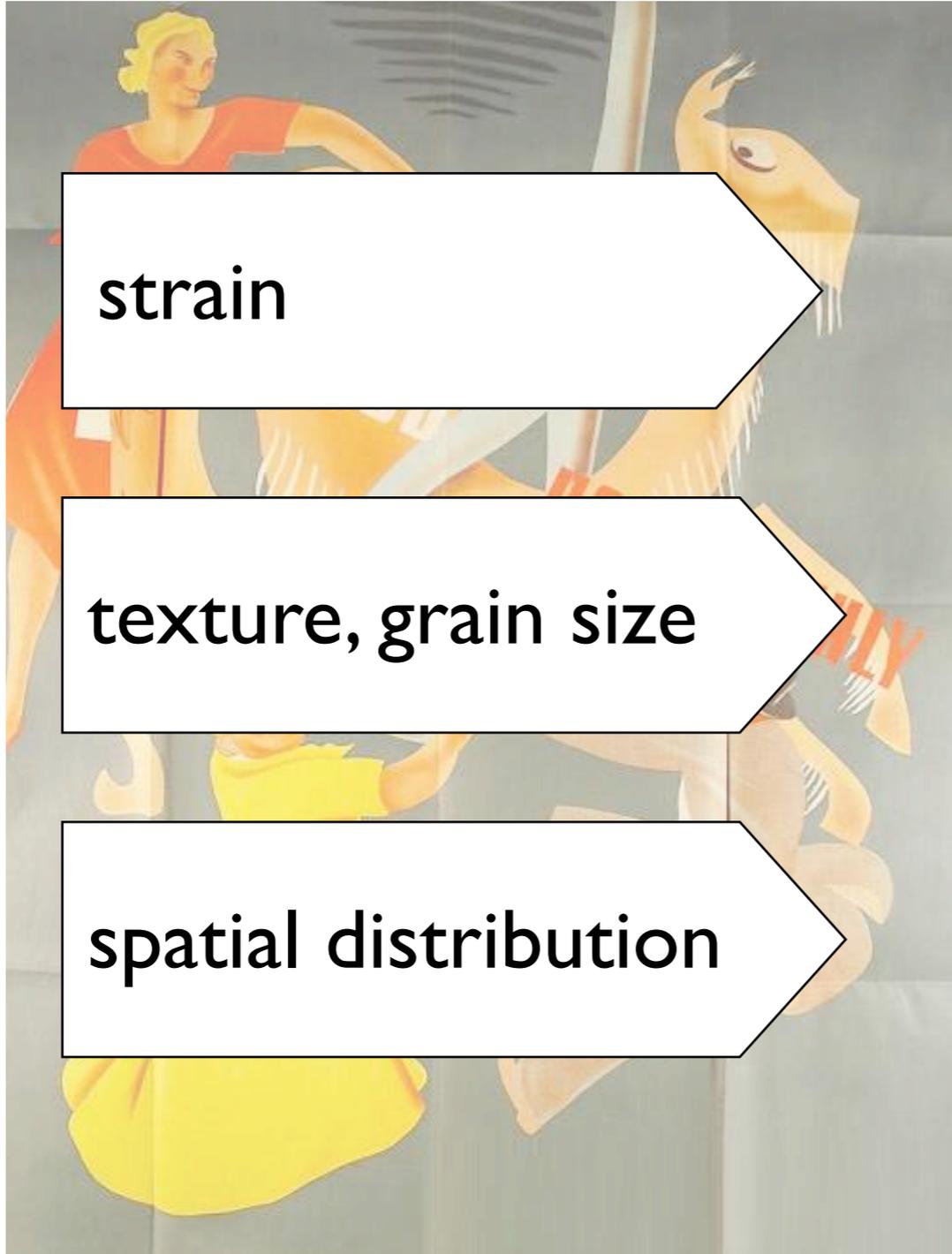
texture, grain size

regime, flow stress

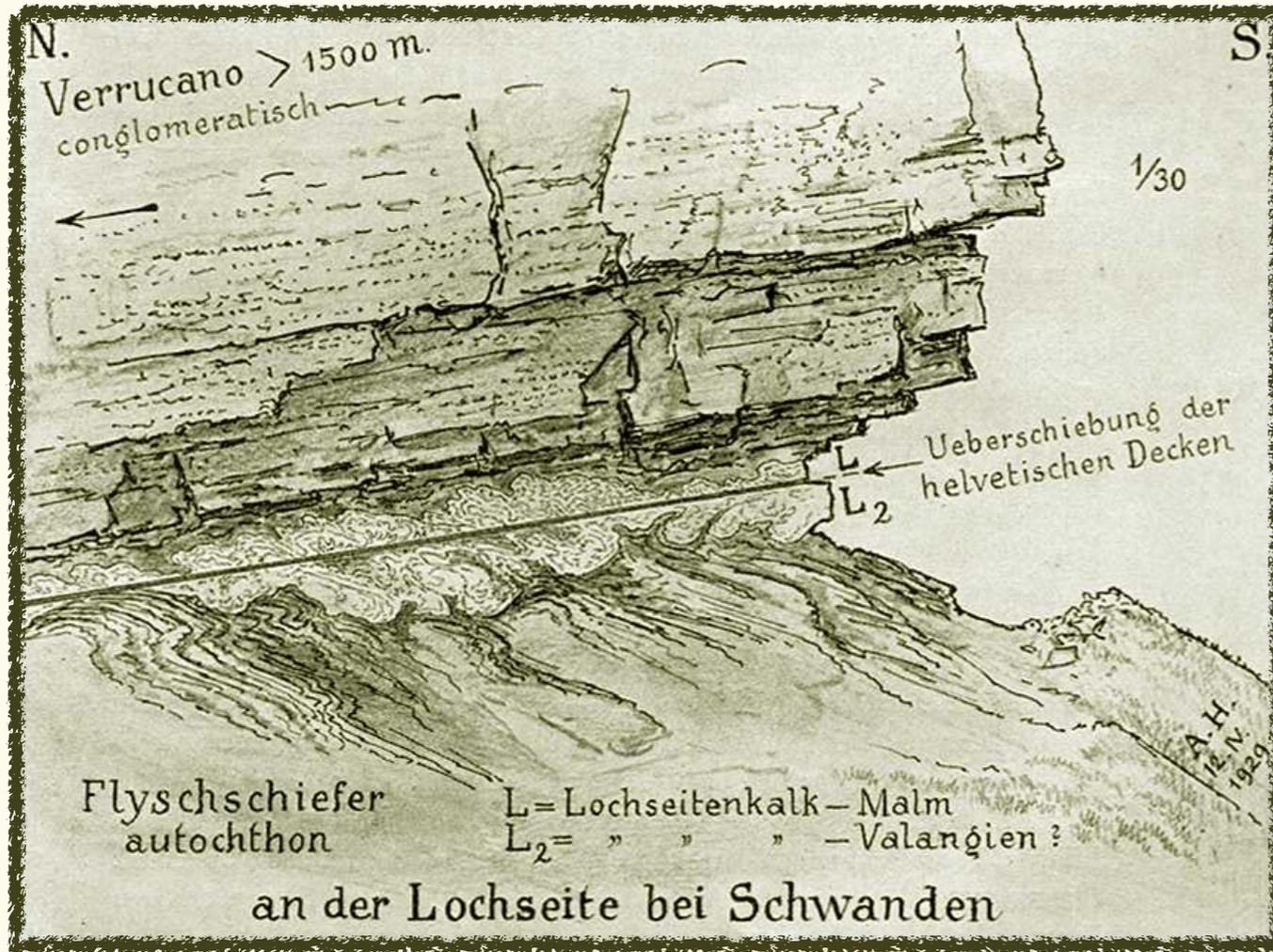
3 Ol-Opx

spatial distribution

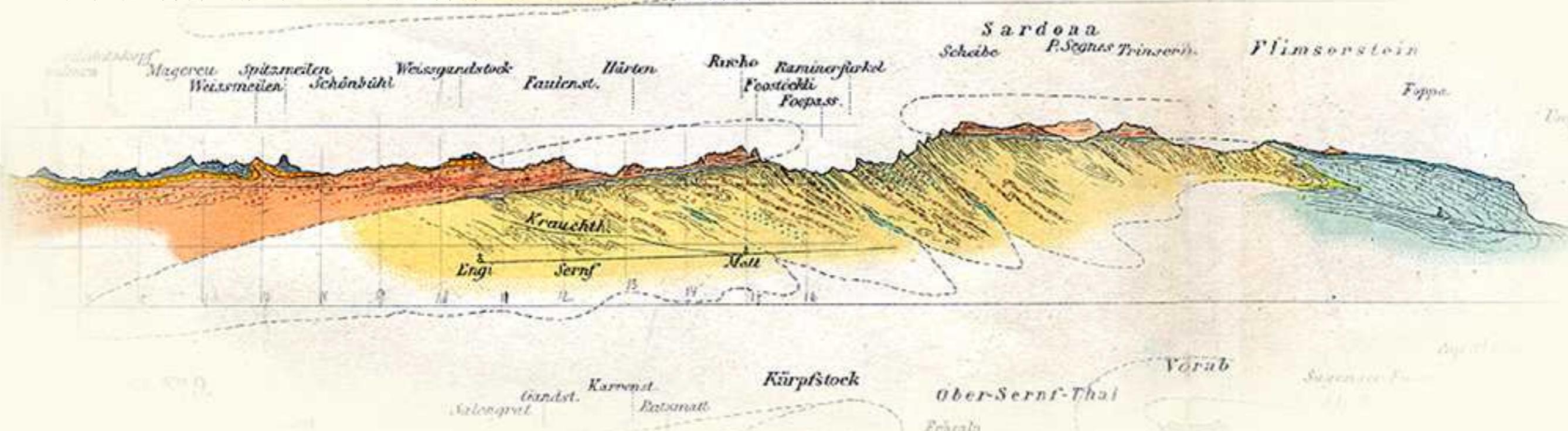
deformation mechanisms?



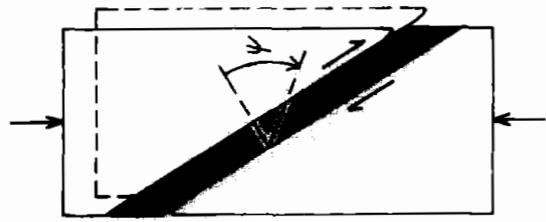
kilometers of displacement



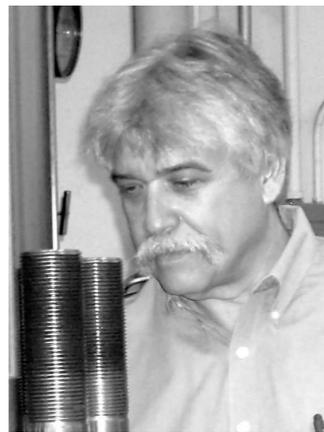
Alber Heim (1929)



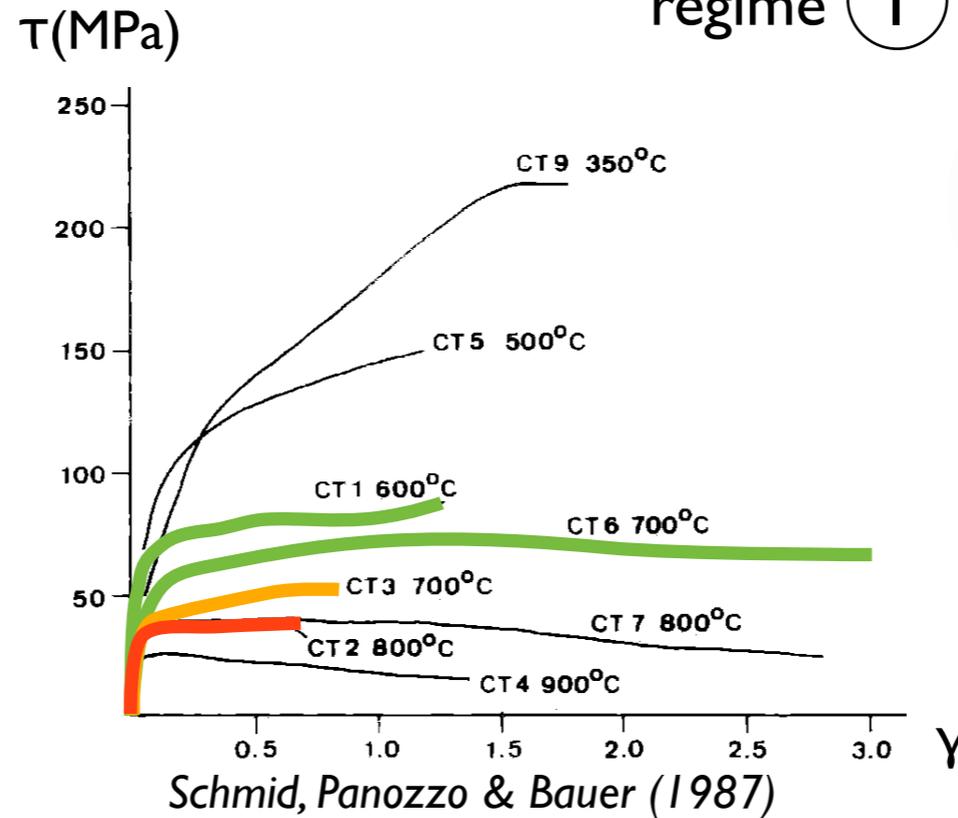
from twinning to superplasticity



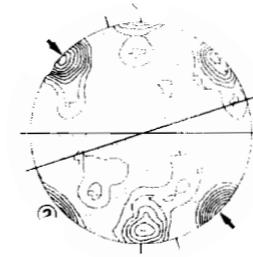
Stefan Schmid



Steve Bauer

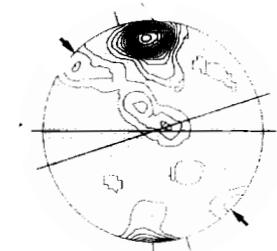


regime ① dislocation glide



CT6

regime ② dislocation creep



CT7

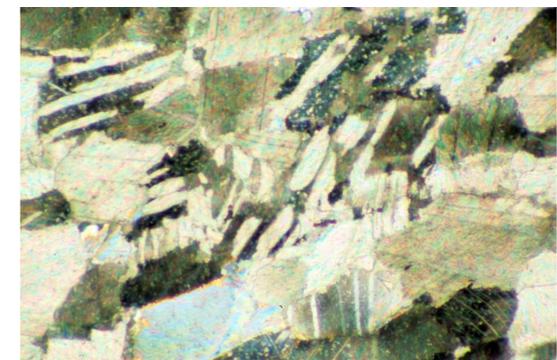
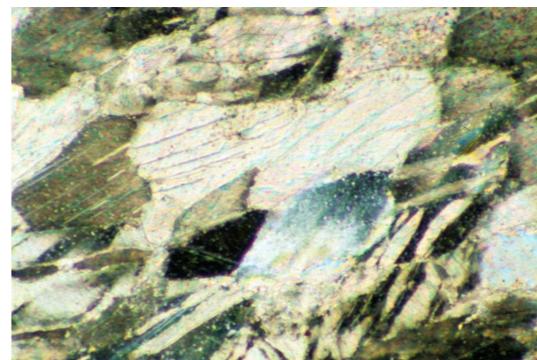
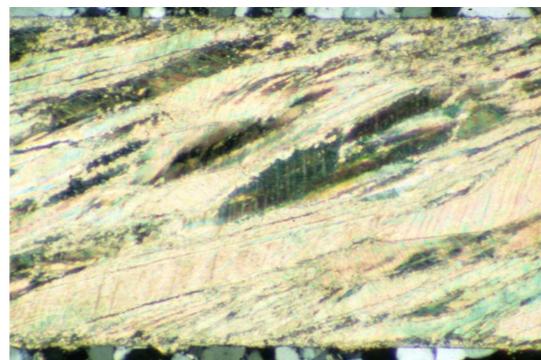
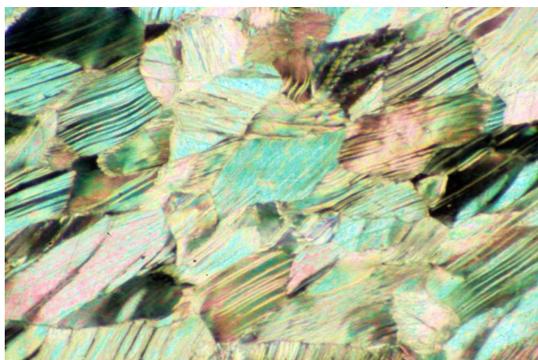


CT1 600°C

CT6 600°C

CT3 700°C

CT2 800°C

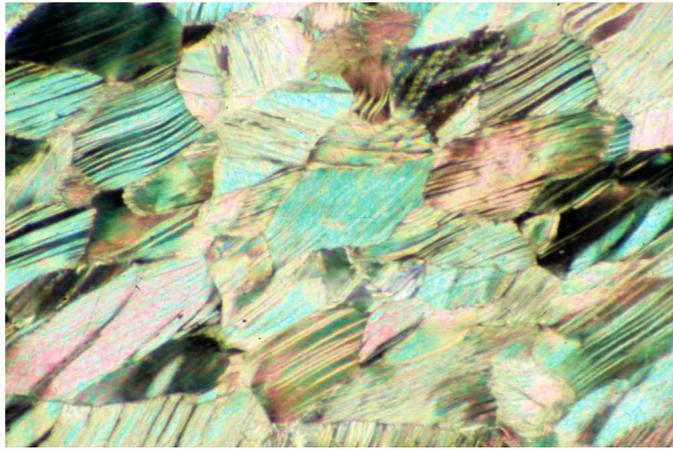


twinning

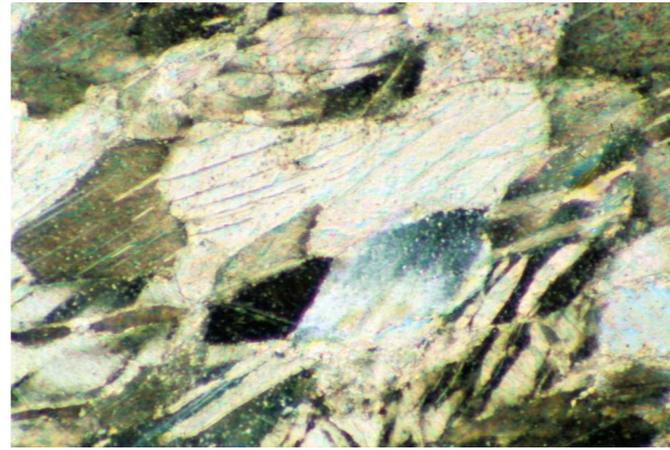
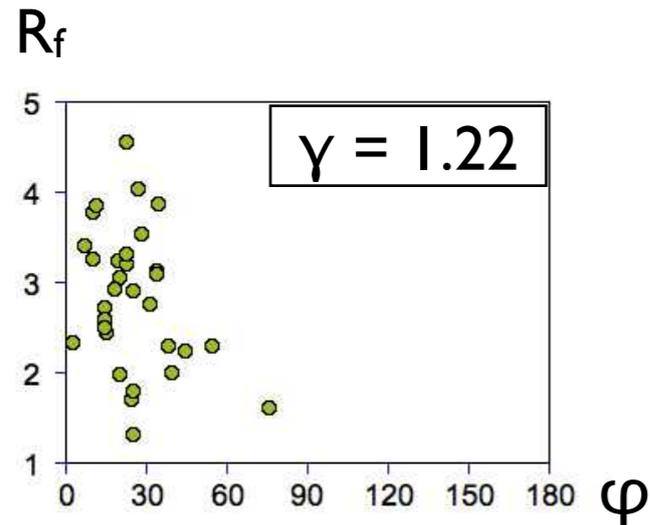
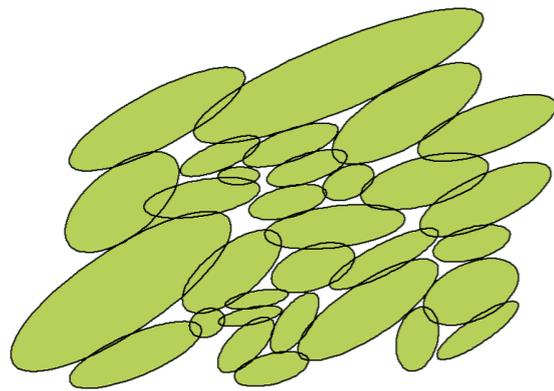
dynamic recrystallization

500 μm

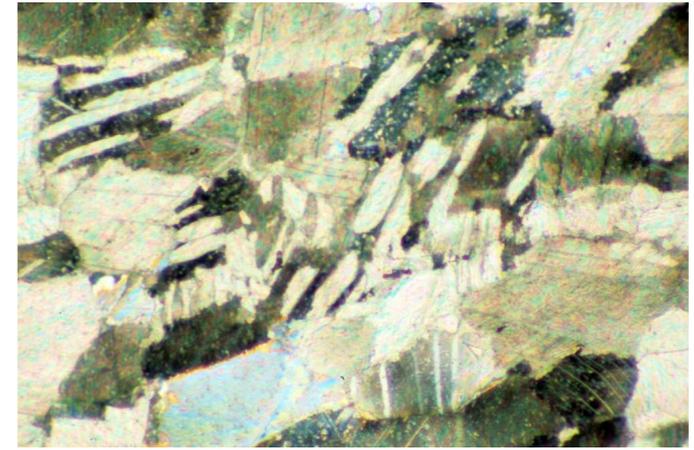
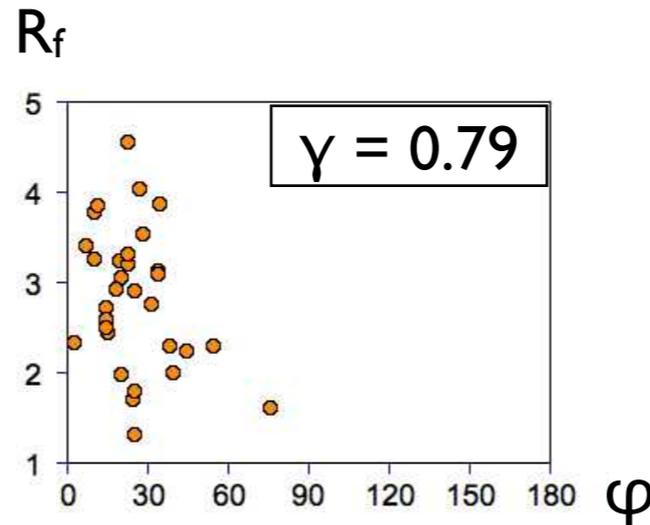
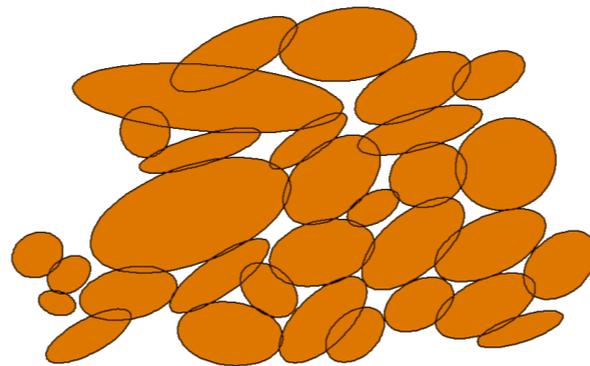
displacement in - shear strain out?



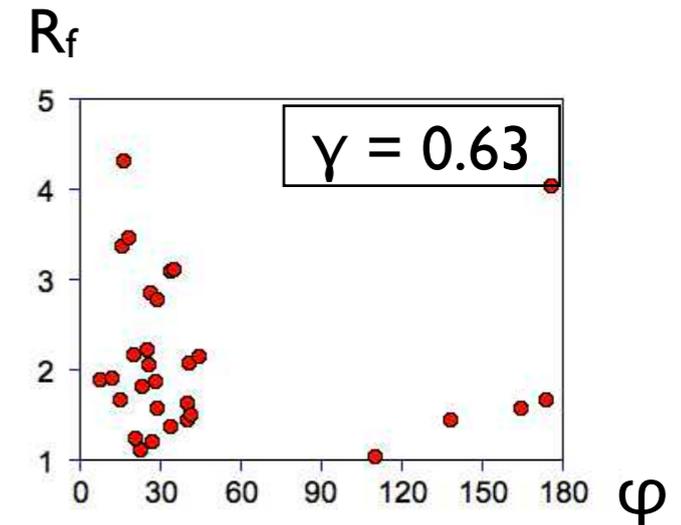
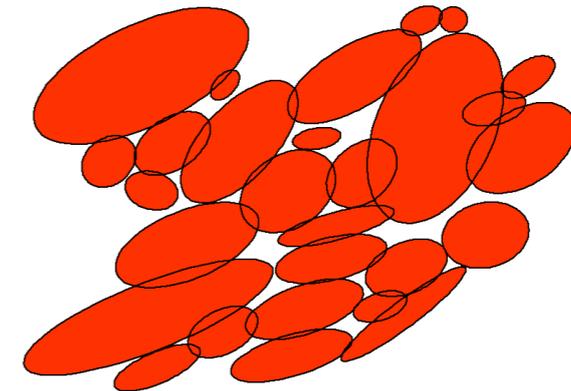
CT1 600°C 500 μm



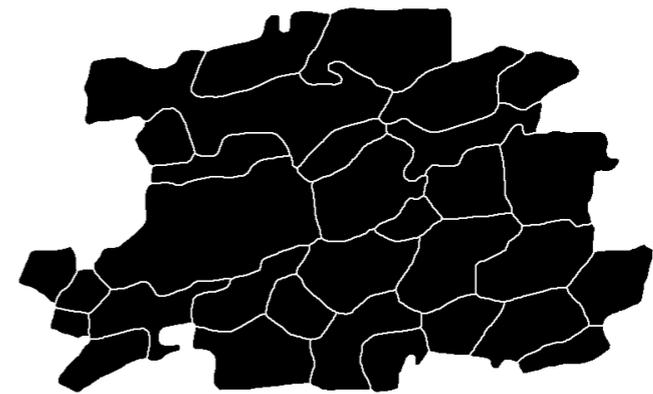
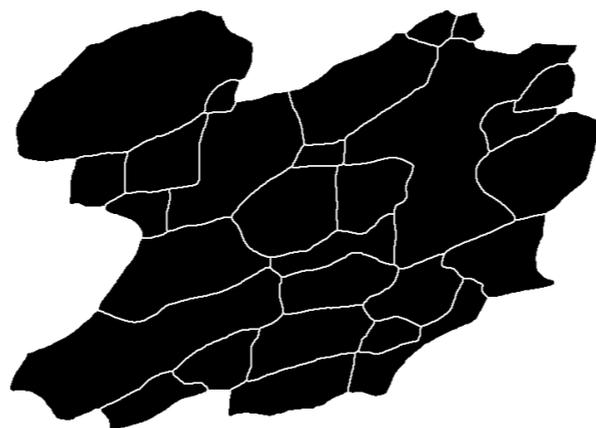
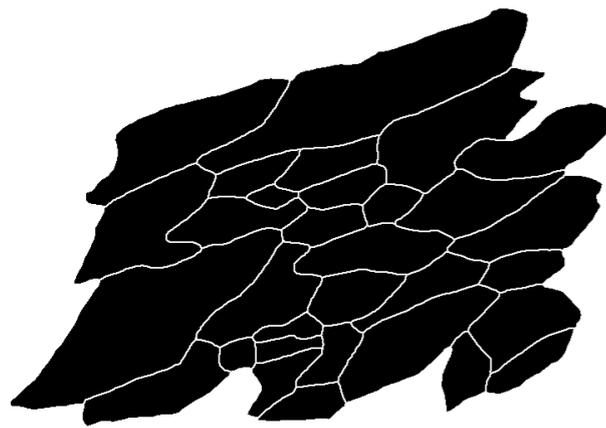
CT3 700°C



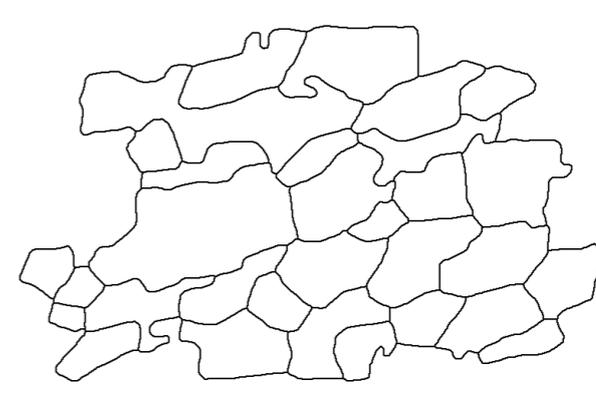
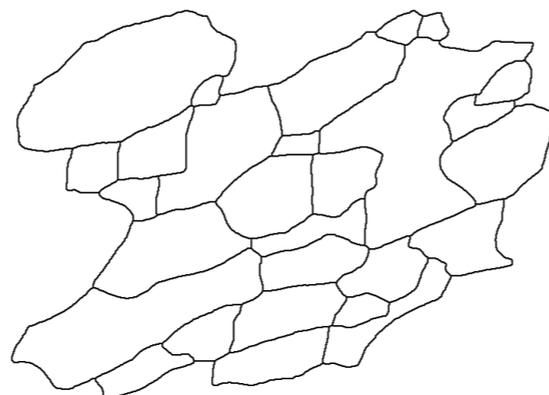
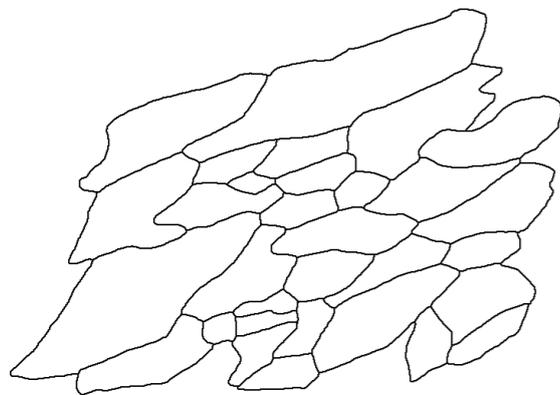
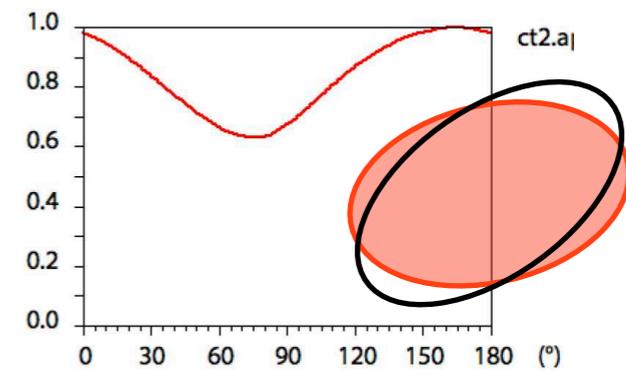
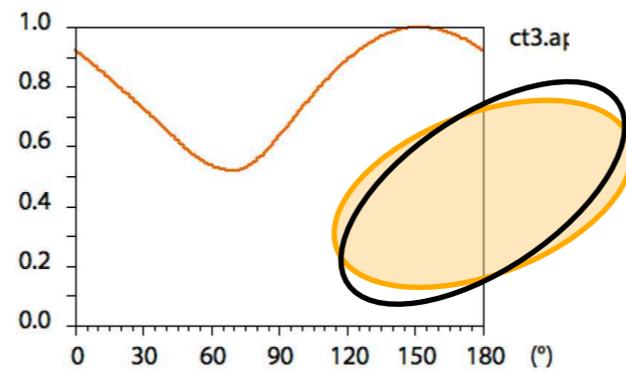
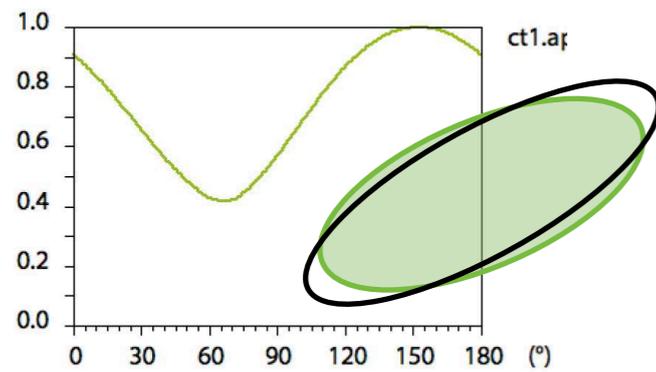
CT2 800°C



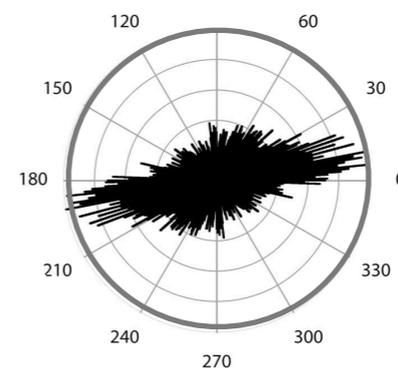
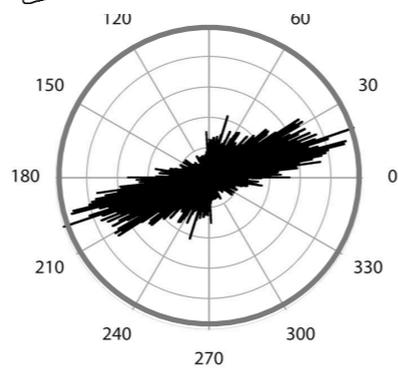
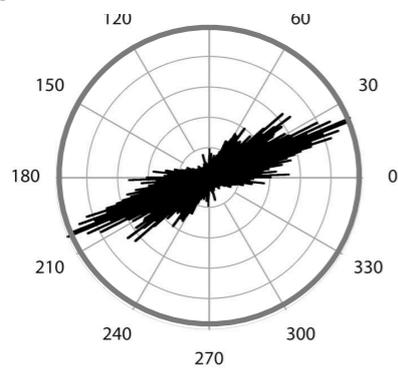
particles and surfaces



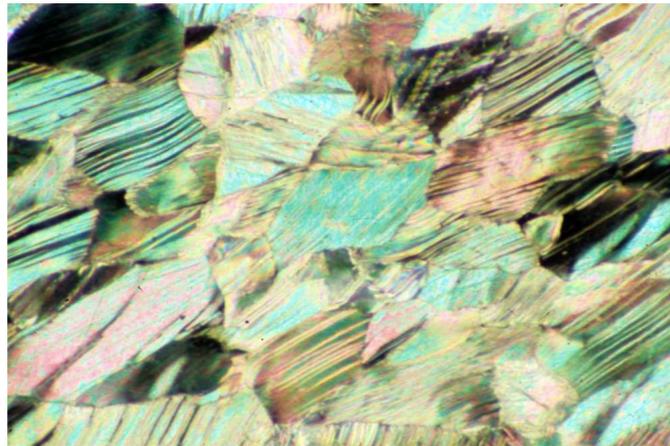
PARFOR



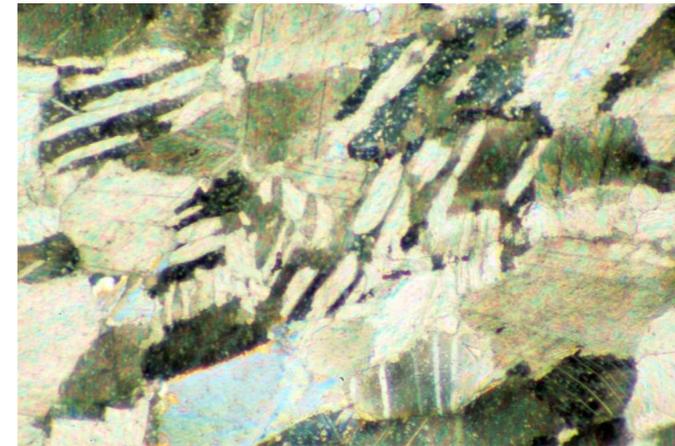
SURFOR



describing 'shape'



CT1 600°C

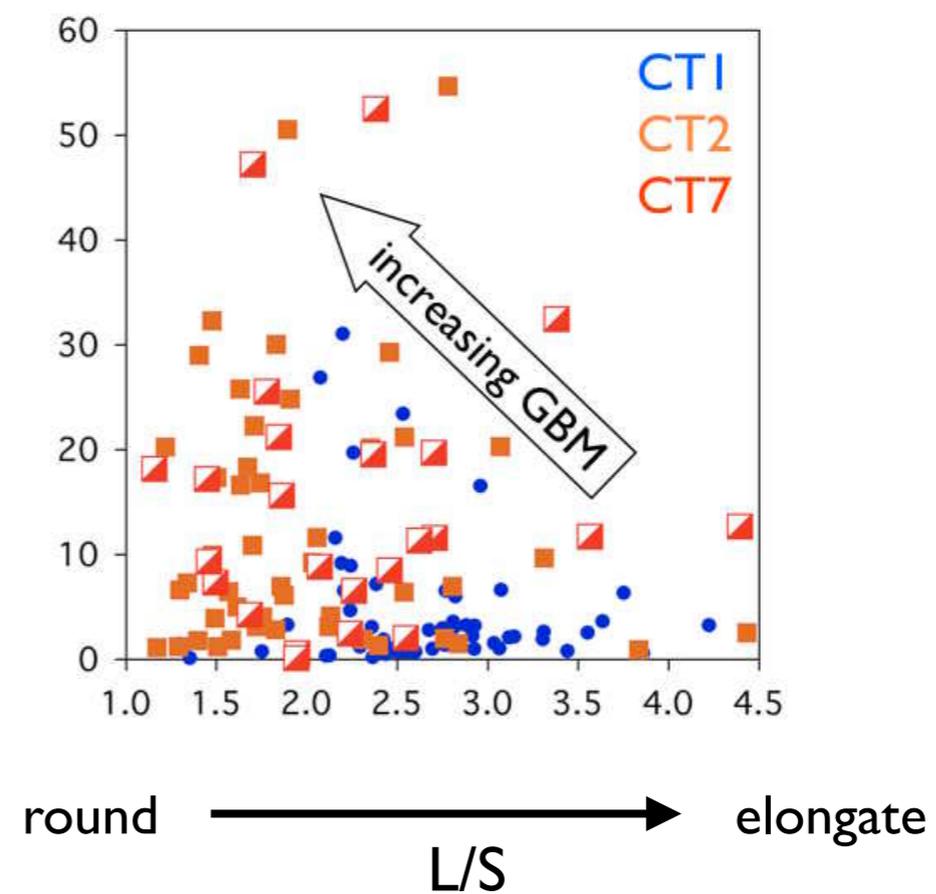


CT2 800°C

500 μm

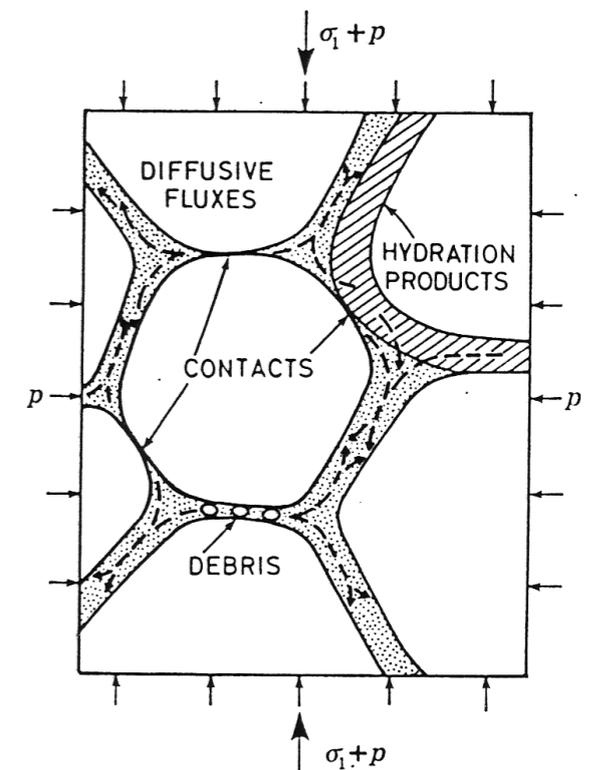
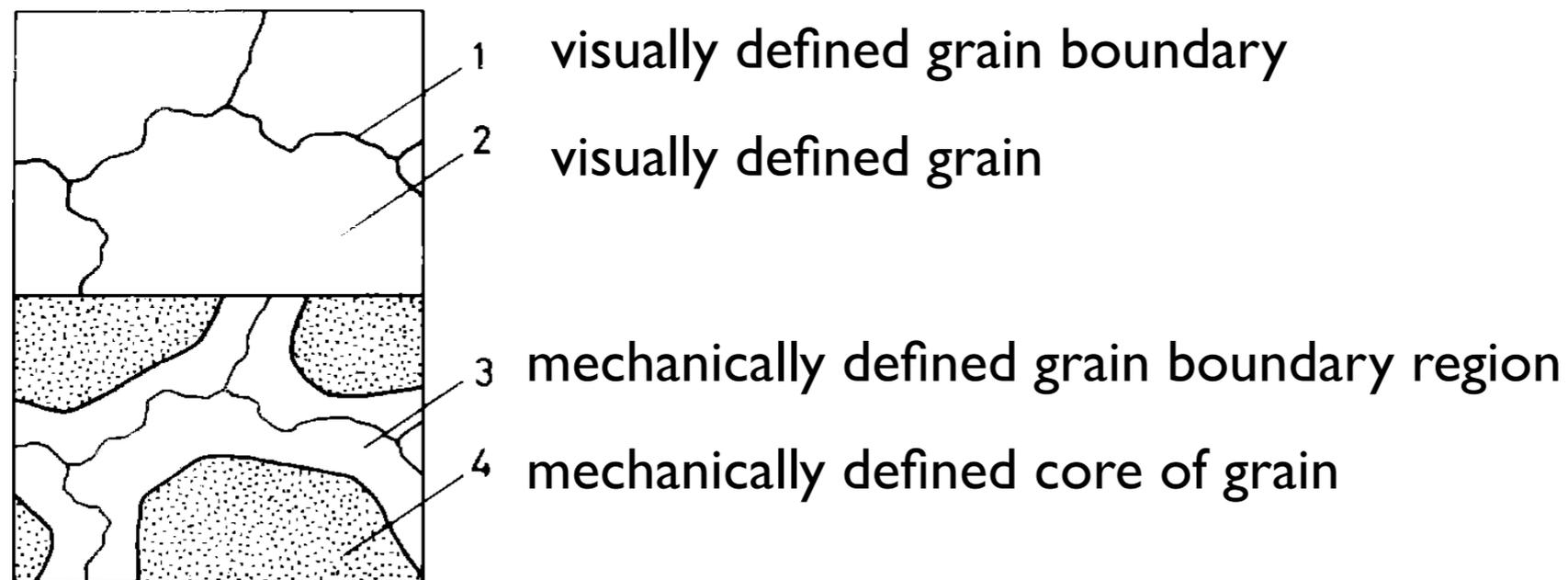
lobate boundaries

↑
PARIS (%)
fully convex

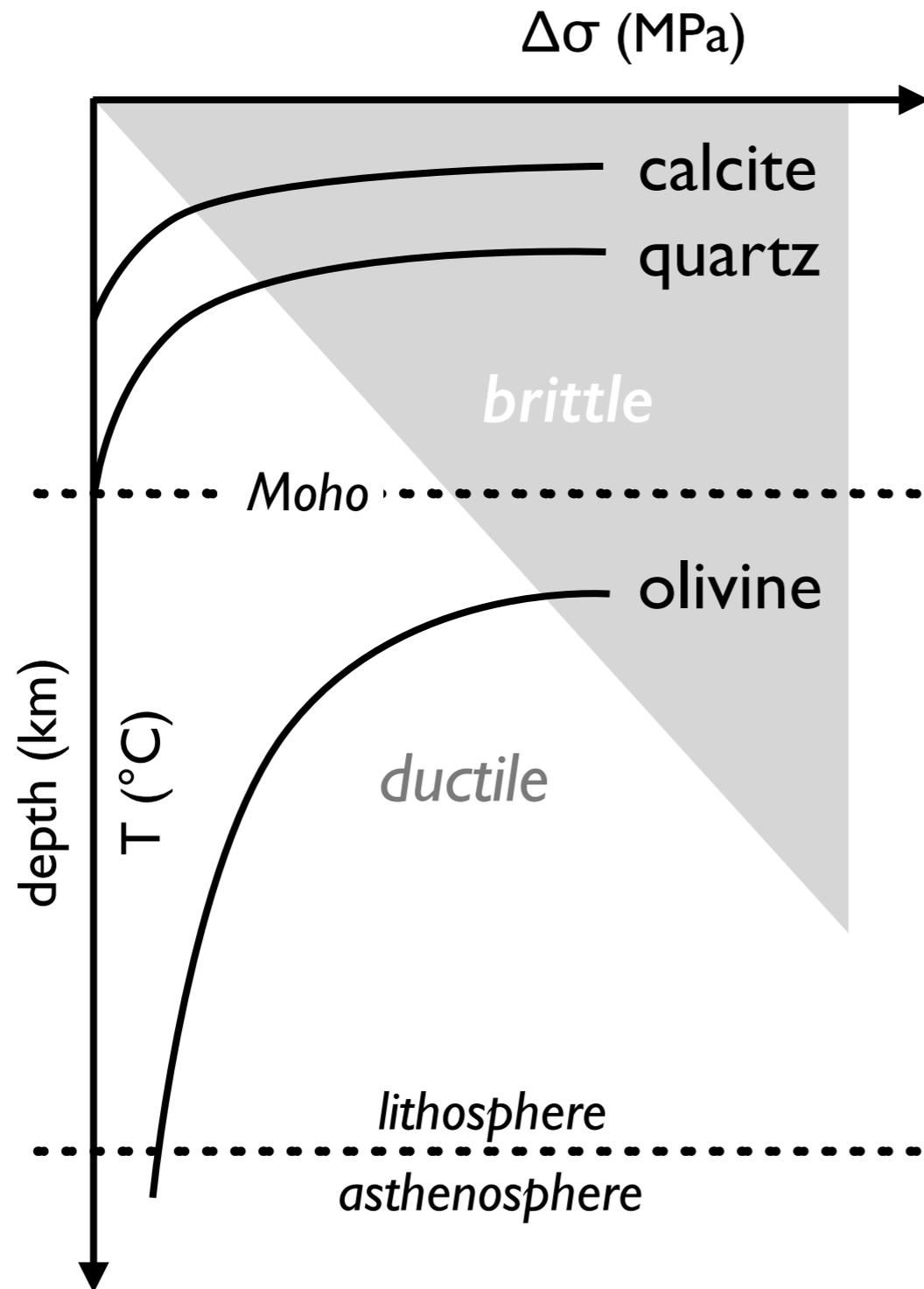


what do we learn ?

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



lithosphere deformation in the lab

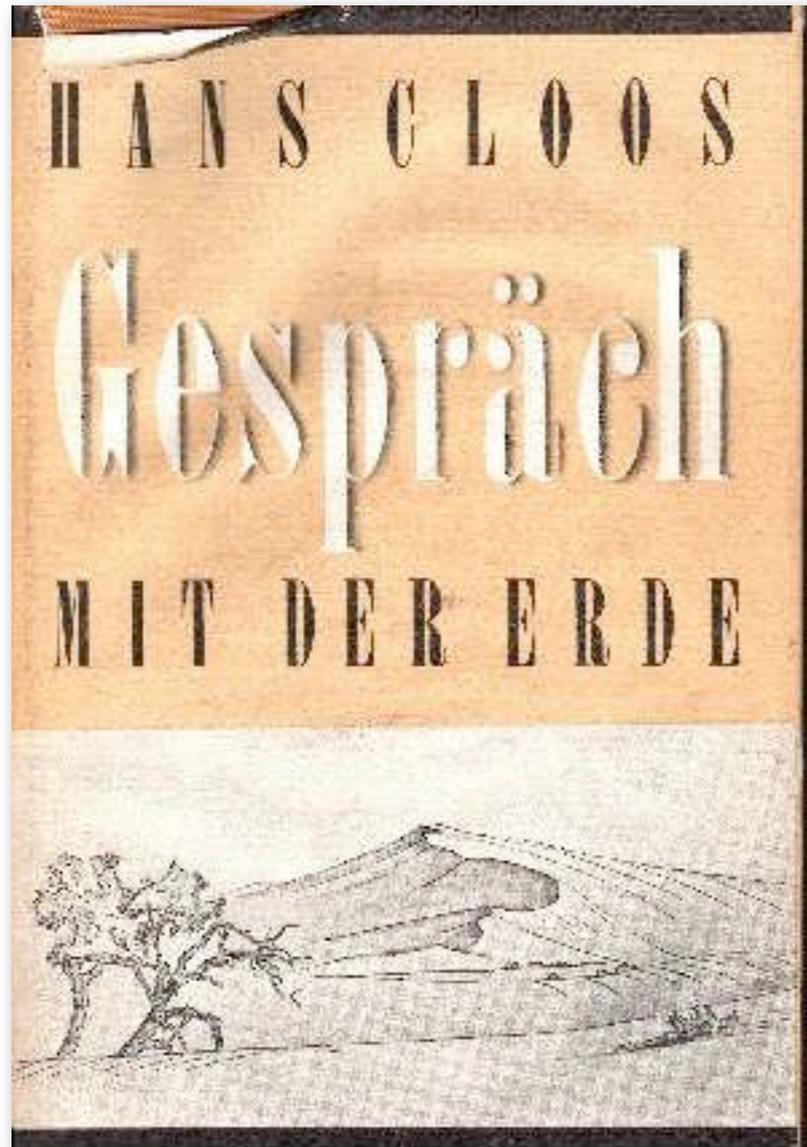


1 Carrara marble
triaxial gas apparatus
Texas A&M University
 $\gamma < 3$

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

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

"... 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.

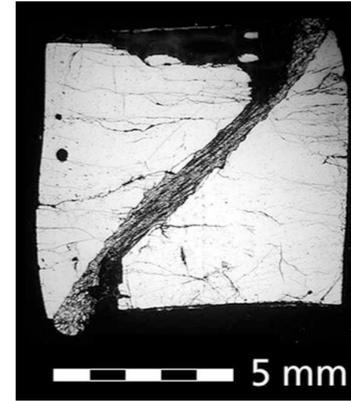
BHQ - texture and grain size



Jan Tullis and ...



her Grigg's apparatus



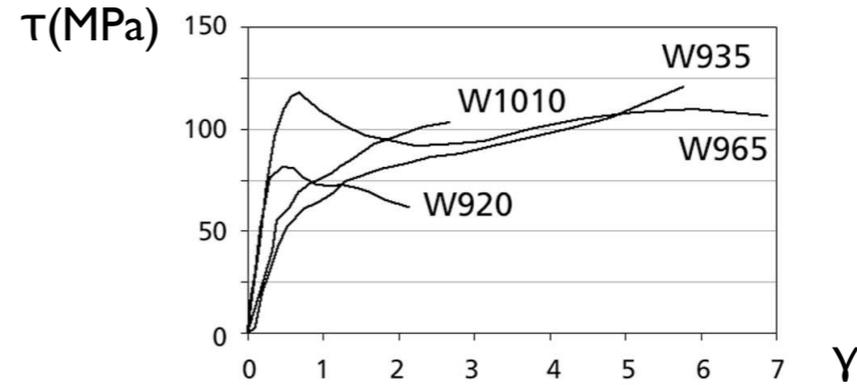
Black Hills quartzite

Dislocation creep regime 3

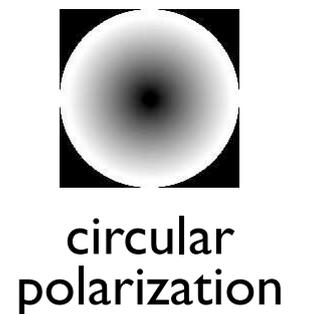
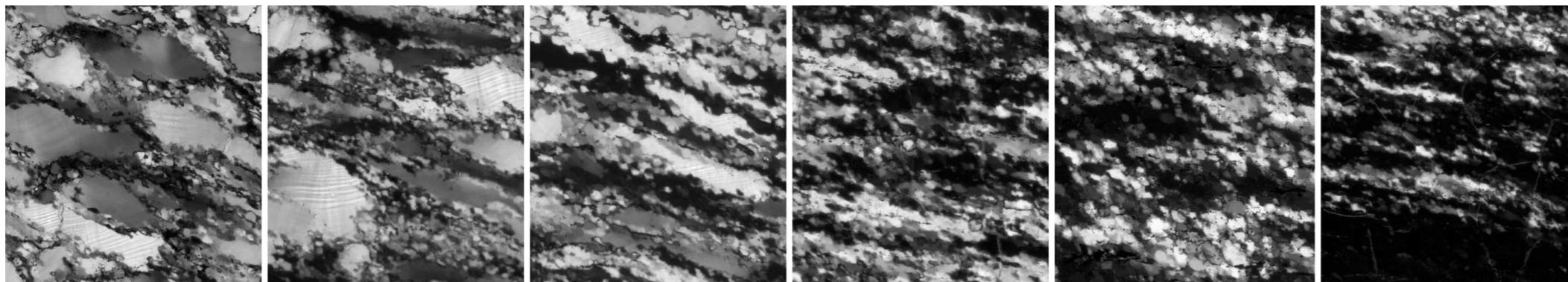
$p_c = 1.5 \text{ GPa}$ $T = 850 - 915^\circ\text{C}$

$\dot{\gamma} = 1-2 \cdot 10^{-5} \text{ s}^{-1}$

up to $\gamma \sim 7$!!!!



Heilbronner & Tullis (2006)

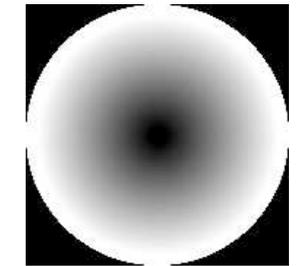
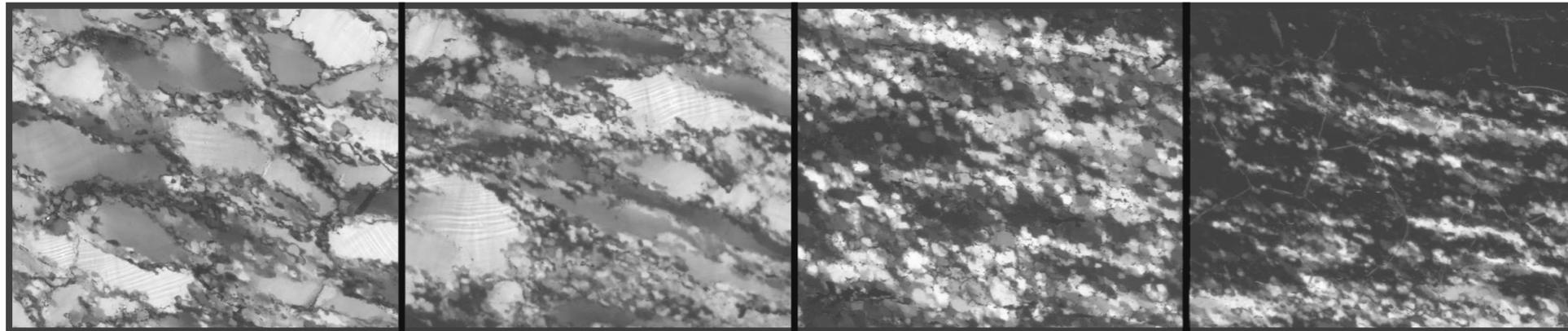


Black Hills Quartzite (circular polarization)

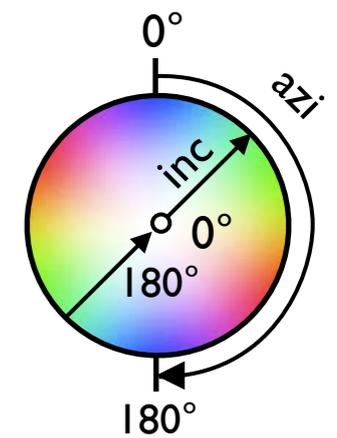
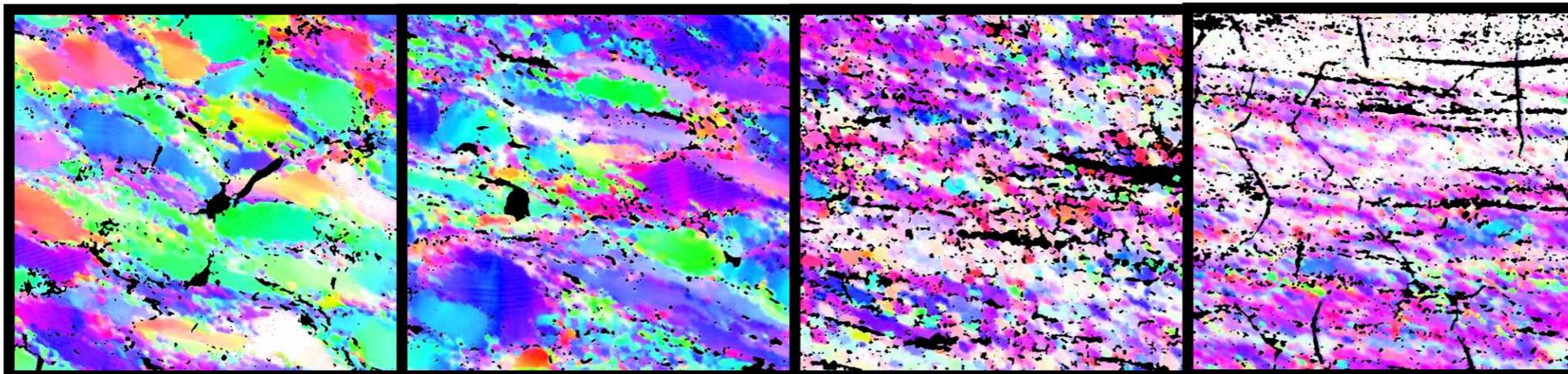
regime 3

do the CIP - get the texture

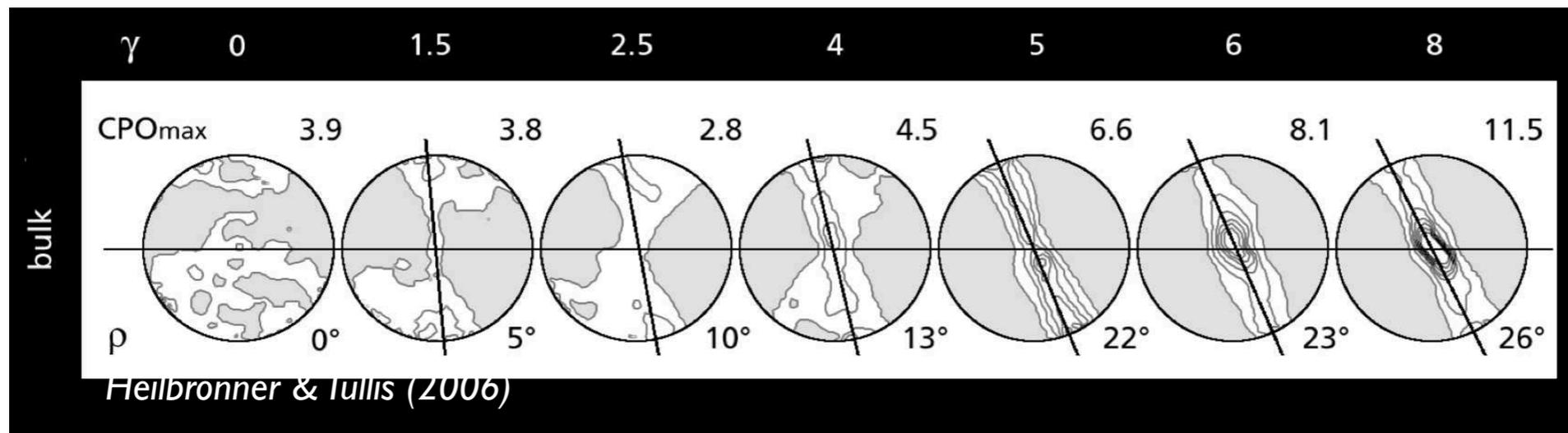
Dislocation creep regime 3



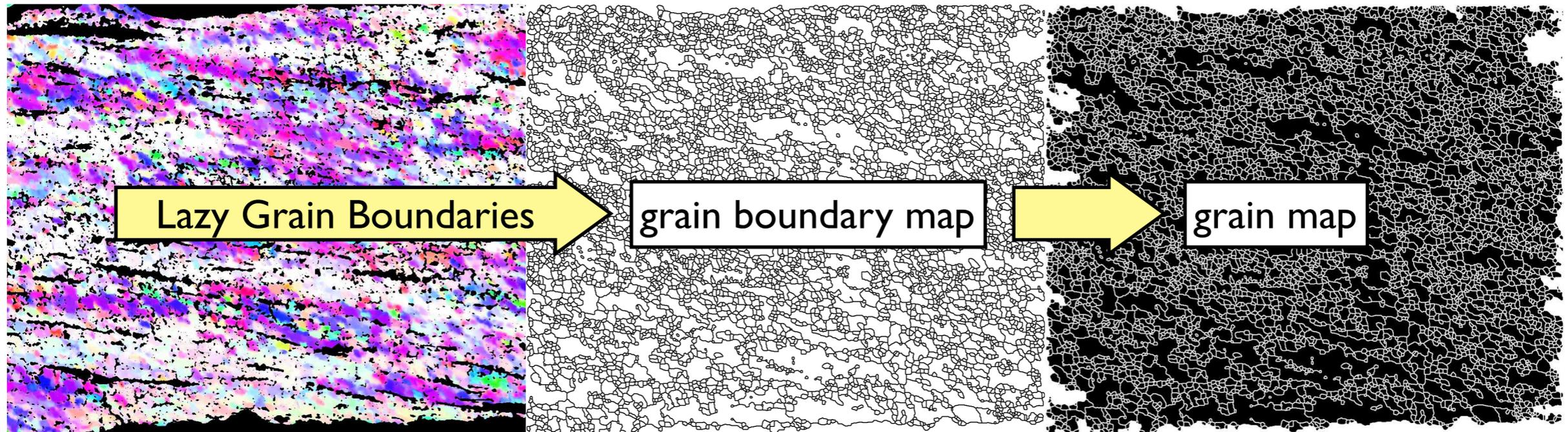
circular
polarization



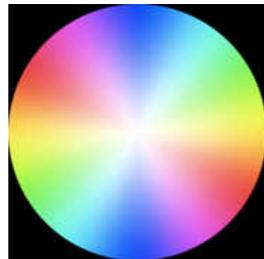
c-axis coloring



from texture to grain size



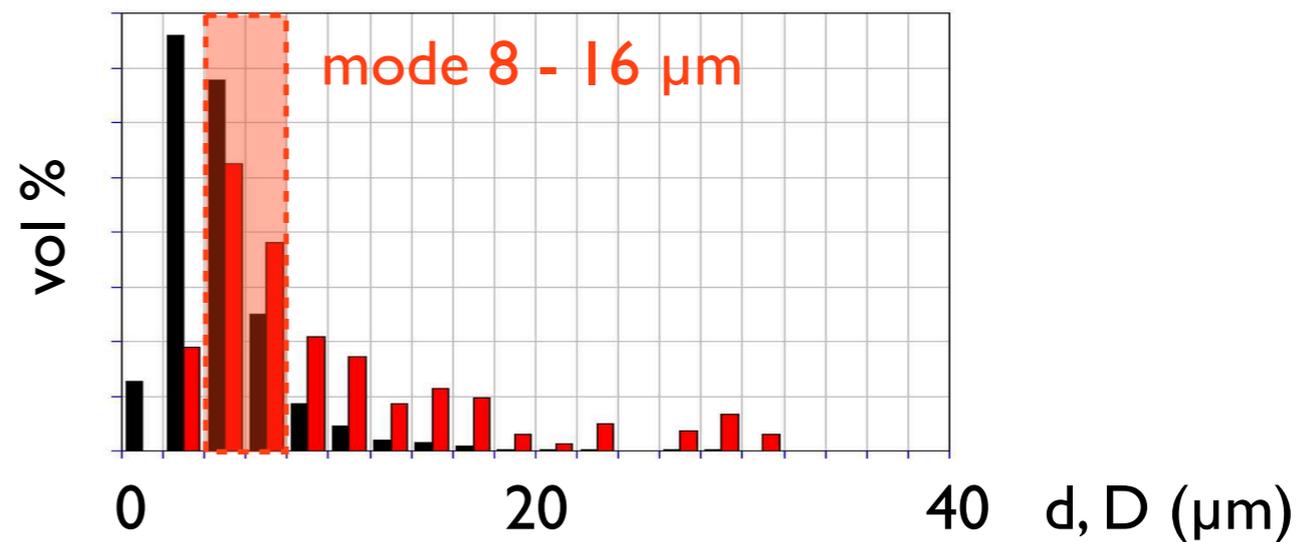
w935 COI



w 935 grain boundary map

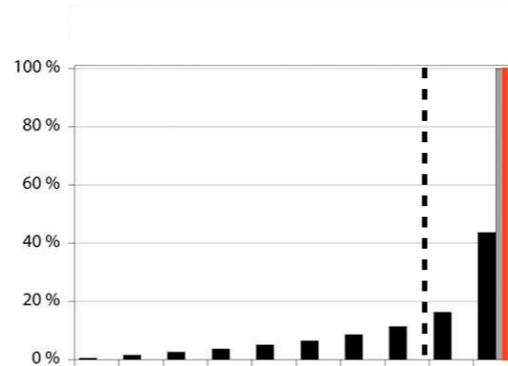
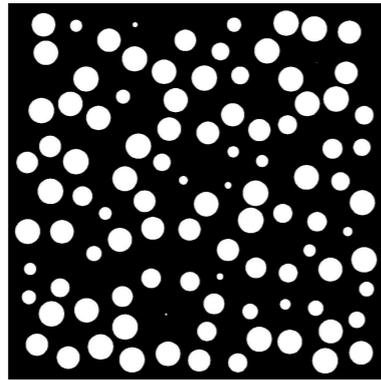
w 935 grain map

$h(d \text{ of circles})$  $v(3D \text{ of spheres})$

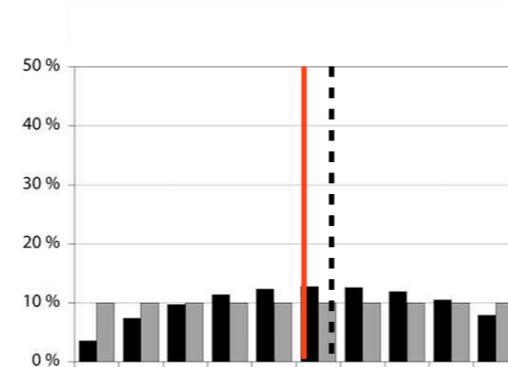
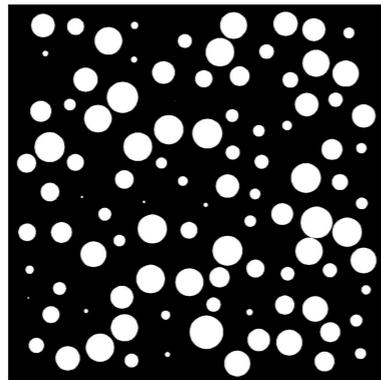


why stripstar ?

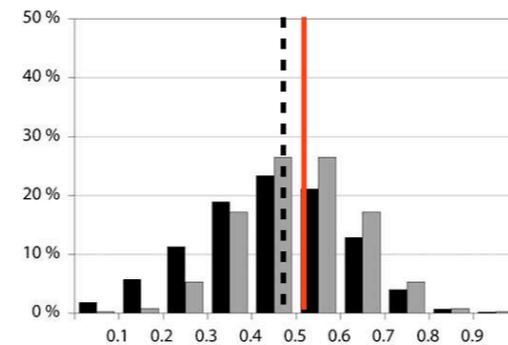
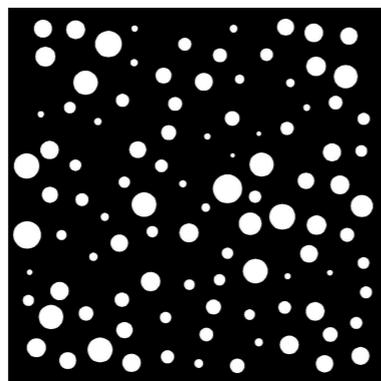
monodisperse



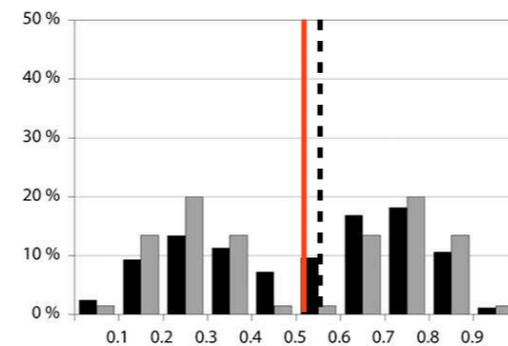
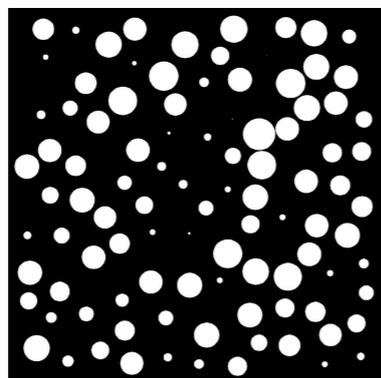
uniform
(random)



Gaussian
(normal)



bimodal



here:

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

3D spheres

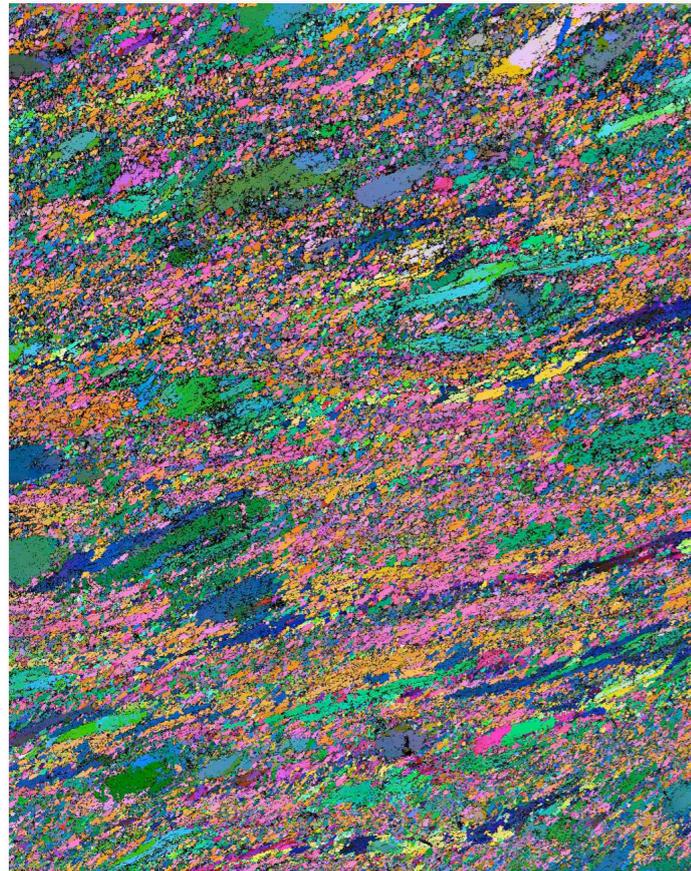
— 3D means of $h(D)$

2D sections

- - - 2D means of $h(d)$

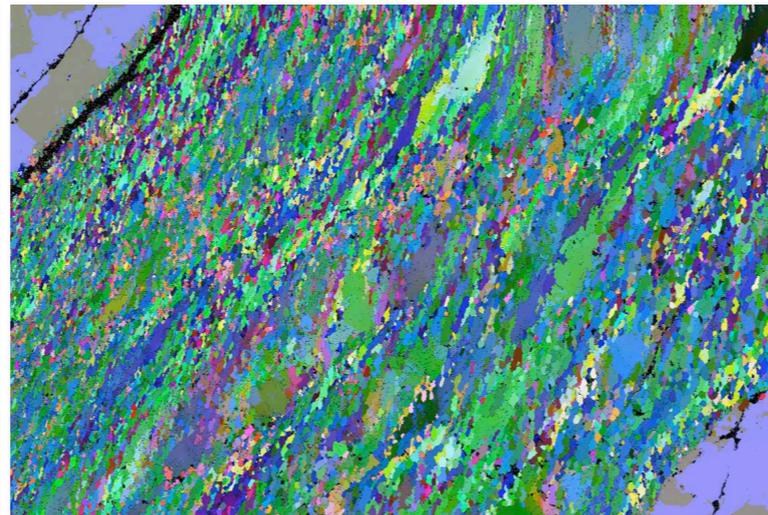
regime 3 ... 2 ... 1 - go EBSD !

— 100 μm



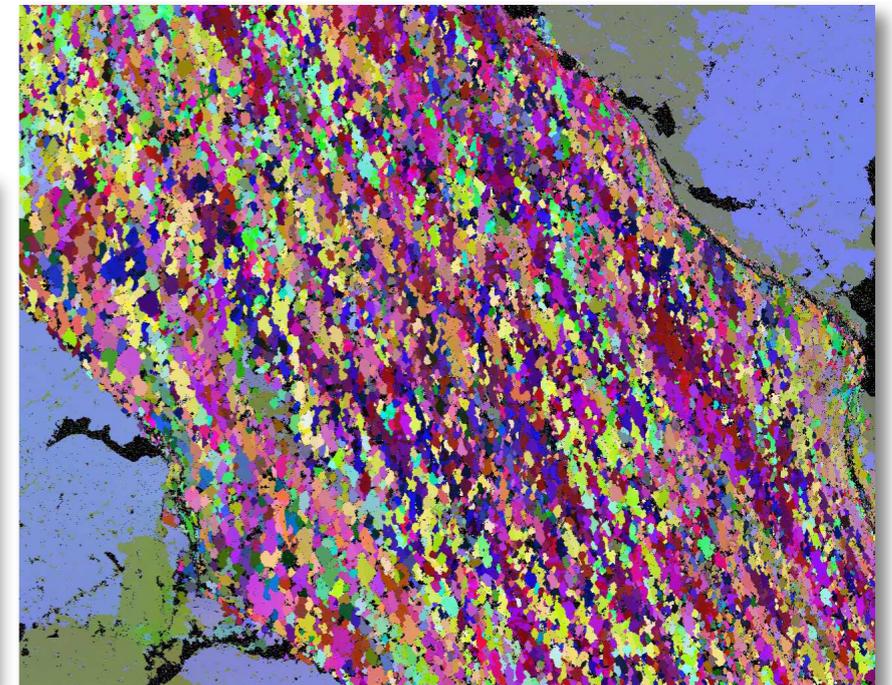
regime 1 (w1092)

— 100 μm



regime 2 (w946)

— 100 μm

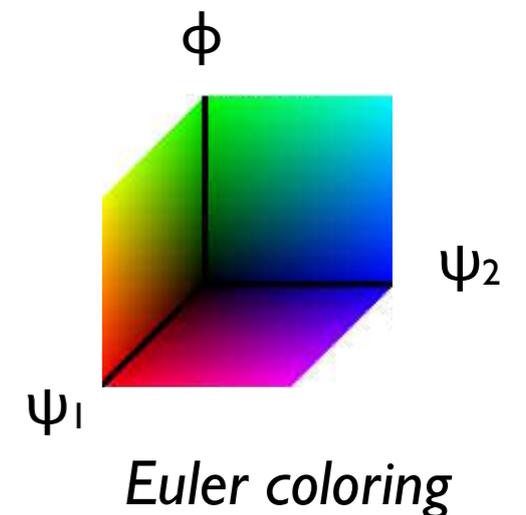


regime 3 (w935)

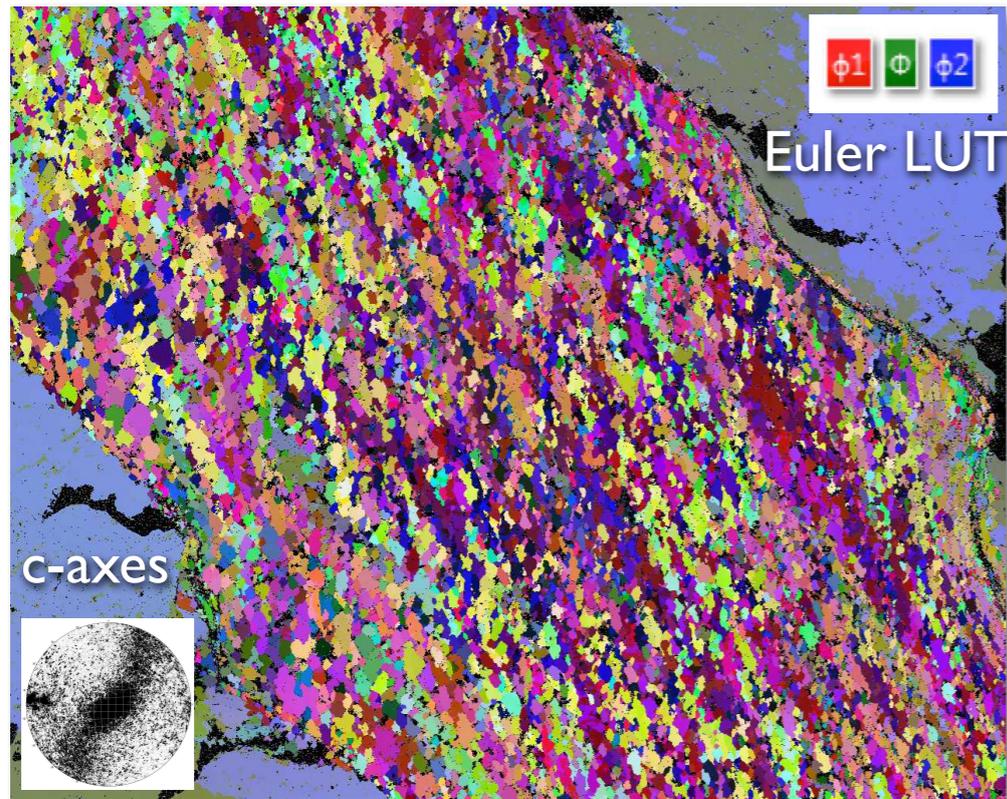
The effect of static annealing on microstructures and crystallographic preferred orientations of quartzites experimentally deformed in axial compression and shear

RENÉE HEILBRONNER¹ & JAN TULLIS²

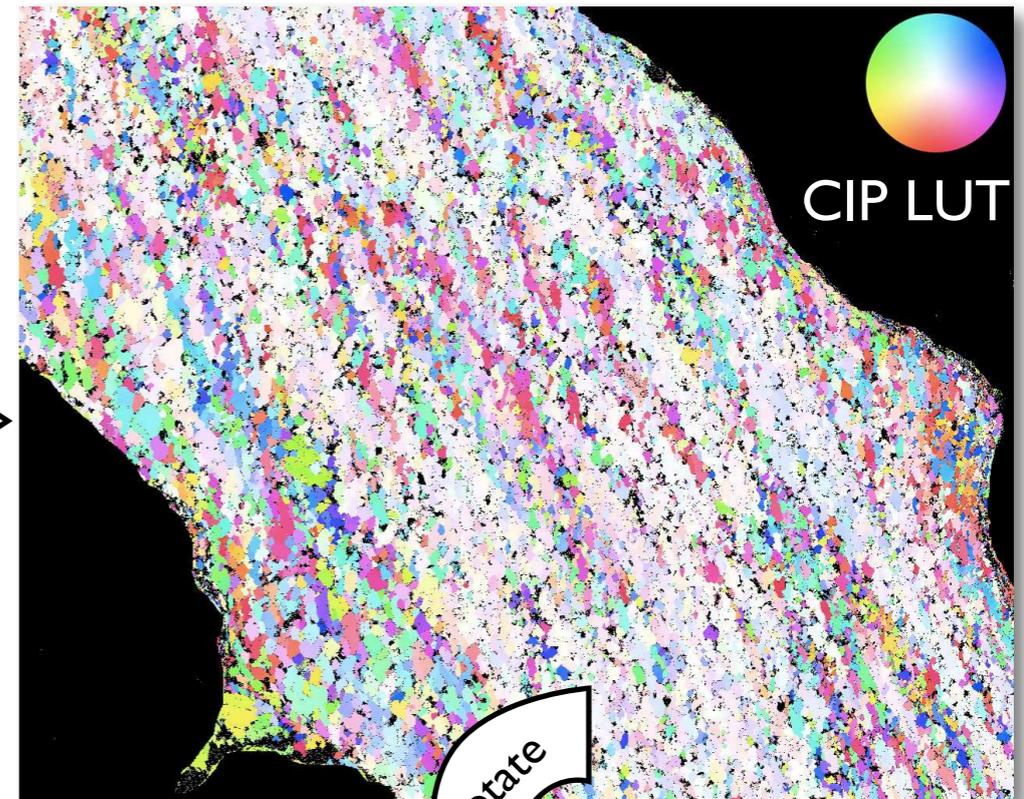
could not do grain size for regime 1 and 2



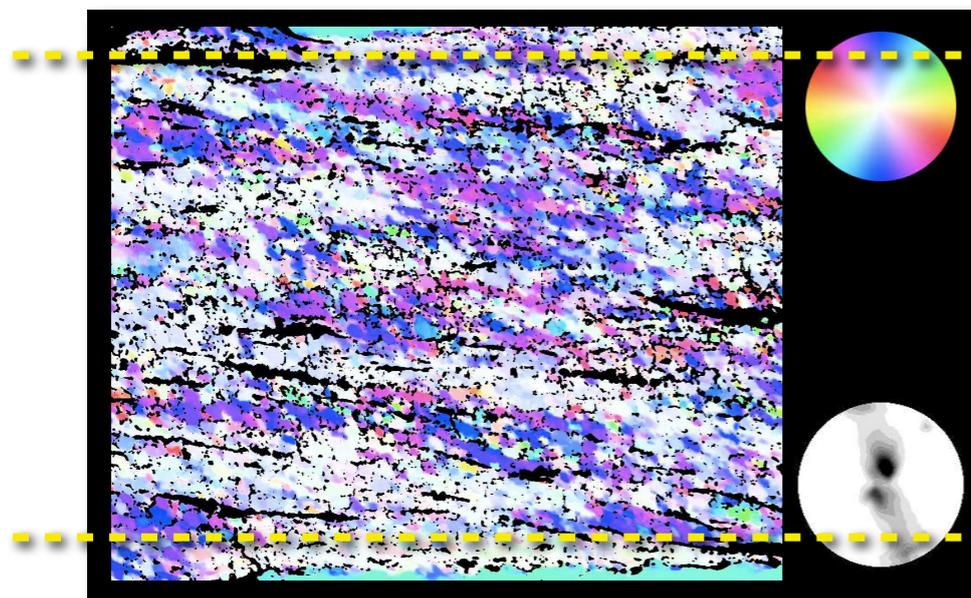
put the CIP glasses on



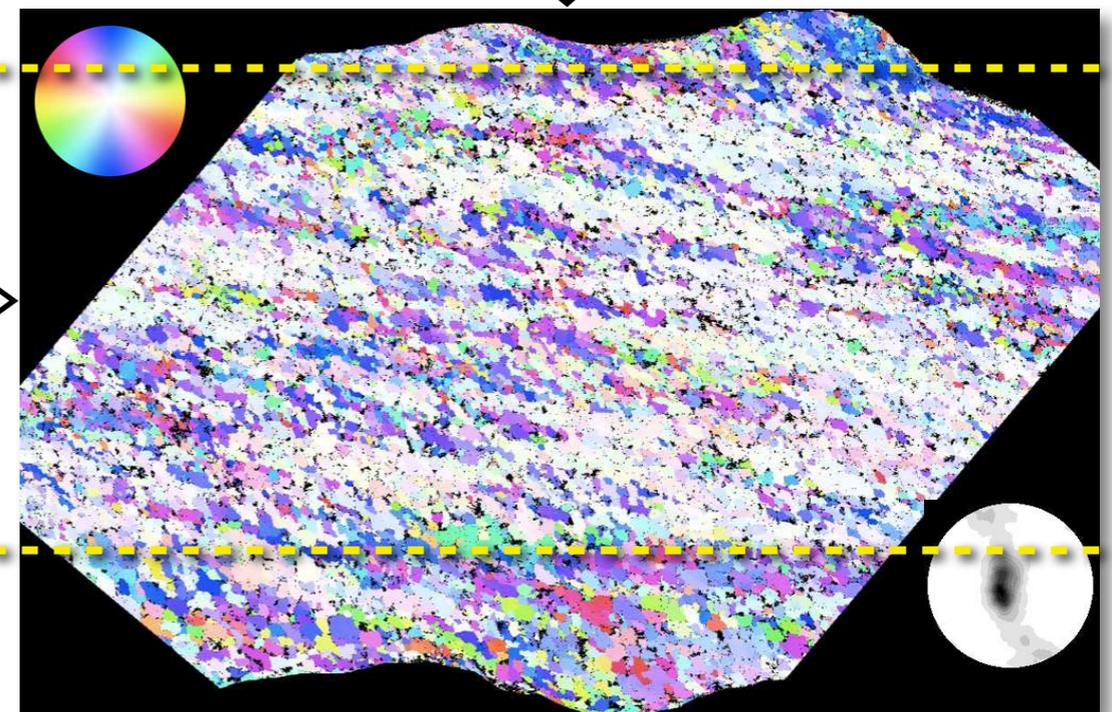
convert



rotate

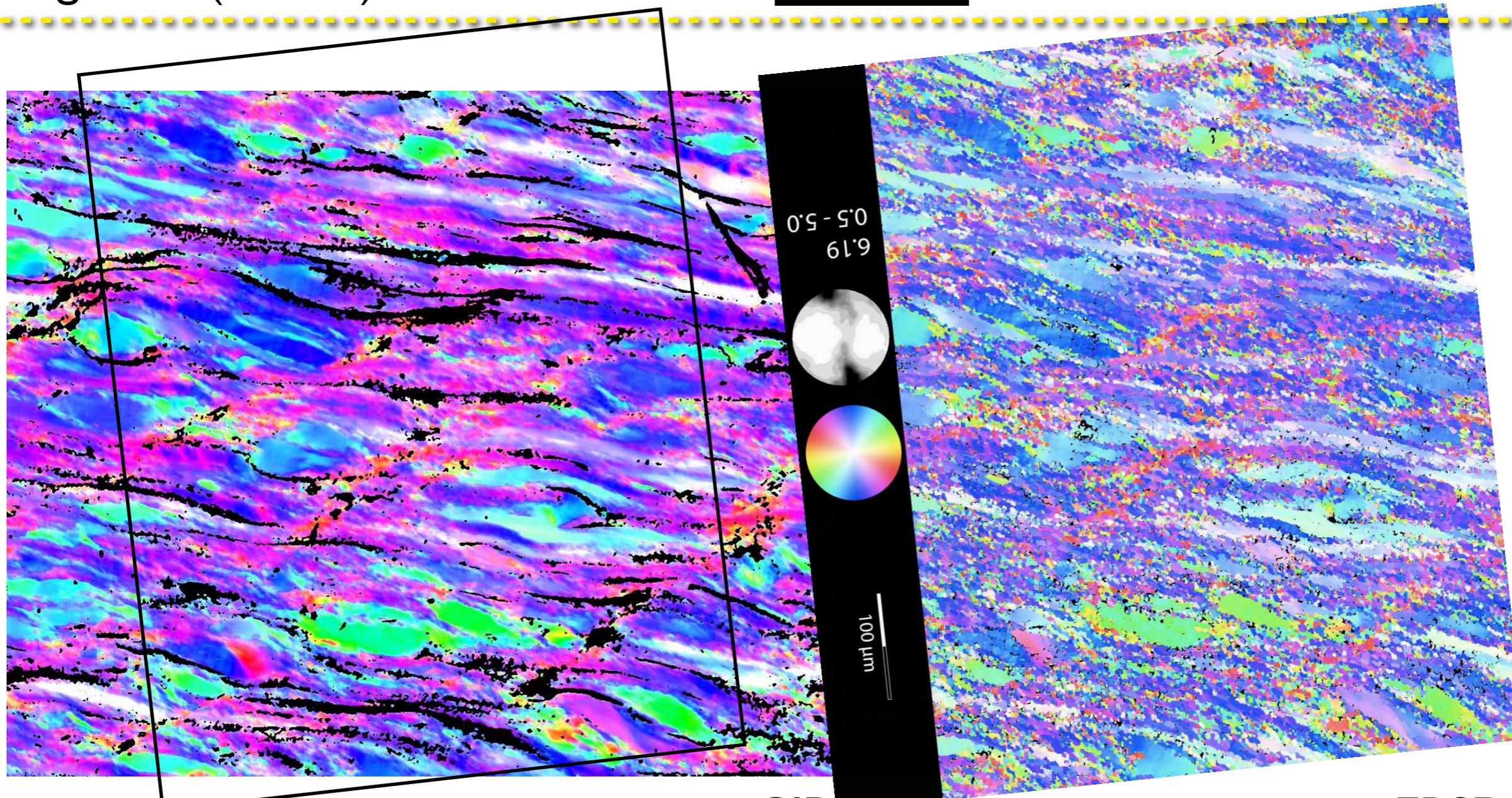


compare



comparing CIP and EBSD

regime I (w1092)

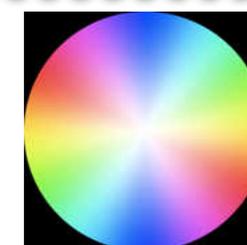


CIP

EBSD

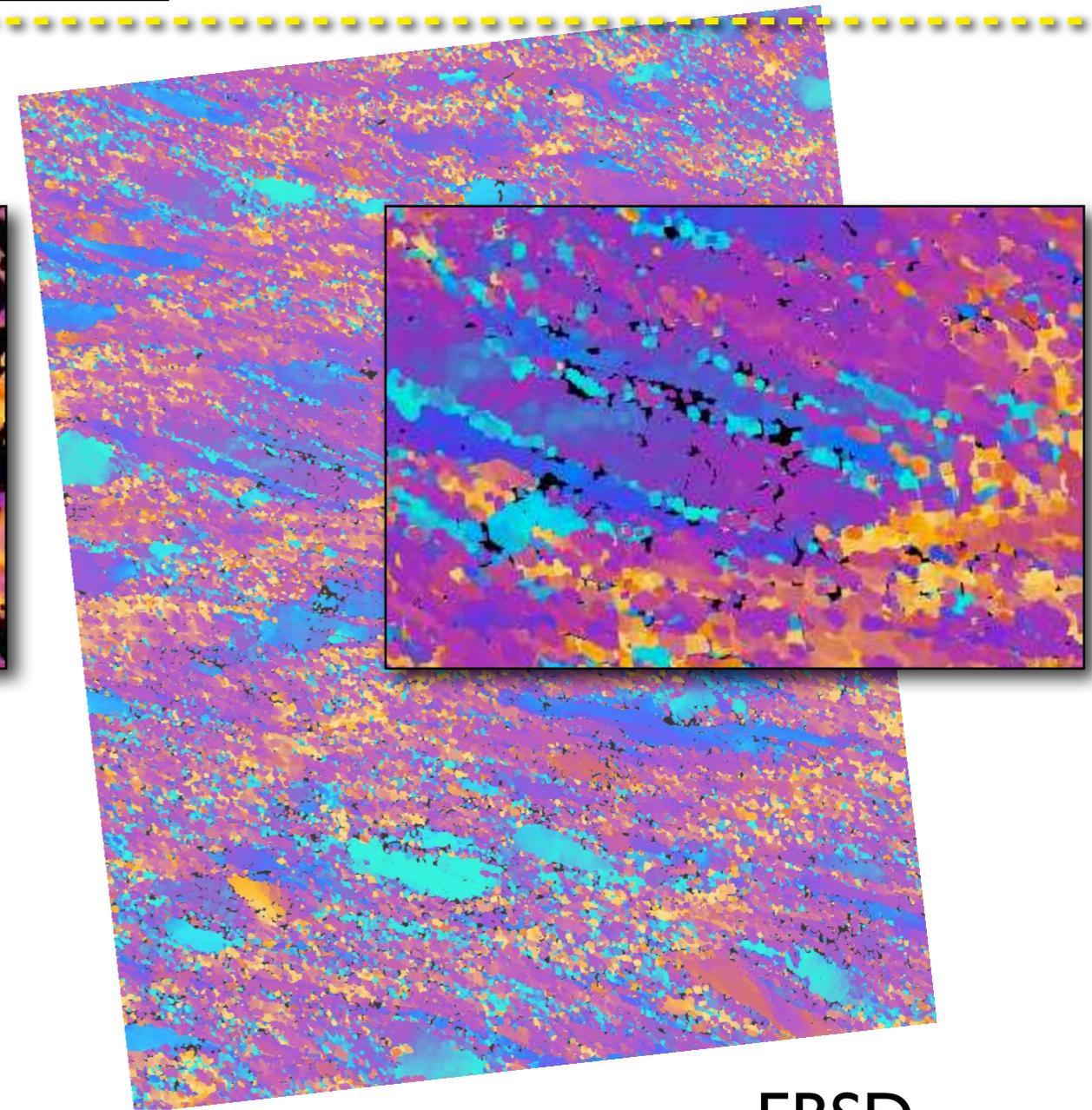
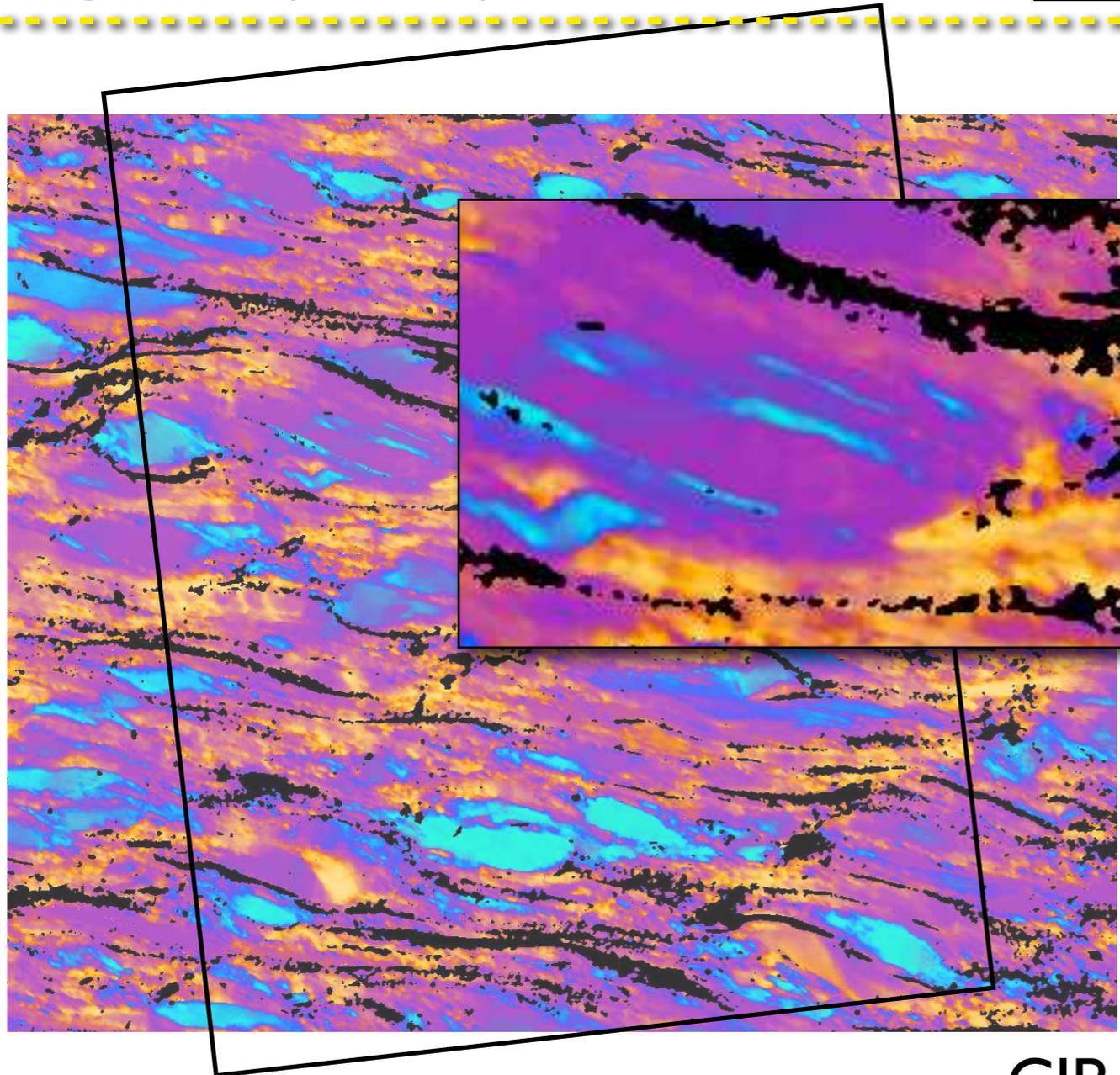
100 μm

Spectrum CLUT



optical microscopy in the SEM

regime I (w1092)

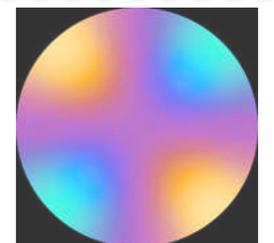


CIP

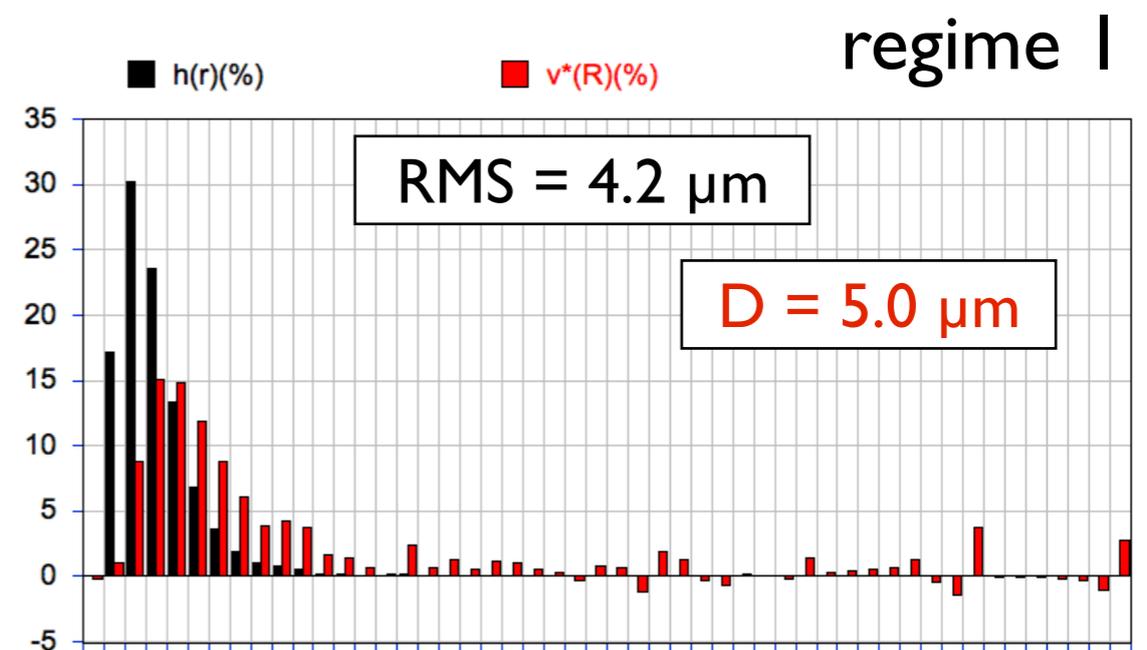
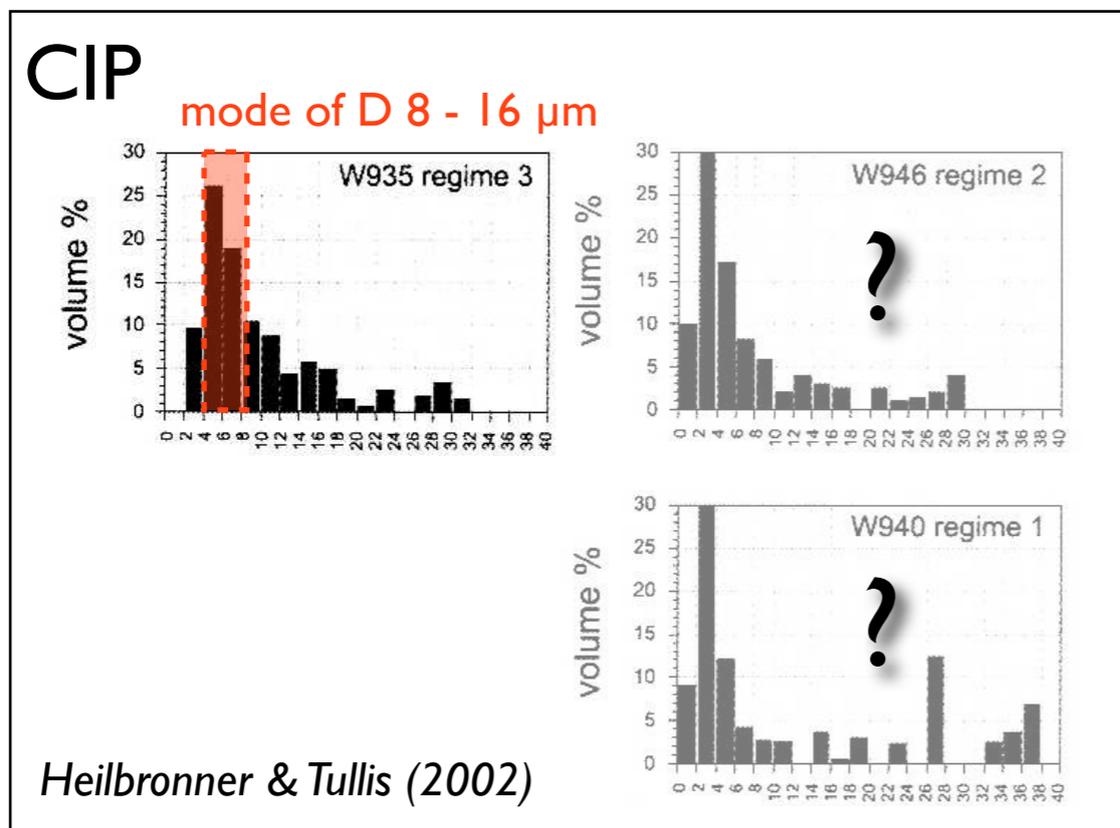
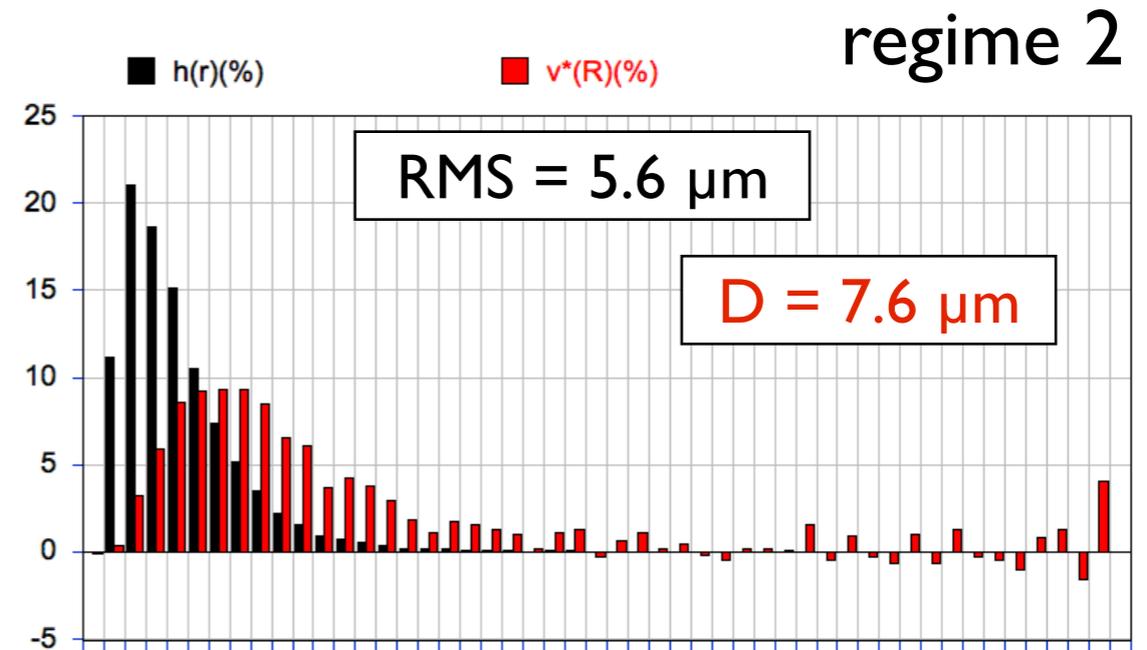
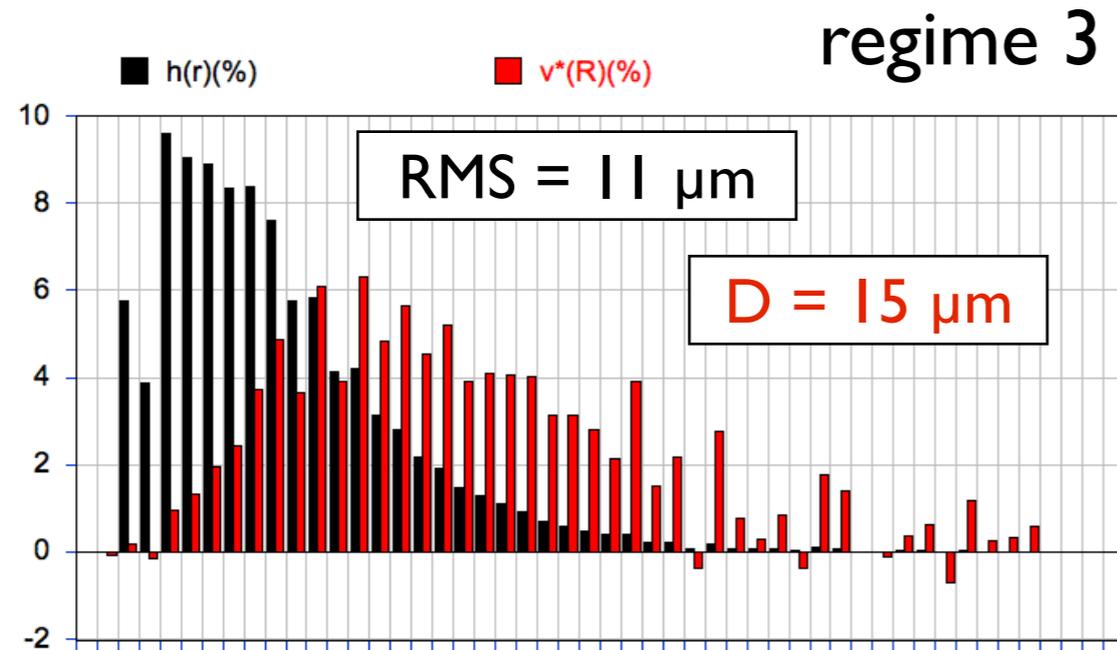
EBSD

100 μm

positive CLUT

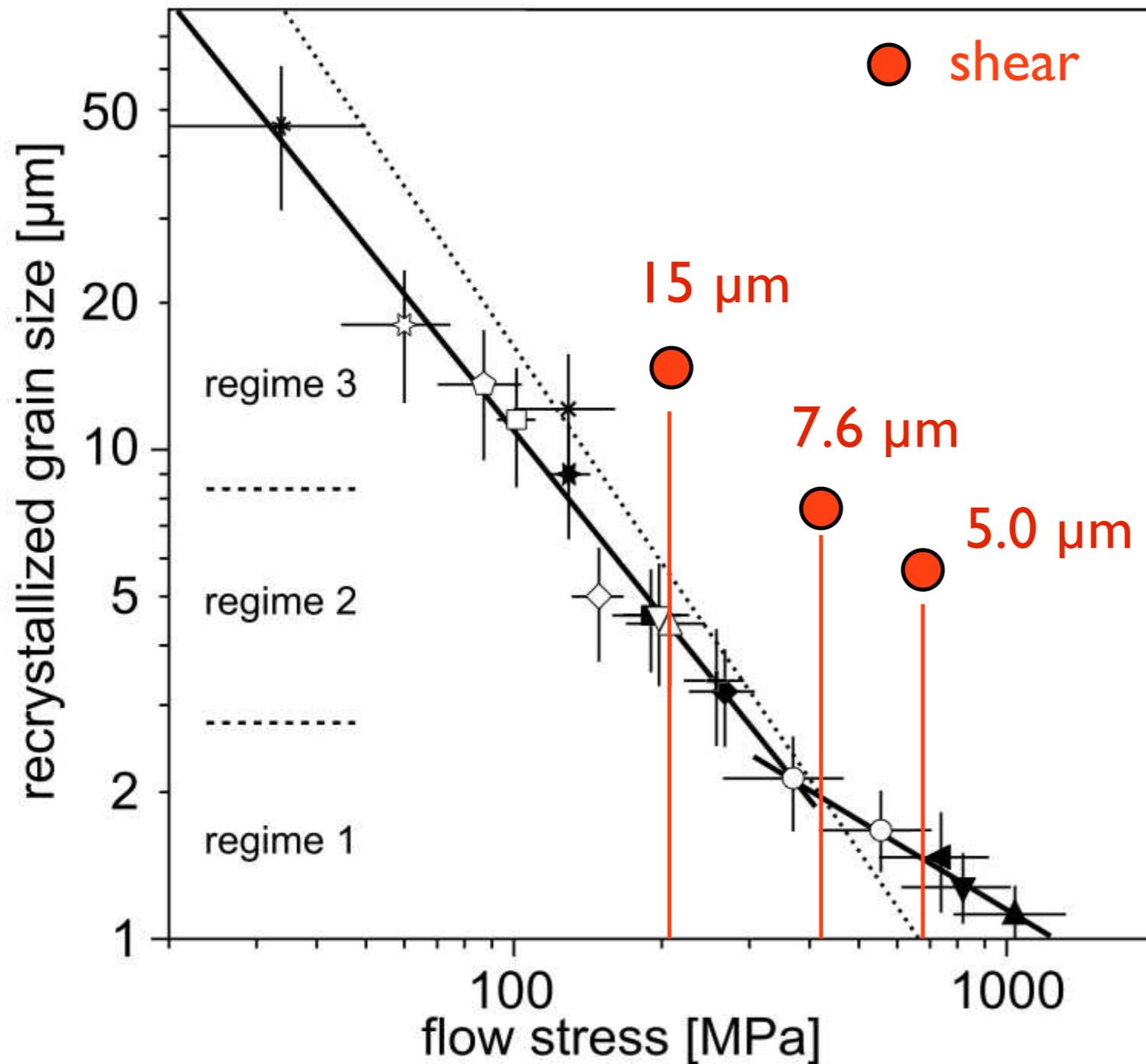


do the stripstar again !



...hmmm...

quartz piezometer



CIP grain boundaries
RMS of 2D sections

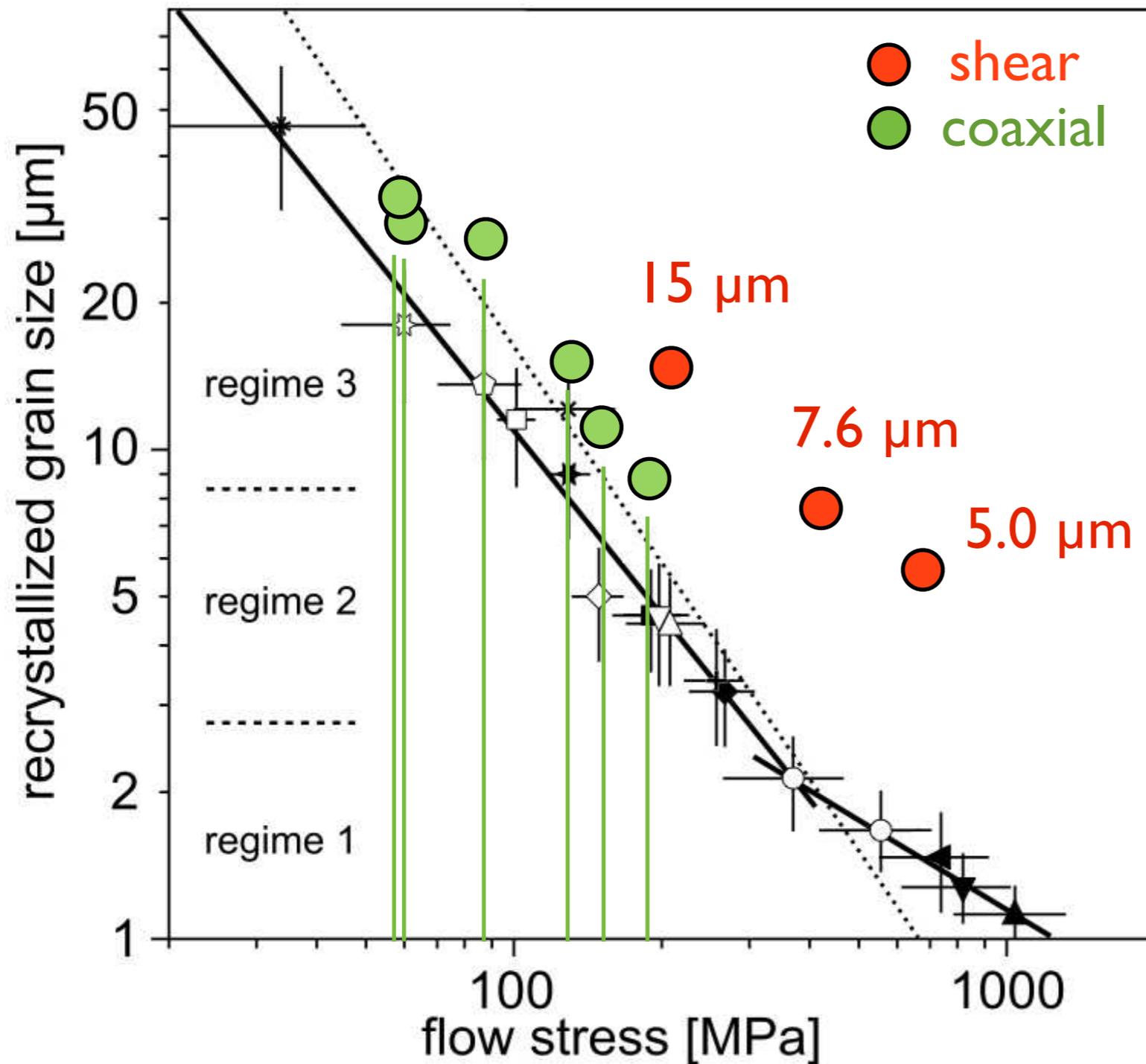
Stipp & Tullis (2003)
original data

EBSD grain boundaries
mode of 3D grains

Heilbronner & Tullis (2002, 2006)
re-measured

re-measure piezometer in EBSD

quartz piezometer



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

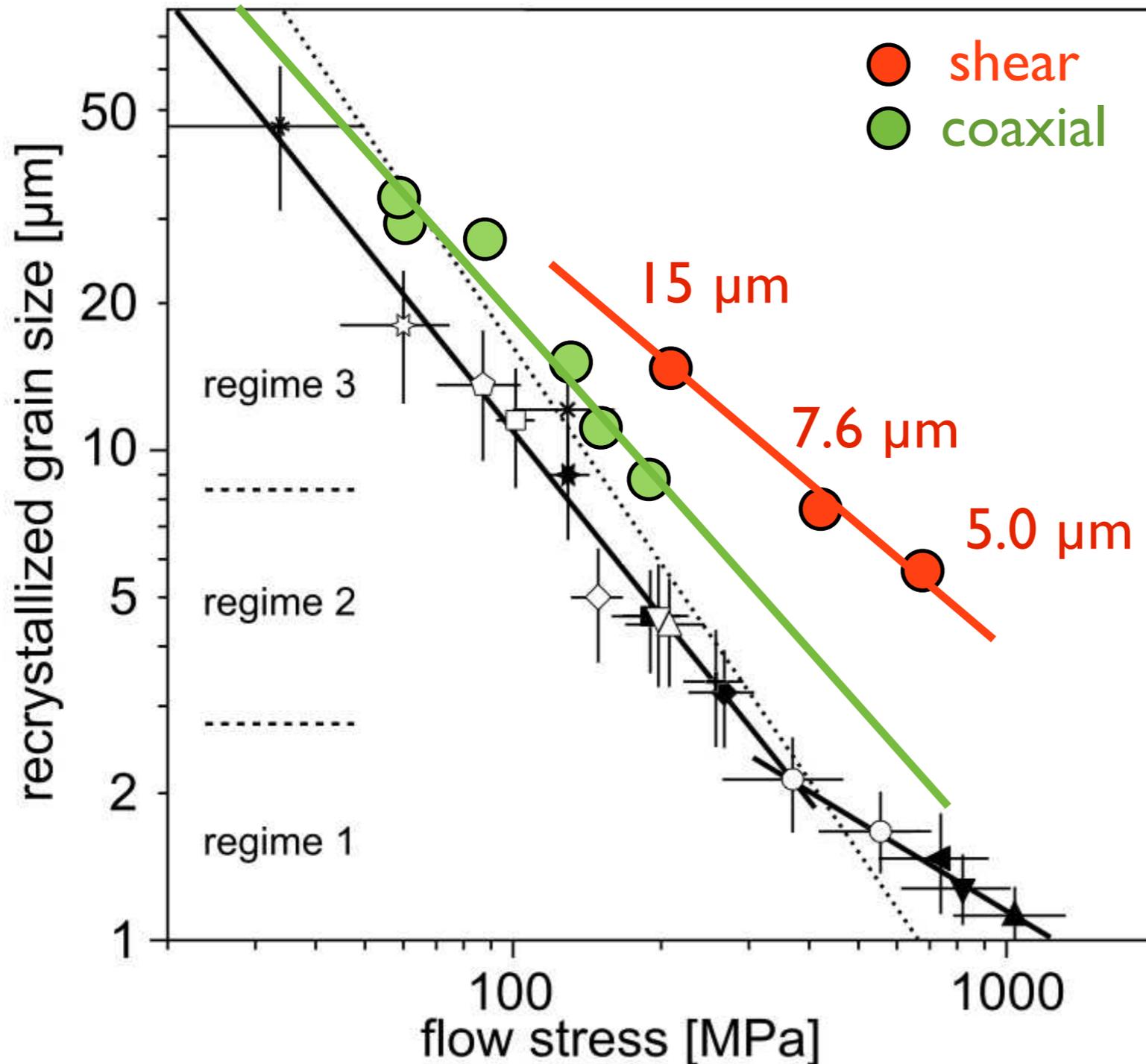
mode of 3D grains

Stipp & Tullis (2003)

original data re-measured by Prior

difference \neq measuring artefact

quartz piezometer



CIP grain boundaries

RMS of 2D sections

published piezometer

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

EBSD grain boundaries

mode of 3D grains

shear

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

EBSD grain boundaries

mode of 3D grains

coaxial (piezo samples)

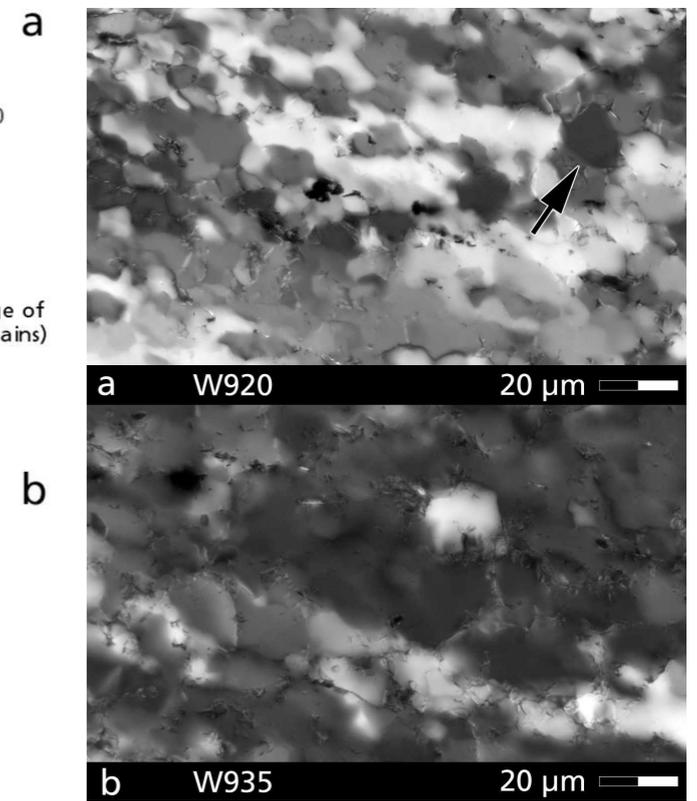
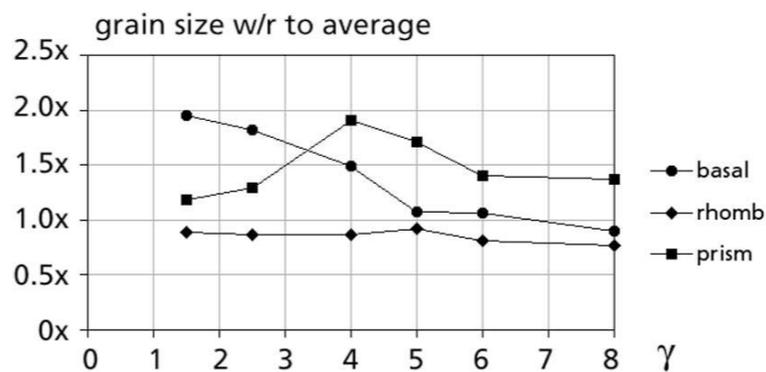
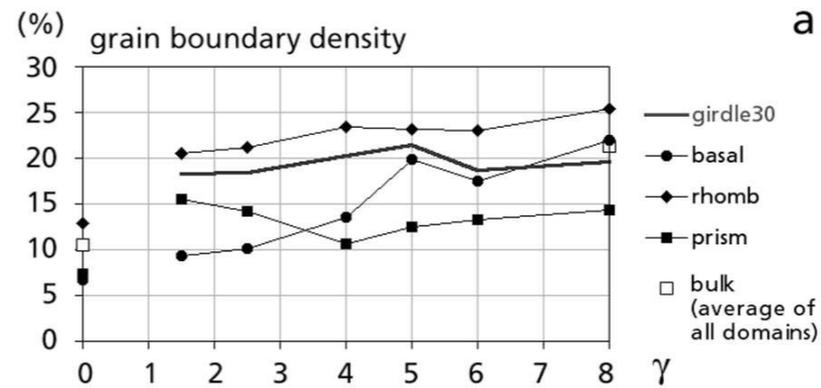
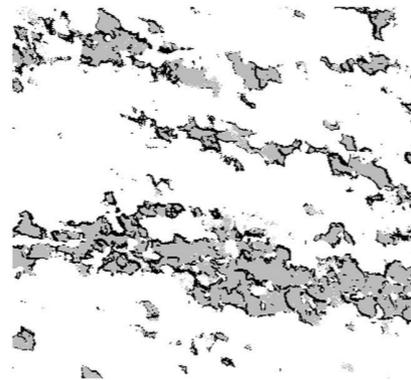
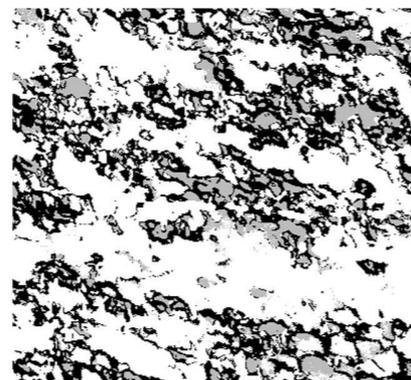
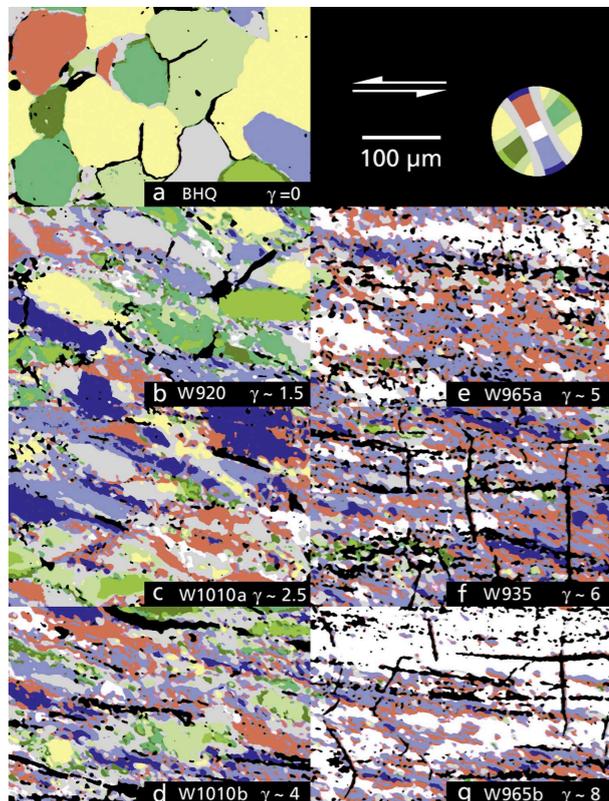
$$D(\mu\text{m}) = 3325 \Delta\sigma^{-1.13}$$

check the grain size in the γ domain

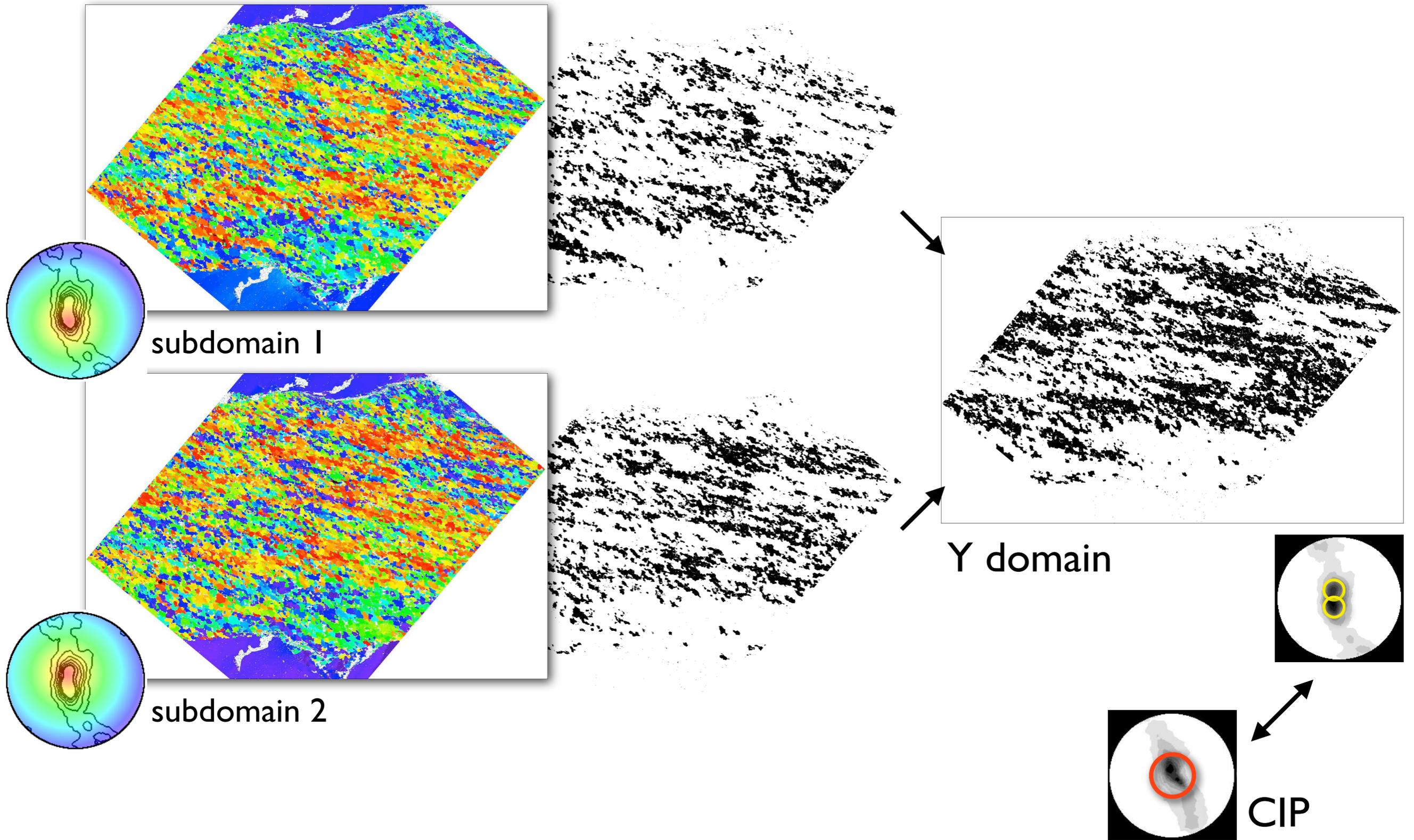
Evolution of c axis pole figures and grain size during dynamic recrystallization:
Results from experimentally sheared quartzite

Renée Heilbronner¹ and Jan Tullis²

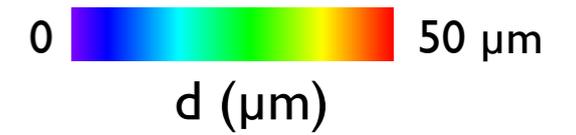
"...the recrystallized grain size of the rhomb domain is approx. 12 μm and that of the prism domain is approx. 19 μm , corresponding to shear stresses of 93 and 64 MPa..."



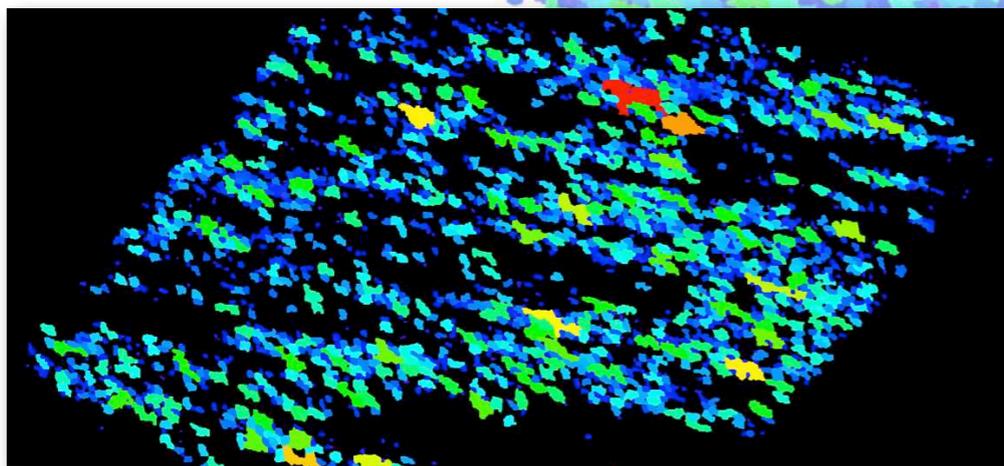
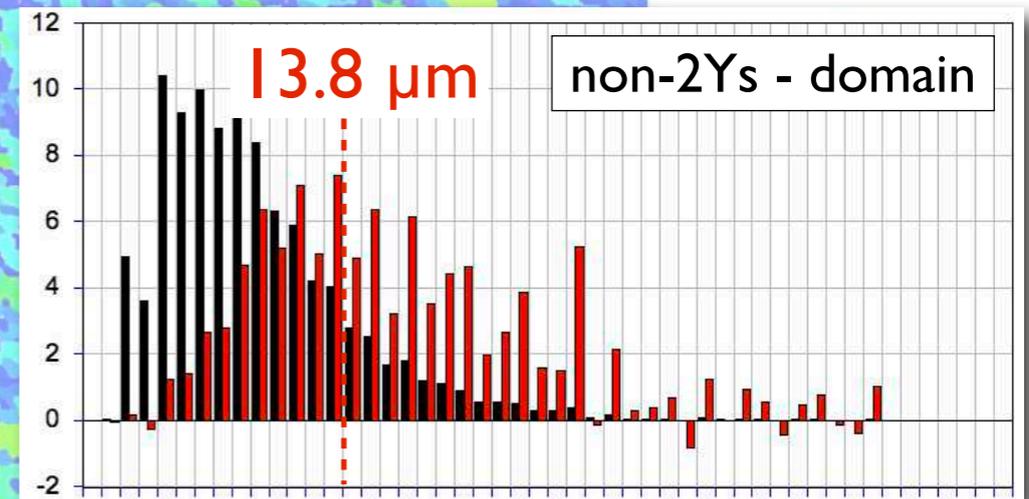
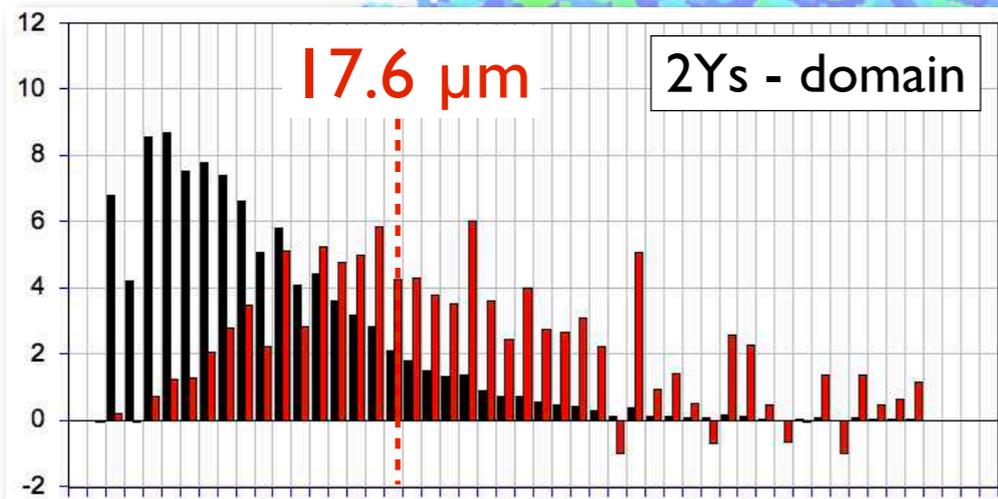
Y domain = 2 subdomains



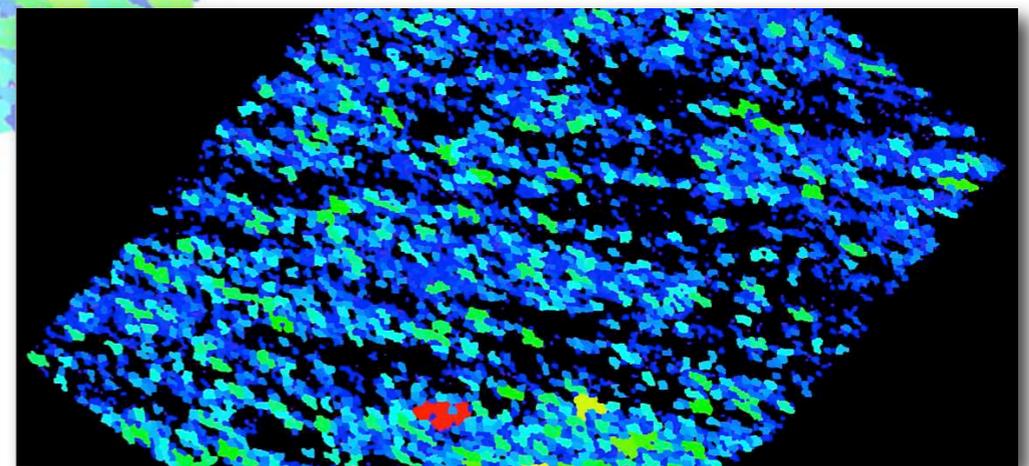
we actually got it right !



 v(D) 3D
 h(d) 2D



$\Rightarrow \tau = 86 \text{ MPa}$

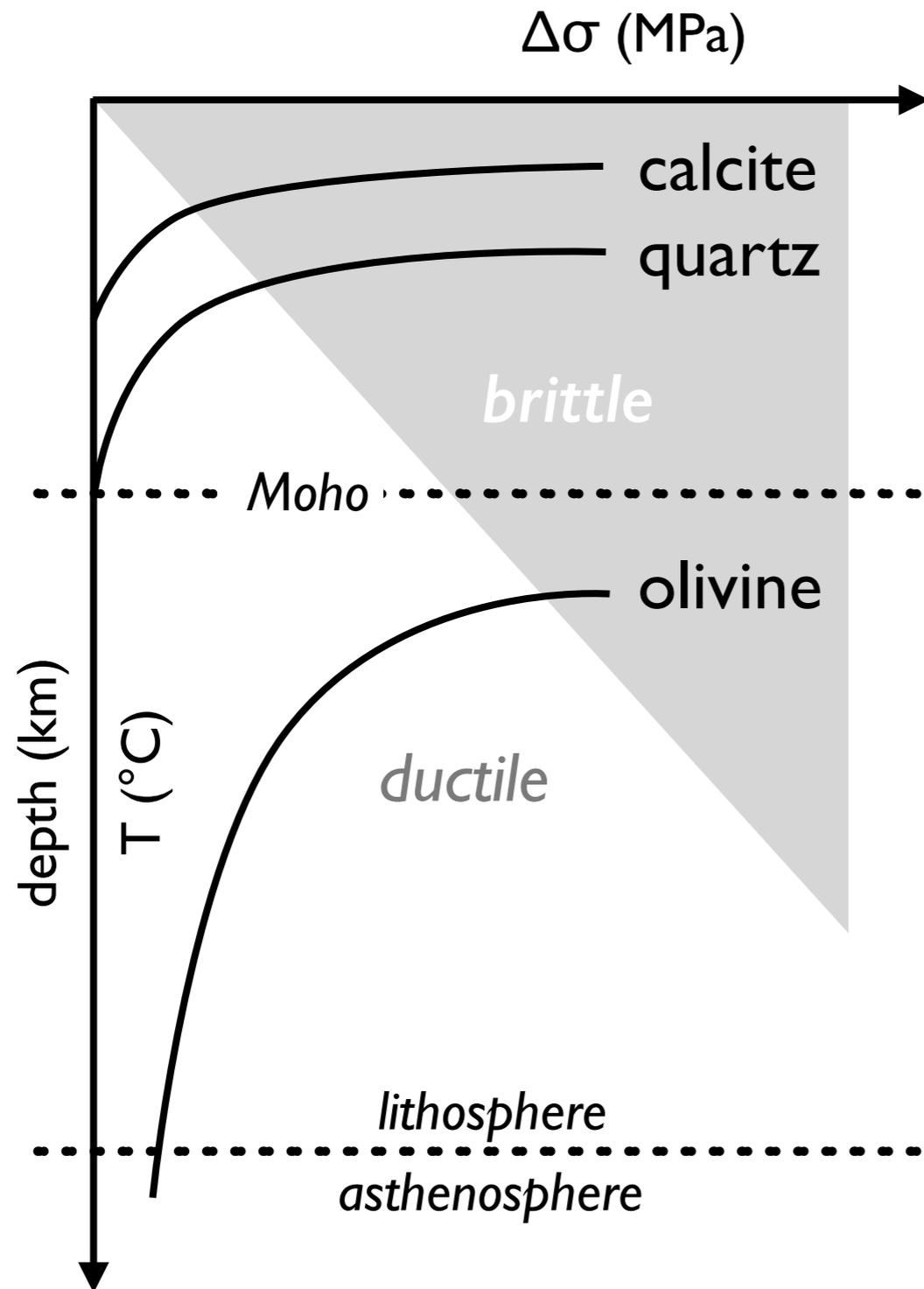


$\Rightarrow \tau = 114 \text{ MPa}$

what do we learn ?

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

lithosphere deformation in the lab



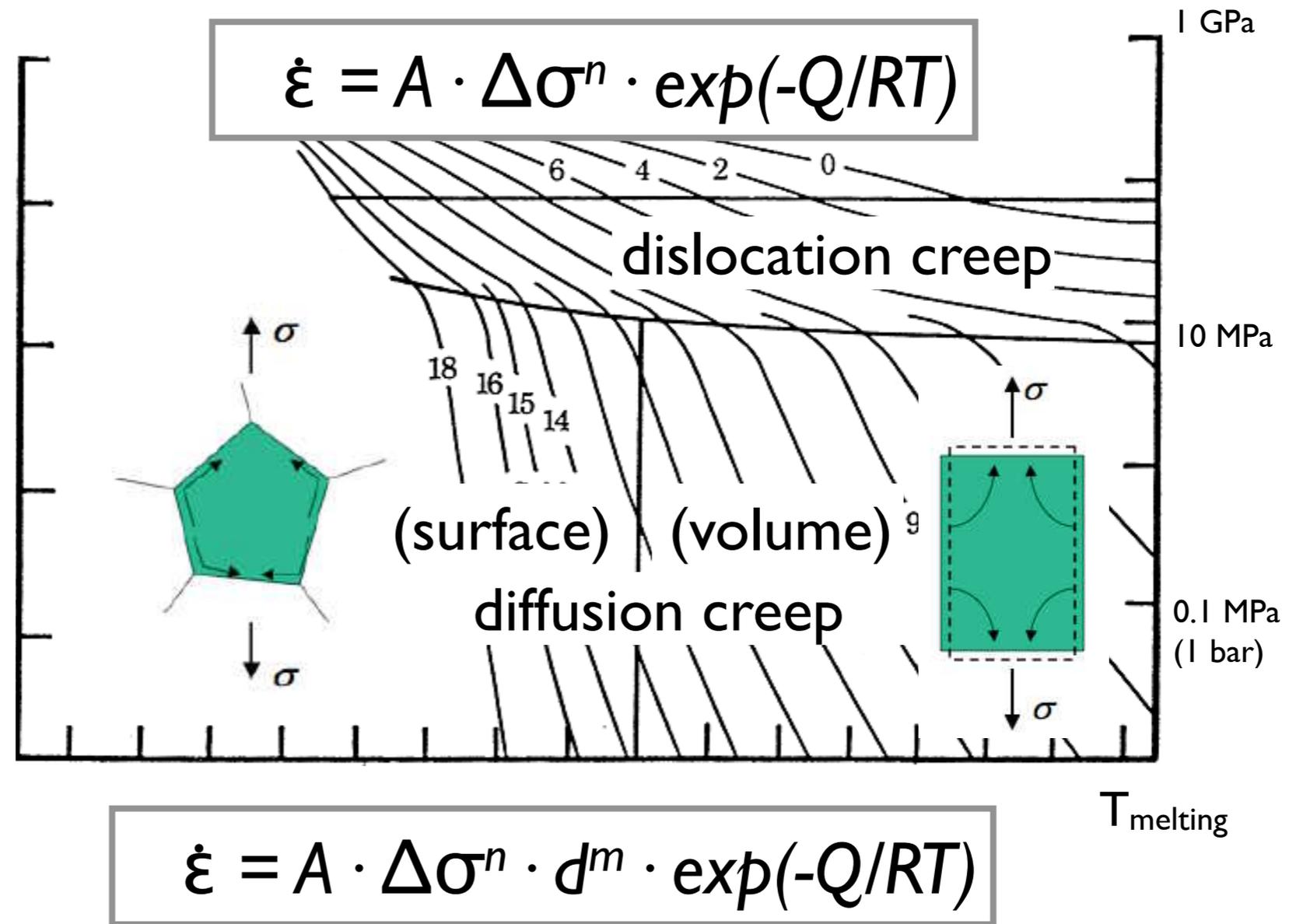
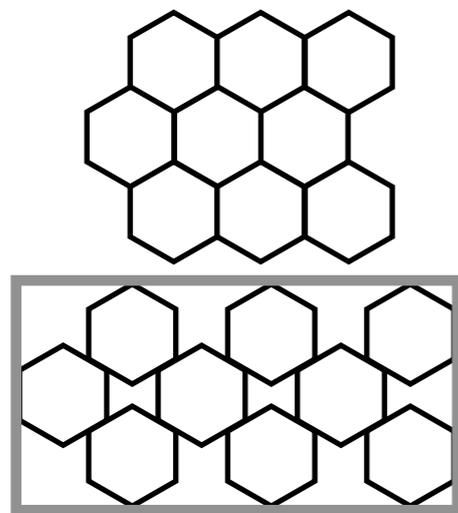
1 Carrara marble
triaxial gas apparatus
Texas A&M University
 $\gamma < 3$

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

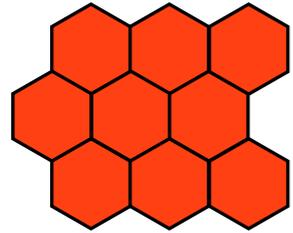
3 Olivine-Orthopyroxene
torsion apparatus
University of Minnesota
 $\gamma < 30$

getting weak in the knees

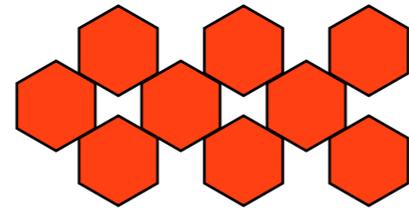
from dislocation creep to diffusion creep



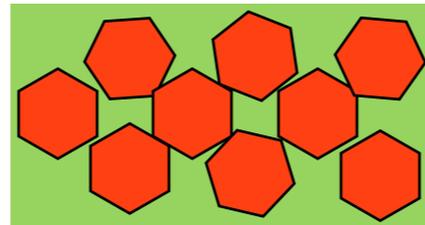
how diffuse is diffusion creep?



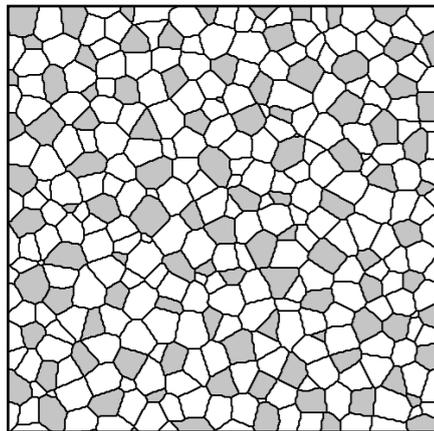
diffusion creep



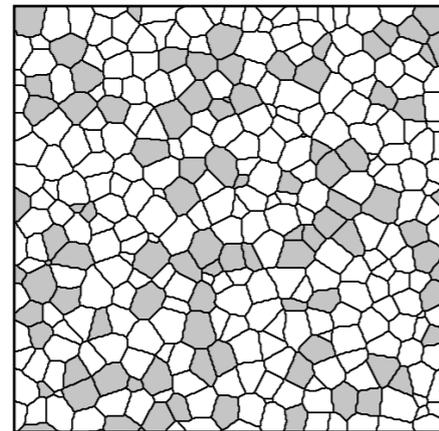
grain boundary sliding



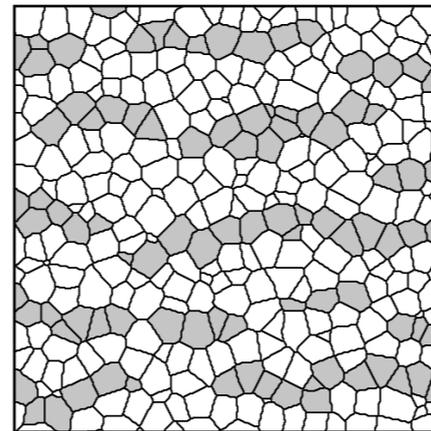
granular flow



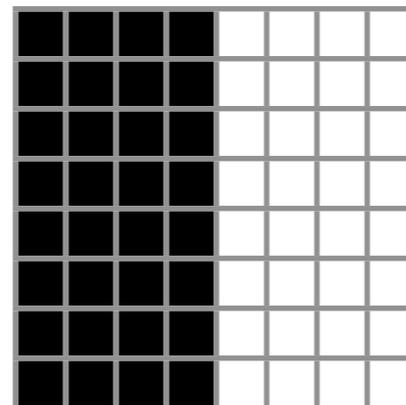
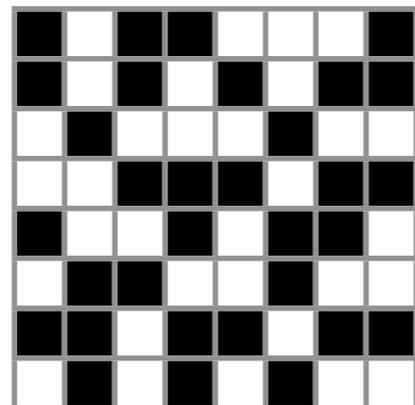
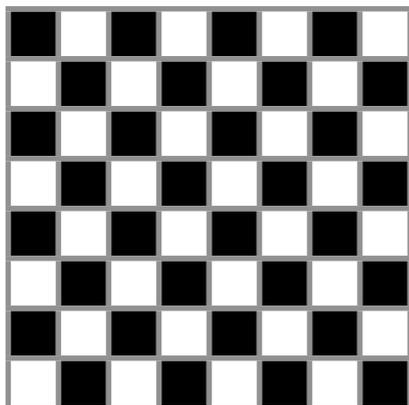
ordered



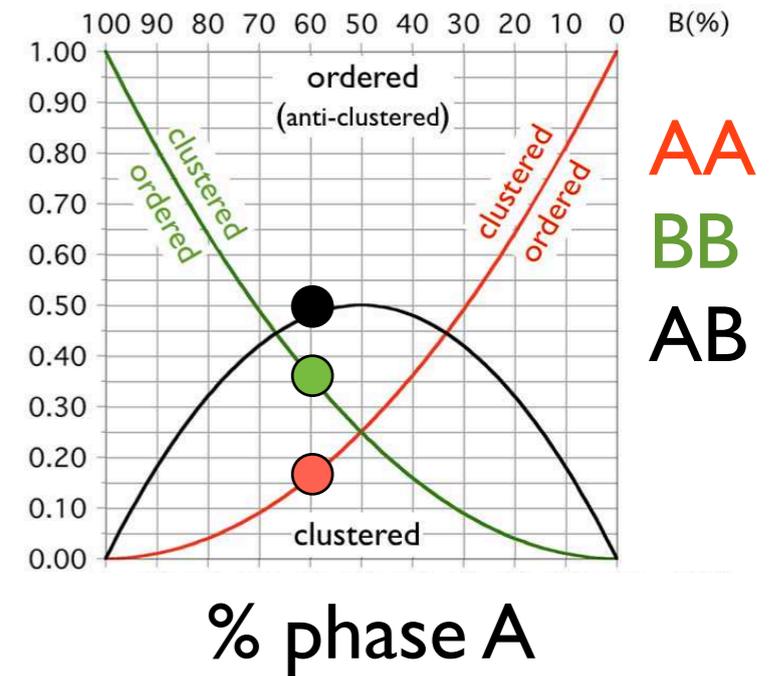
random



clustered



% contact surfaces

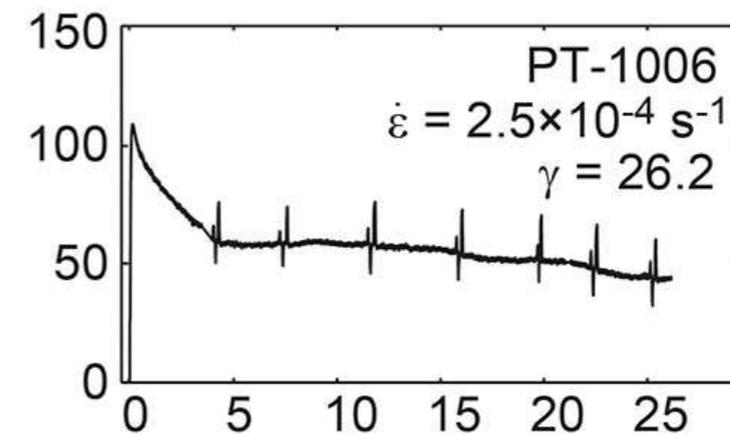


going to high strains



Gas medium High pressure Torsion apparatus (UMN)

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



Miki Tasaka



Mark Zimmerman

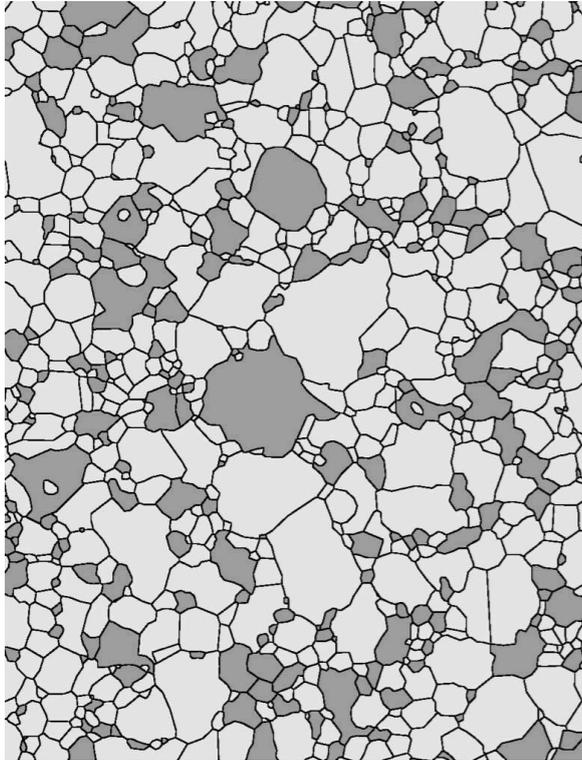


David Kohlstedt

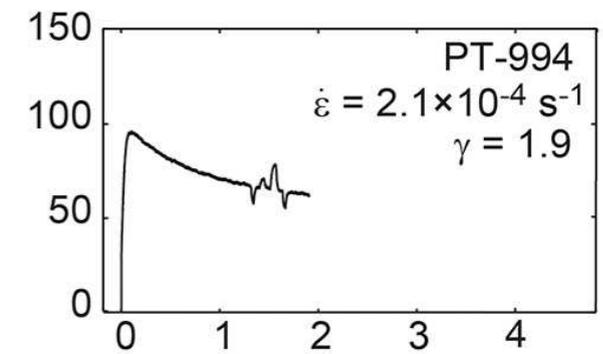
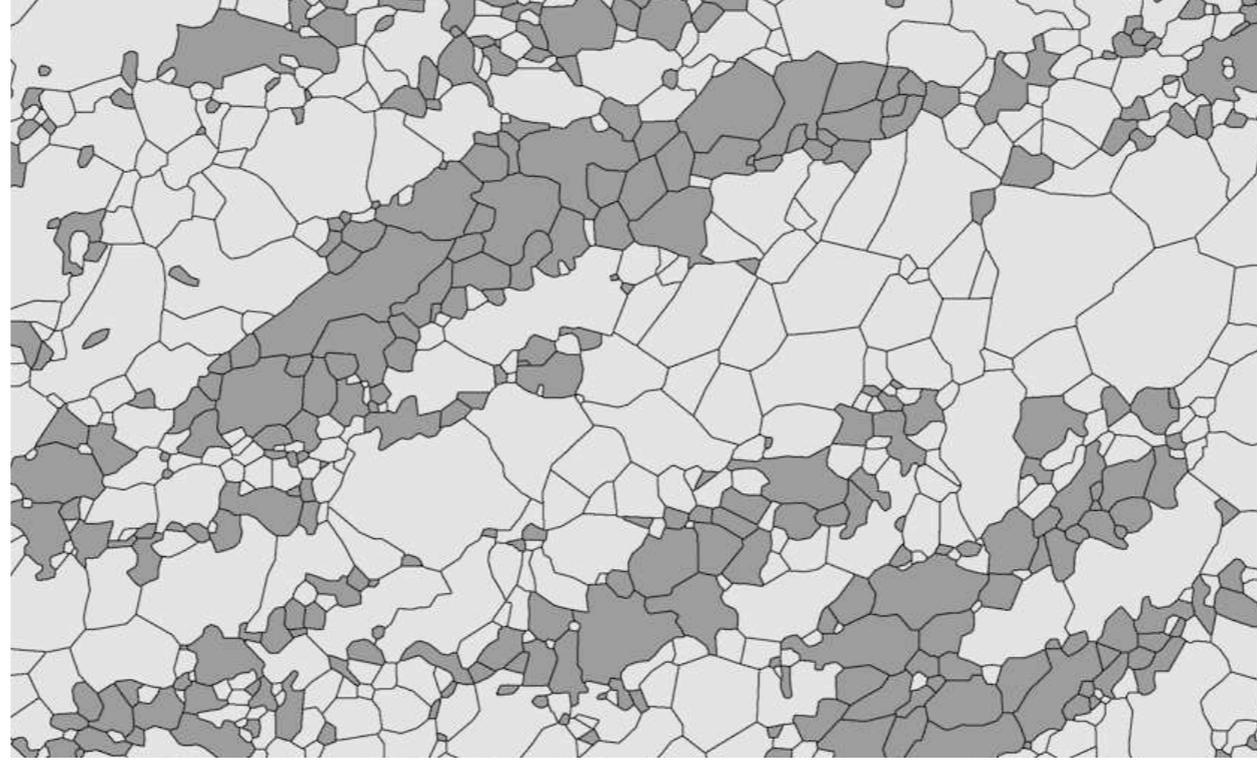
$p_c = 300 \text{ MPa}$
 $T = 1200^\circ\text{C}$
 $\dot{\gamma} = 2.6 \cdot 10^{-5} \text{ to } 6.8 \cdot 10^{-4} \text{ s}^{-1}$
 $\tau = 35 \text{ to } 226 \text{ MPa}$
up to $\gamma \sim 26$

diffusion creep \neq random

undeformed

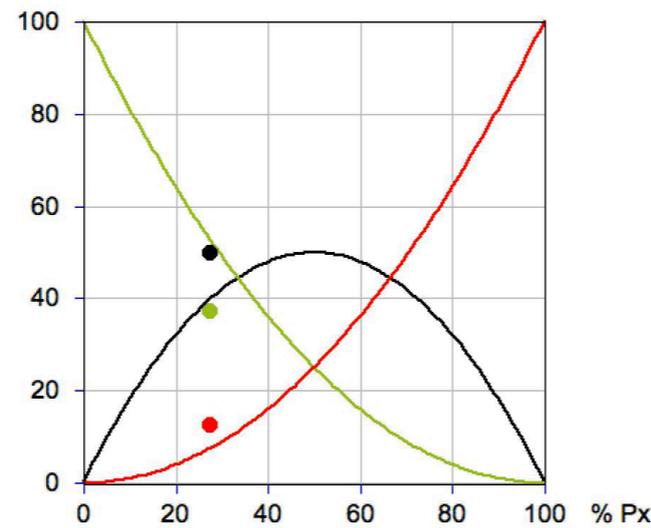
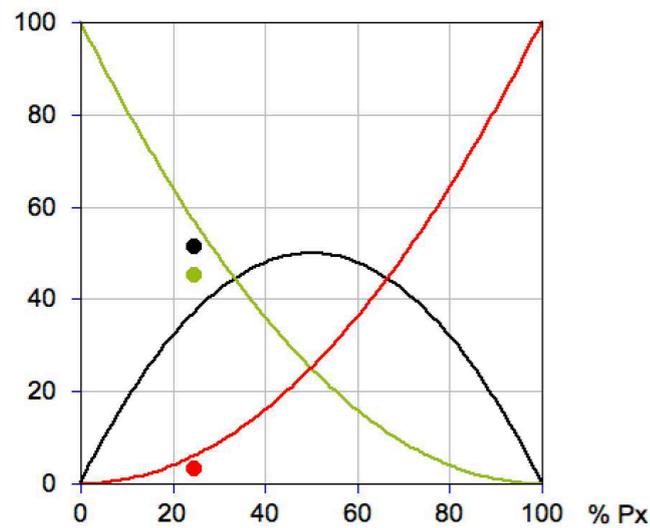


sheared ($\gamma = 1.9$)

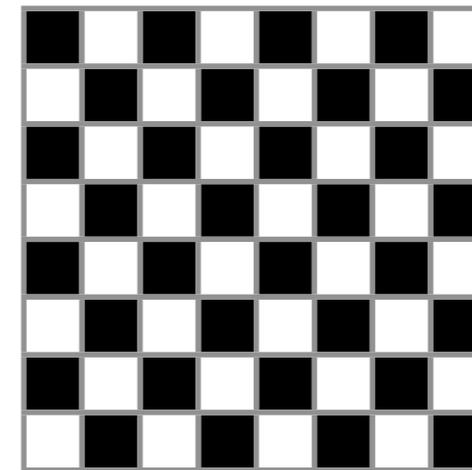


Tasaka et al. (in prep)

50 μm



=



!

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."

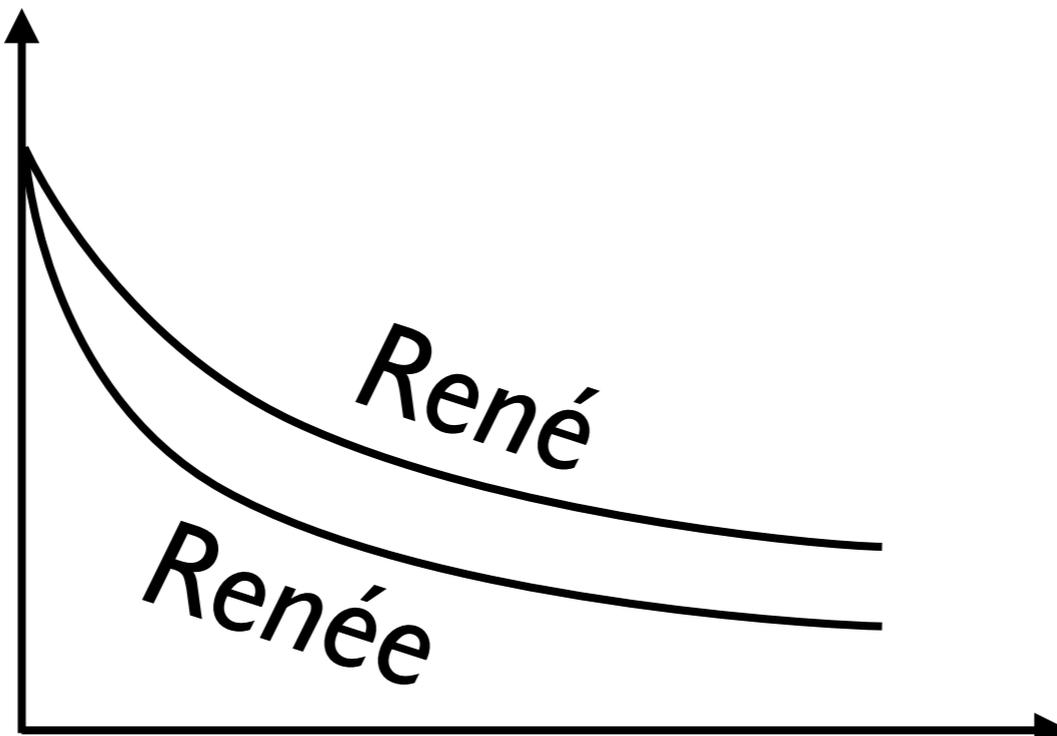


bla bla bla



bla bla bla

% of talk remembered by audience



time after talk



bla bla bla



bla ..?.. bla

"Finally..."



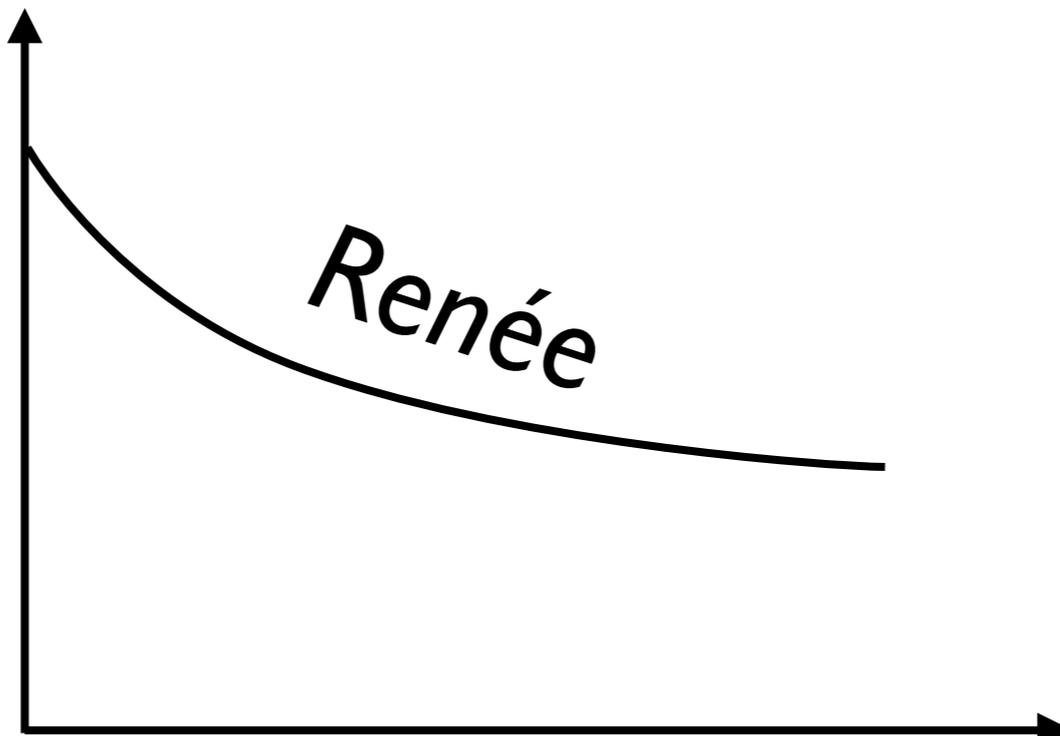
bla bla bla



bla bla bla

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

% of talk remembered by audience



time after talk



bla bla bla

Betti Richter

Rüdiger Kilian

Sina Marti

Renée Heilbronner



FNSNF

FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION



ONCE UPON A TIME IN THE WEST