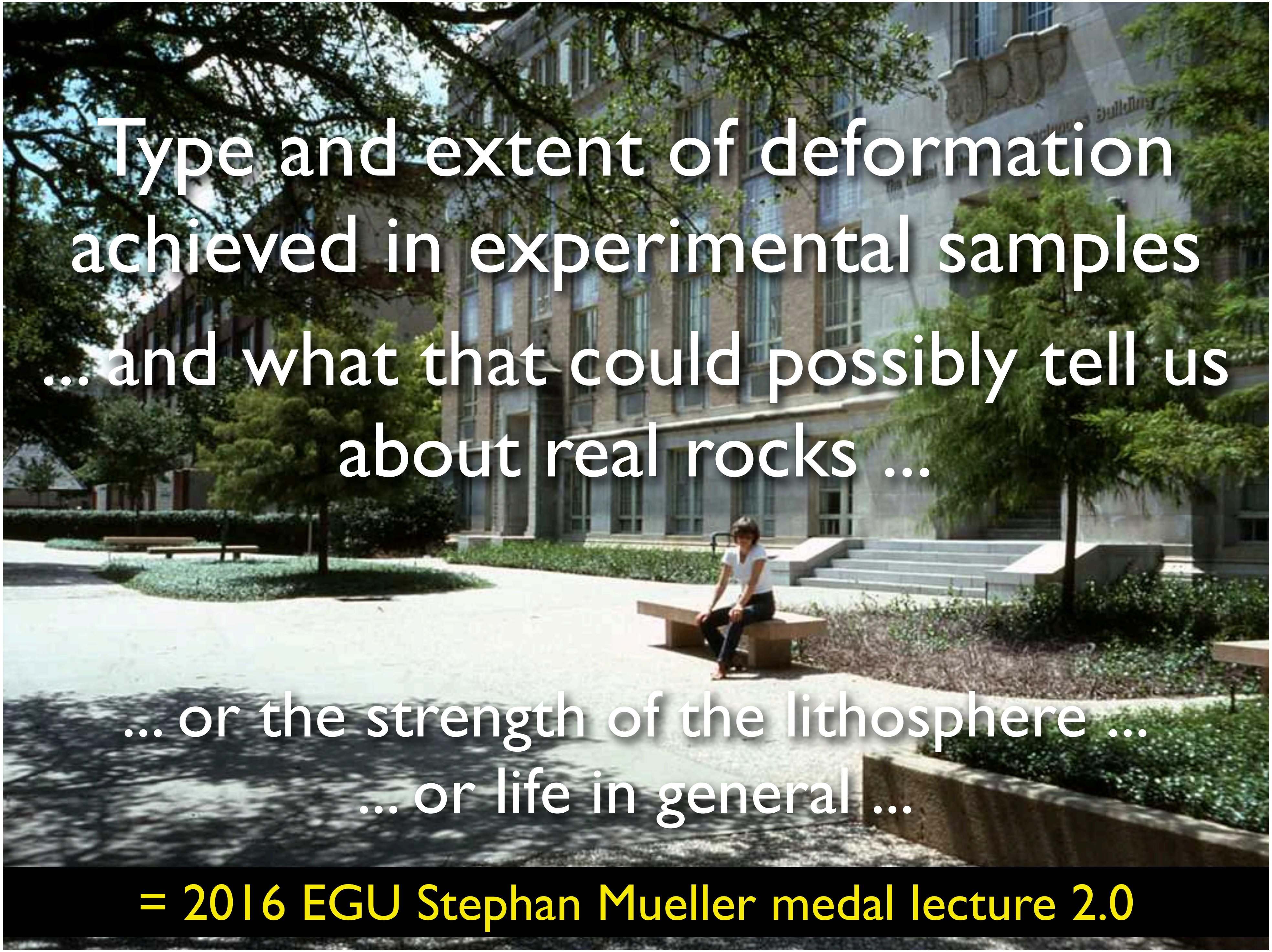

Type and extent of deformation
achieved in experimental samples
... and what that could possibly tell us
about real rocks ...
... or the strength of the lithosphere ...
... or life in general ...
= 2016 EGU Stephan Mueller medal lecture 2.0

not the born geologist ...

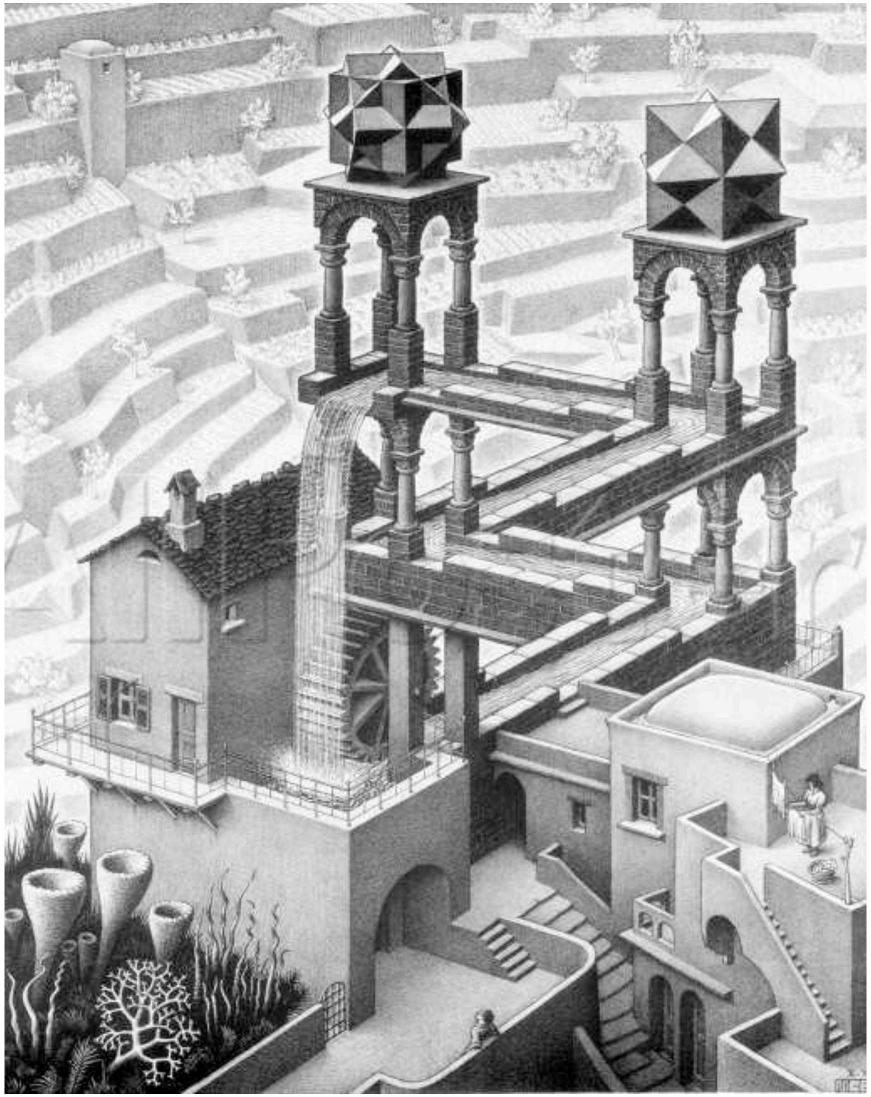
... but the trained photographer

the fascinating nature of images

René Magritte

... image analysis is object analysis

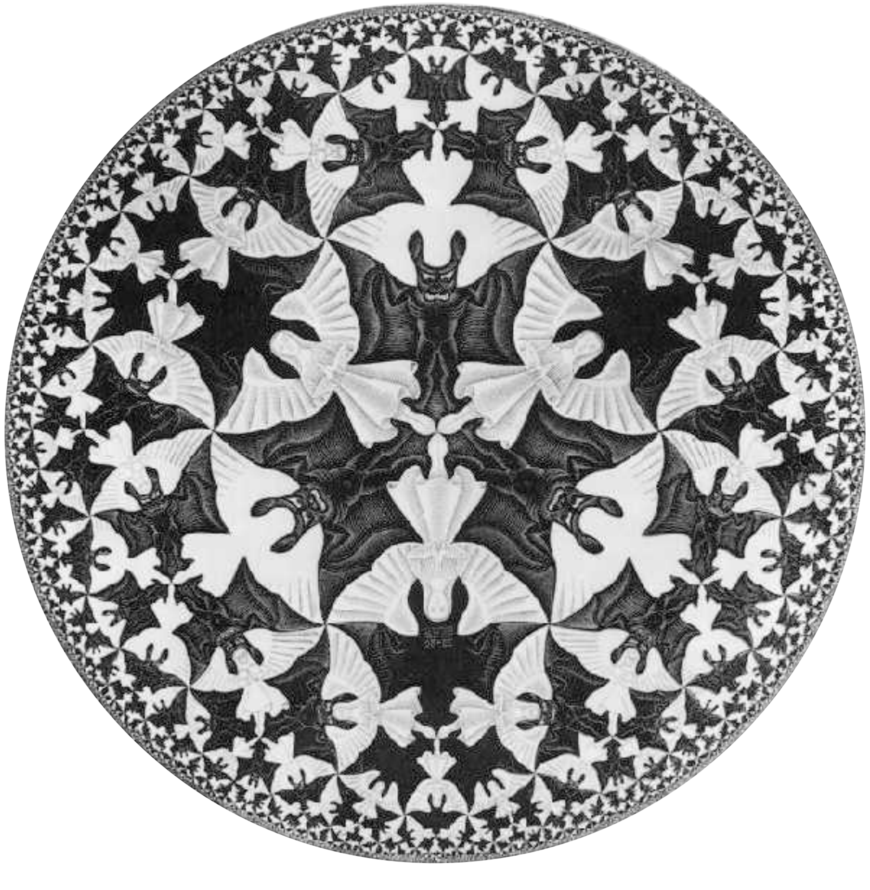
the worlds of 2 and 3 dimensions

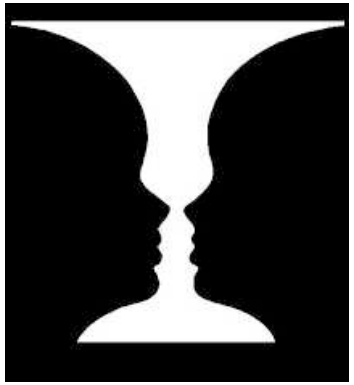


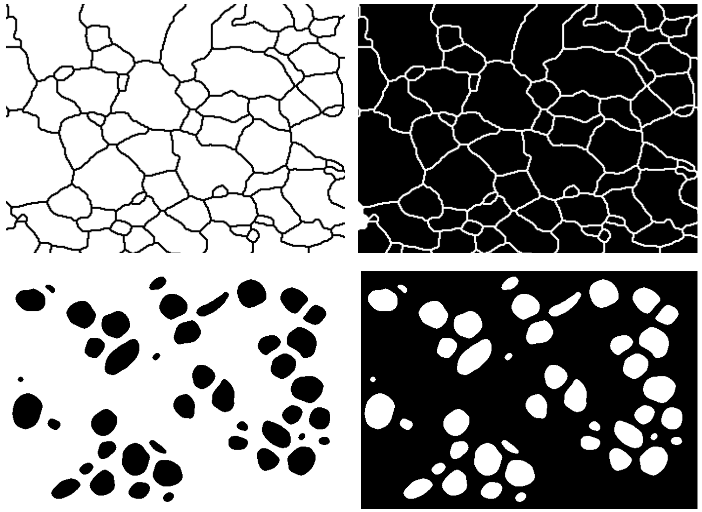
Maurits Escher

... and how to get from one to the other

symmetry and the space between





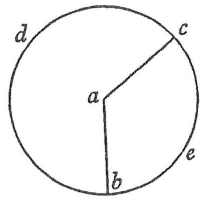


black or white - plus or minus - grains or boundaries ...

chance and probability ...

Newton

Isaac Newton (1643-1727)
- chance of hitting one of two unequal areas of a circle by a ball



Newton (1967 (sic!))

Comte de Buffon

Georges-Louis Leclerc Comte de Buffon (1707–1788)
- solutions of franc-carreau and needle problems

Saltykov

Sarkis Andreevich Saltykov (1905-1983)
- ... stereological theorems

... the statistics of spatial processes

thin sections are random draws...

Delesse

Rosiwal

Glagolev

Underwood

Achille Ernest Oscar Joseph Delesse (1817-1881)

$V_V = A_A$

August Karl Rosiwal (1860-1923)

$V_V = A_A = L_L$

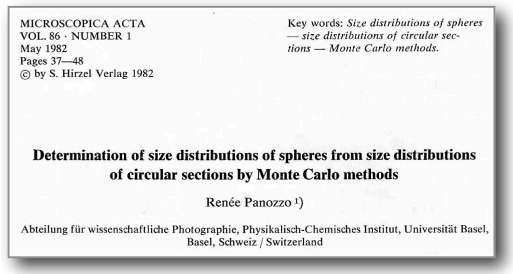
Nil Alexandrovich Glagolev (1888-1945)

$V_V = A_A = L_L = P_P$

Ervin E. Underwood (1918-1995)

'Quantitative Stereology' (1970)

... and Renée Panozzo (1982)



MICROSCOPICA ACTA
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Key words: *Size distributions of spheres — size distributions of circular sections — Monte Carlo methods.*

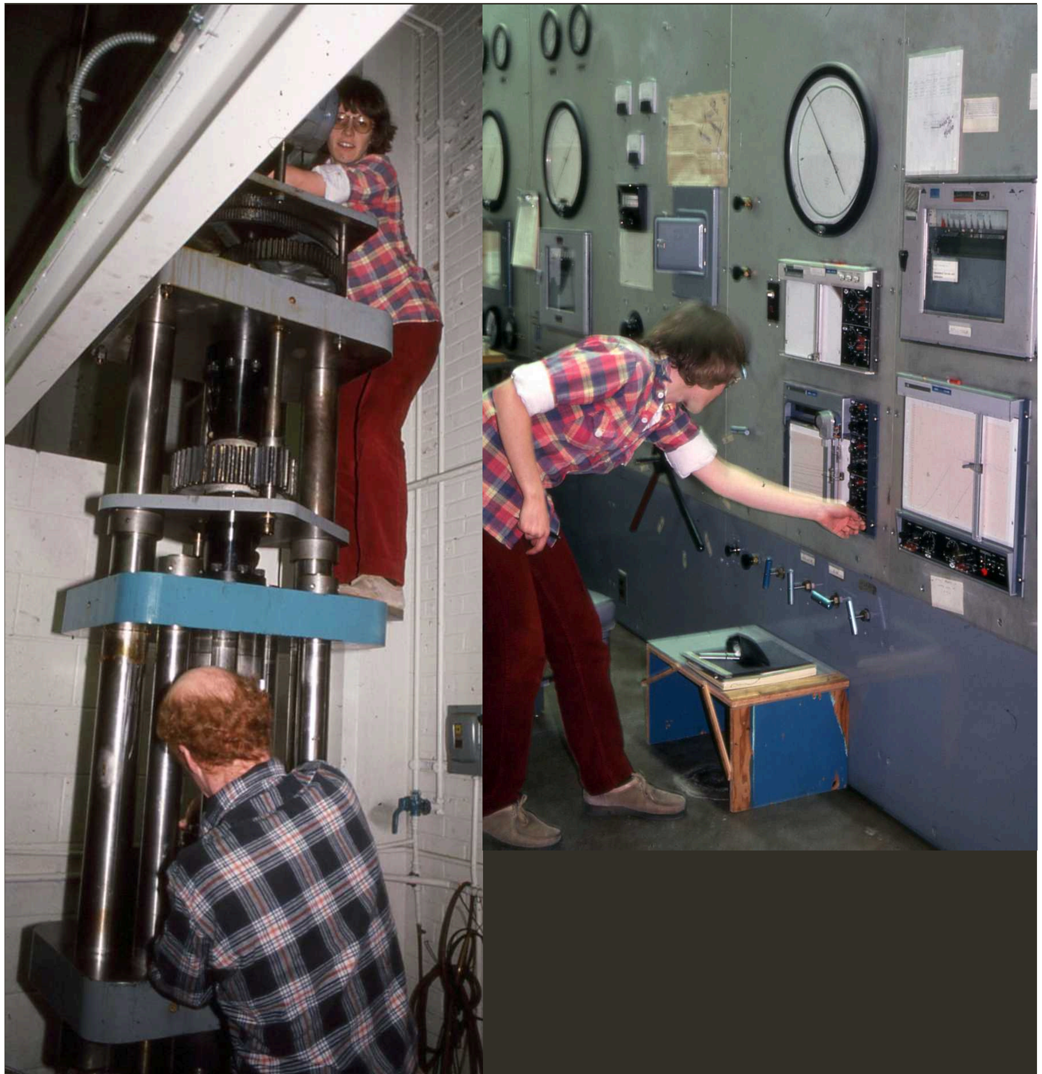
Determination of size distributions of spheres from size distributions of circular sections by Monte Carlo methods

Renée Panozzo [1])

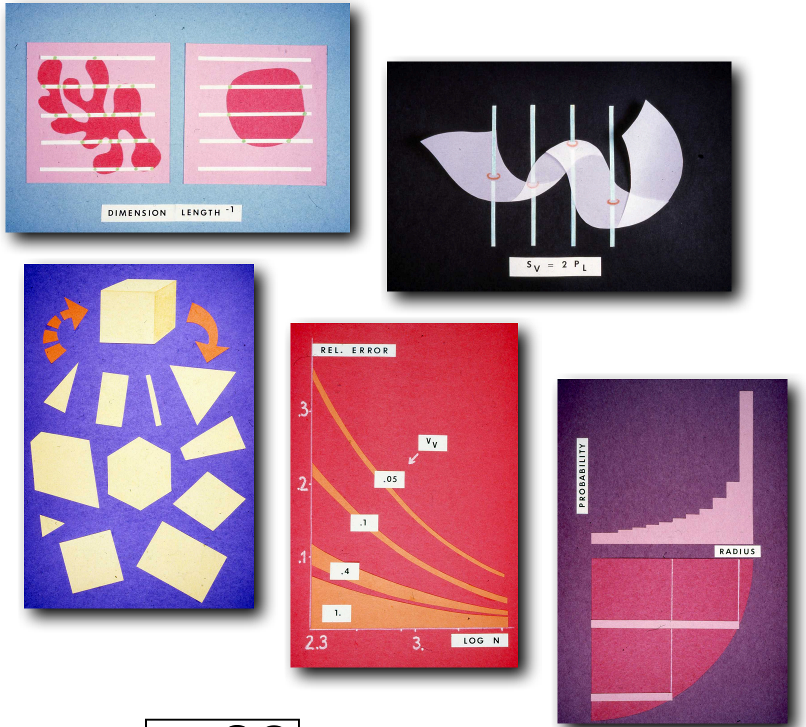
Abteilung für wissenschaftliche Photographie, Physikalisch-Chemisches Institut, Universität Basel, Basel, Schweiz / Switzerland

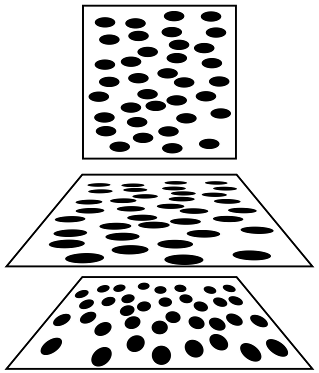
... taking chances with Monte Carlo

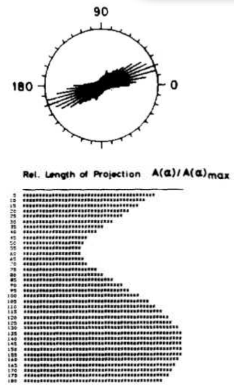
go West ! and do experiments !



... you can observe a lot by just watching (Yogi Berra)





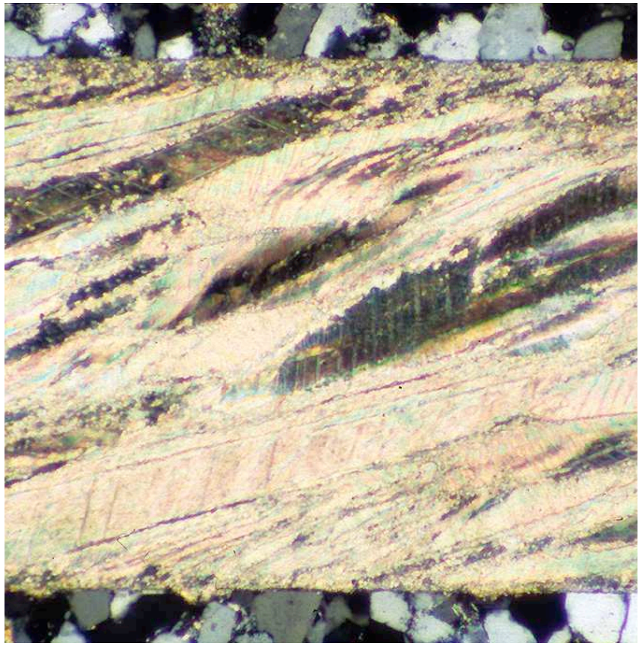


... and publish on fabric analysis (?) ...

from workshops ...

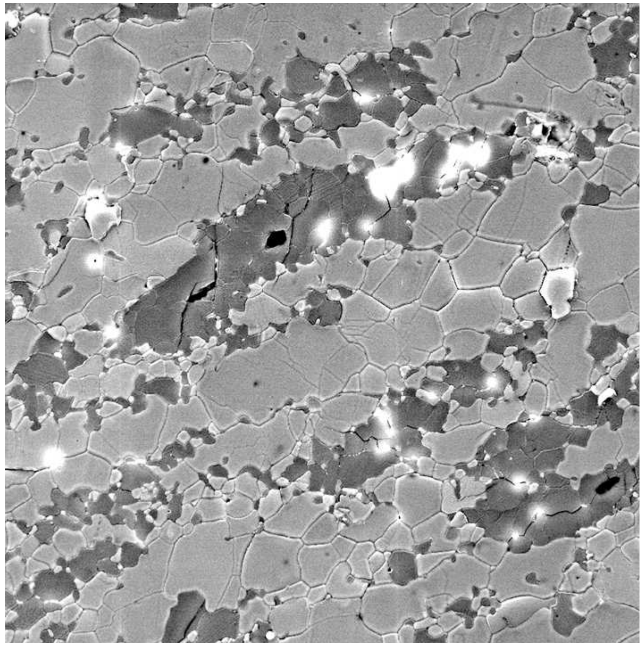
... to the textbook

let's take a look at three suites of samples ...



Carrara marble

Black Hills quartzite



synthetic mantle

Stefan Schmid
Steve Bauer

Triaxial gas appartus
Center for Tectonophysics

Jan Tullis

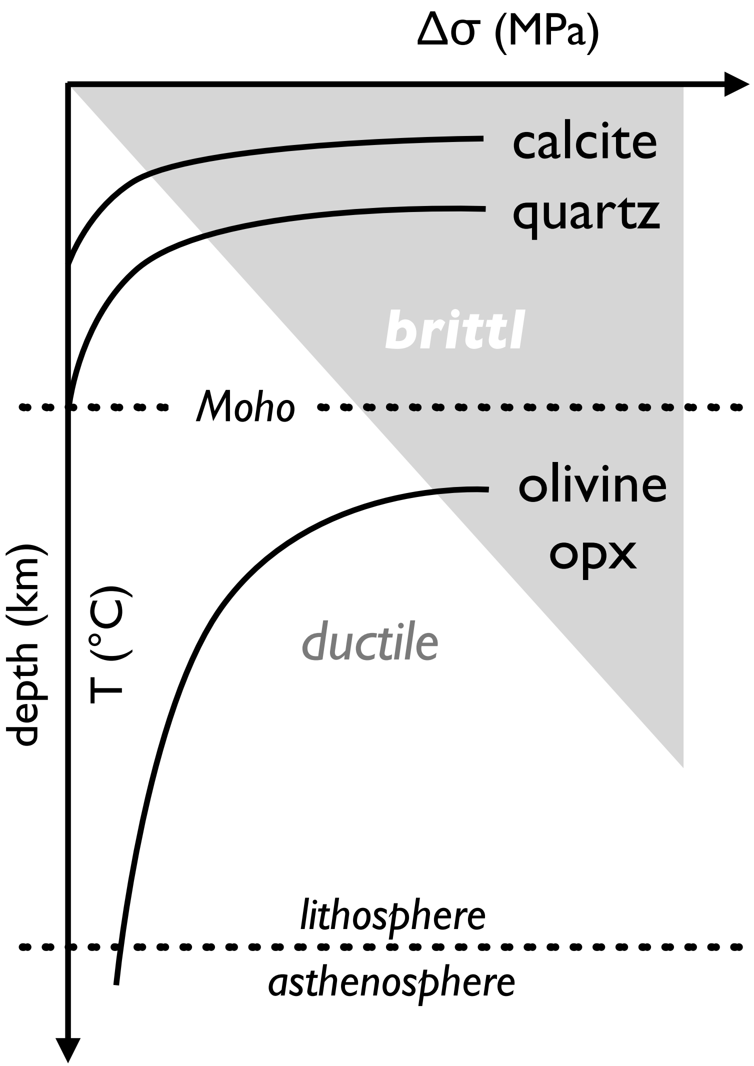
Solid medium apparatus
Brown University

Miki Tasaka
David Kohlstedt
Mark Zimmerman

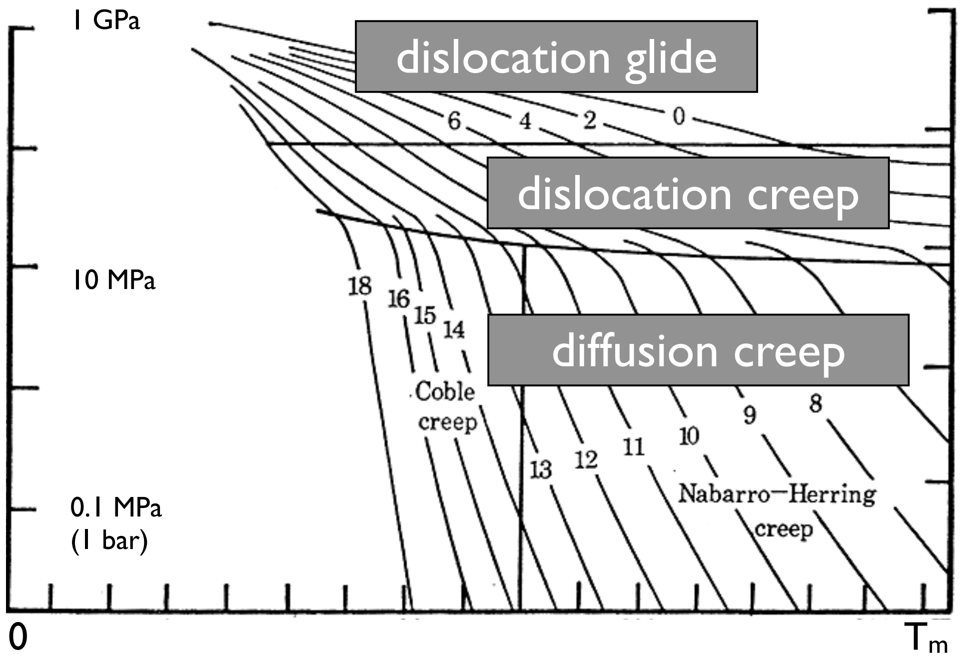
Torsion apparatus
University of Minnesota

... to see how rheology and microstrcuture are connected

a journey from the upper crust into the mantle ...



$$\dot{\varepsilon} = A \cdot exp(\, B \cdot \Delta\sigma \,)$$

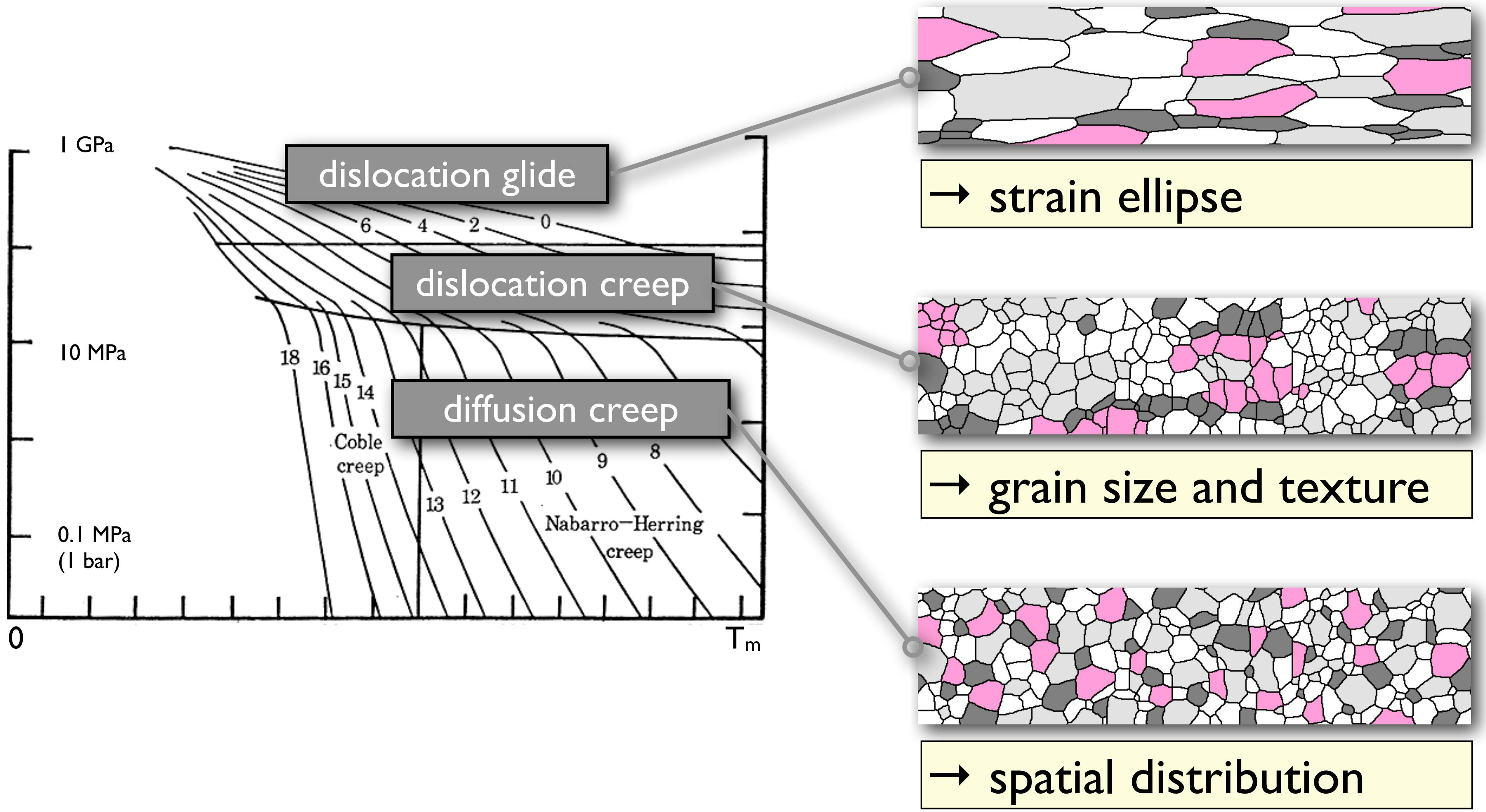


$$\dot{\varepsilon} = A \cdot \Delta\sigma^n \cdot exp(-Q/RT)$$

$$\dot{\varepsilon} = A \cdot \Delta\sigma^n \cdot d^m \cdot exp(-Q/RT)$$

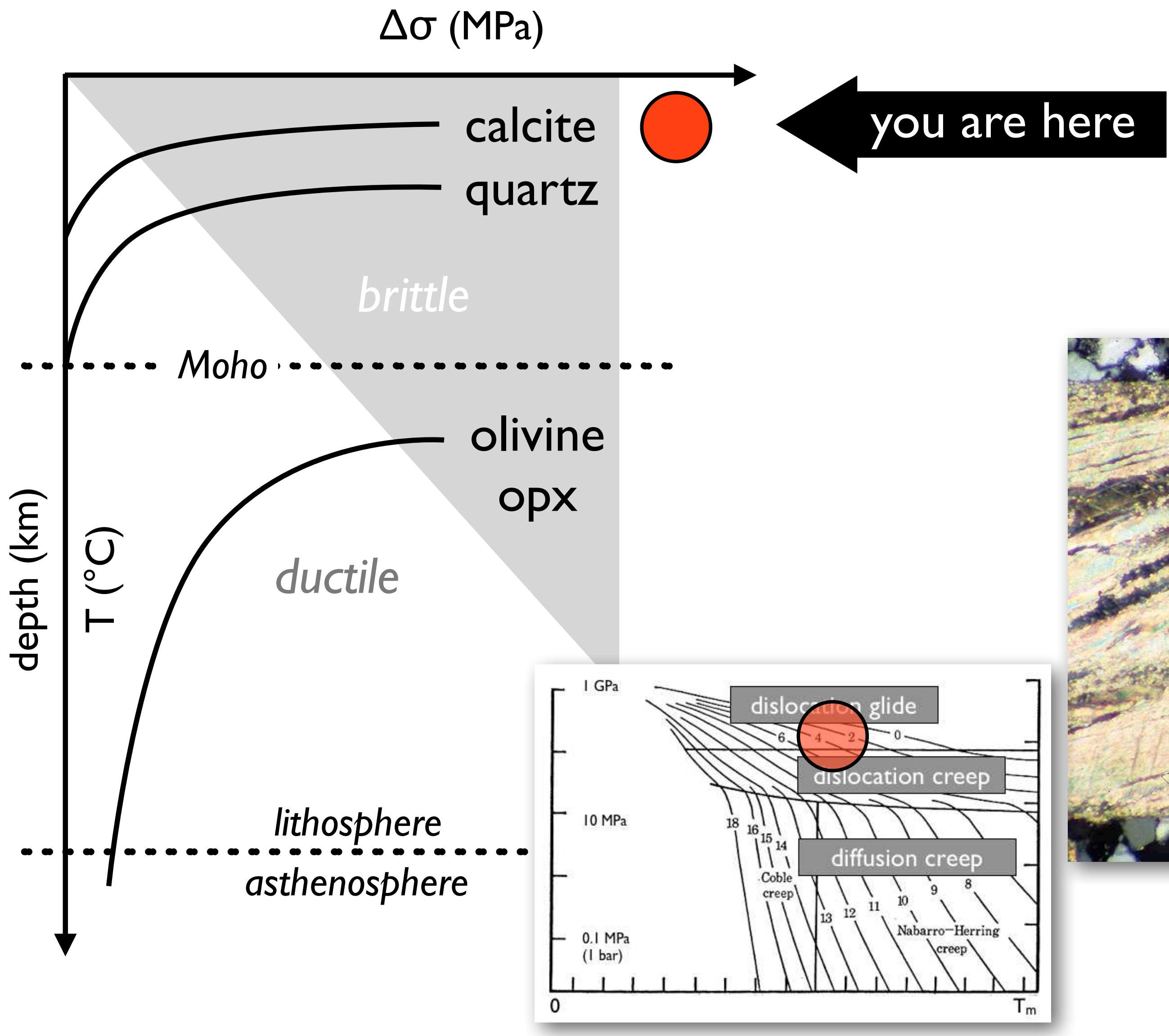
... and across the deformation mechanism map

Q: how to recognize deformation mechanisms ...

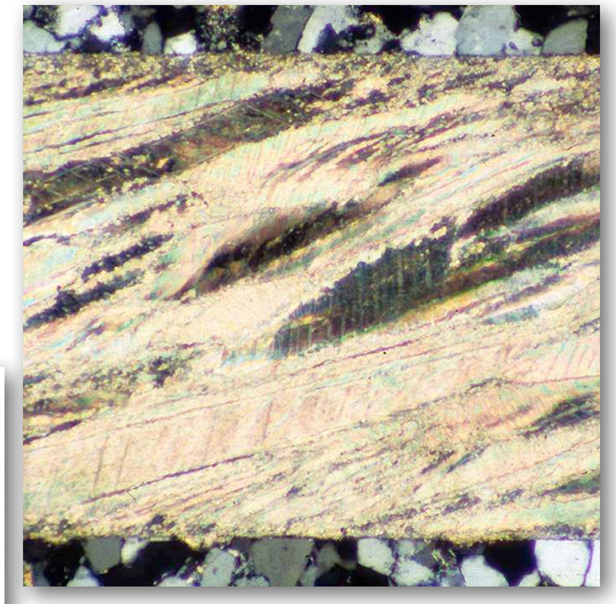


... when looking at a deformed samples ?

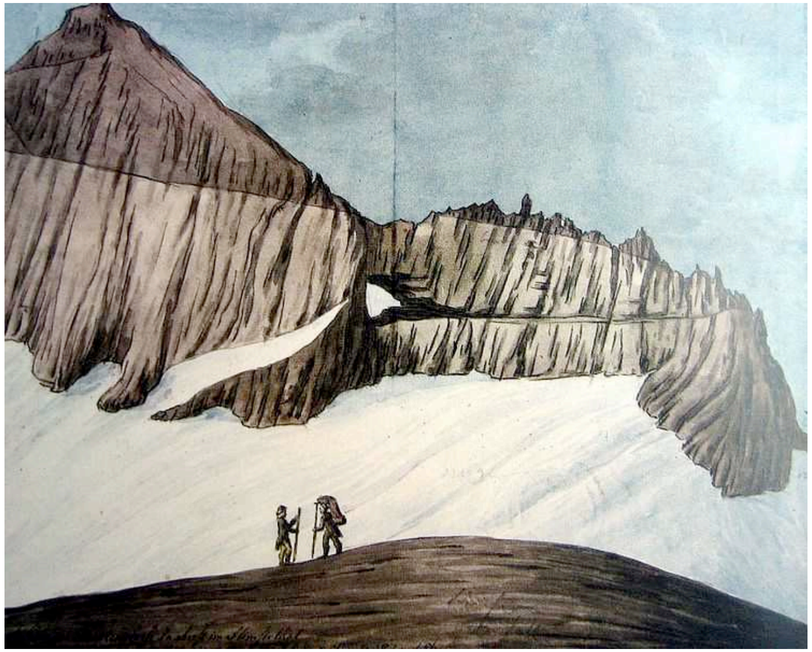
1st stop:



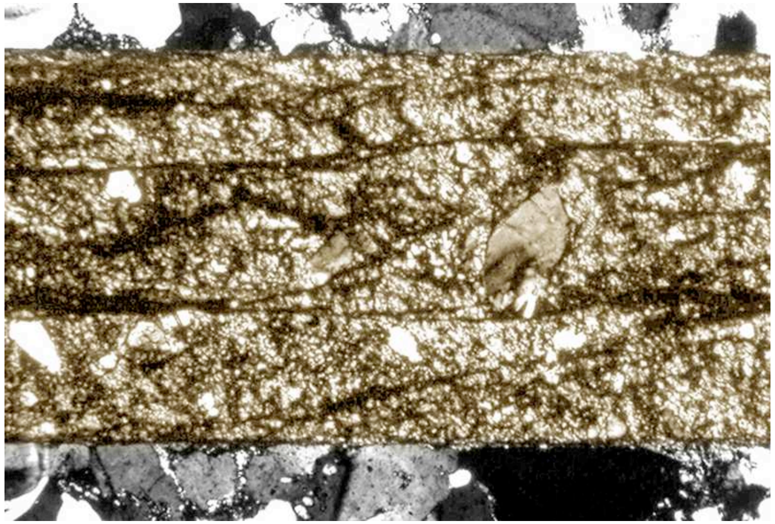
Δσ (MPa)
you are here
calcite
quartz
brittle
Moho
olivine
opx
ductile
depth (km)
T (°C)
lithosphere
asthenosphere
1 GPa
10 MPa
0.1 MPa
(1 bar)
dislocation glide
dislocation creep
diffusion creep
Coble creep
Nabarro–Herring creep
0
Tm



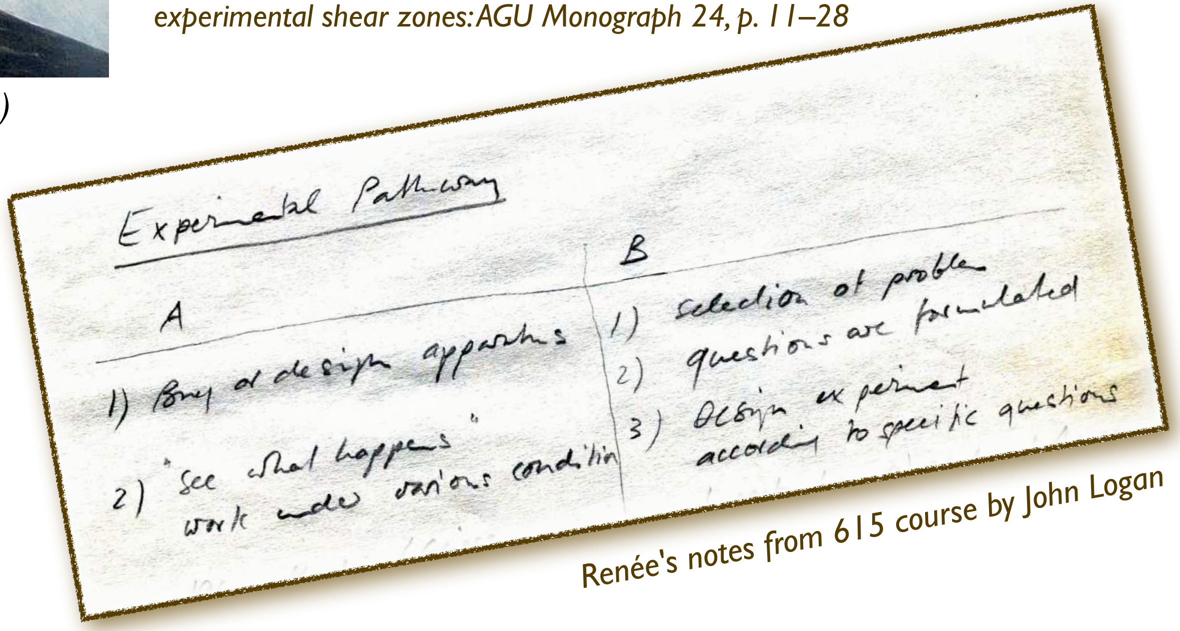
motivation: do the Glarus thrust in the lab



Glarus Thrust, drawing by Hans Conrad Escher (1812)



Friedman, M. and Higgs, N. G.(1981) Calcite fabrics in experimental shear zones: AGU Monograph 24, p. 11–28



Experimental Pathway

A

1) Buy or design apparatus

2) "See what happens" work under various conditions

B

1) selection of problem questions are formulated

2) Design experiment

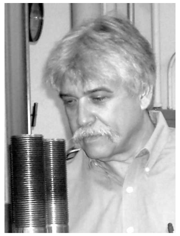
3) according to specific questions

Renée's notes from 615 course by John Logan

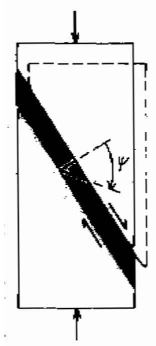
... and remember 615

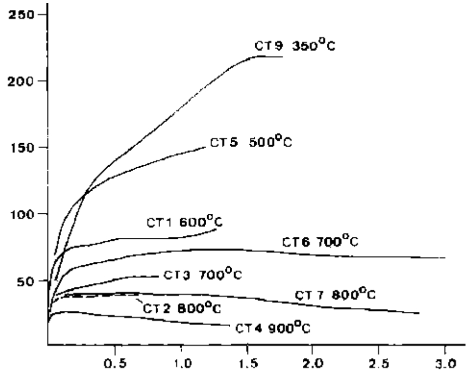
celebrating 30 years of simple shear ...

Stefan Schmid

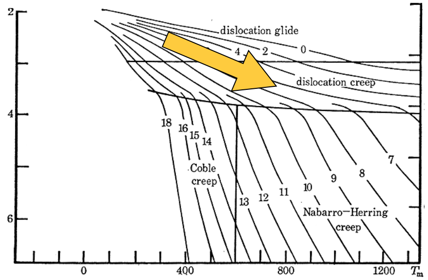


Steve Bauer



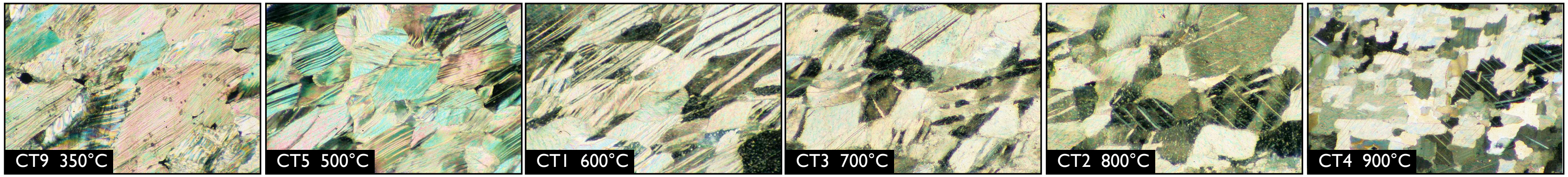


dislocation glide



dislocation creep

diffusion creep



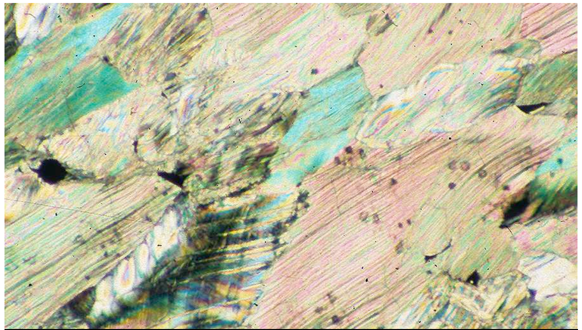
regime 1 | transition | regime 2

flow law	exponential	powerlaw n = 4.2
deformation mechanism	dislocation glide twinning	dislocation creep dynamic recrystallization

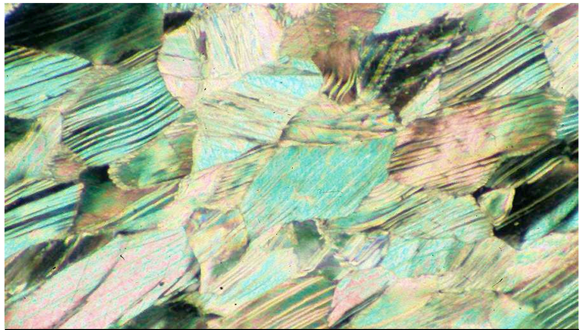
... 50 years of Center for Tectonophysics

deforming grains of Carrara marble ...

regime 1



CT9 350°C $\gamma = 1.27$



CT5 500°C $\gamma = 1.08$

Special Research Paper*

Simple shear experiments on calcite rocks: rheology and microfabric

S. M. Schmid,† R. Panozzo† and S. Bauer‡

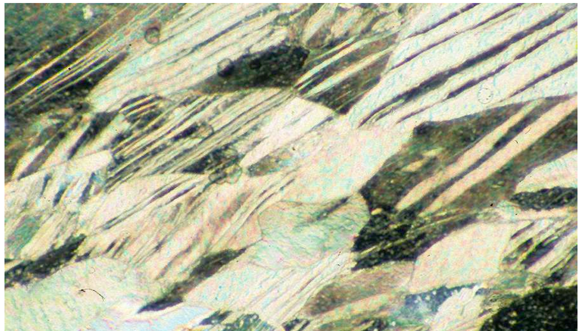
† Geologisches Institut, ETH-Zentrum, 8092 Zürich, Switzerland and ‡ Center for Tectonophysics, Texas A & M University, College Station, Texas 77843. Now at: Sandia National Laboratories, Div. 6314, Albuquerque, NM 87185, U.S.A.

(*Received* 20 *June* 1986; *accepted in revised form* 26 *February* 1987)

J. Struct. Geol., 1987

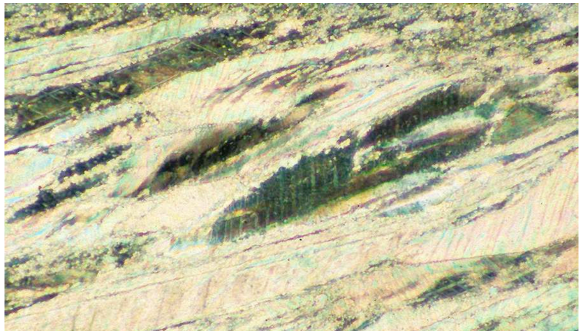
500 μm

transition 1-2



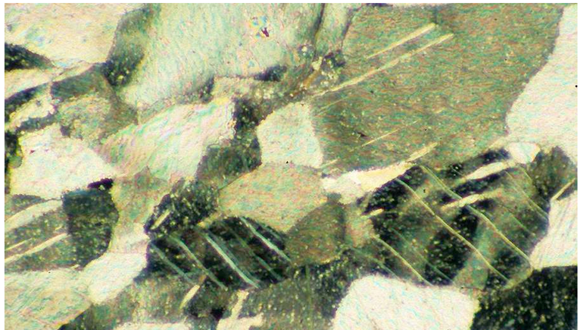
CT1 600°C $\gamma = 1.22$

CT3 700°C $\gamma = 0.79$

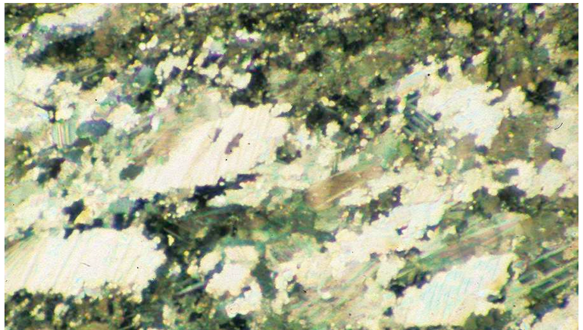


CT6 700°C $\gamma = 2.85$

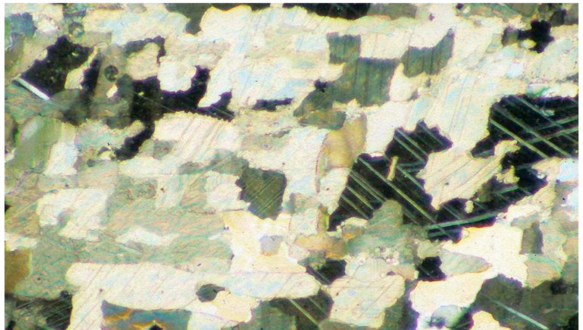
regime 2



CT2 800°C $\gamma = 0.63$



CT7 800°C $\gamma = 2.74$



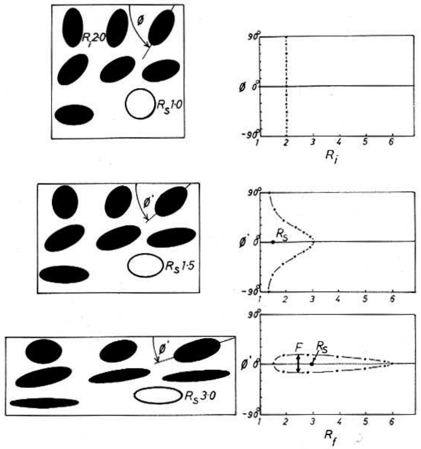
CT4 900°C $\gamma = 1.31$

... now you see them - now you don't ...

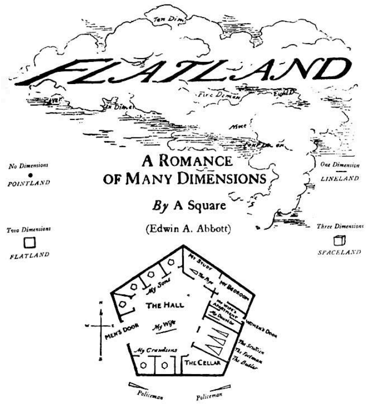
how to measure strain

step 1: use R_f - φ technique

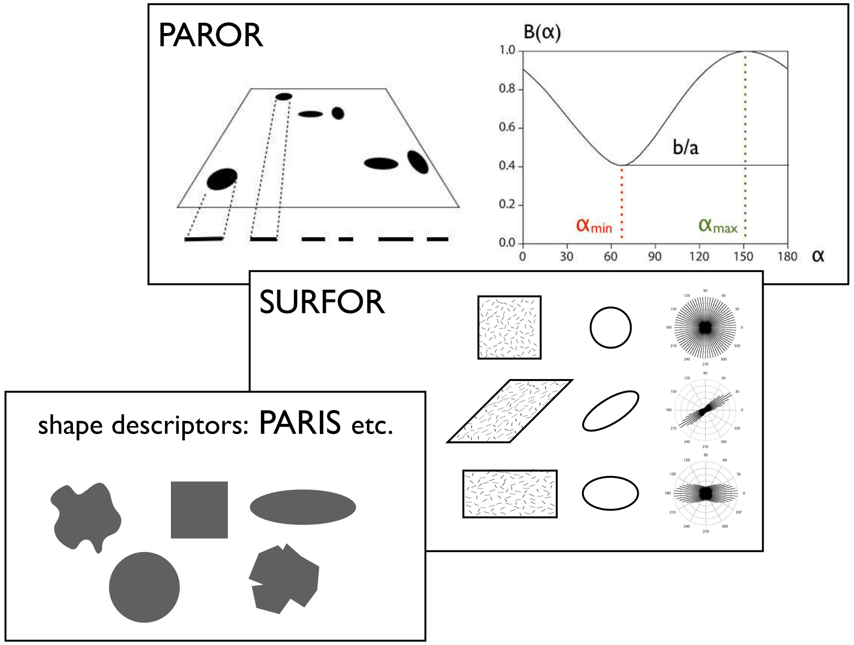
John G. Ramsay



Edwin A. Abbott



step 2: write own software



Two-dimensional strain from the orientation of lines in a plane

RENÉE PANOZZO

Abteilung für wissenschaftliche Photographie, Universität Basel, Klingelbergstr. 80, CH-4056 Basel, Switzerland

(Accepted in revised form 30 June 1983)

Tectonophysics, 1983

TWO-DIMENSIONAL ANALYSIS OF SHAPE-FABRIC USING PROJECTIONS OF DIGITIZED LINES IN A PLANE

RENÉE H. PANOZZO

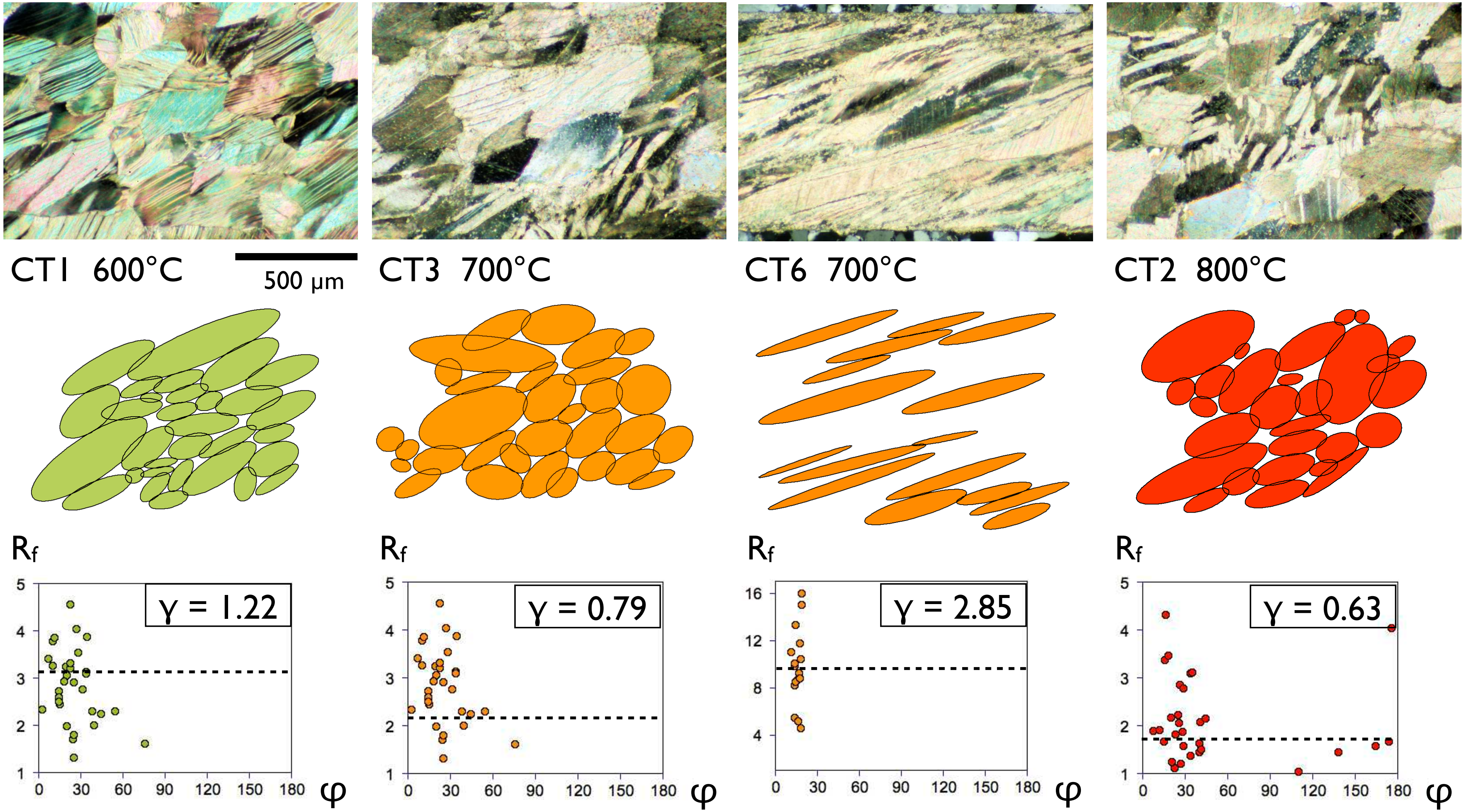
Abteilung für Wissenschaftliche Photographie, Physikalisch-Chemisches Institut, Klingelbergstr. 80, CH-4056 Basel (Switzerland)

(Accepted November 10, 1982)

J. Struct. Geol., 1984

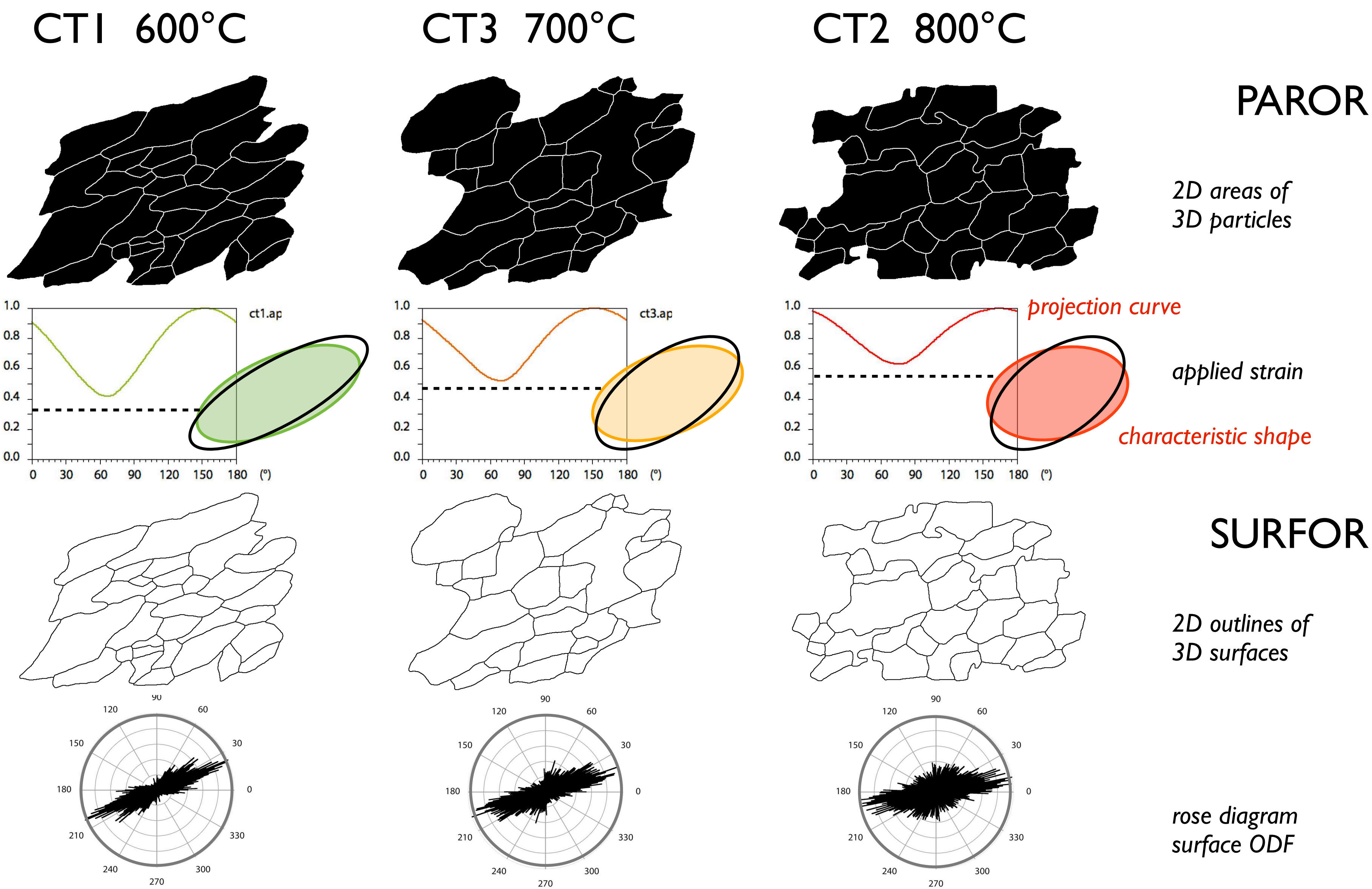
... from polyhedra in flatland ...

Ramsay's Rf-φ technique works well ...



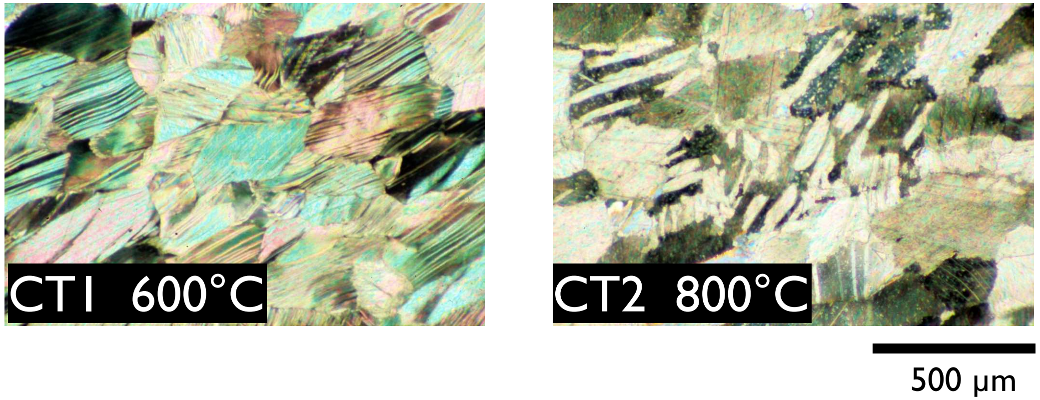
... if grain boundaries do not begin to migrate ...

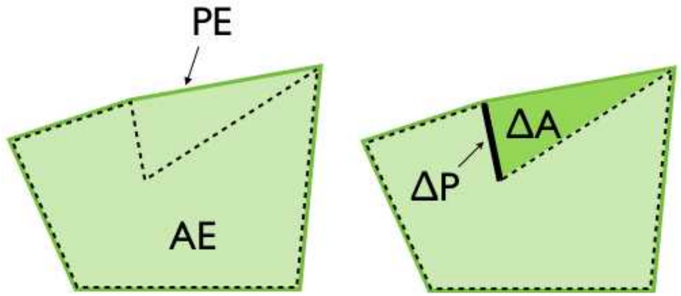
but the world is not an ellipse ...



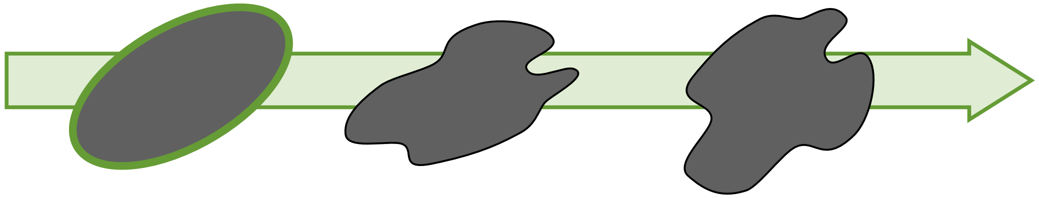
... and 'strain fact or fiction' is a paper that never made it

how to describe the shape change





the convex hull

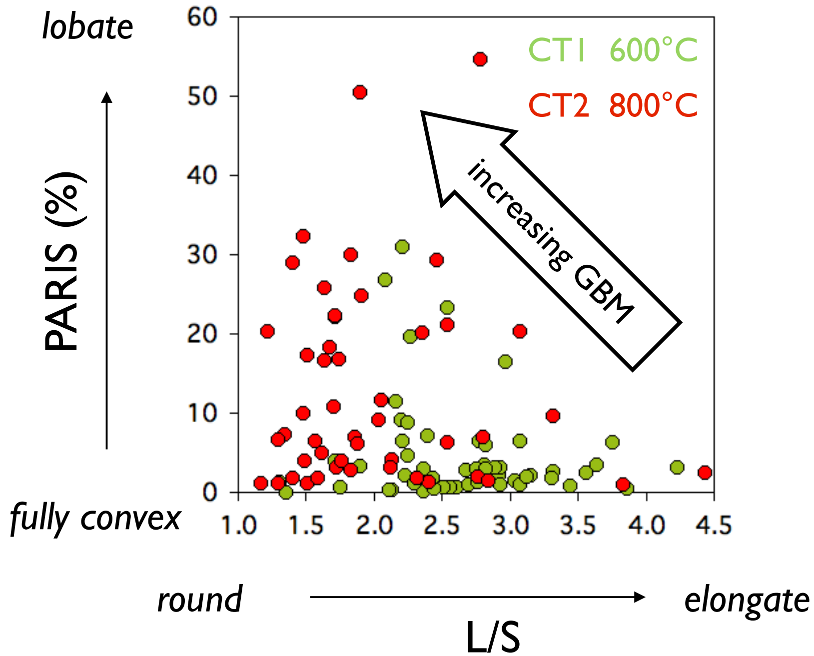


A simple method for the quantitative discrimination of convex and convex-concave lines
Renée Panozzo, and Helga Hürlimann [1])

Microscopica Acta, 1983

Grain size and grain shape analysis of fault rocks
Renée Heilbronner *, Nynke Keulen

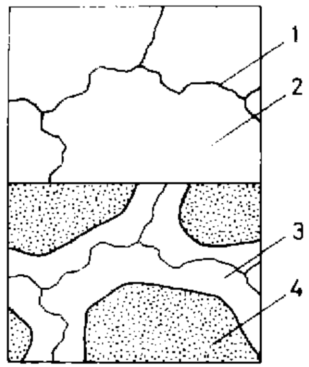
Tectonophysics 2006



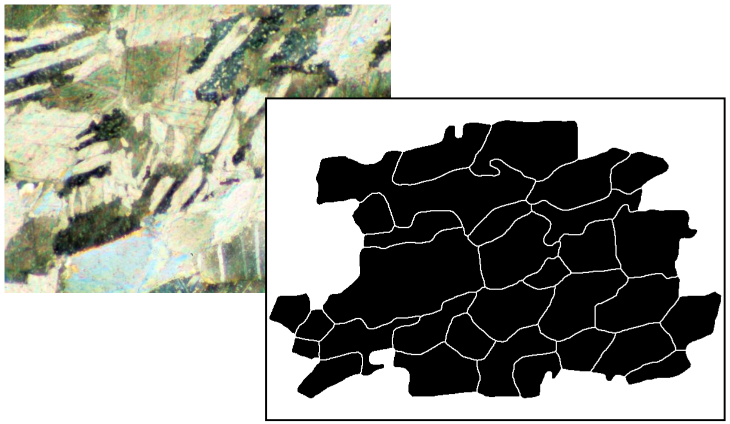
... use the famous PARIS factor

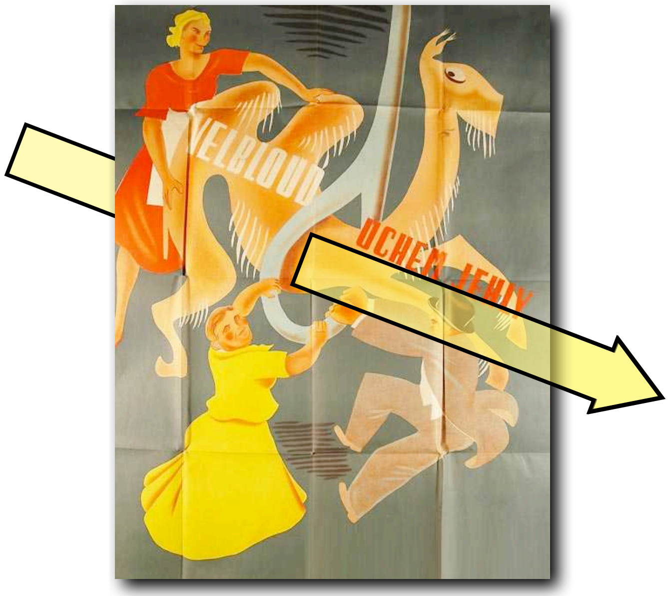
... so what does that tell you about real rocks ?

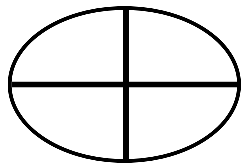
- grain boundaries lead there own life
  not every outline of a grain is a strain marker
- one mineral can act like two rheological phases
  strain partitionning is possible - even probable
- locally high strain rates are possible
- symmetry is the eye of the needle ...



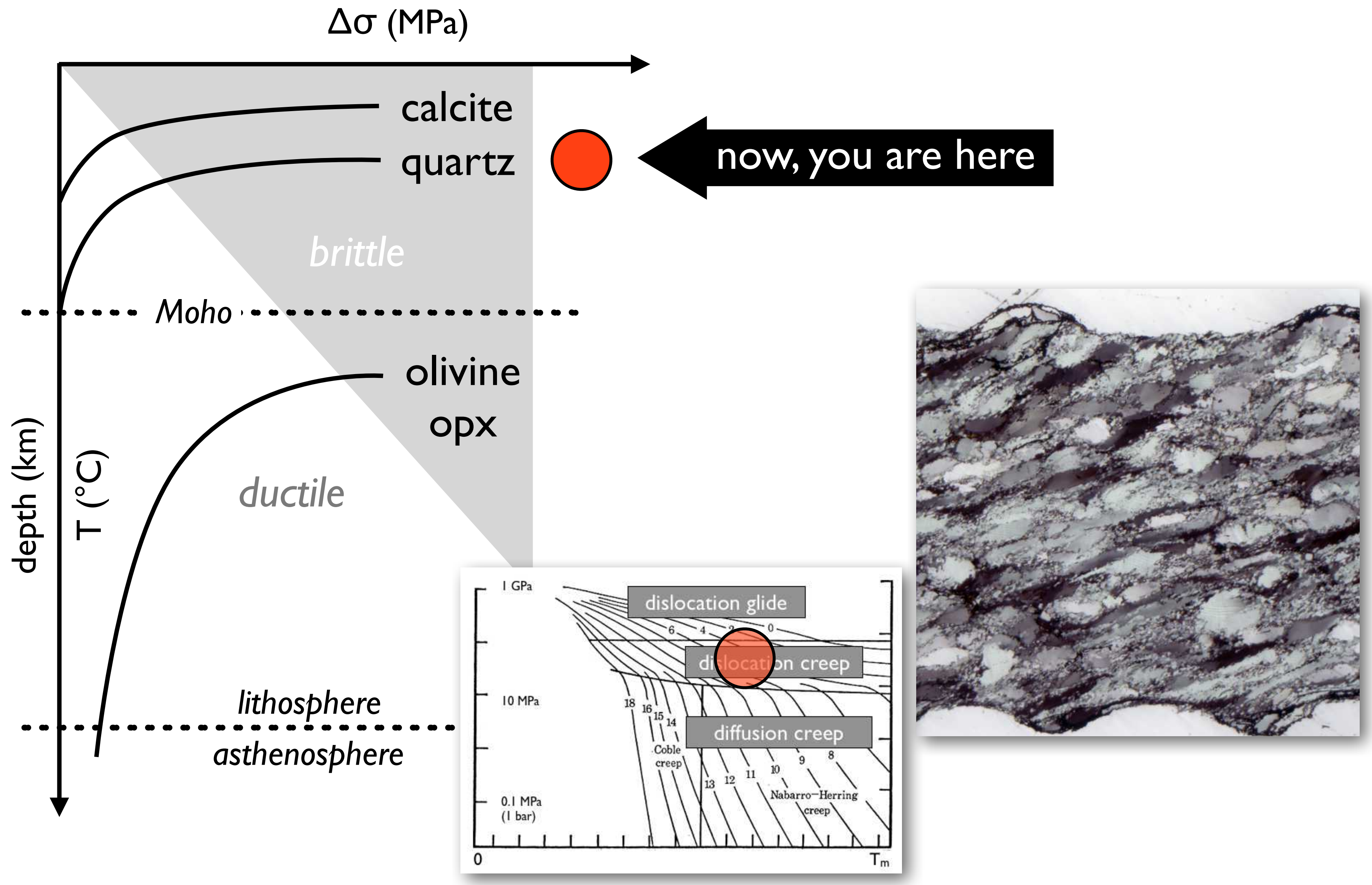
Schmid et al., JSG 1987





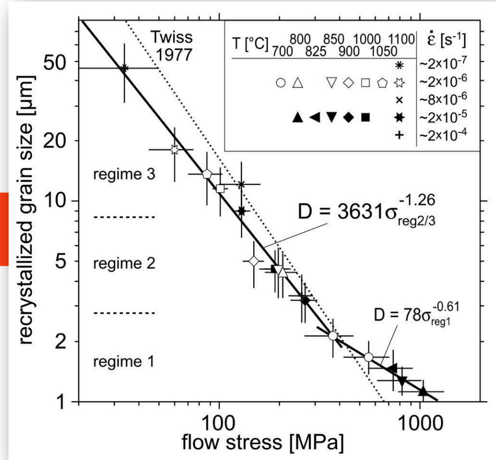


2nd stop:



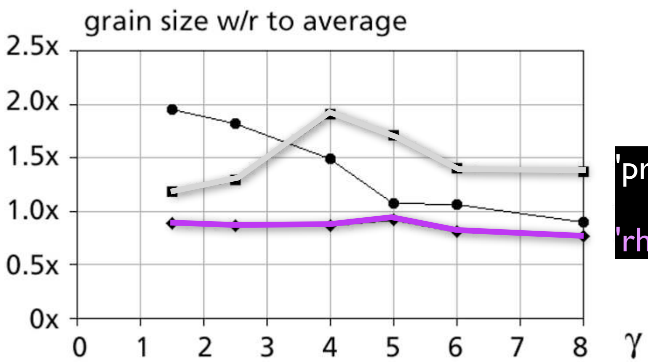
Δσ (MPa)
calcite
quartz
now, you are here
brittle
Moho
olivine
opx
depth (km)
T (°C)
ductile
lithosphere
asthenosphere
1 GPa
dislocation glide
6
4
2
0
dislocation creep
10 MPa
18
16
15
14
diffusion creep
Coble creep
9
8
13
12
11
10
Nabarro–Herring creep
0.1 MPa
(1 bar)
0
Tm

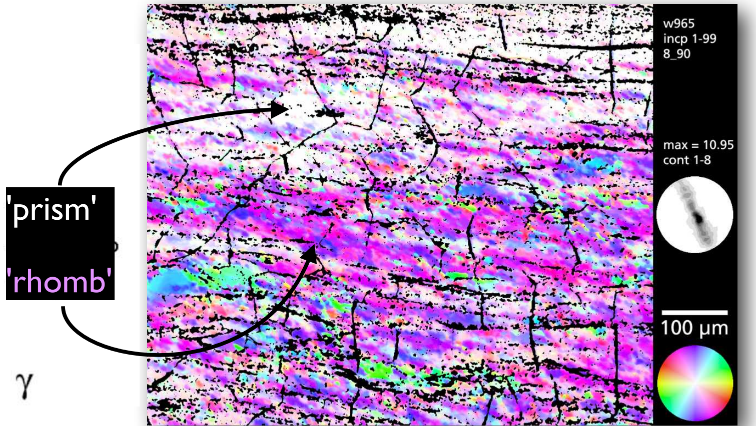
motivation: the grain size of recrystallized quartz



the piezometer - does it hold for shear deformation ?

"...the recrystallized grain size of the <u>rhomb</u> domain is approx. 12 µm and that of the <u>prism</u> domain is approx. 19 µm, correspond-ing to shear stresses of 93 and 64 MPa..."



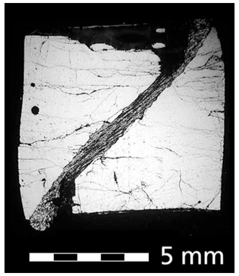


texture dependence of grain size: does it really exist ?

axial and shear experiments ...

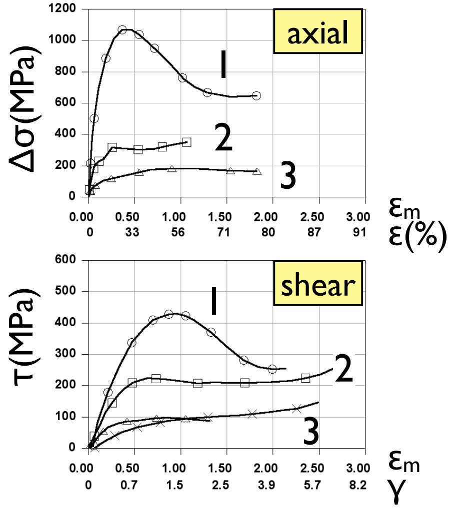
Jan Tullis and ...

her Grigg's apparatus

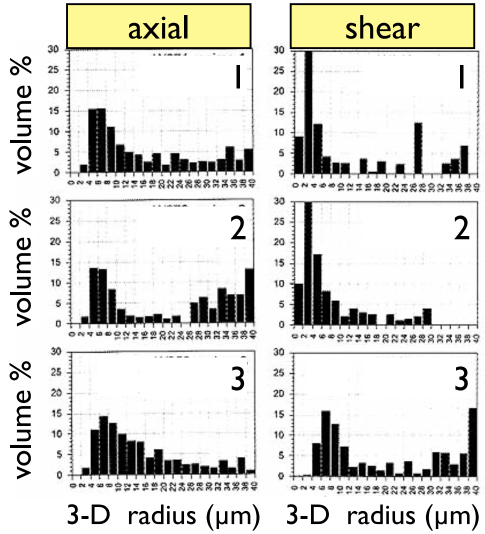


Heilbronner & Tullis (2006)

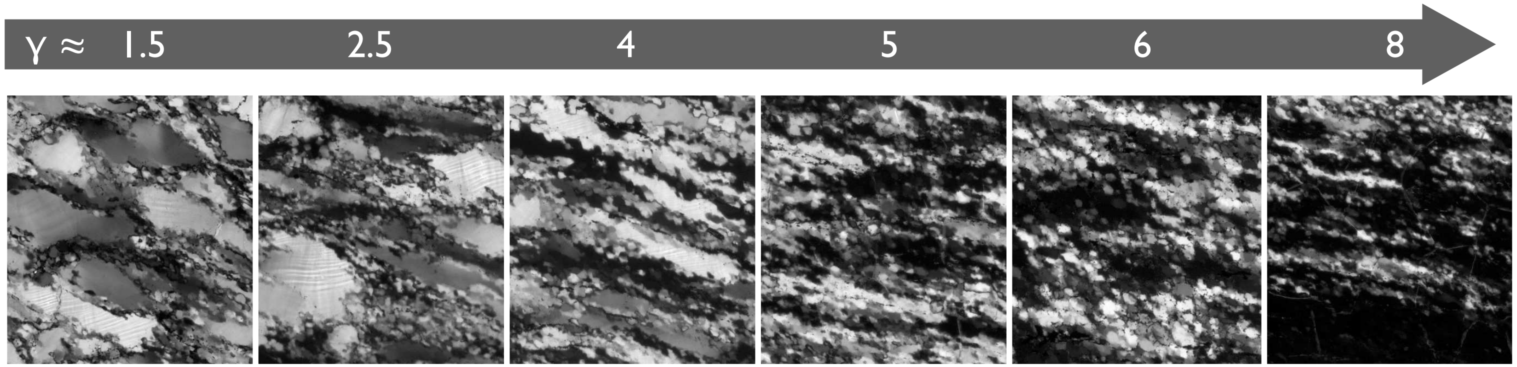
dislocation creep
regimes 1, 2, 3

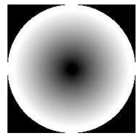


Heilbronner & Tullis (2002)



estimated mode of 3-D diameter (μm)		
	axial	shear
1	12 μm	6 μm
2	12 μm	6 μm
3	14 μm	14 μm

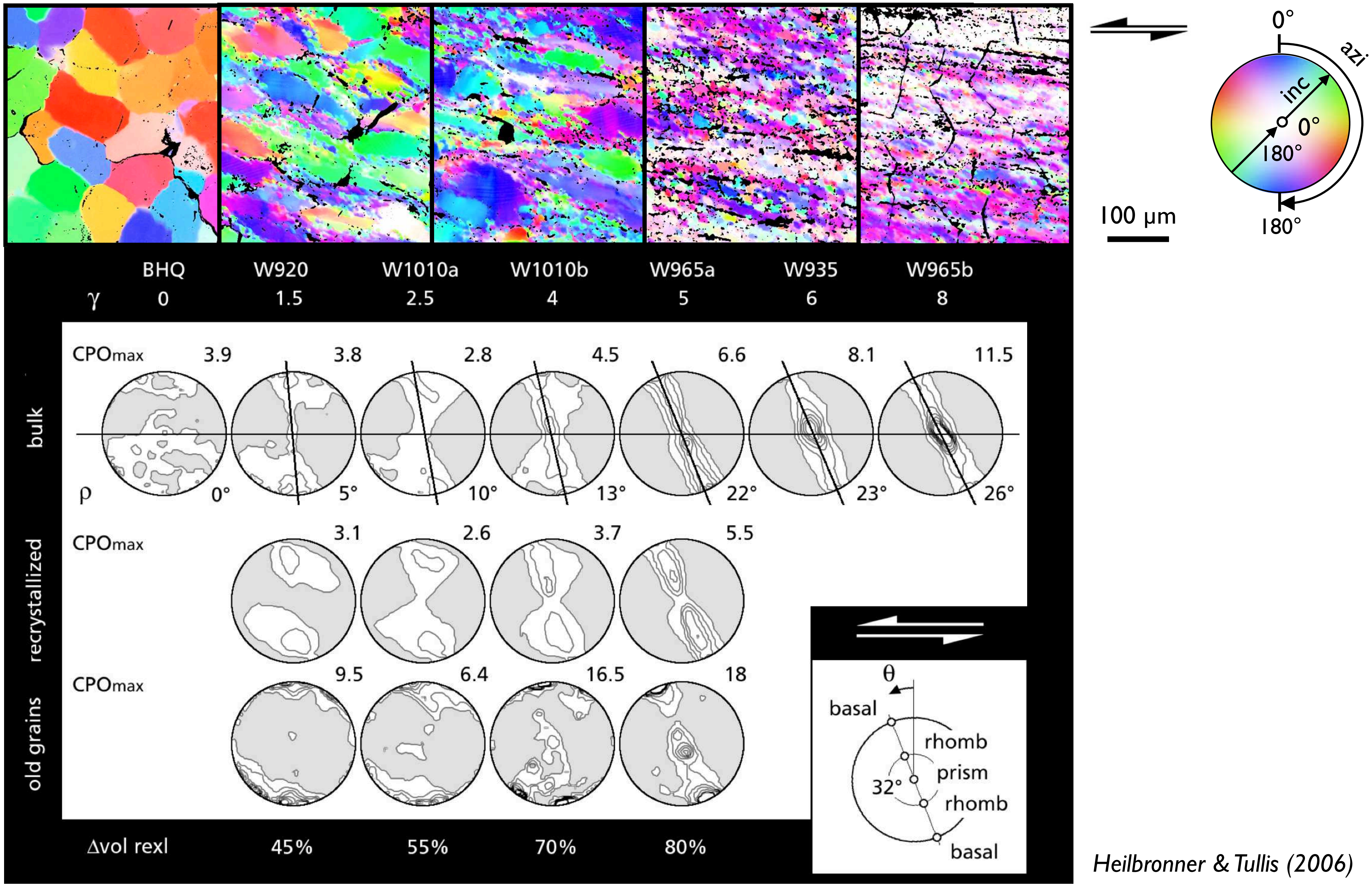




circular
polarization

... of Black Hills Quartzite ...

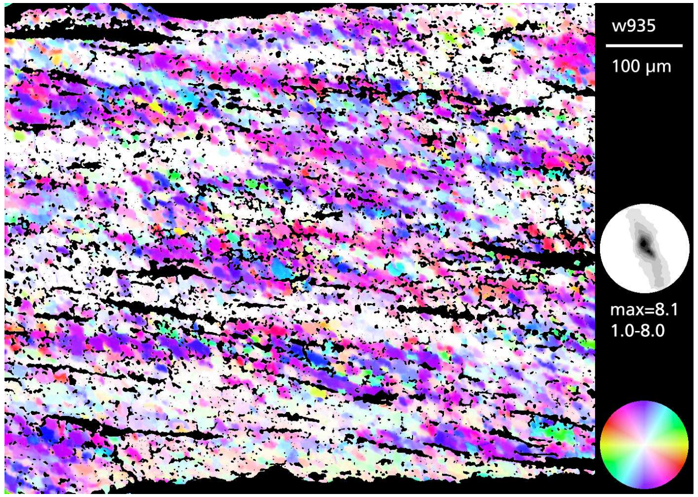
we used CIP-derived orientation images



Heilbronner & Tullis (2006)

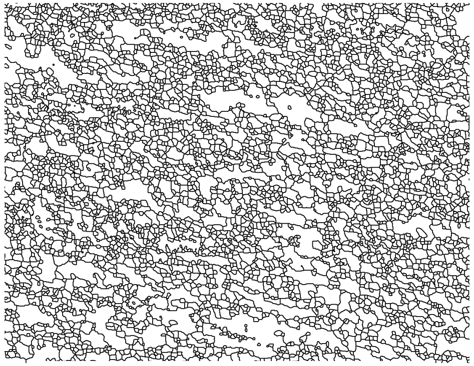
... to derive the c-axis pole figures

and performed segmentation in texture space ...



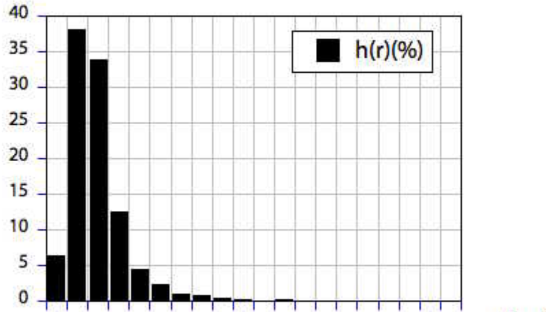
c-axis orientation image

Lazy Grain Boundaries



grain boundary map

Image SXM Analyze



area equivalent radius (µm)

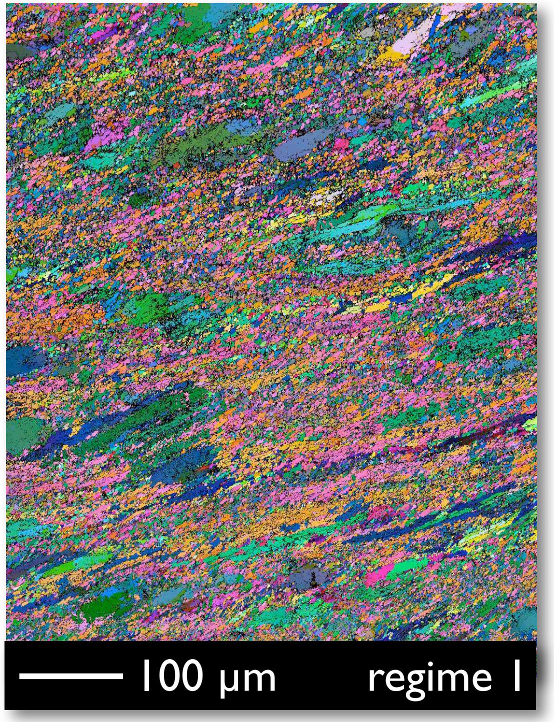
same technique was used for piezometer

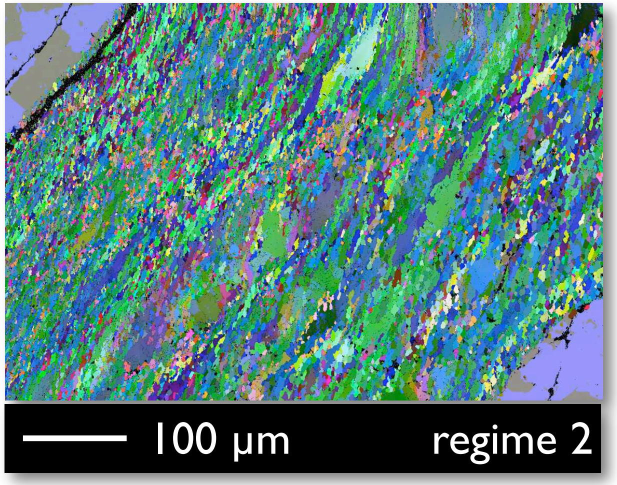
Kaleidagraph

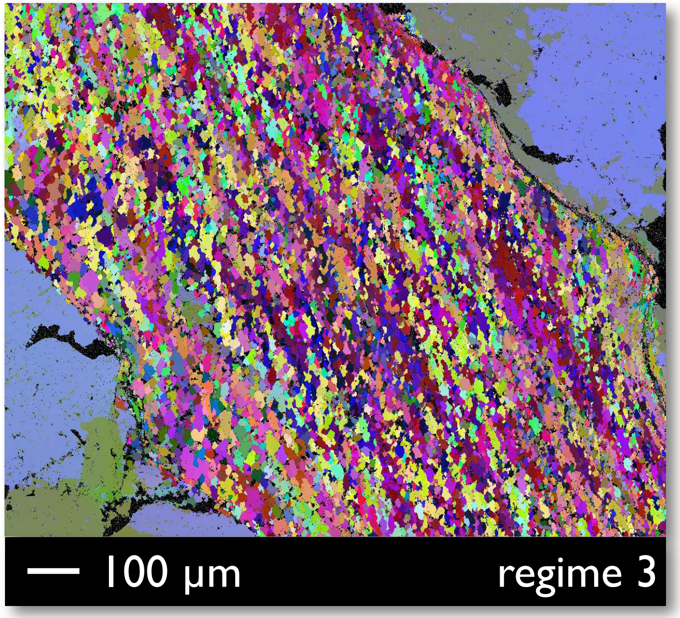
	r equ (µm)
Points	3605
Mean	4.86
Median	4.24
RMS	5.68

... to derive the grain size

ten years later: BHQ revisited







The grain size(s) of Black Hills Quartzite deformed in the dislocation creep regime.

Renée Heilbronner[1] and Rüdiger Kilian[1]

[1] Department of Environmental Sciences Geological Institute Bernoulli...

Correspondence to: Renée Heilbronner (renee.heilbronner@unibas.ch)

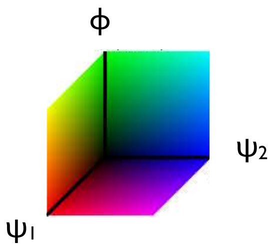
Solid Earth

Analysis of crystallographic preferred orientations of experimentally deformed Black Hills Quartzite

Rüdiger Kilian[1] and Renée Heilbronner[1]

[1] Department of Environmental Sciences Geological Institute Bernoullistrasse 32 CH-4056 Basel Switzerland

Correspondence to: Rüdiger Kilian (ruediger.kilian@unibas.ch)

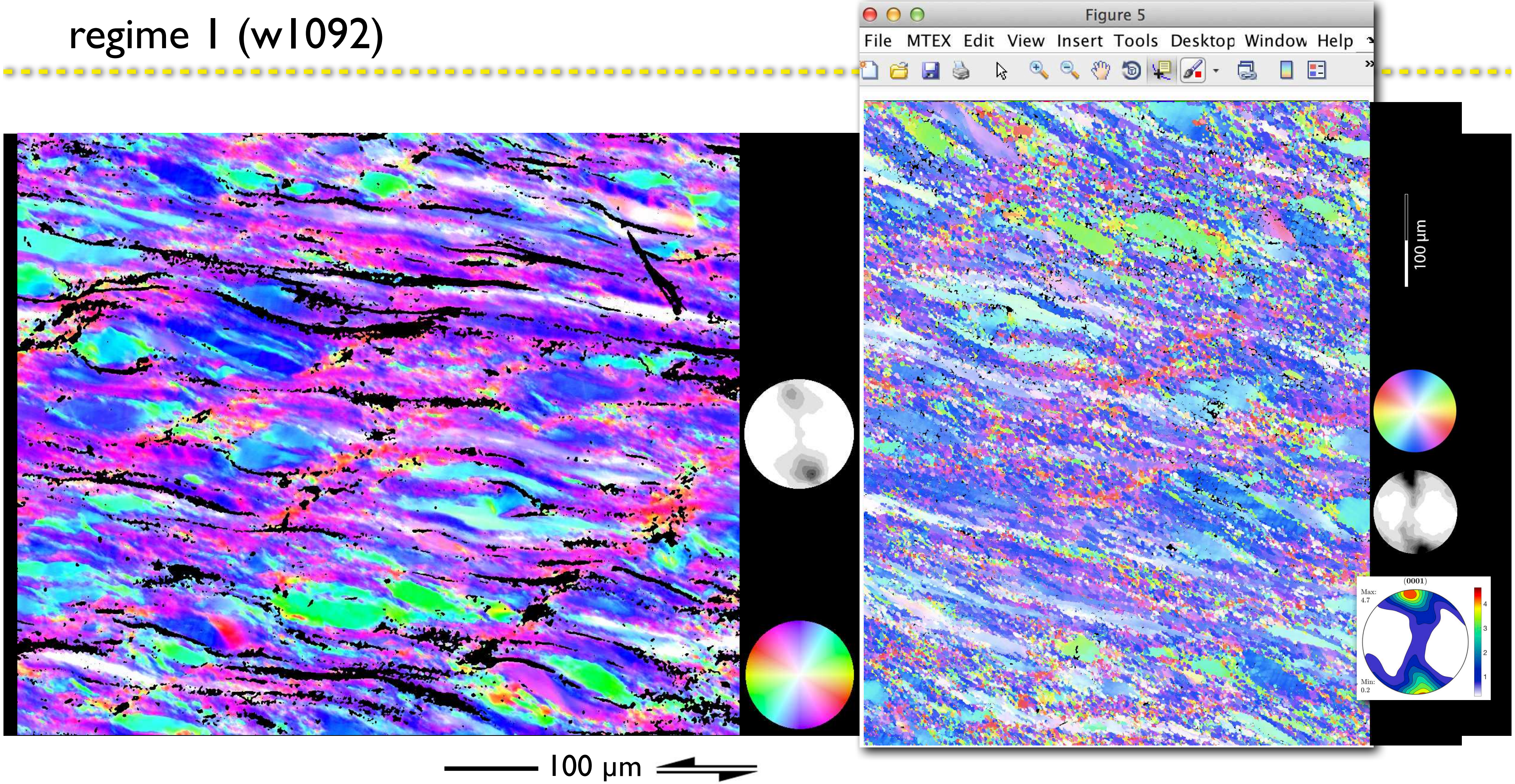


Euler coloring

... remeasured with increased EBSD resolution ...

from CIP to EBSD

regime 1 (w1092)



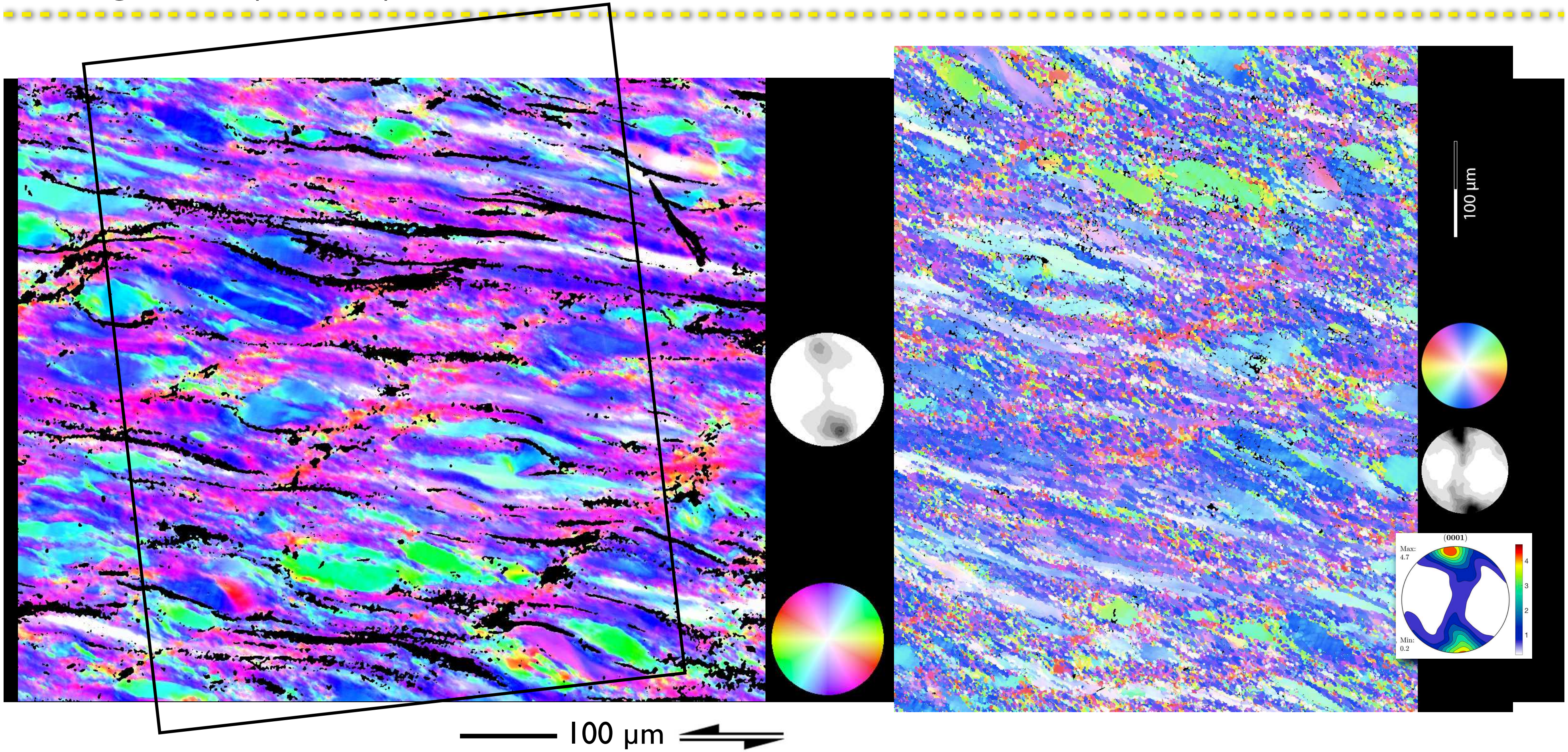
CIP

EBSD

from IPF to CIP look-up tables

from CIP to EBSD

regime 1 (w1092)



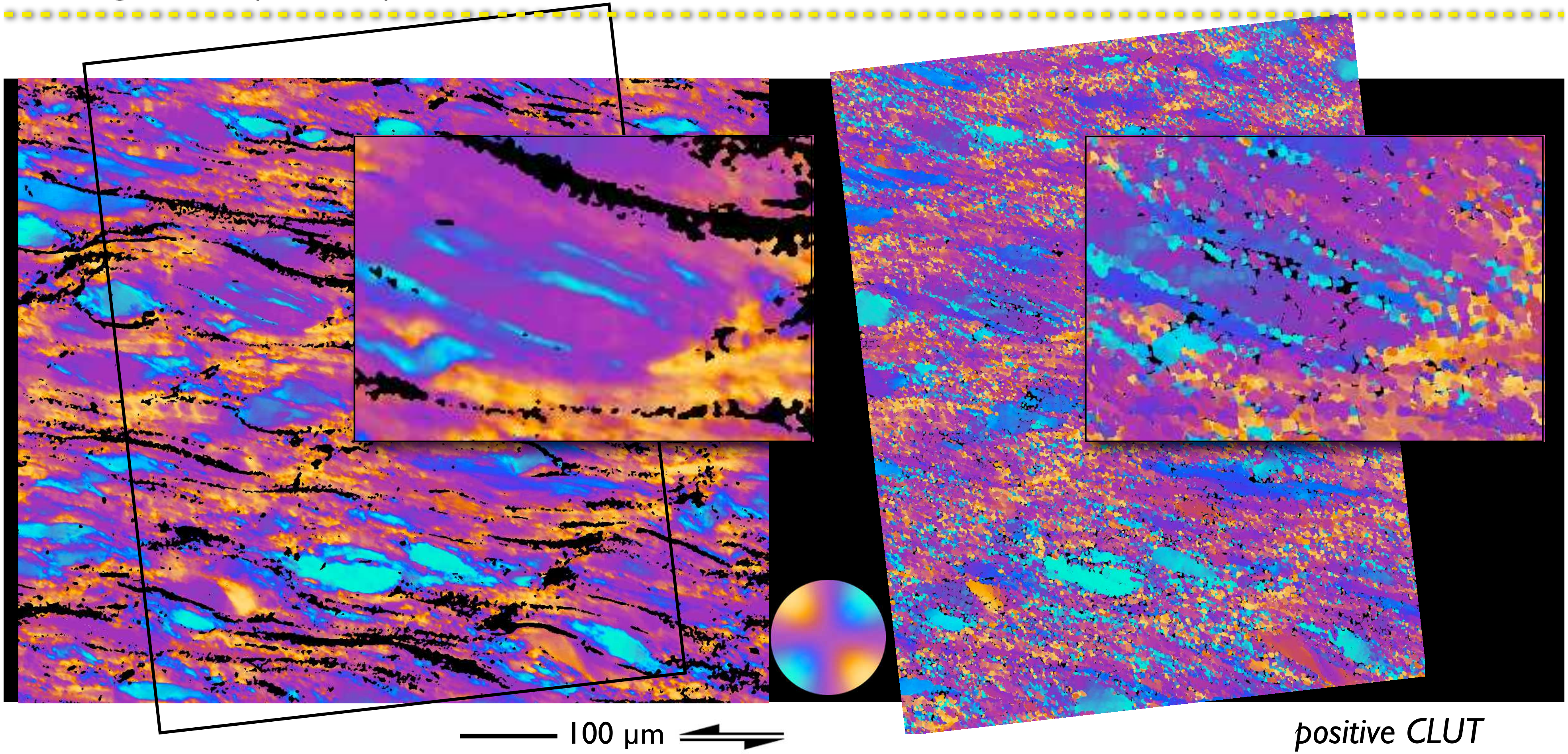
CIP

EBSD

from IPF to CIP look-up tables

compare EBSD to coptical microscopy

regime 1 (w1092)

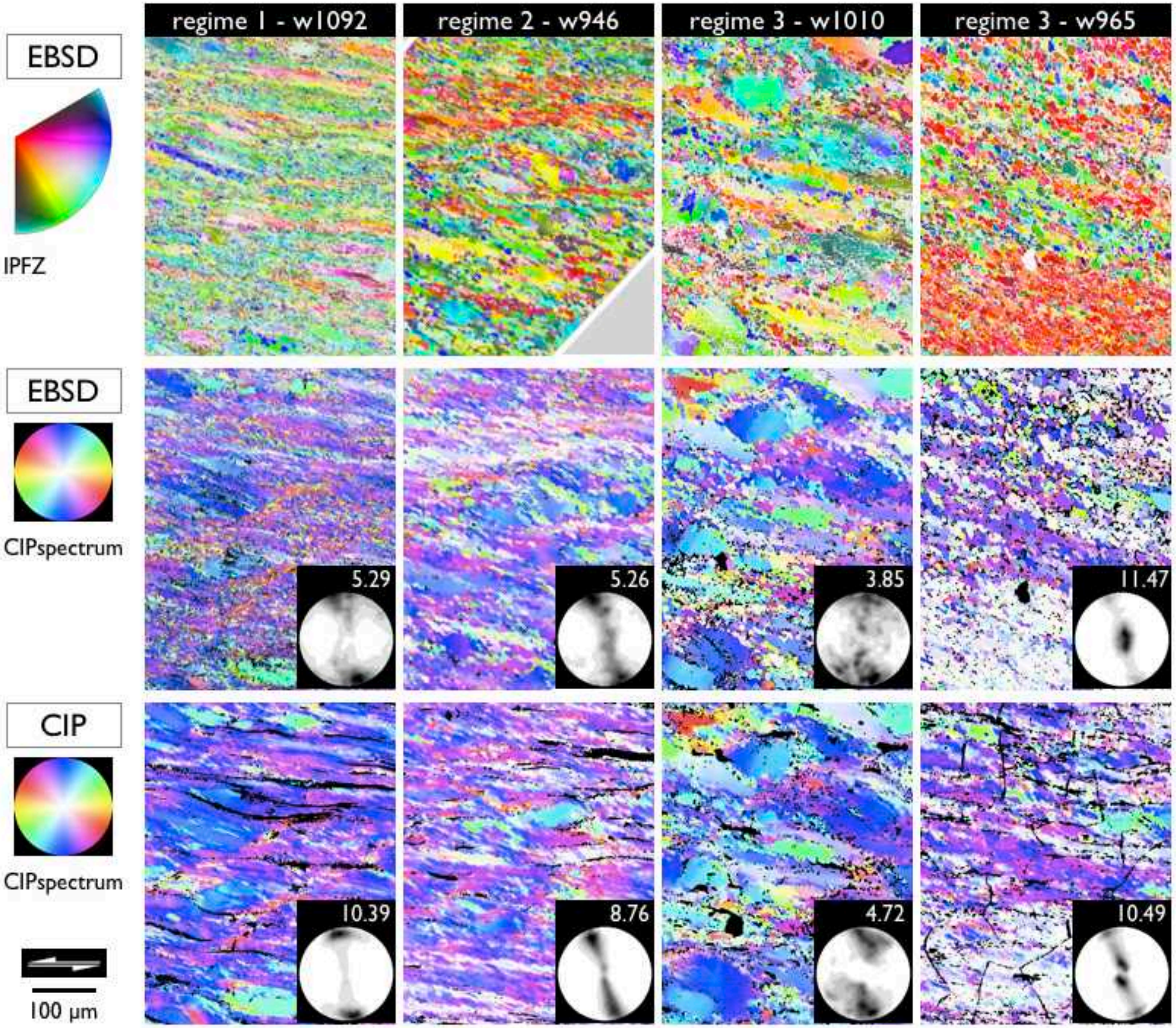


CIP

EBSD

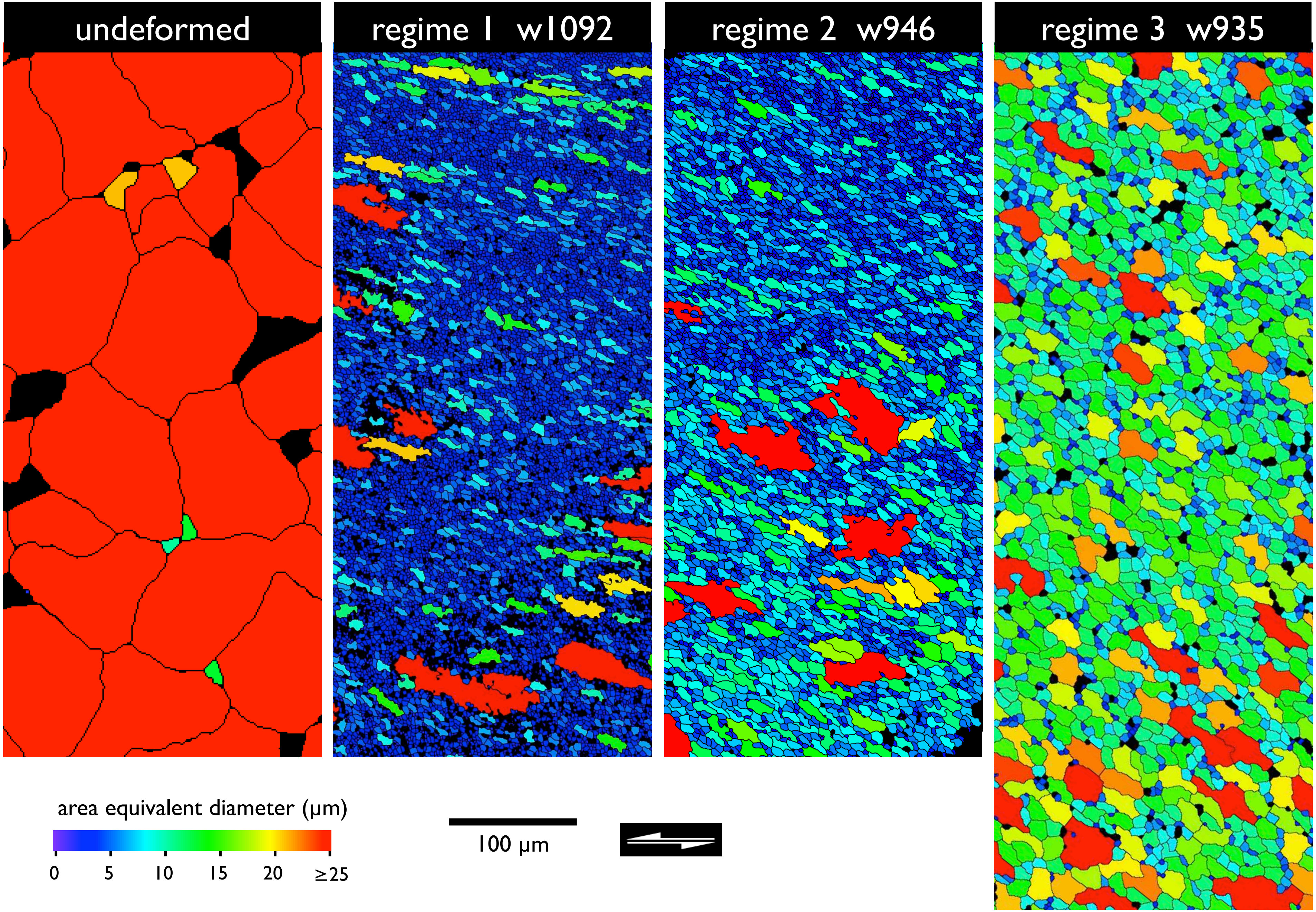
... using the conoscopic CLUT

texture and grain size of BHQ ... revisited

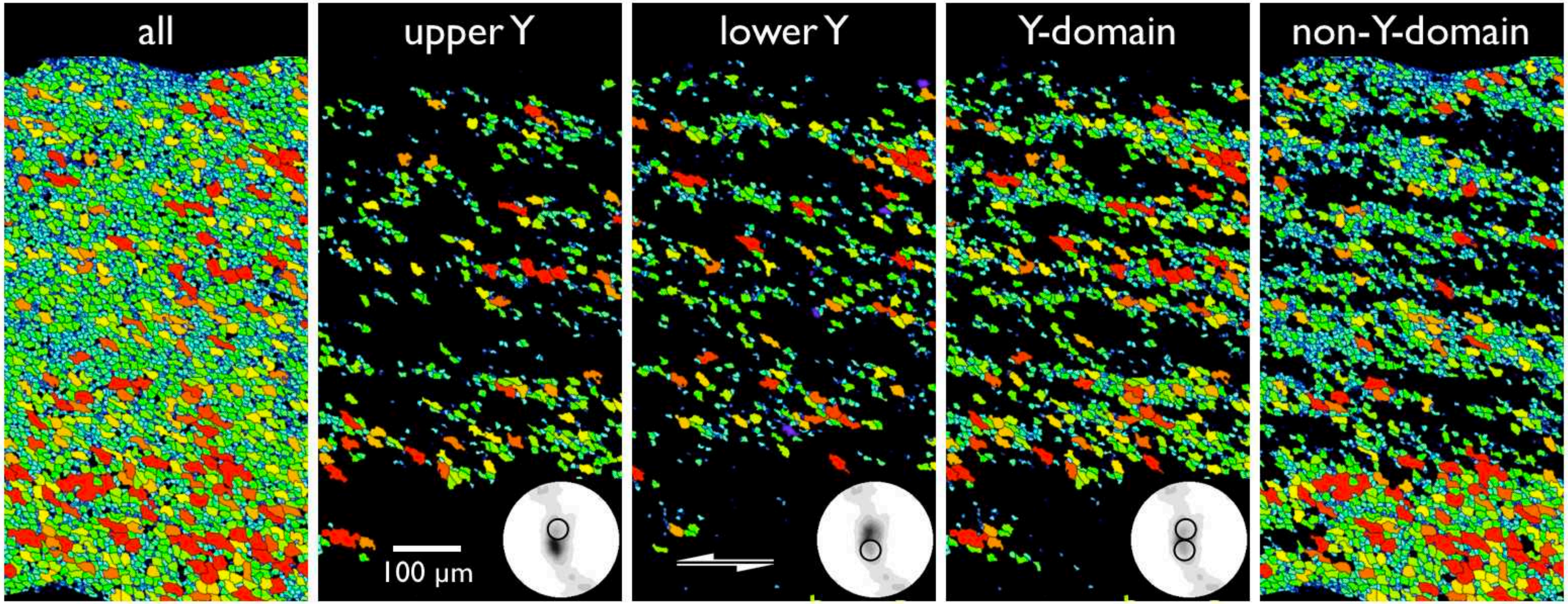


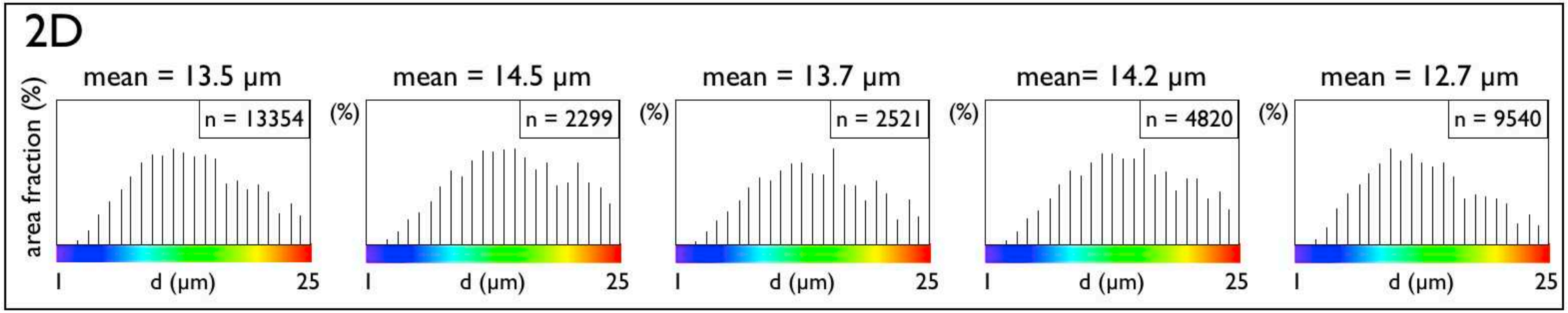
... using SEM / EBSD full resolution !

grain size maps



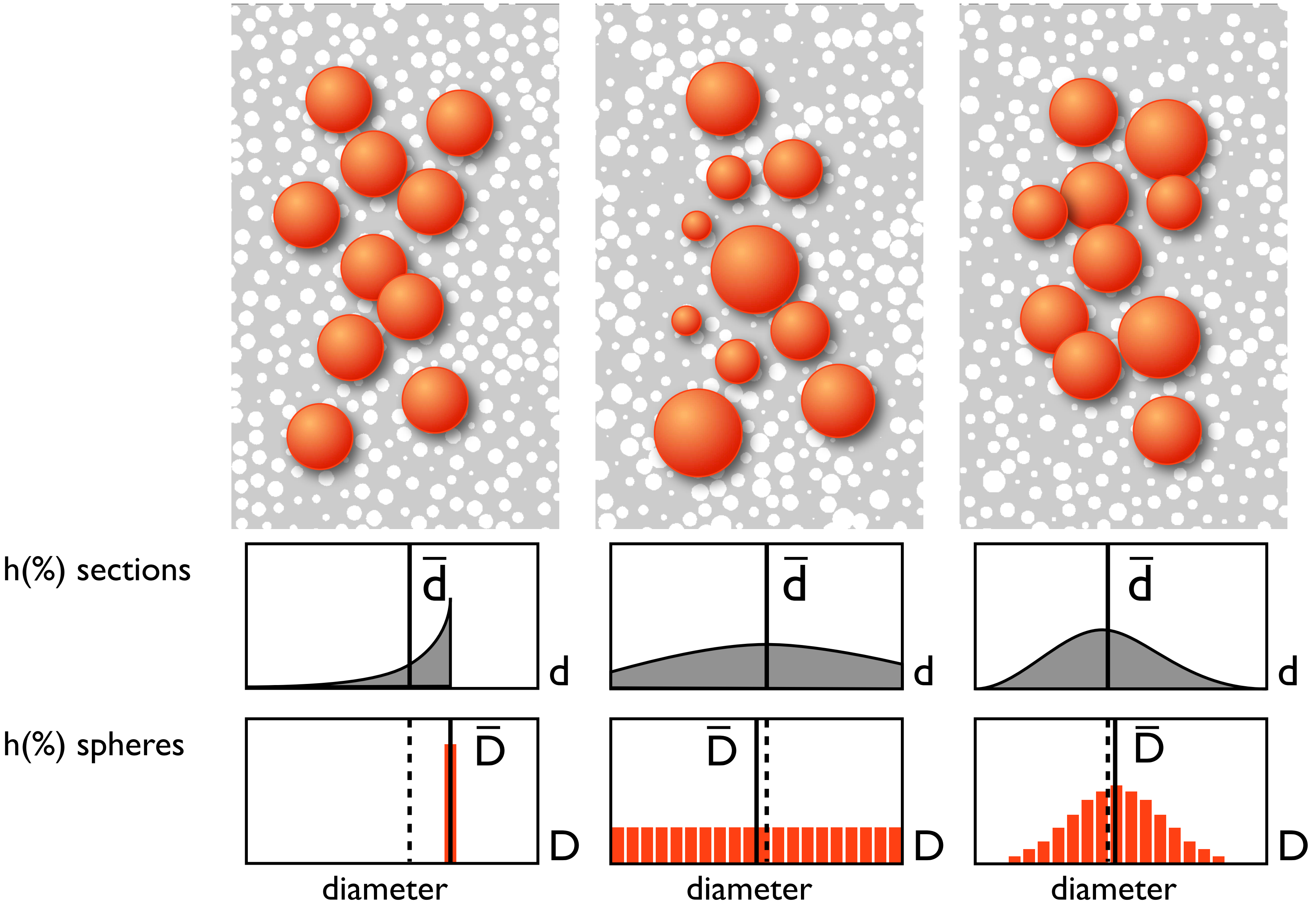
checking the Y domain





... and the subdomains (...)

... what do 2D means tell us about 3D means ?

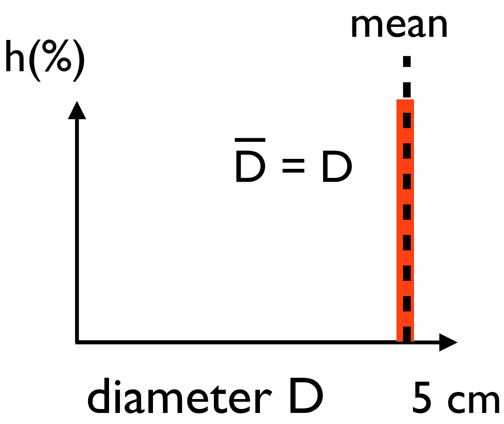


... nothing !

so what is an average diameter really ?

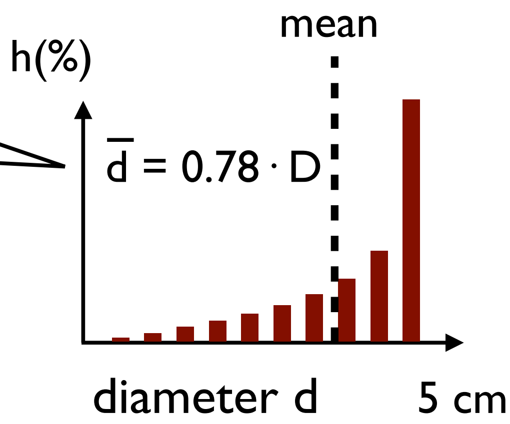
D

d



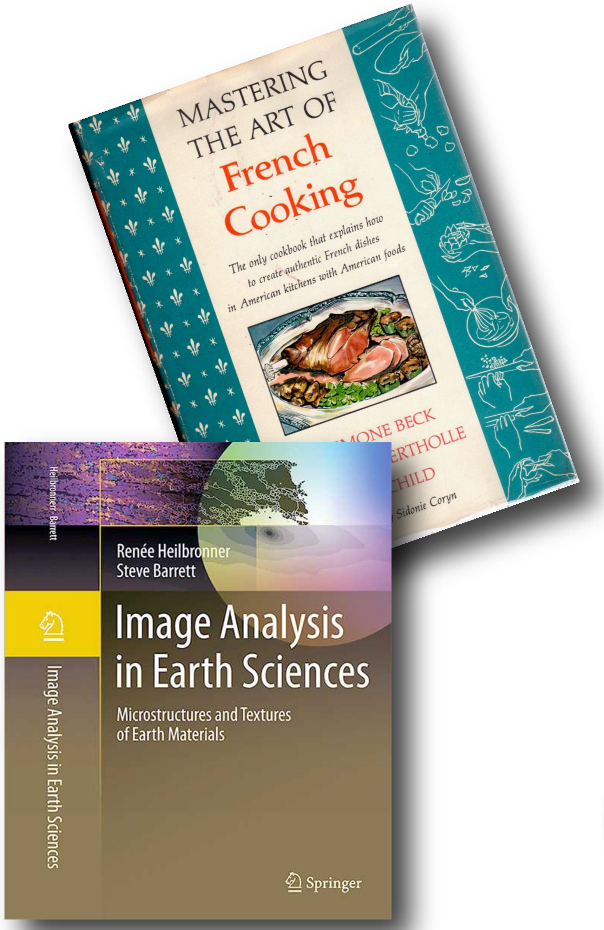
$$\frac{\text{mean of h(D)}}{\text{mean of h(d)}} = 1.3$$

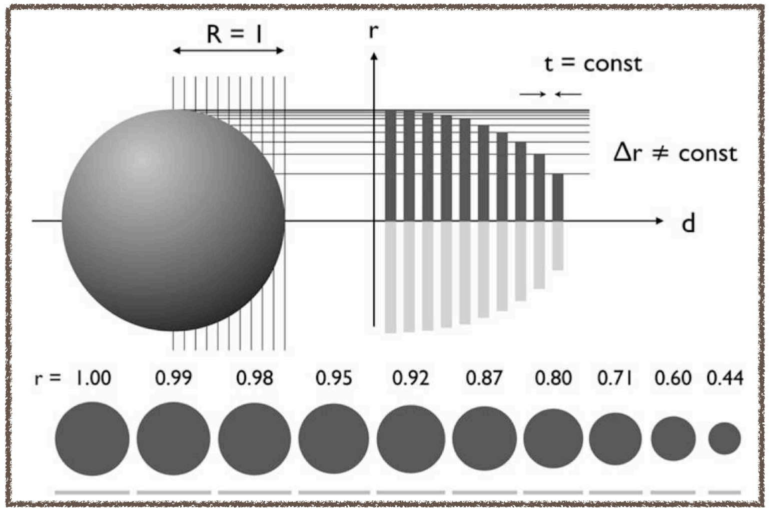
... the origin of the famous 'correction factor' ...



... 2D or 3D diameters ? means? or modes ?

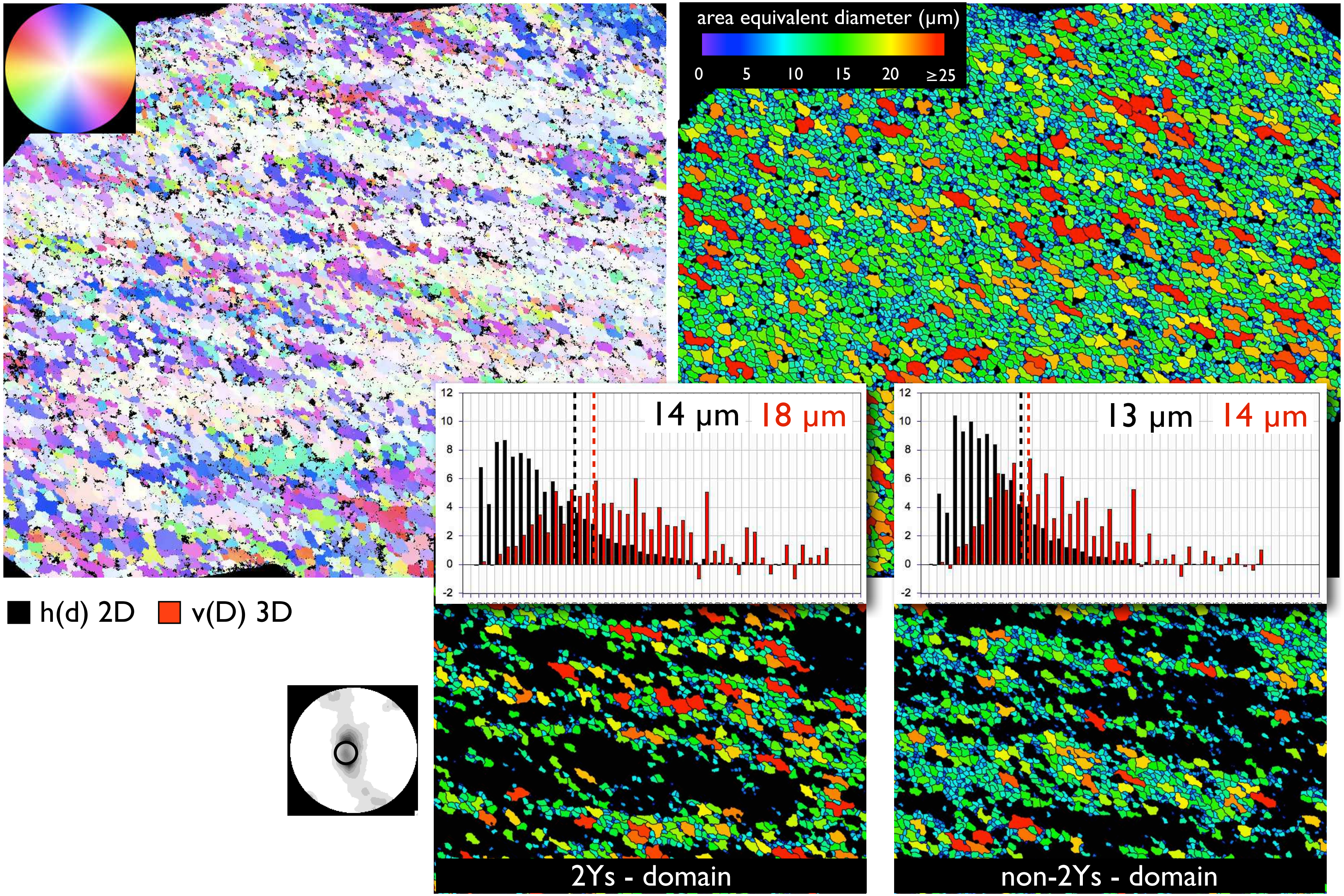
we need the full (3D) picture





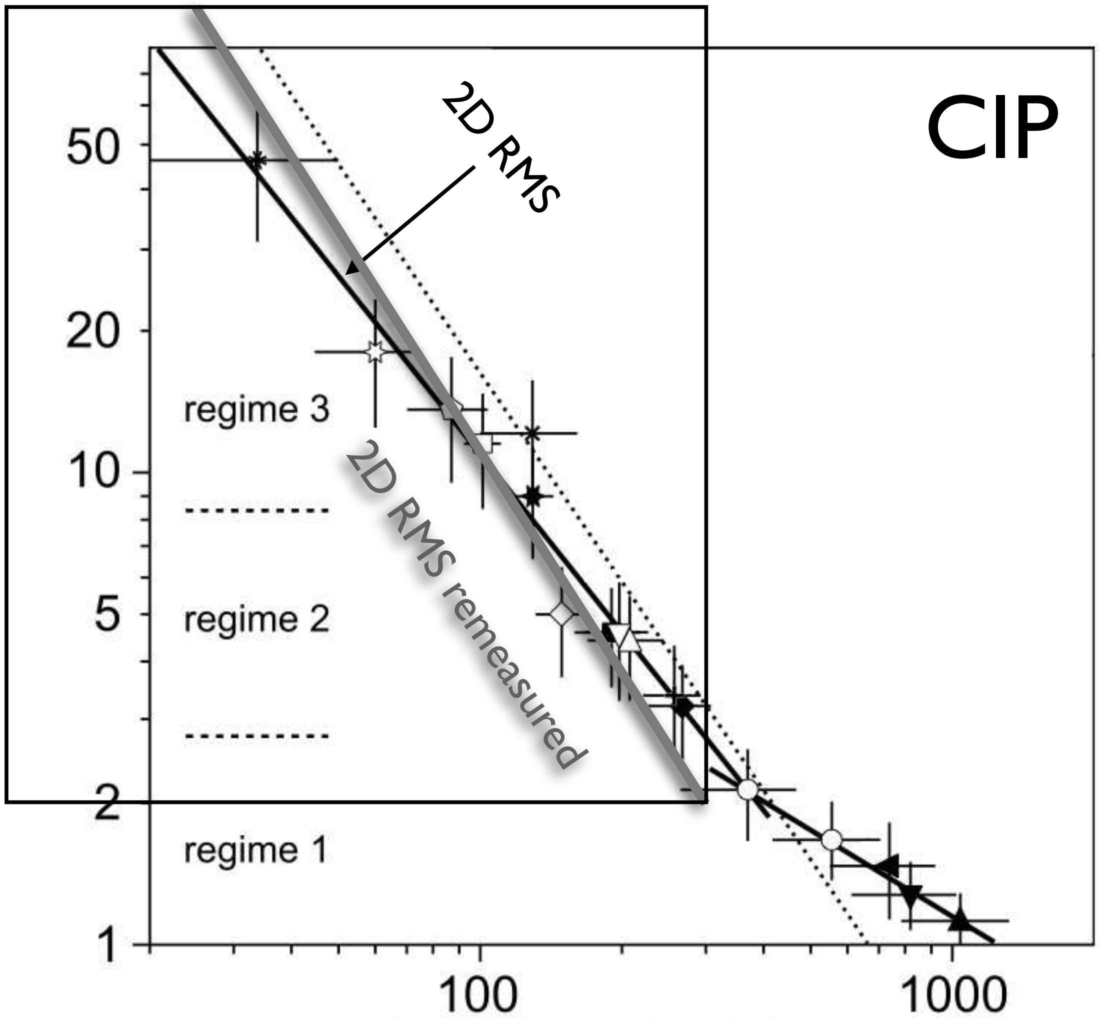
... mastering the art of Image Analysis in Earth Sciences

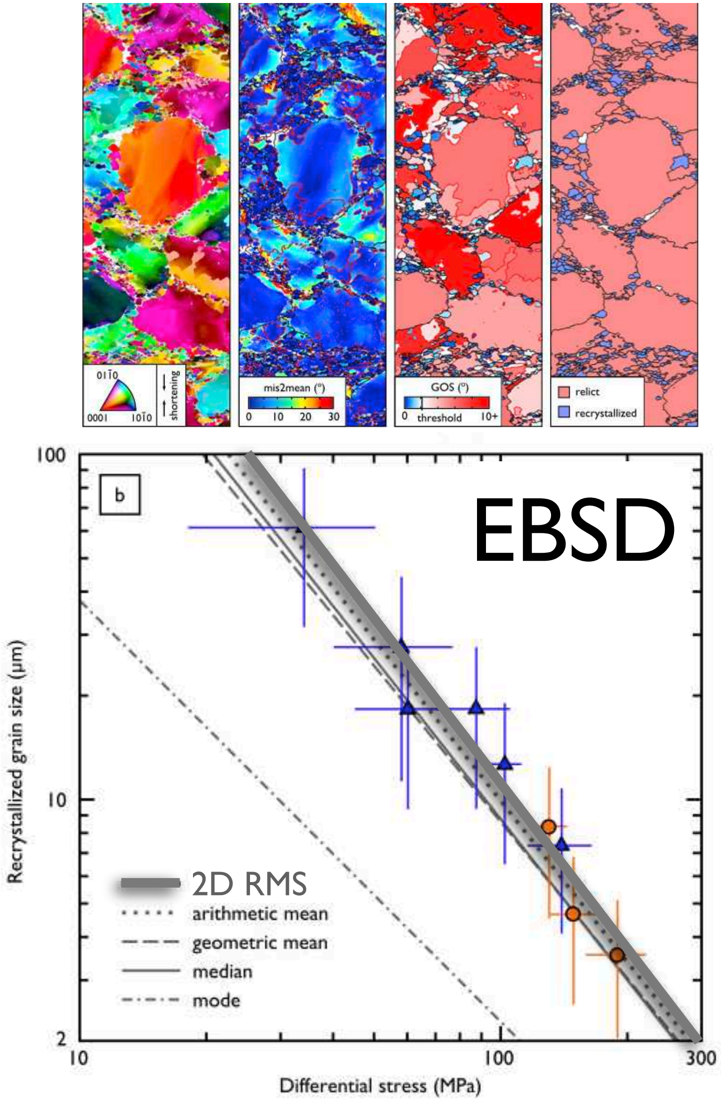
mode of the volume weighted distribution ...



... of diameters (D_{equ}) of volume equivalent spheres ...

check against the piezometer !



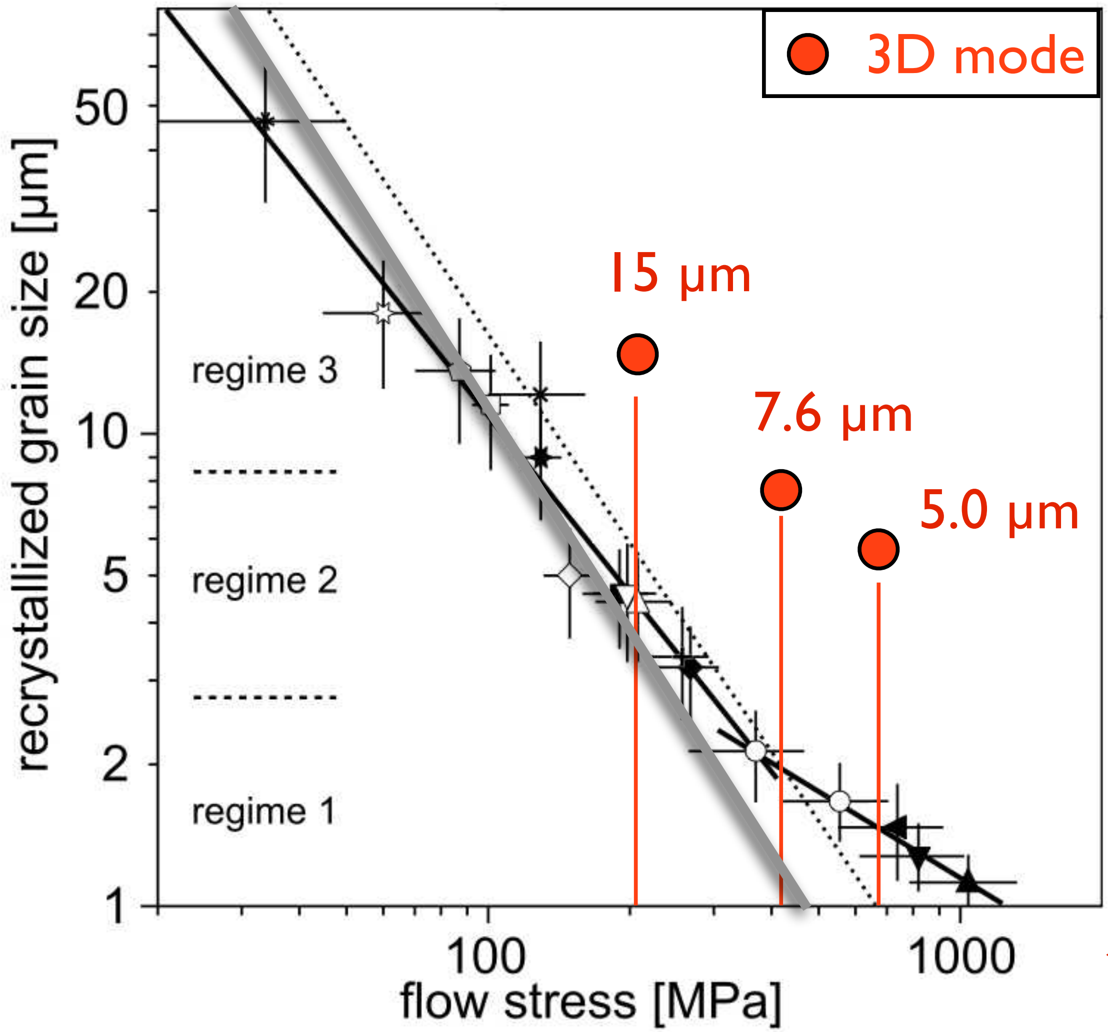


Cross et al., 2017

... 'good old' Stipp & Tullis, remapped by Prior ...

plot the shear experiments on it

quartz piezometer



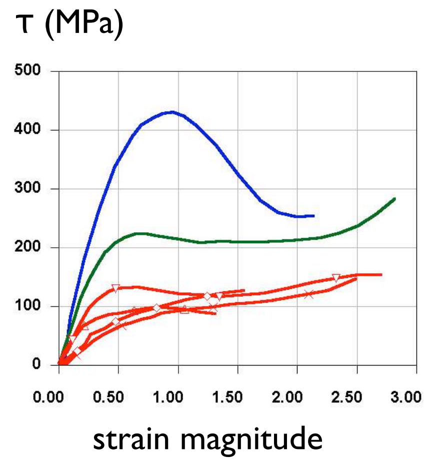
CIP grain boundaries
RMS of 2D sections

Stipp & Tullis (2003)

EBSD grain boundaries
mode of 3D grains

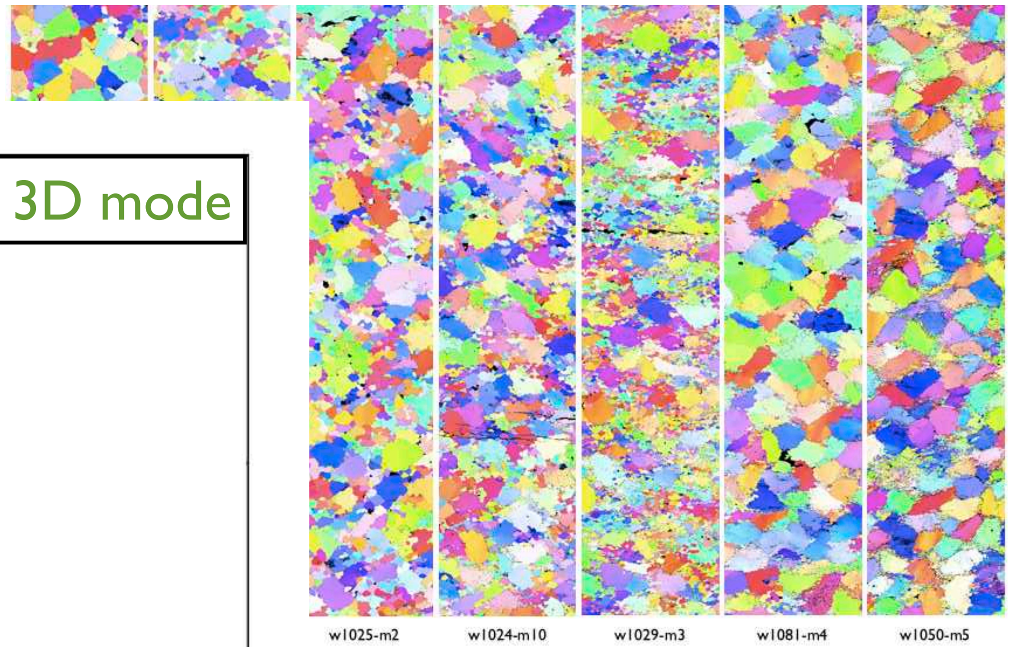
Heilbronner & Tullis (2002, 2006) re-measured

flow stresses

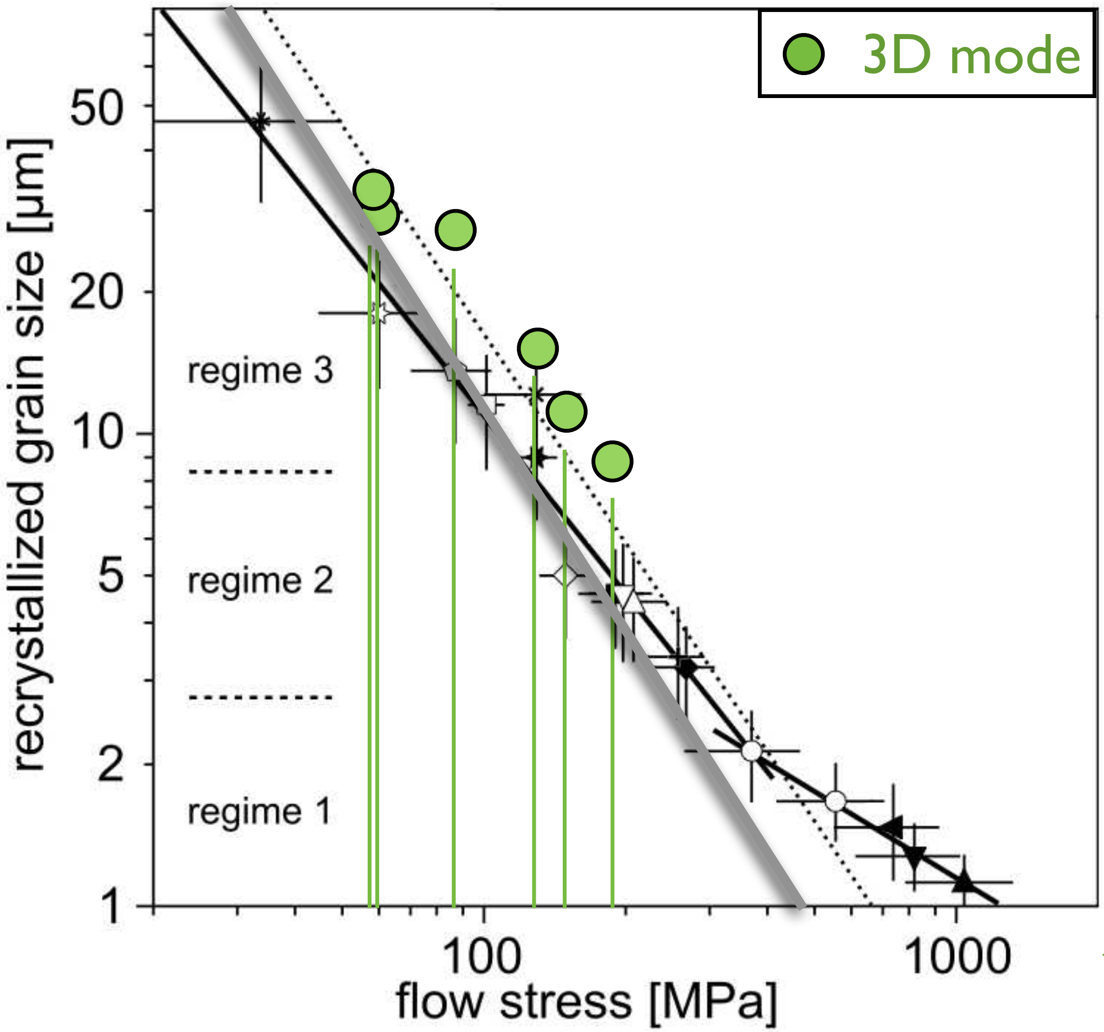


... 3D modes are not the same as 2D RMS !

get the EBSD maps of the axial experiments



EBSD maps by Prior
experiments by Stipp & Tullis

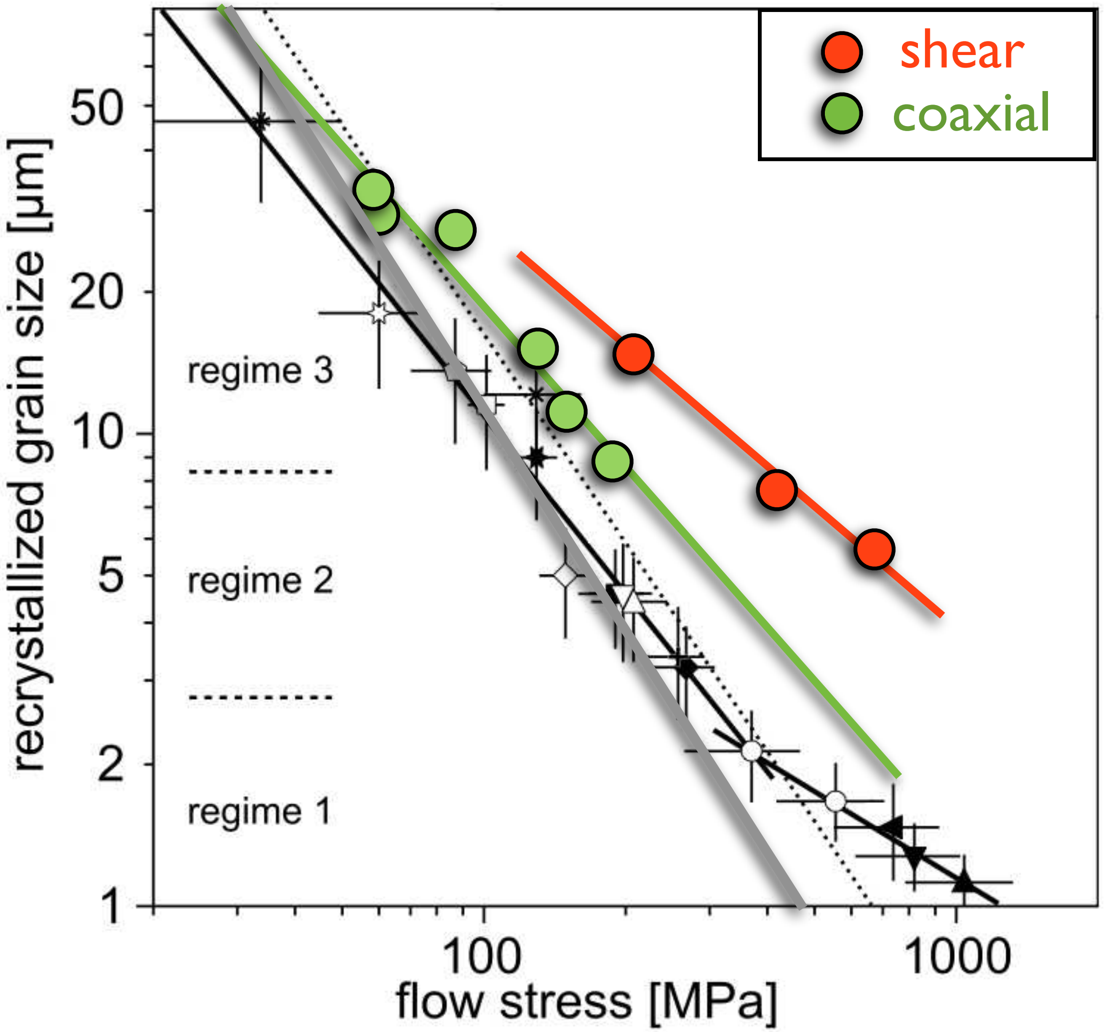


stresses from axial experiments

... and calculate the 3D modes for the piezometer

apples and ... different apples

quartz piezometer



published piezometer

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

$d(\mu m) = 8128\ \Delta\sigma^{-1.41}$

using 3D modes

coaxial (piezometer)

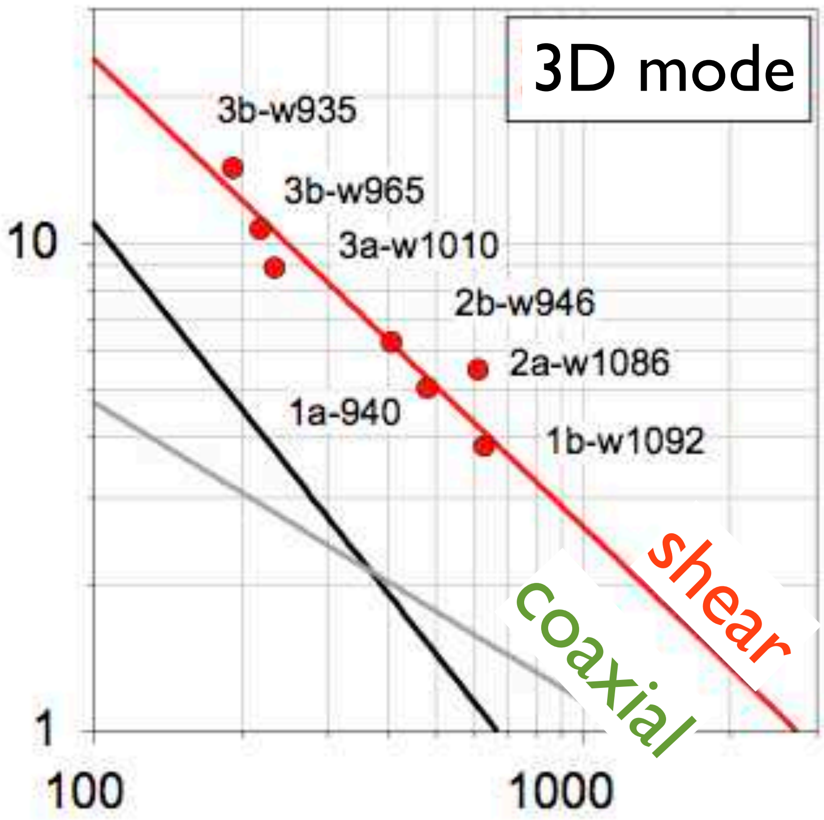
$D(\mu m) = 3325\ \Delta\sigma^{-1.13}$

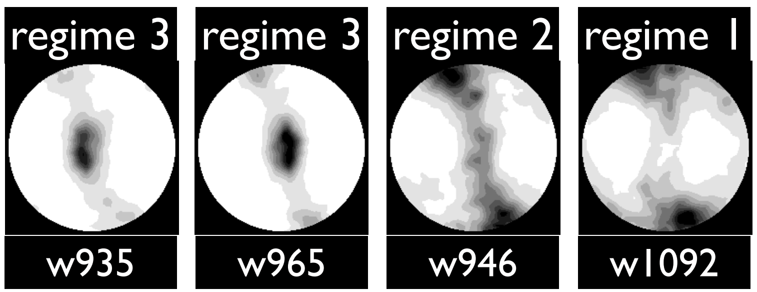
shear

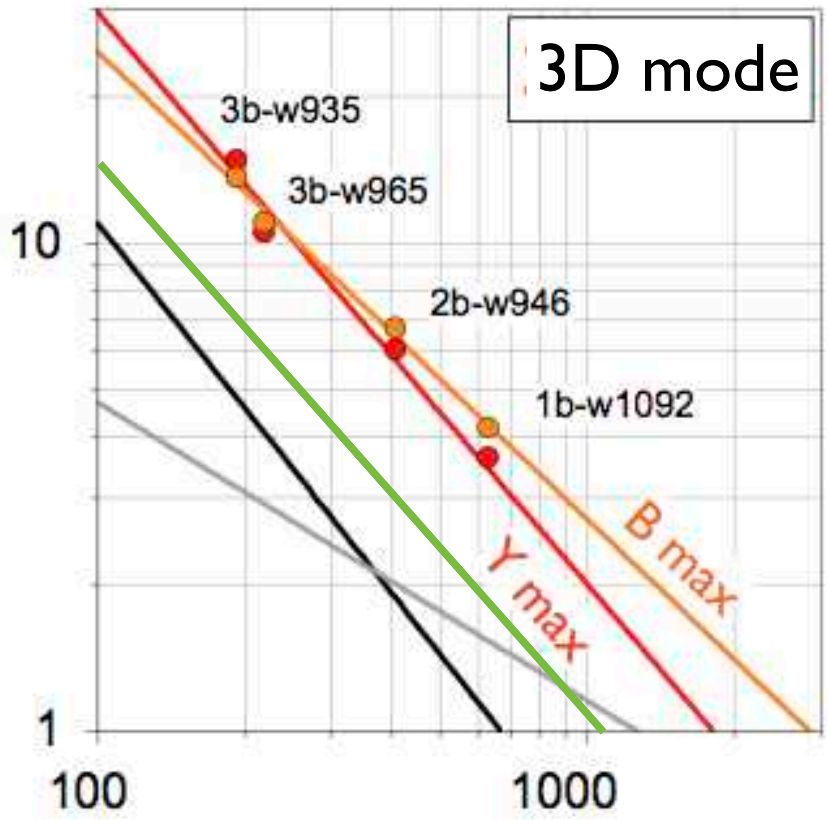
$D(\mu m) = 1473\ \Delta\sigma^{-0.86}$

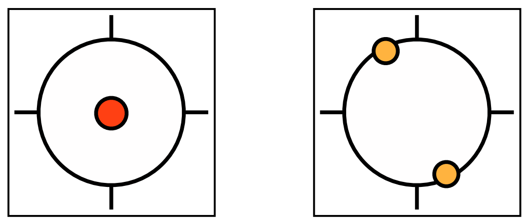
... you ask a silly question you get a silly answer ...

different piezometer for shear vs. axial







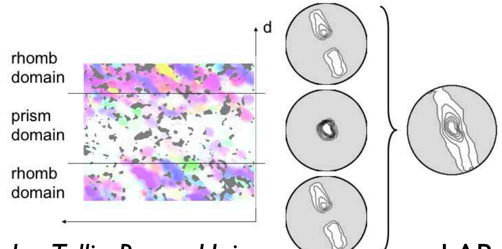


Y-max B-max ('basal')

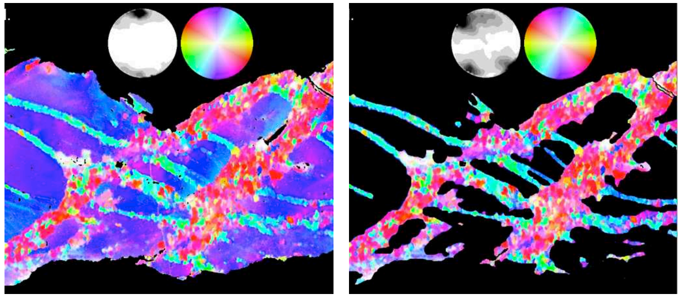
and different for Y-texture domian ?

... so what about the strength of the lithosphere ?

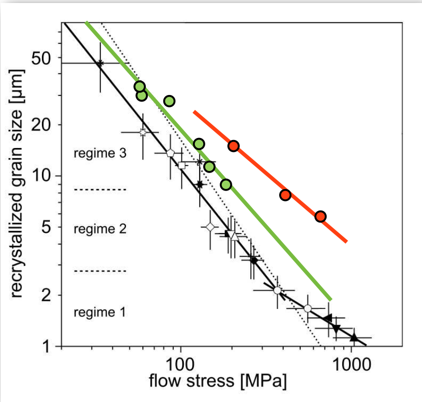
- texture domains → composite material
- bulk textures don't exist
  ⇒ bulk properties don't exist locally
- piezometer for axial versus shear
- different grain sizes coexist
  ⇒ different flow stresses may co-exist
  ⇒ viscosity contrasts among domains

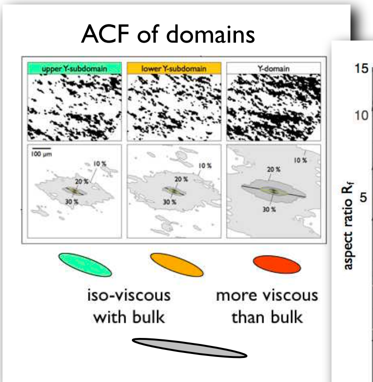


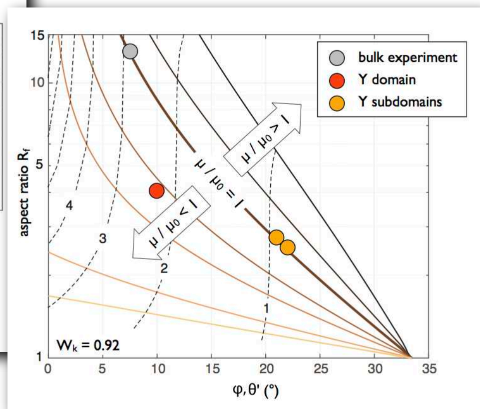
Jan Tullis, Brown Univ. LAB

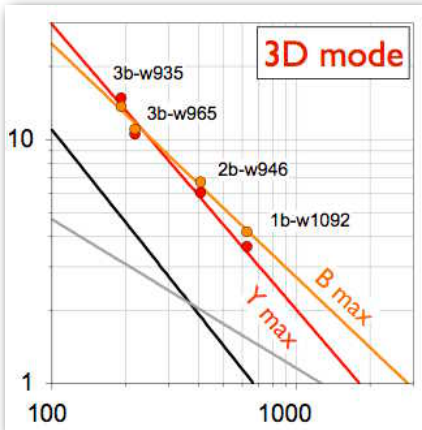


Luca Menegon, Padova NATURE



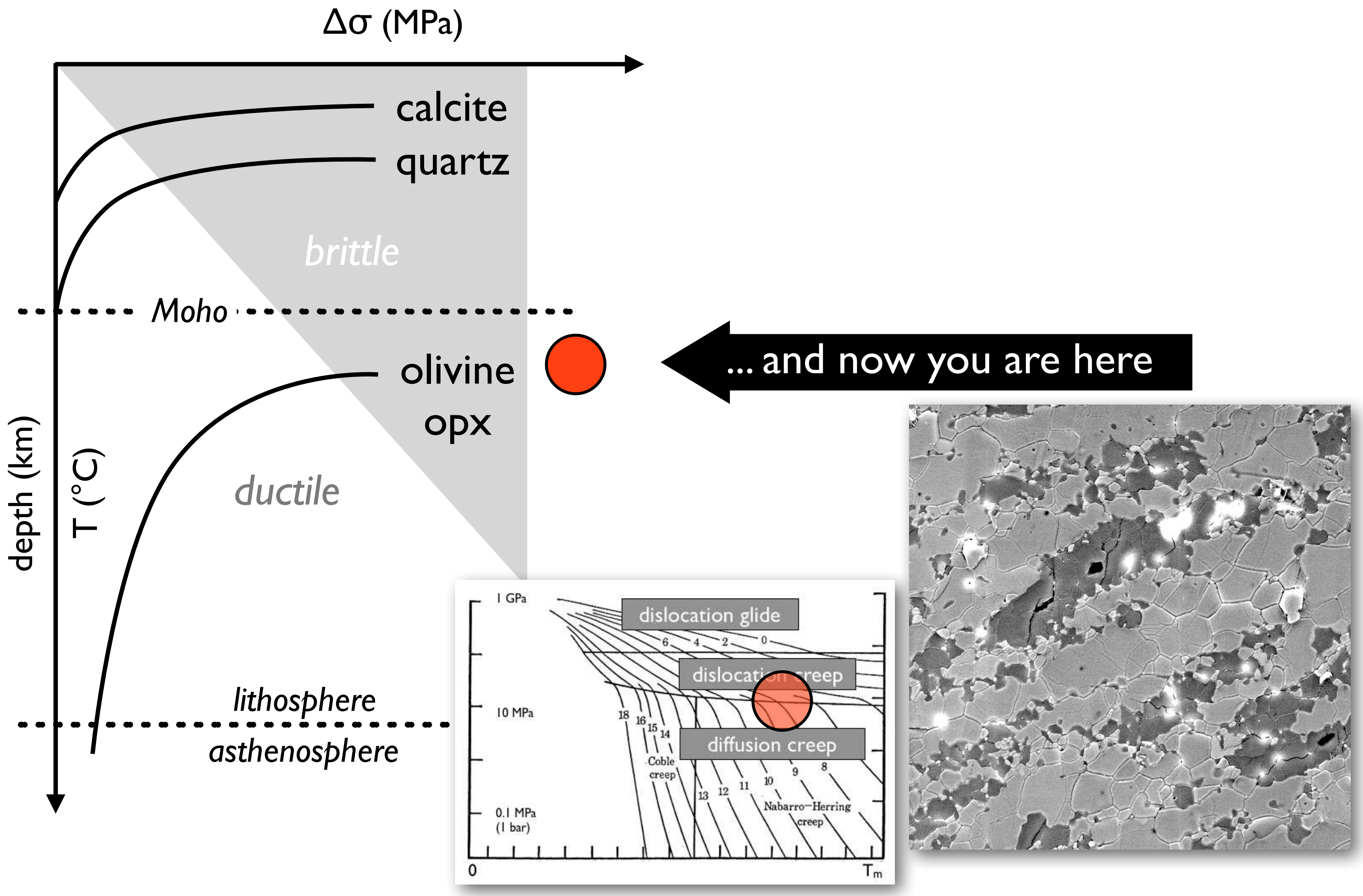






- different piezometer for different domains
- ... or does the recrystallized piezometers have a problem ?

3rd stop:



Δσ (MPa)
calcite
quartz
brittle
Moho
olivine
opx
ductile
depth (km)
T (°C)
lithosphere
asthenosphere
... and now you are here
1 GPa
10 MPa
0.1 MPa
(1 bar)
dislocation glide
dislocation creep
diffusion creep
Coble creep
Nabarro–Herring creep
0
Tm

motivation: weakening of lower lithosphere

$\dot{\varepsilon} = A \cdot \Delta\sigma^n \cdot exp(-Q/RT)$

increasing strain

$\dot{\varepsilon} = A \cdot \Delta\sigma^n \cdot d^m \cdot exp(-Q/RT)$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Research Article

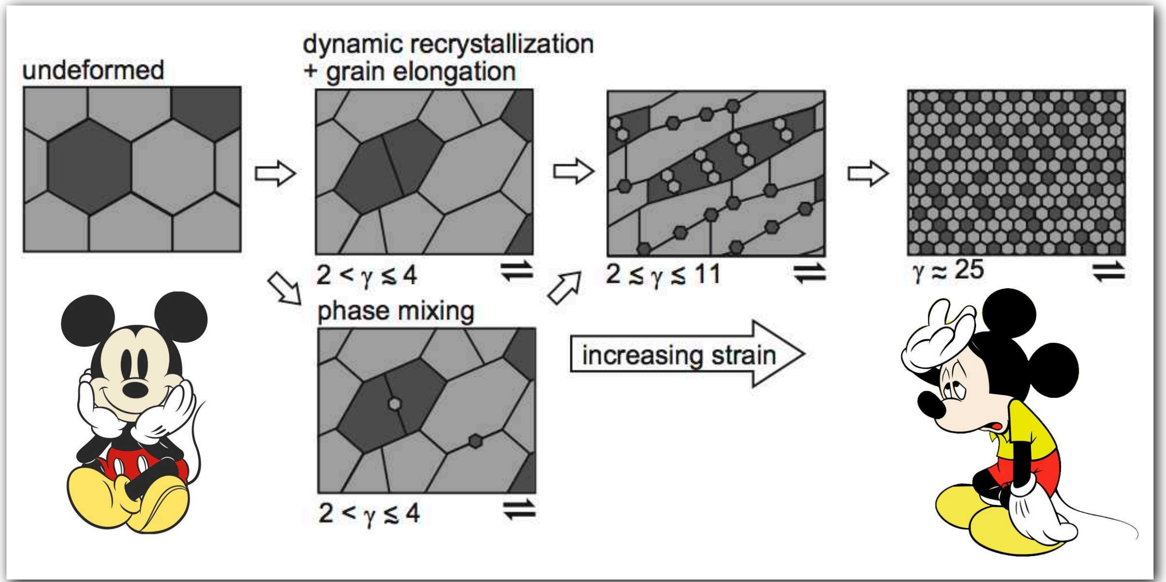
Rheological weakening of olivine + orthopyroxene aggregates due to phase mixing, Part 1: Mechanical behavior

Miki Tasaka, Mark E. Zimmerman, David L. Kohlstedt

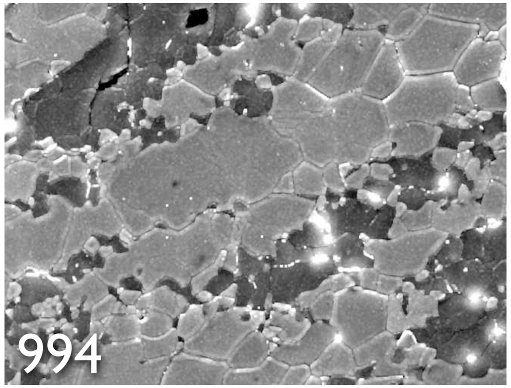
Accepted manuscript online: 8 September 2017 Full publication history

DOI: 10.1002/2017JB014333 View/save citation

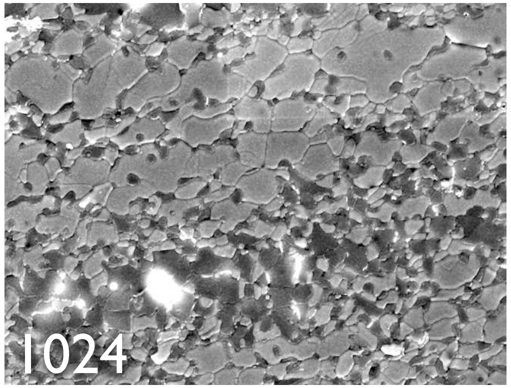
Tasaka et al. (JGR, 2017)



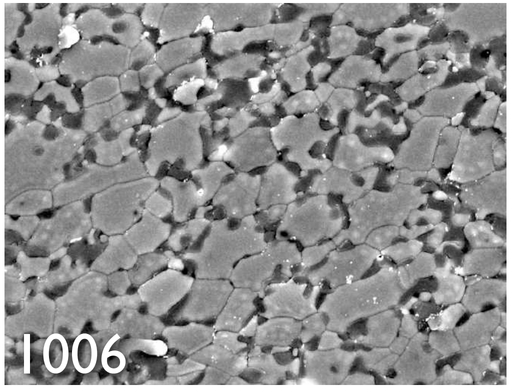
dislocation creep ?



phase mixing ?



diffusion creep ?



10 μm

how to mix olivine and orthopyroxene ...

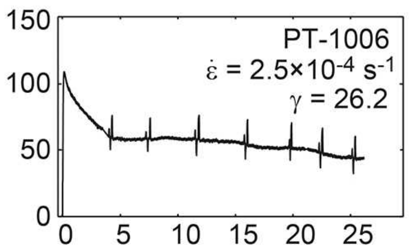
Gas medium High pressure Torsion apparatus (UMN)

Miki Tasaka

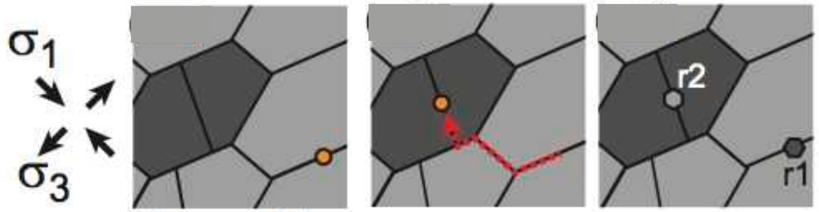
Mark Zimmerman

David Kohlstedt

70% iron-rich olivine
30% orthopyroxene
hotpressed @1200°C
d ~15 μm

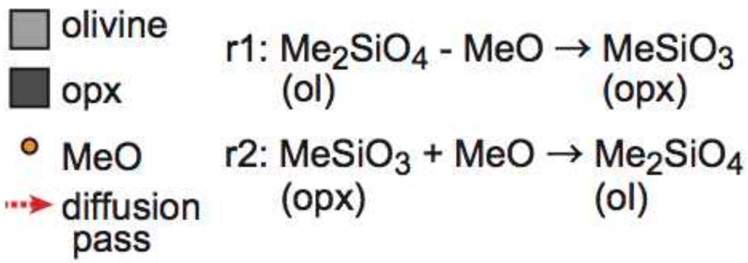


p_c = 300 MPa
T = 1200°C



in olivine:
MeO dissolves at maximum σ1.
Reaction ol → opx

in orthopyroxene:
MeO diffuses to tension σ3.
Reaction opx → ol

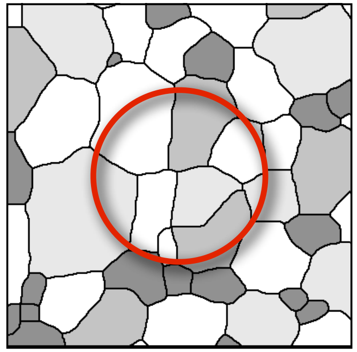


... by mechanical mixing and heterogeneous nucleation

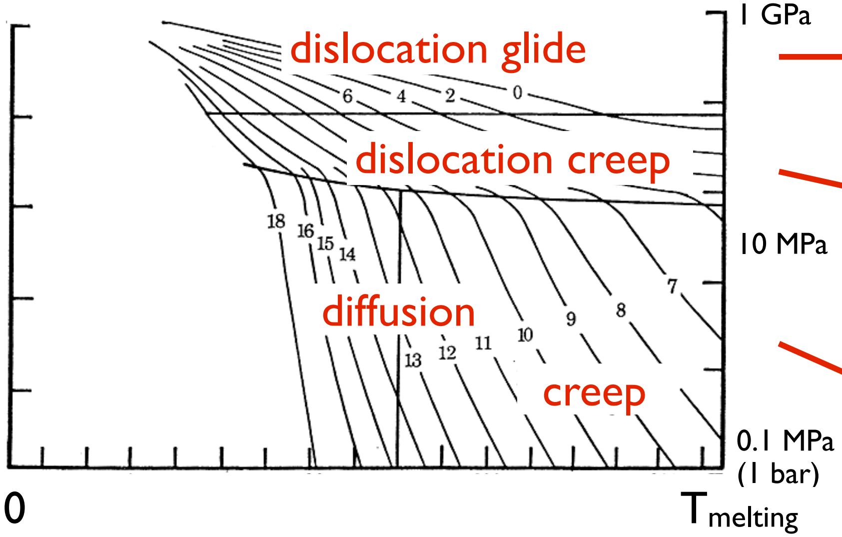
the geometry of dislocation and diffusion creep

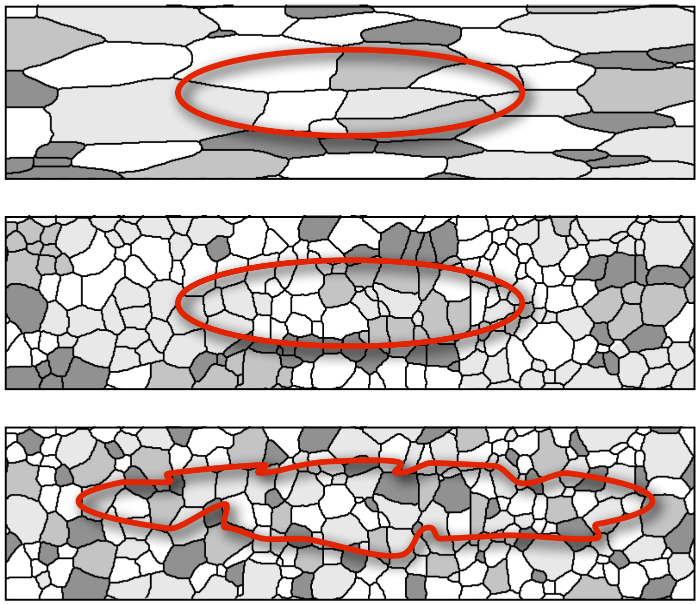
sample preparation

mechanical mixing



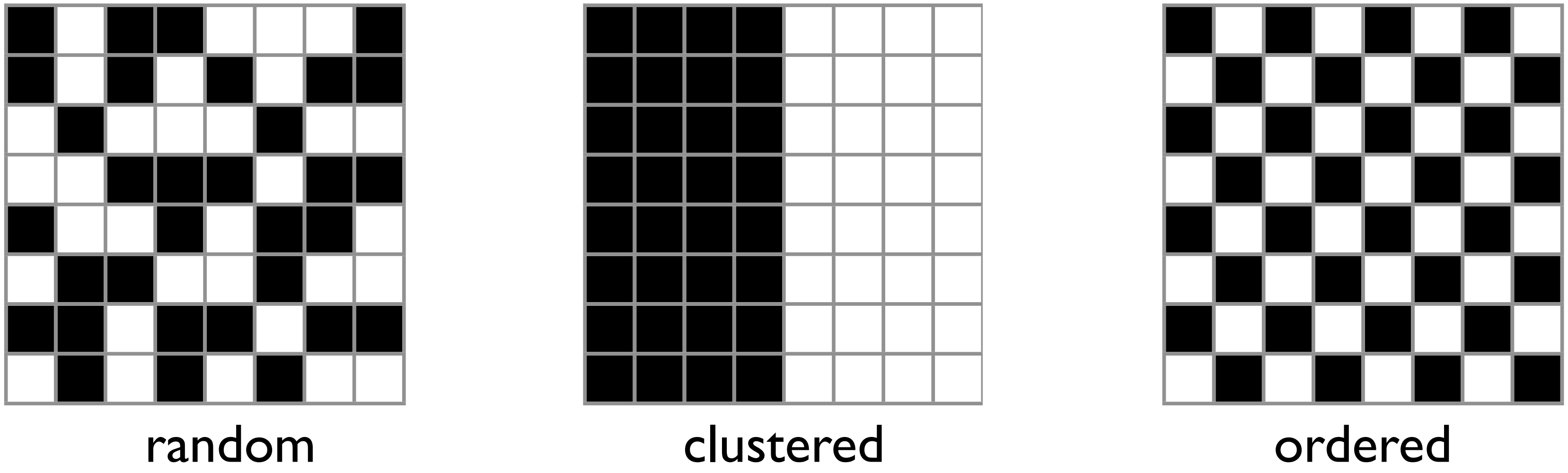
deformation

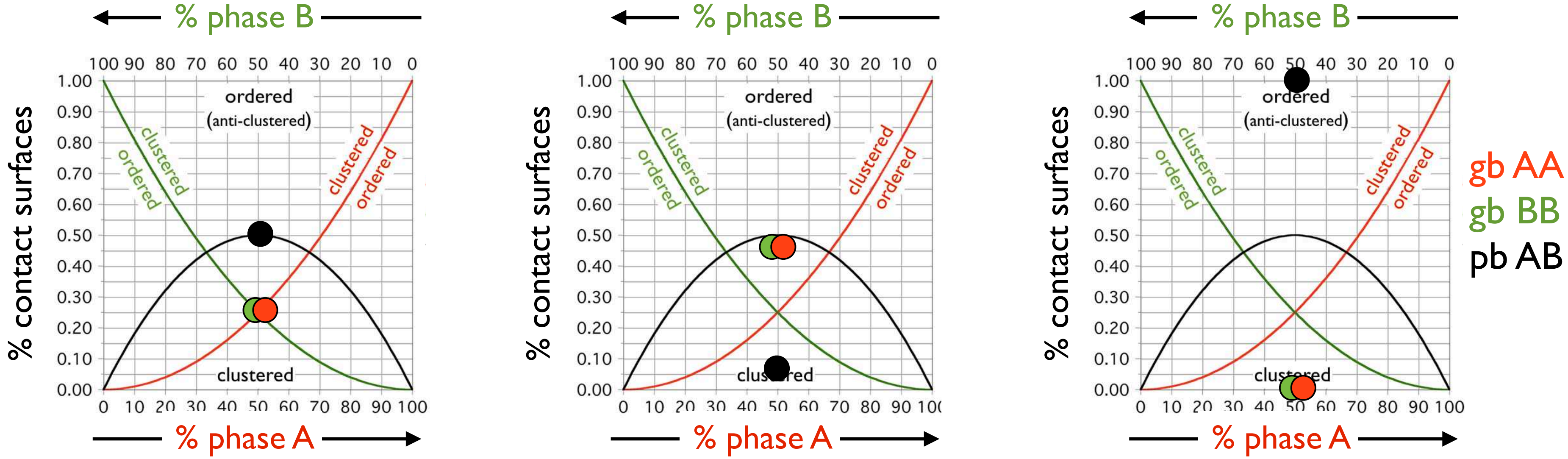




... models for mixing and deformation

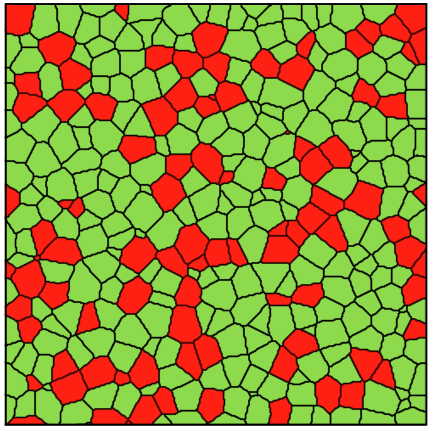
describing spatial distributions ...



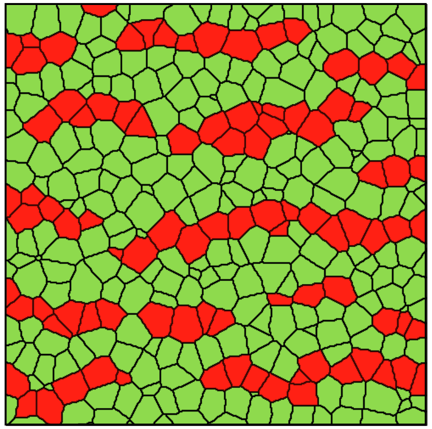


... in terms of phase and grain boundary probability ...

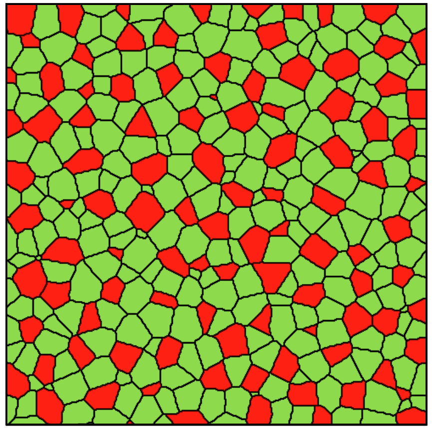
describing spatial distributions ...



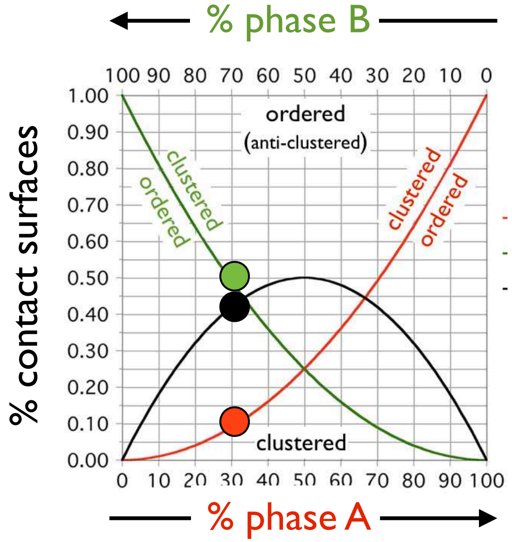
random

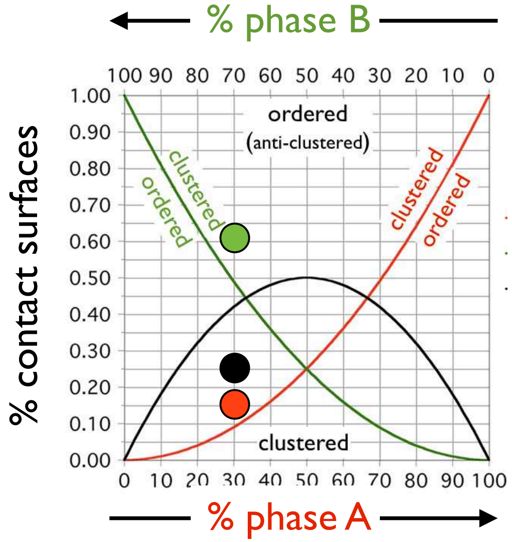


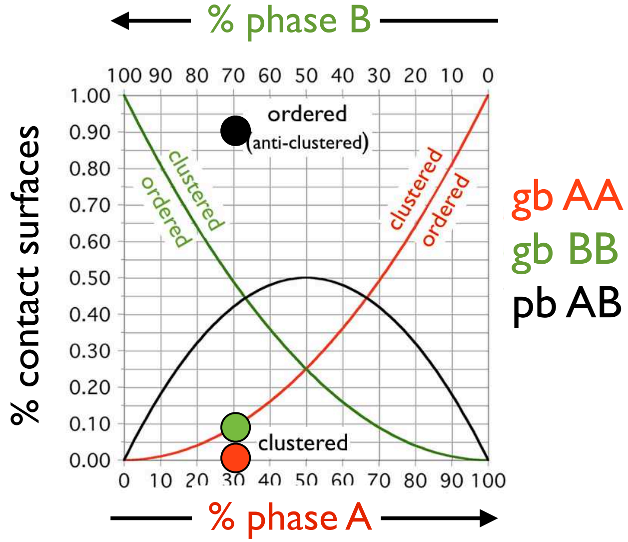
clustered



ordered

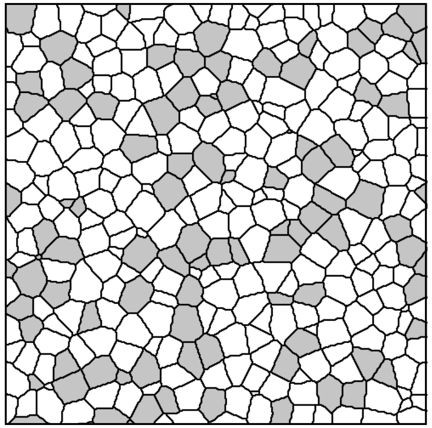




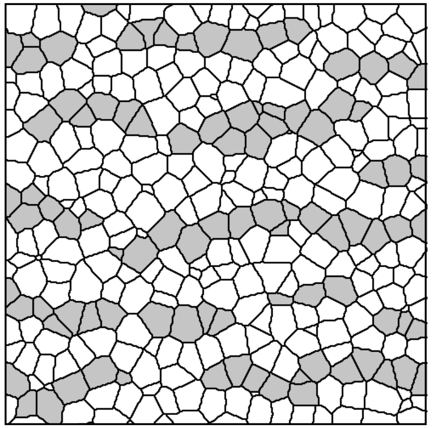


... in terms of phase and grain boundary probability ...

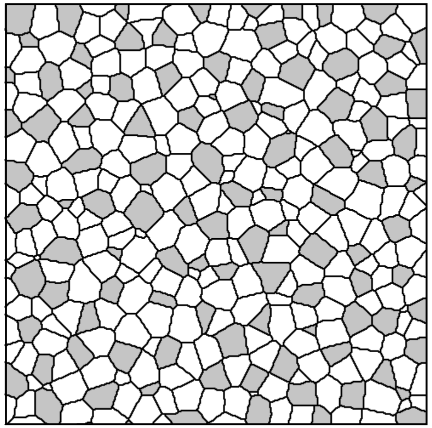
describing spatial distributions ...



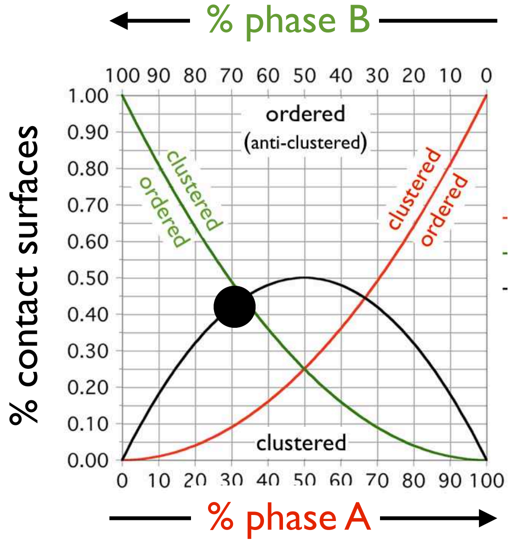
random

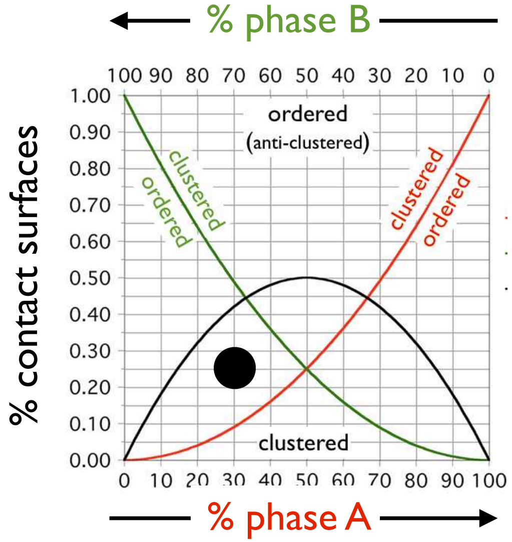


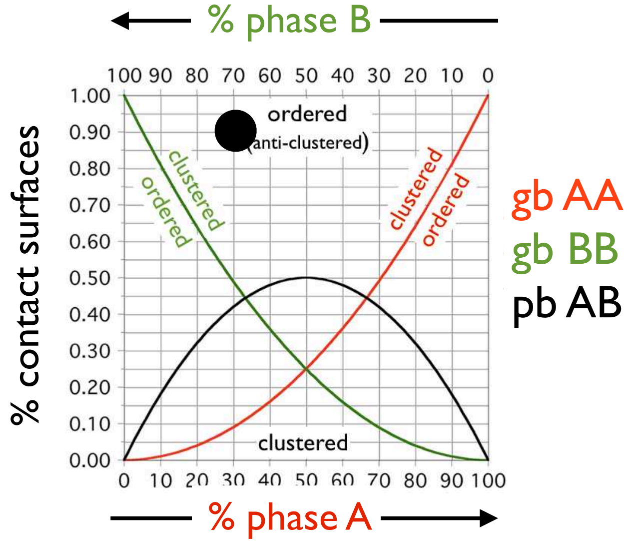
clustered



ordered



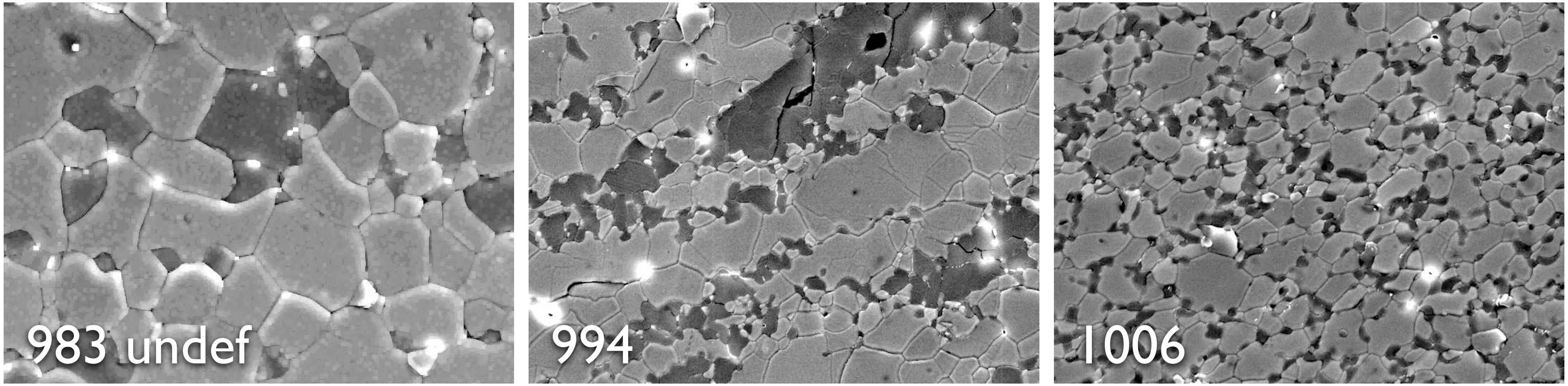


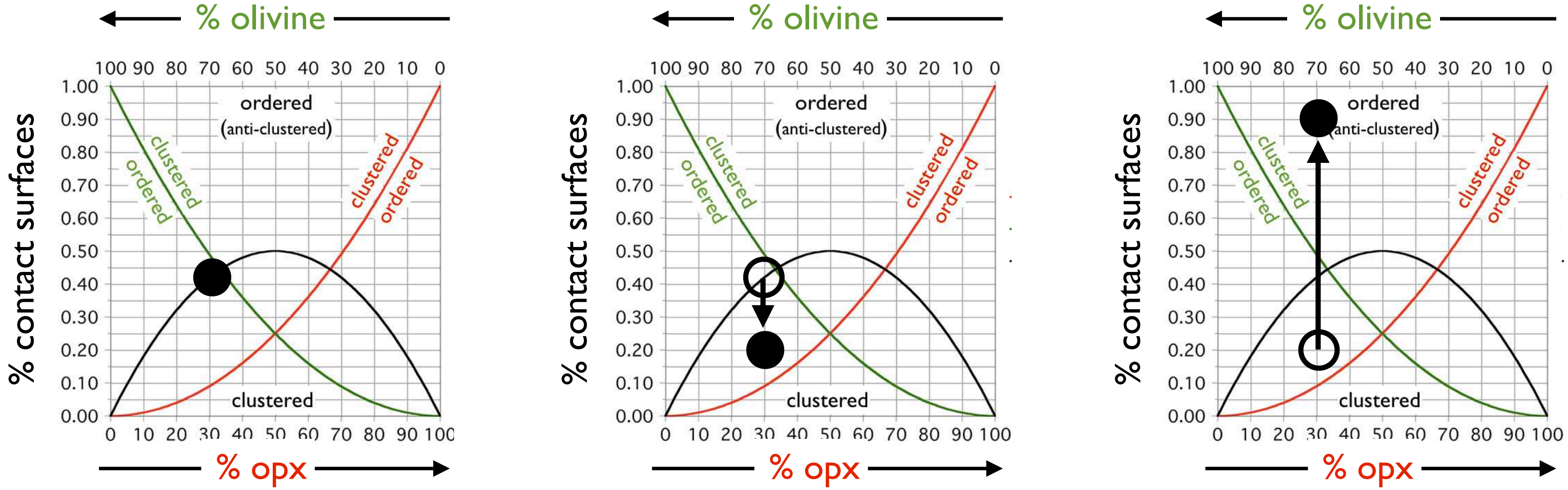


... in terms of phase and grain boundary probability ...

so which spatial distributions do we expect ...

starting material — dislocation creep ⇌ diffusion creep



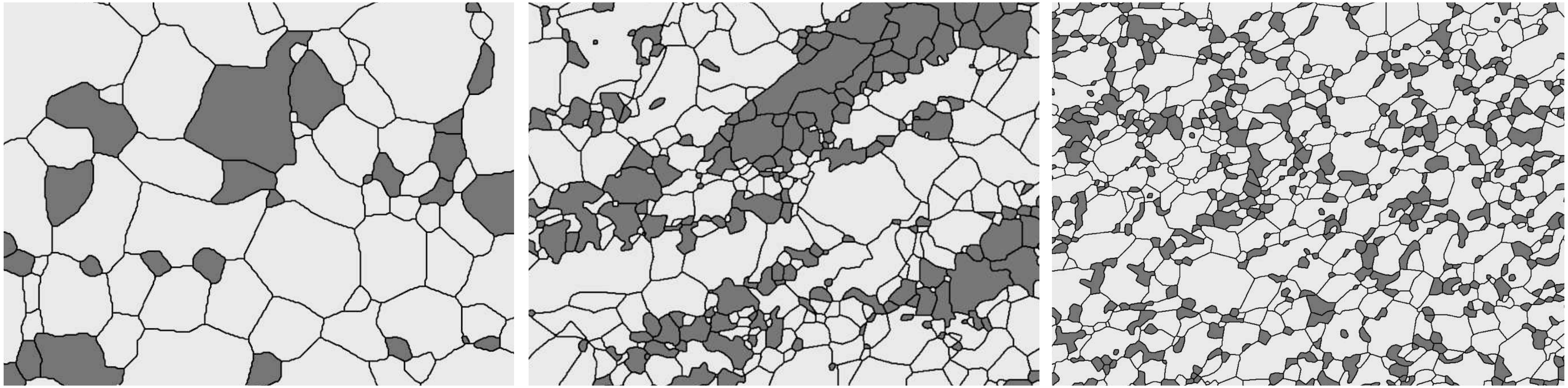


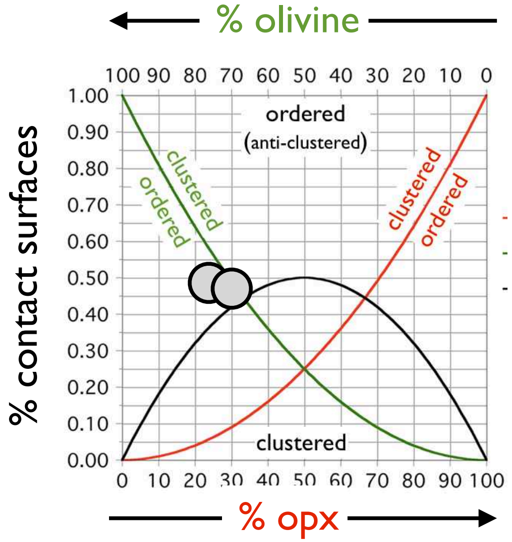
pb
ol-opx

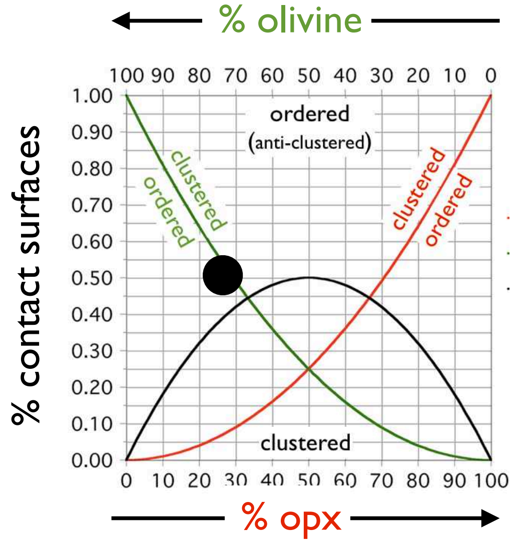
... from mixing to dislocation creep to diffusion creep ?

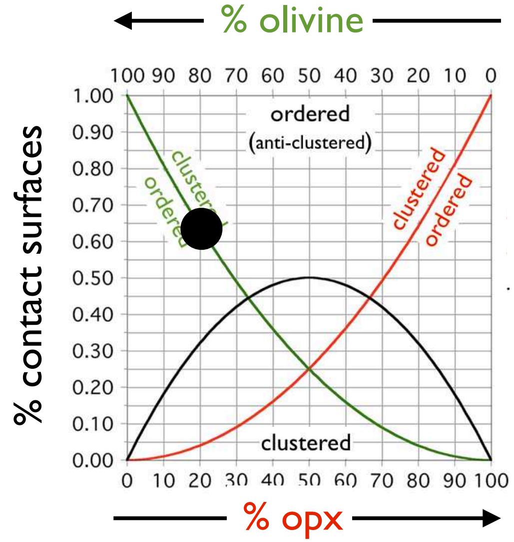
and which spatial distributions do we get ?

983 starting material | 994 dislocation creep | 1006 diffusion creep









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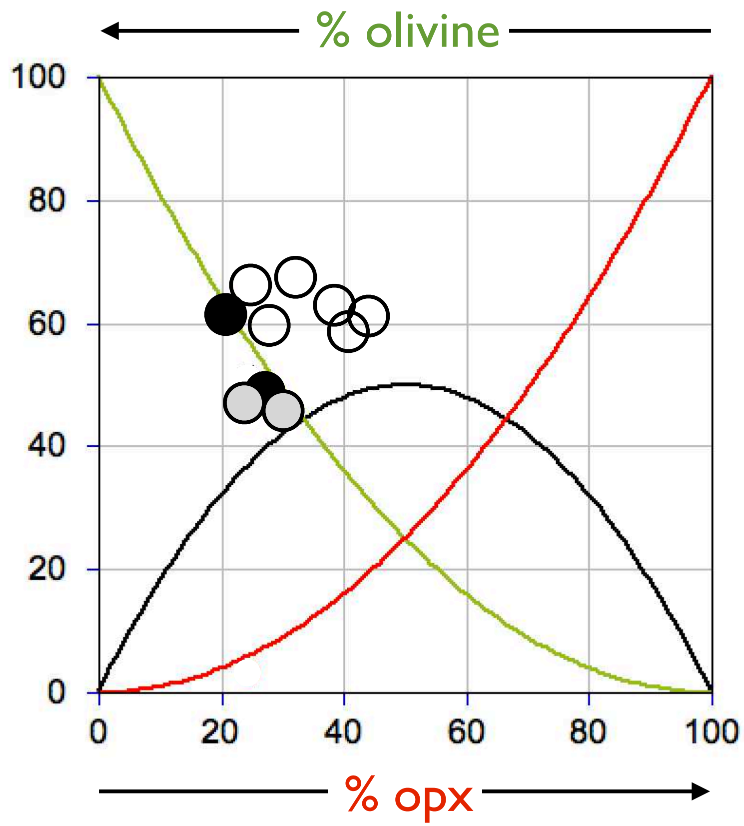
ol-opx

... not what we expect !

even the starting material is ordered !!

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Research Article

Rheological weakening of olivine + orthopyroxene aggregates due to phase mixing, Part2: Microstructural development

Miki Tasaka, Mark E. Zimmerman, David L. Kohlstedt, Holger Stünitz, Renée Heilbronner

Accepted manuscript online: 8 September 2017 Full publication history

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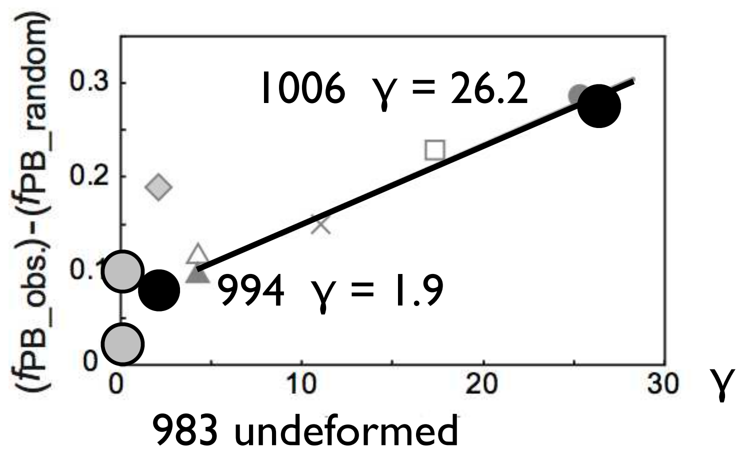
Tasaka et al. (JGR, 2017)



and 'perfect mixing' ≠ random process !

... and what about life in general ?

- thing sare often not what you think they are !
  random processes create clustering
  perfect mixing is not random
  strain often does not leave any trace

- take nothing for granted !
  ... not even the recrystallized quartz piezometer !

- learn to live without steady state
  life - as any process of deformation - may be transitional ...

- enjoy research while it lasts
  ... small samples require big statistics
  ... diffuse data require precise measurements

Slow Food


Betti Richter
Rüdiger Kilian
Sina Marti
Renée Heilbronner
no animals were hurt during any of the experiments
... except maybe some cock roaches ...
ONCE UPON A TIME IN ... BASEL