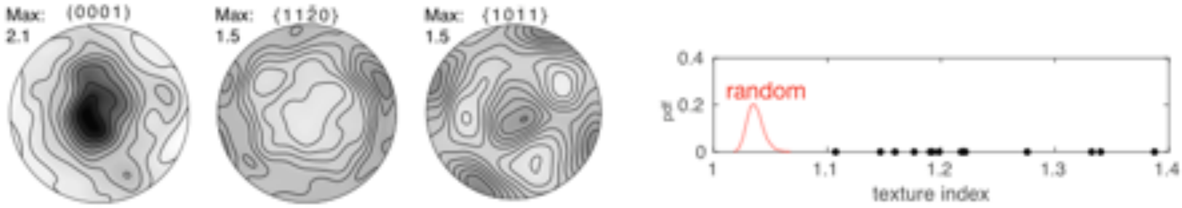
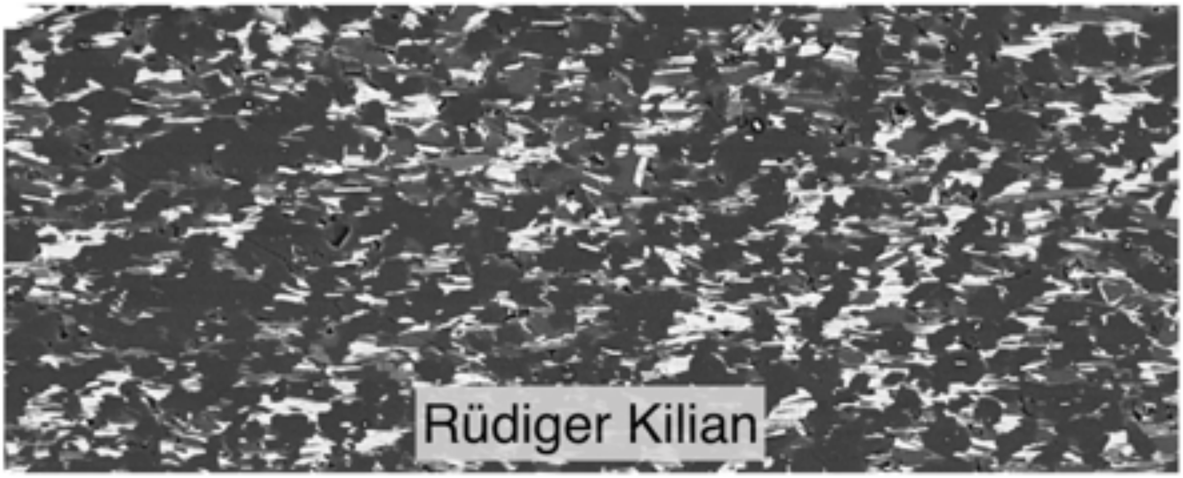
Textures in ultramylonites: weak or random ?





Rüdiger Kilian

Overview

Introduction

- What is an ultramylonite?
- How do they deform?
- Why does it matter?
- Samples from the Normanvik nappe N-Norway

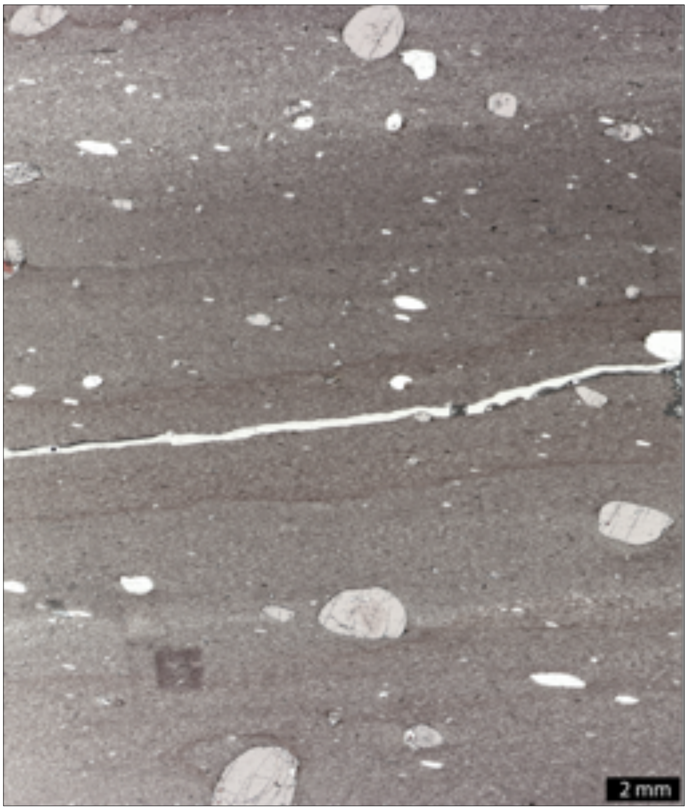
Textures in ultramylonites?

- Measures of texture strength
- Distinction from randomness
- Combining microstructure and texture

Model and implications

Introduction: ultramylonites

- highly deformed rock
- fine grain size
- equiaxed grains*
- often polyphase mixture

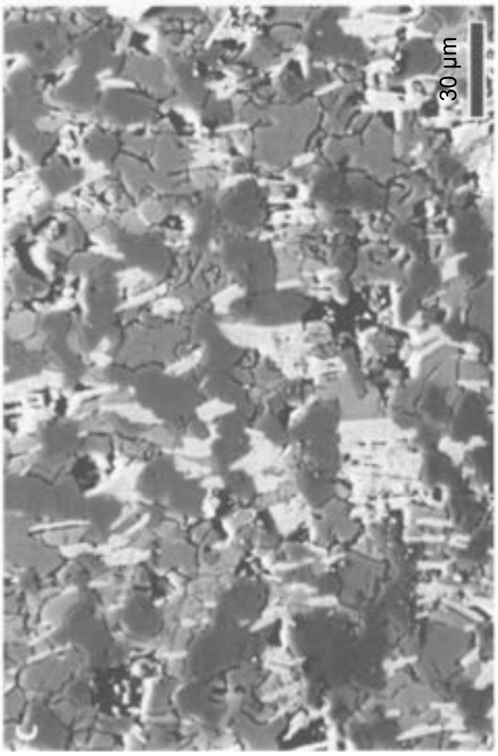


* if the mineral permits it

plane polarized light micrograph

Introduction: ultramylonites

phase mixing

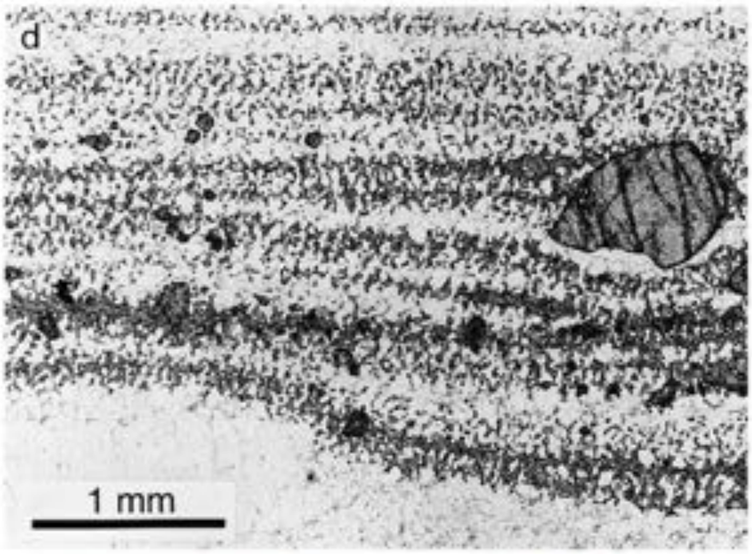


Fliervoet et al., 1997

- grain boundary sliding (neighbour switching)

or/and

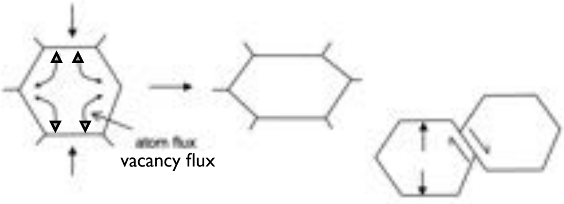
- heterogeneous nucleation

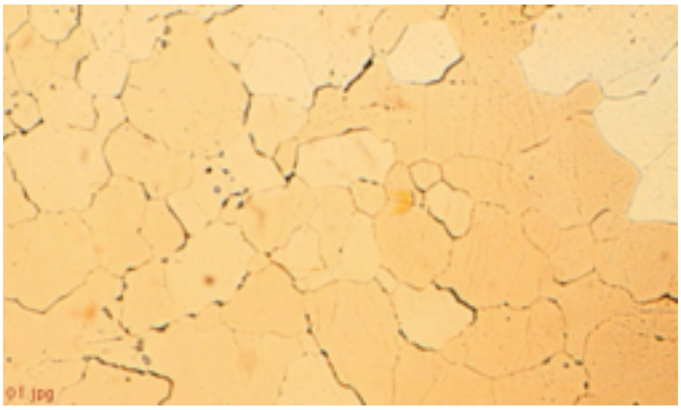


Kruse & Stünitz, 1999

Introduction: mechanical behaviour

diffusion creep (s.l.):





Ree 2000, gbs and cavitation in OCP

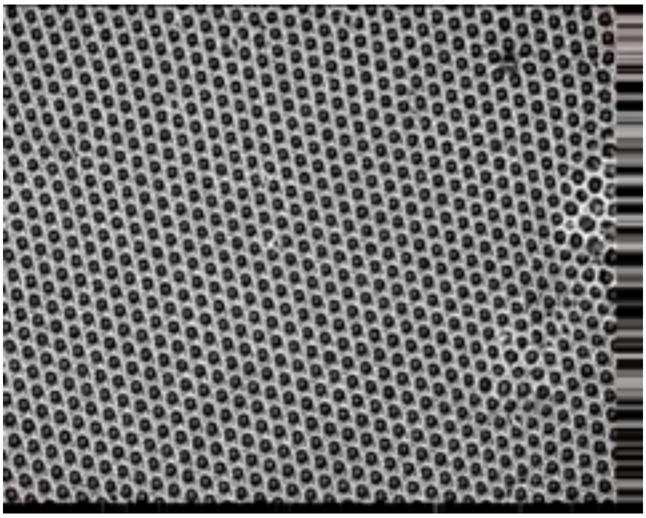
linear viscous n = 1
grain size dependent: m = -2 to -3
- diffusion of atoms/vacancies or dissolution-precipitation
- grain boundary sliding (Rachinger or Lifshitz)

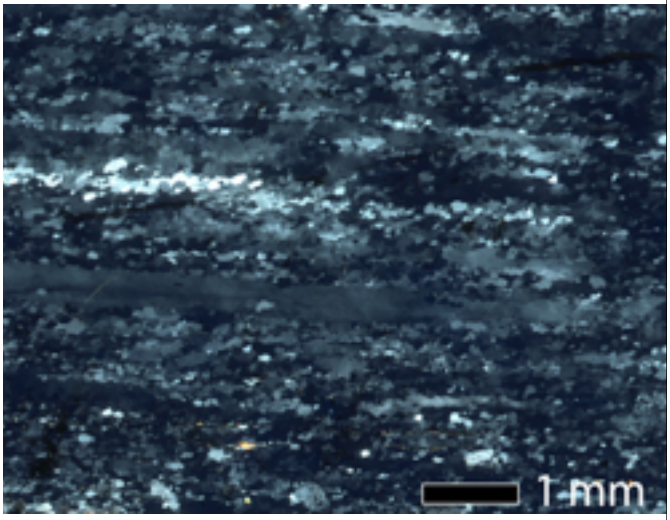
$$\dot{\epsilon} = A\sigma^n \; D^m \; exp^{\left(\frac{-Q}{RT}\right)}$$

gbs involves rigid body rotation of grains
stresses are low
-> no texture expected to form
-> preexisting texture may be randomized

Introduction: in contrast to dislocation creep

extension and compression of a bubble raft





https://www.doitpoms.ac.uk/tlplib/dislocations/index.php

power law viscosity: n > 2
grain size independent: m = 0
glide and climb of dislocations
recovery: subgrain rotation and grain boundary migration
“moderate stresses - monophase material -> usually related to texture formation

$$\dot{\epsilon} = A\sigma^n \; D^m \; exp^{\left(\frac{-Q}{RT}\right)}$$

Introduction

Why does it matter?

Ultramylonites found in cores of shear zones

-> result of strain localization

-> seem to be able to accommodate huge strains

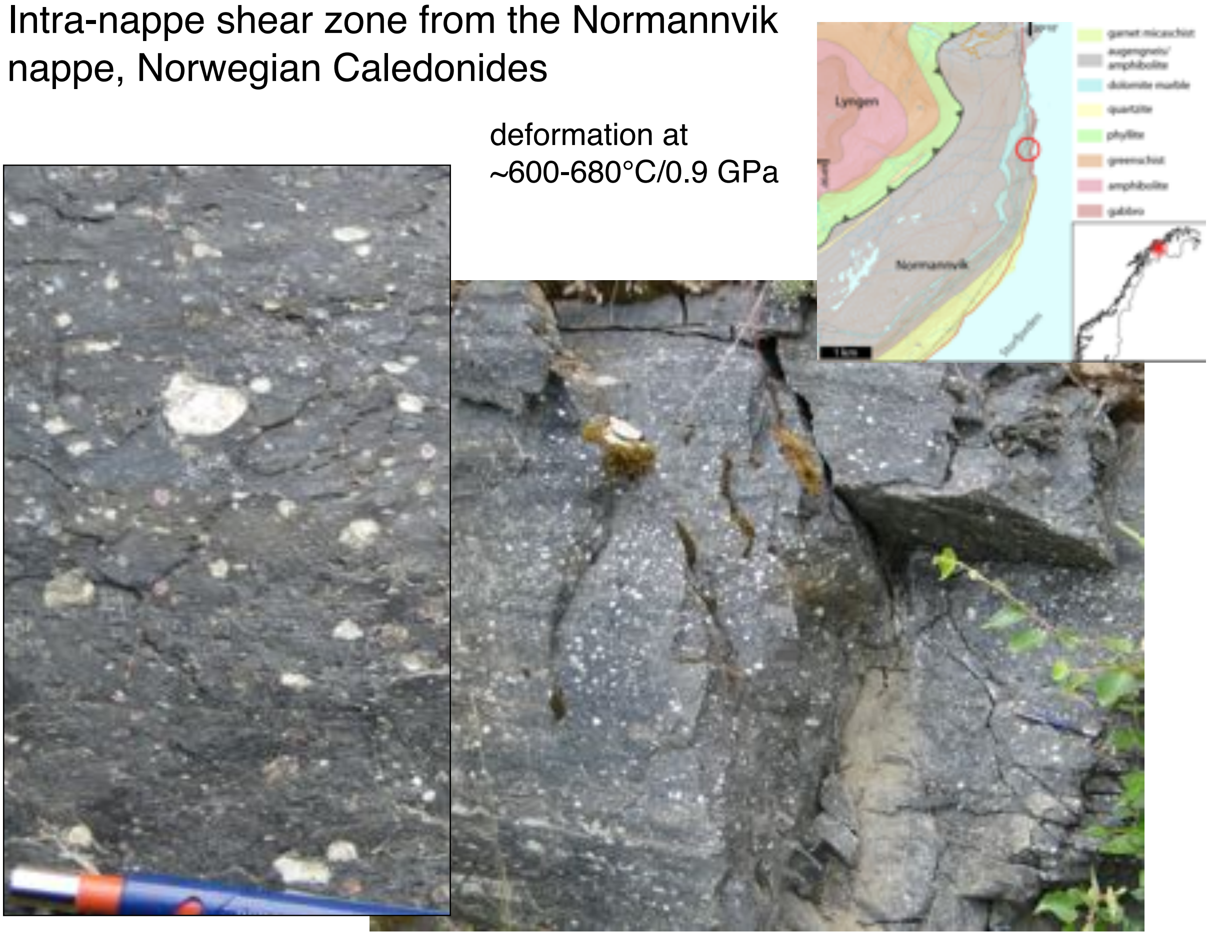
-> usually associated with weakening behaviour

maybe best compared to superplasticity/gbs in certain alloys

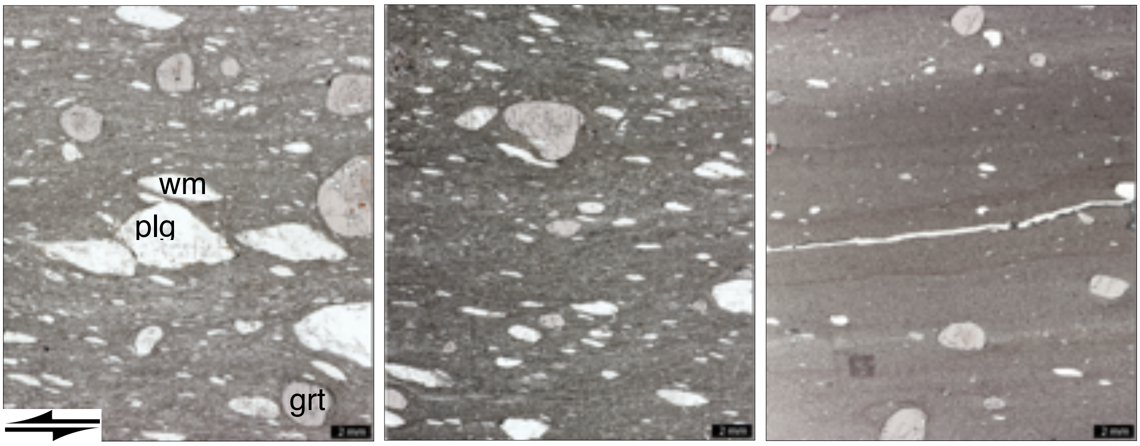
(while involved processes might be very different)

Intra-nappe shear zone from the Normannvik nappe, Norwegian Caledonides

deformation at
~600-680°C/0.9 GPa



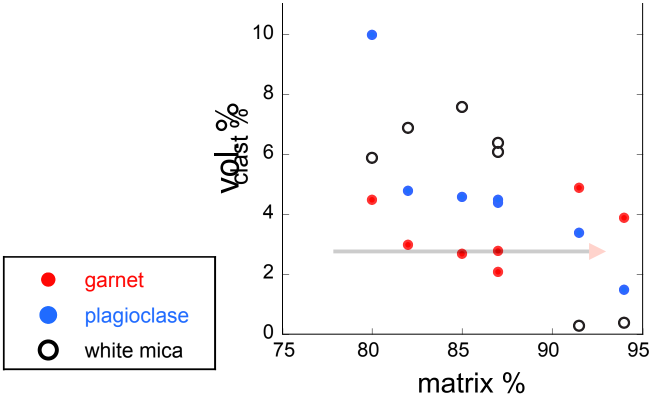
Samples



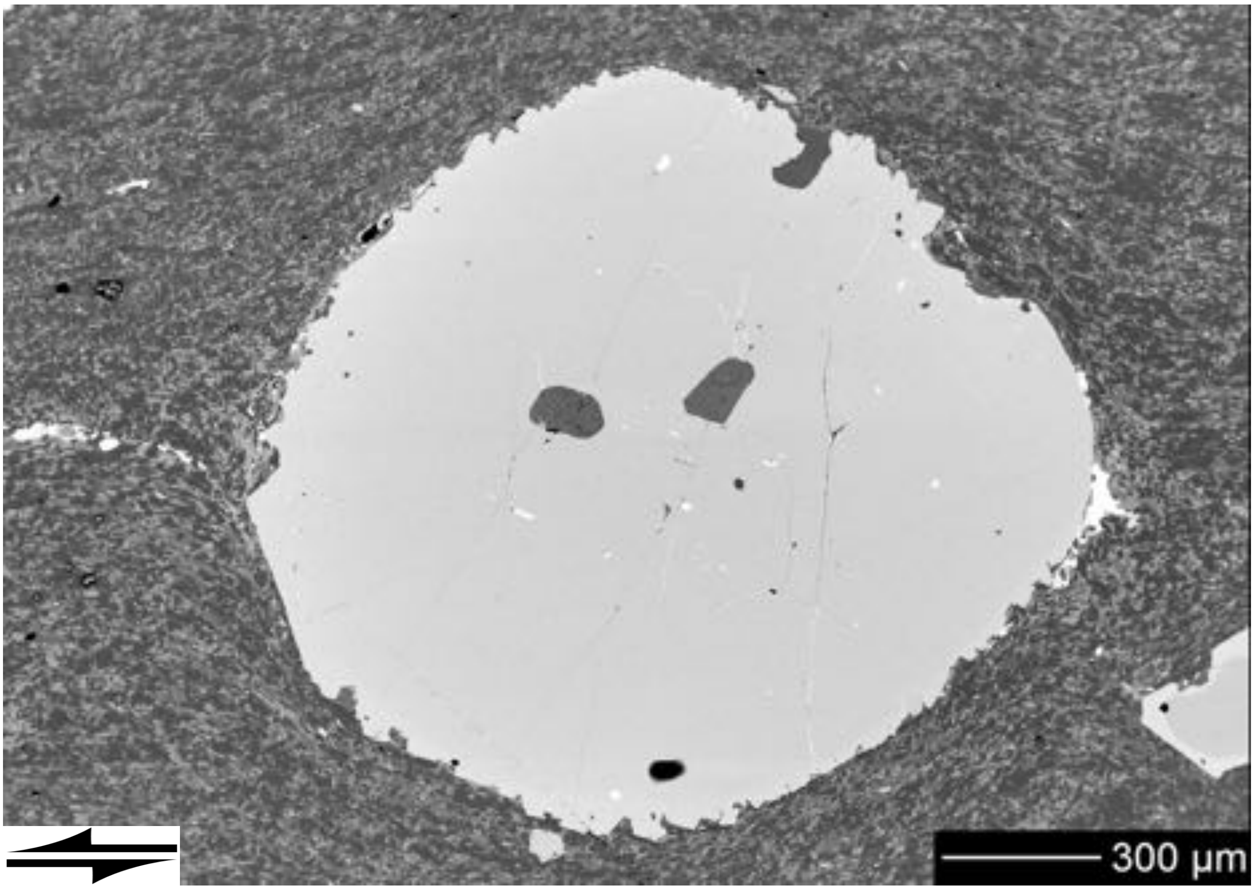
80 % 87 % 94 %

With increasing matrix fraction:

- increase of matrix homogeneity
- vol. % of garnet porphyroclasts remains constant at ~3 %
- white mica and plagioclase porphyroclasts disappear

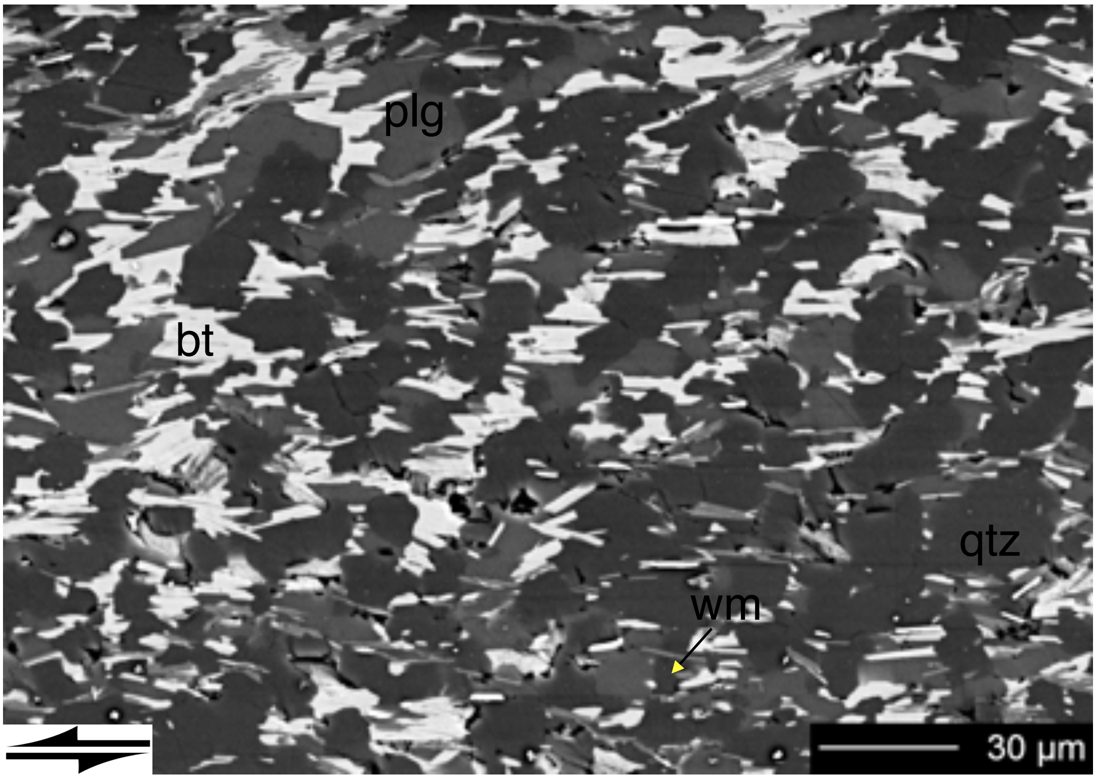


Samples: clasts & matrix



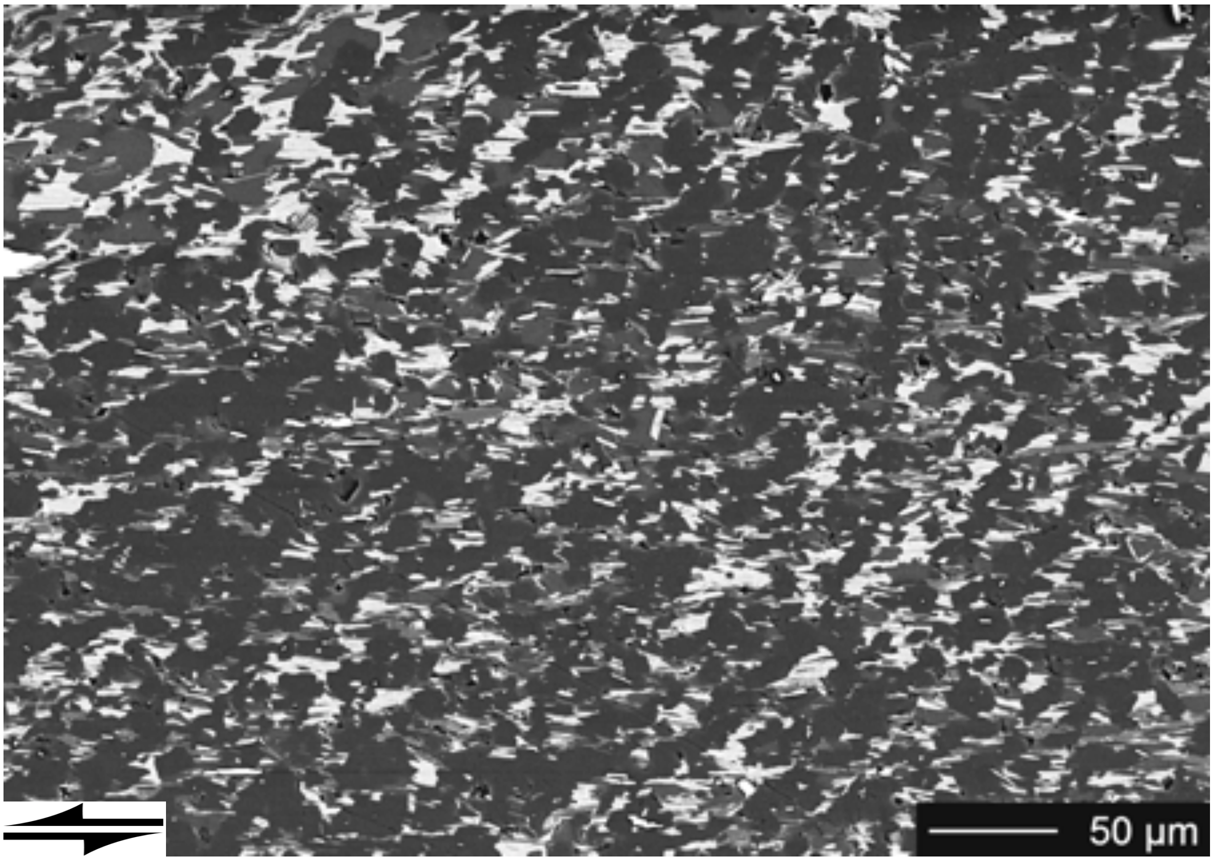
Samples: matrix

fine grained qtz, plg, bt, wm ,ilm/tit



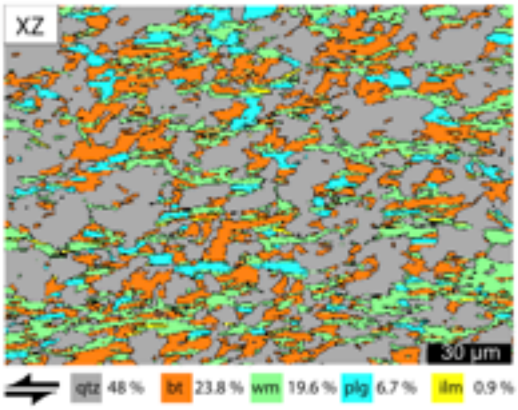
SEM/BSE

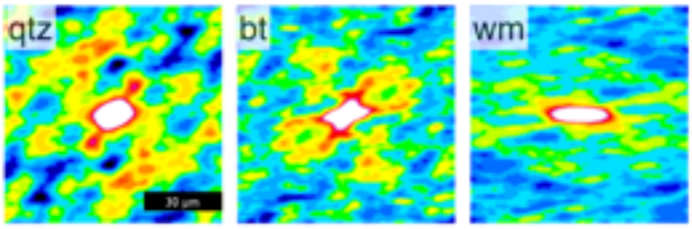
Samples: matrix microstructure



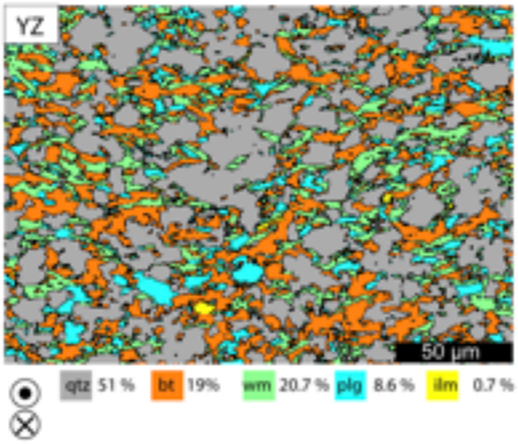
SEM/BSE

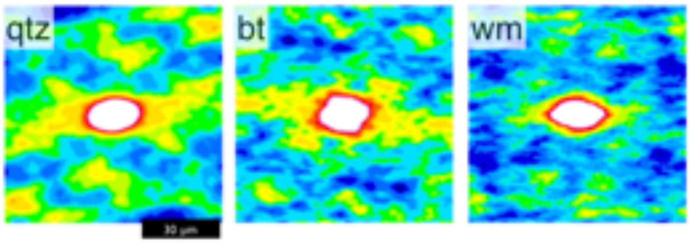
Samples: ACF of matrix phases



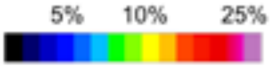


- qtz ≈ bt, oblique direction
- bt ≠ wm, share 001





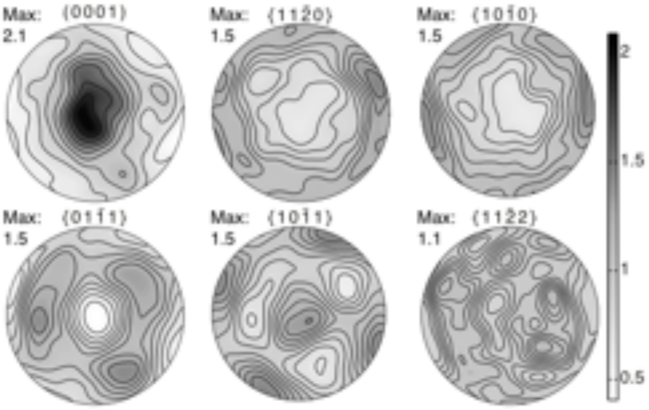
- no oblique high correlation of qtz/bt in YZ
- bt ≈ wm



white: average aggregate size
color: higher order correlation

Samples: Texture in ultramylonites ?

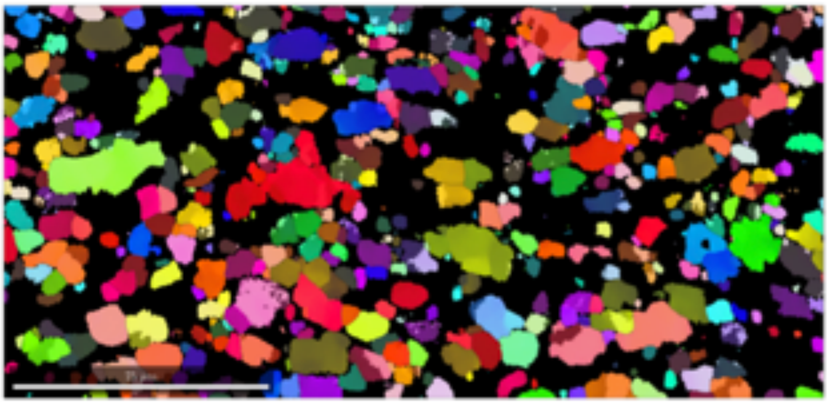
Quartz crystallographic preferred orientation

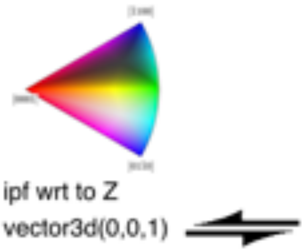


Pole figure of mean grain orientations (n ~ 10000) of 14 individual maps:

- weak preferred orientation
- central maximum of 0001
- orthogonal maxima of 10-11

Distinct from random?

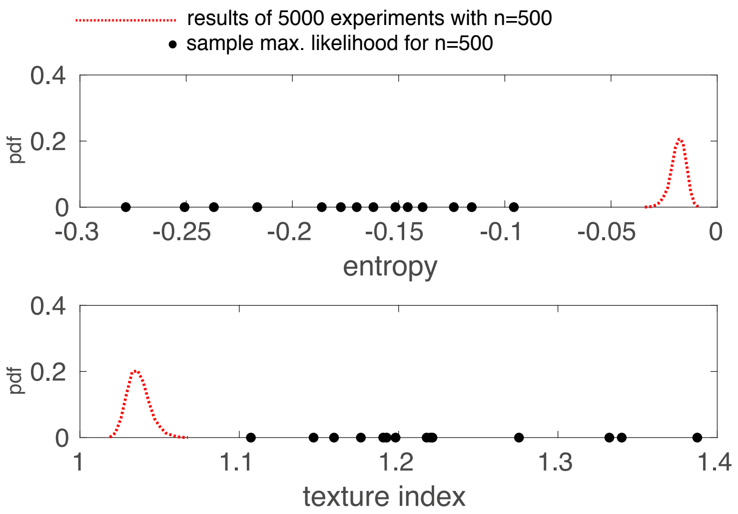




ipf wrt to Z
vector3d(0,0,1)

Samples: Weak texture, but distinct from random?

measures of texture strength



logarithm of an odf * odf

```
% entropy
tentropy = odf.entropy
```

$$S_{\mathrm{ODF}} = -\int f(g) \ln f(g)\,\mathrm{d}g$$

L2 - norm of an odf

```
% texture index (or J-Index)
tindex = odf.textureindex
```

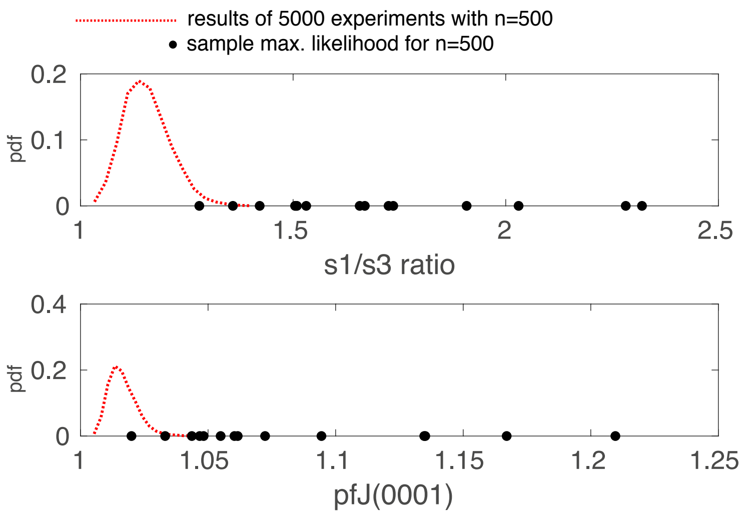
$$J_{\mathrm{ODF}} = \int |f(g)|^2\,\mathrm{d}g = \|f\|^2_{L^2}$$

samples compared to results of repeated experiments drawn form uniform

---

Samples: Weak texture, but distinct from random?

measures of ordering of directions



ratio largest to smallest eigenvalue of a pole figure,

```
% for discrete directions
v= o.*Miller(0,0,0,1,o.CS)
[evector, evalue] = eig(v)
%or if a S2Fun should be used
sf = calcDensity(v)
[evector, evalue] = eig(sf)
```

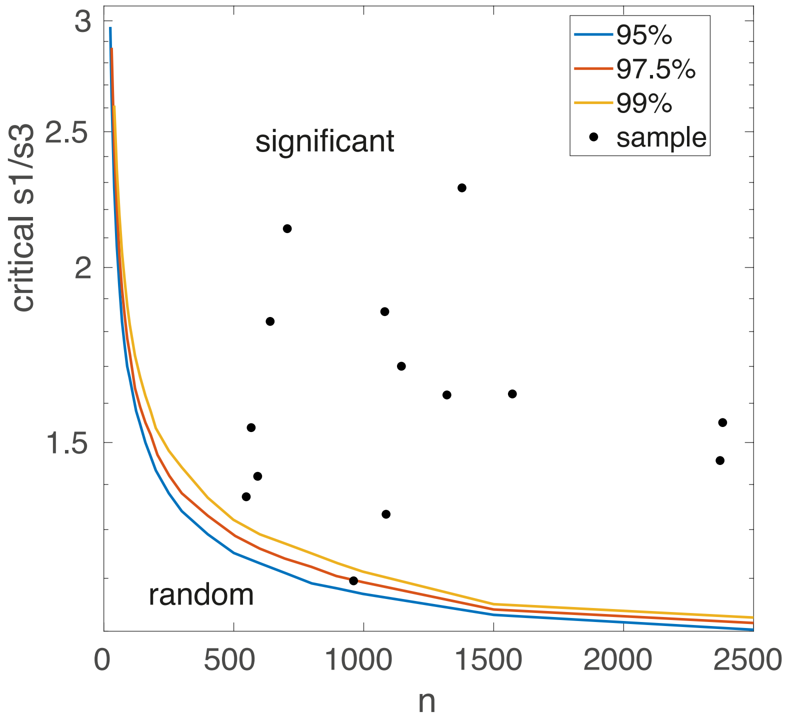
L2 - norm of a pole figure

```
% from a S2Fun
pfJ = pfg.norm/sqrt(4*pi);
```

samples compared to results of repeated experiments drawn form uniform

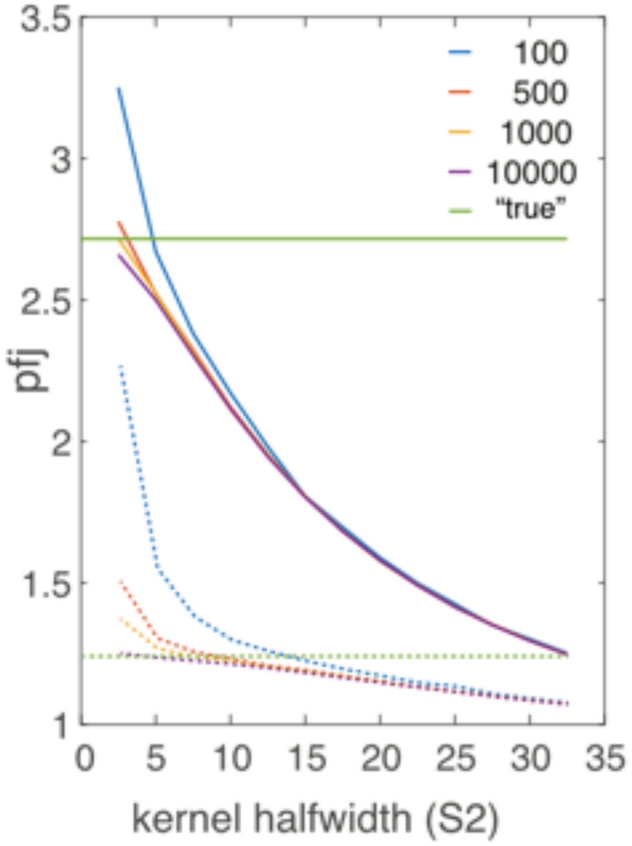
Samples: Weak texture, but distinct from random?

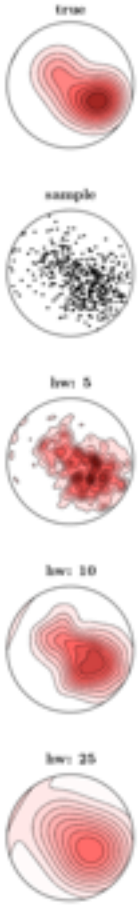
Level of significance for measures derived from discrete orientations/directions



recalculated after Woodcock& Naylors (1983)

What is the best estimator for a continuous function?

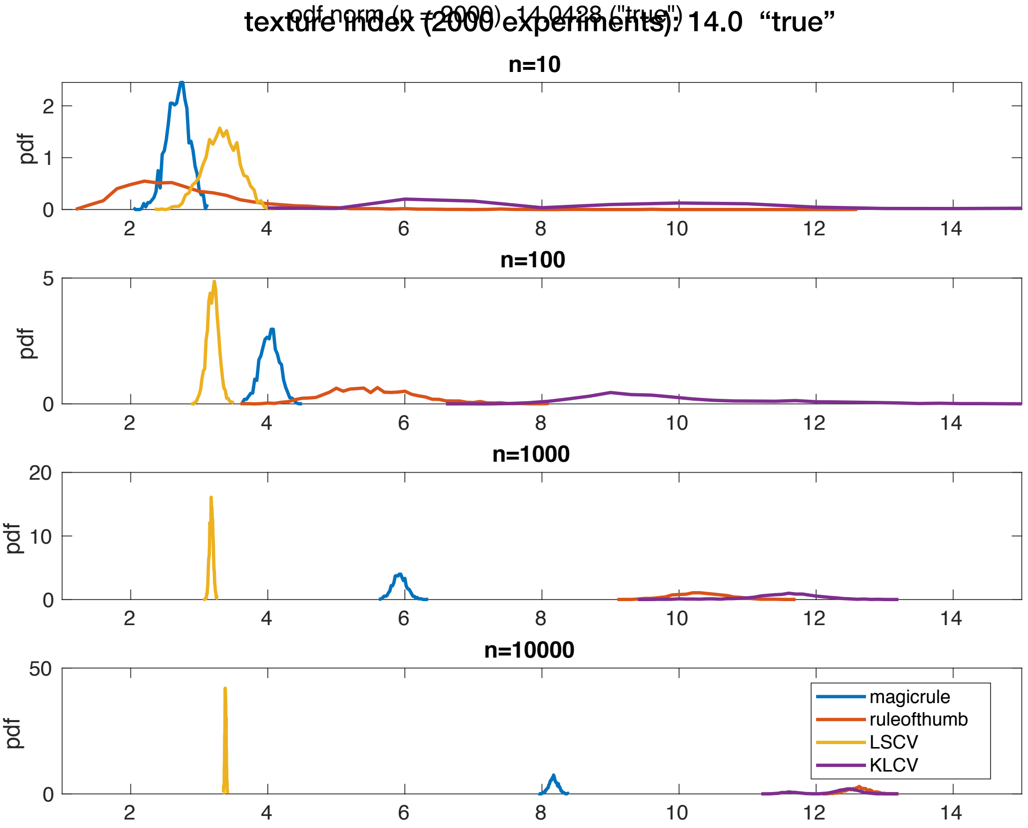




What is the best estimator for a continuous function?

in Mtex, `calcKernel()` might help to estimate a suitable kernel width

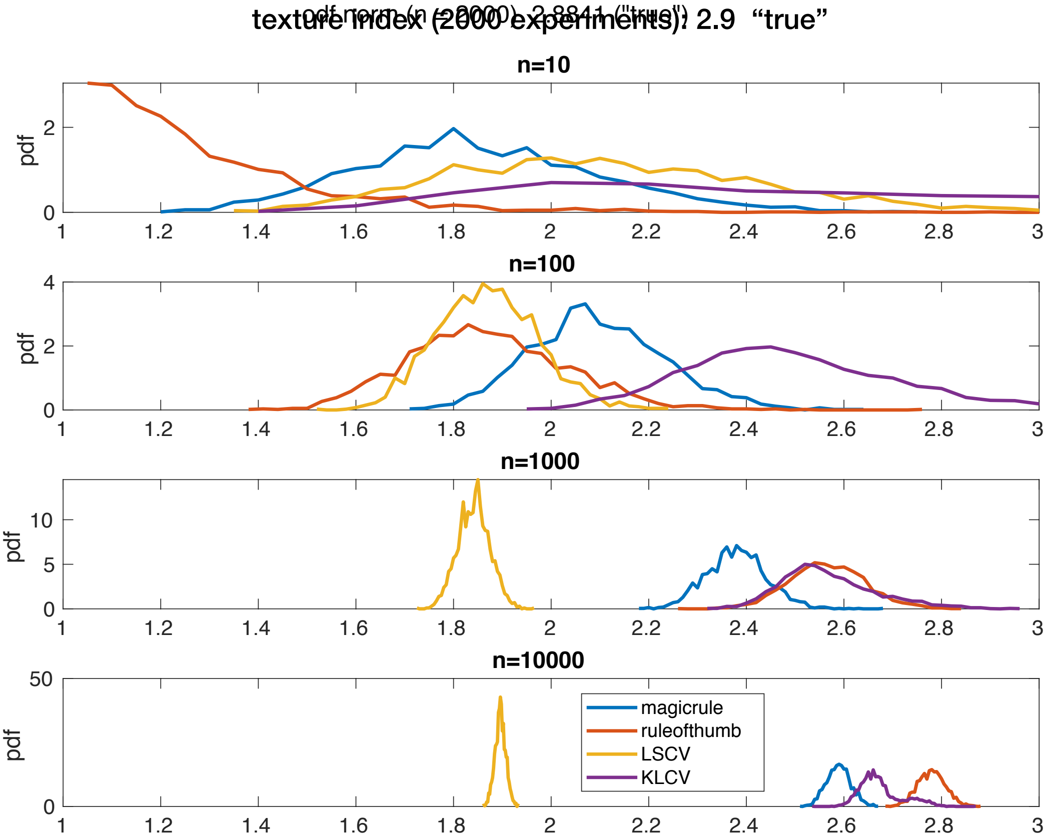
texture index (2000 experiments): 14.0 “true”



What is the best estimator for a continuous function?

in Mtex, `calcKernel()` might help to estimate a suitable kernel width

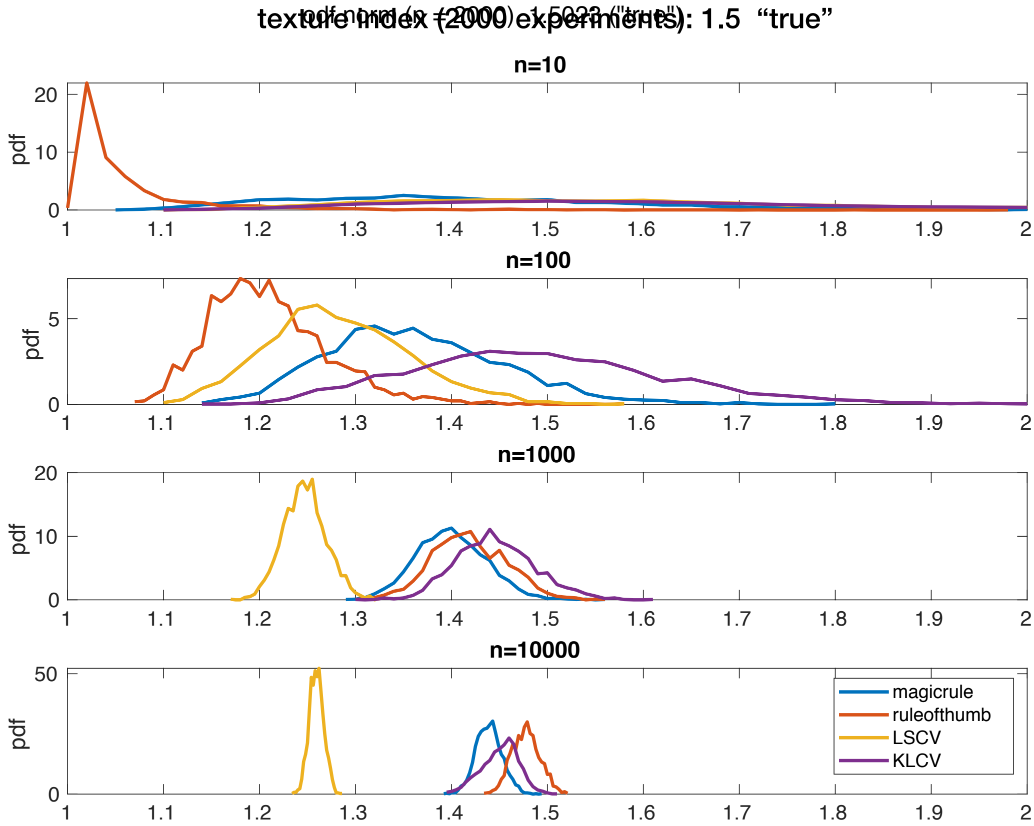
texture index (2000 experiments): 2.9 “true”



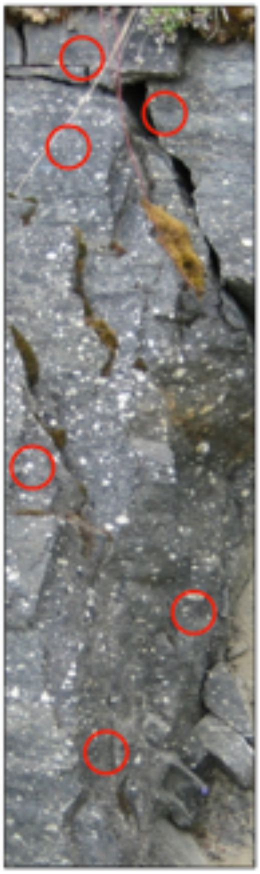
What is the best estimator for a continuous function?

in Mtex, `calcKernel()` might help to estimate a suitable kernel width

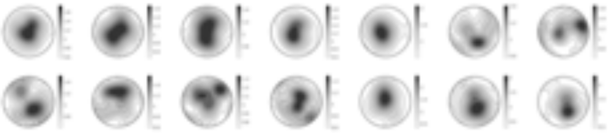
texture index (2000 experiments): 1.5 “true”



Looking at CPO geometry



[0001] [c]

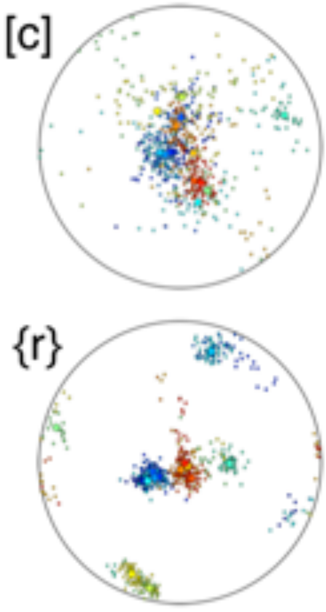


{10-11} {r}

individual pole figures: 50, averaged, constant n=100 subsamples

⇄

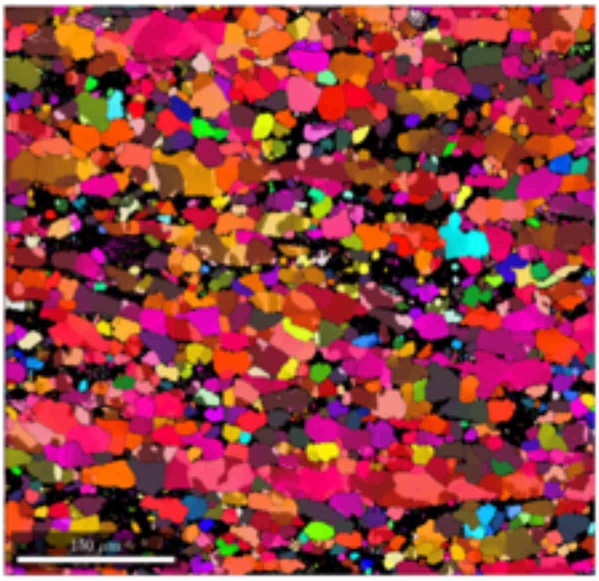
maximum likelihood
position of maxima of
14 samples

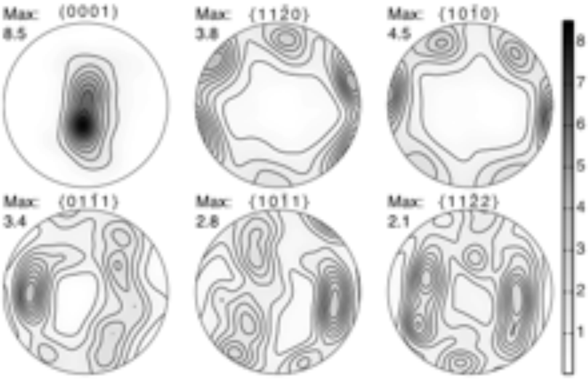


Pole figures from 13 of 14
dataset are very similar.

origin of CPO: new or inherited

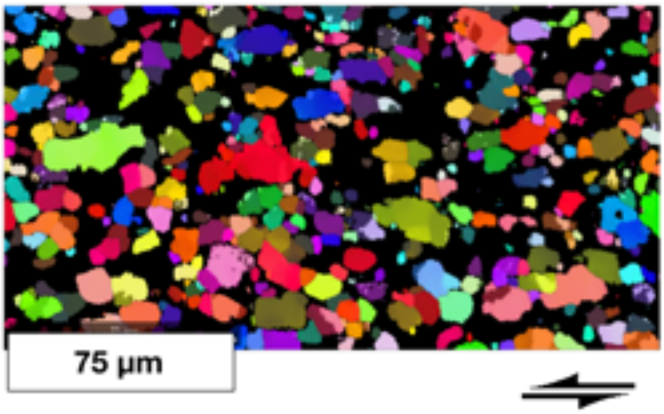
comparison with quartz-rich parts of the shear zones (most likely undergoing dislocation creep): bulk textures

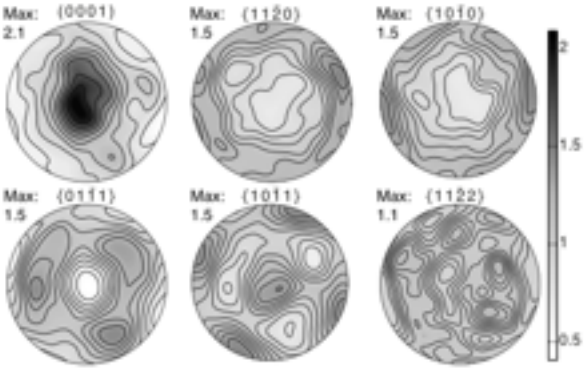




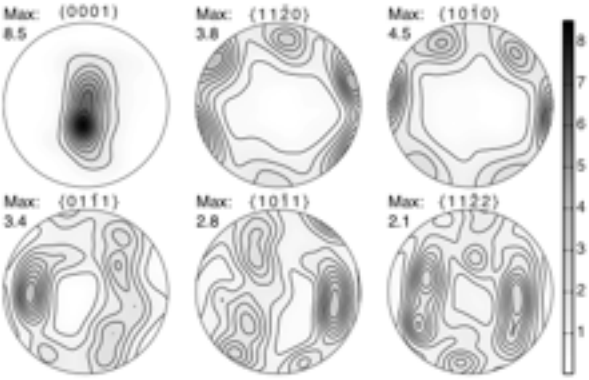
textureIndex: 4.9 (@ 10° hw)
83 % quartz

ipf 001





textureIndex: 1.3 (@ 10° hw)
83 % quartz

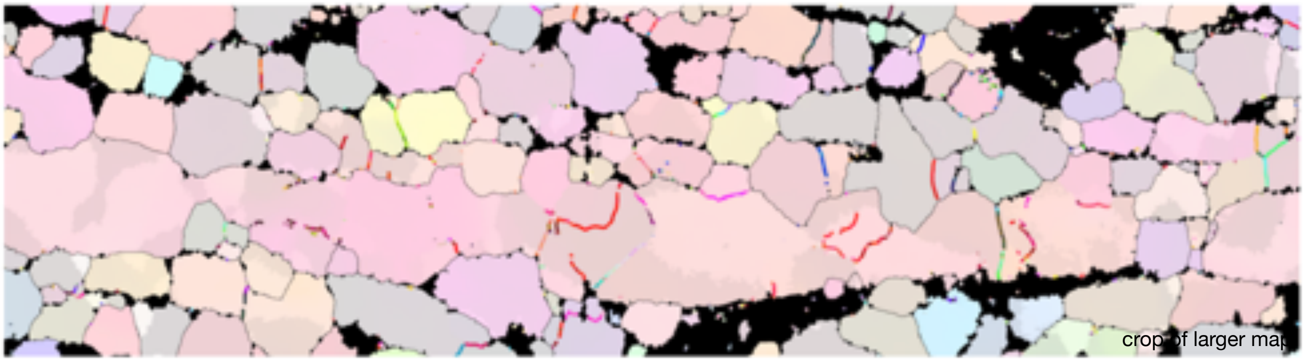


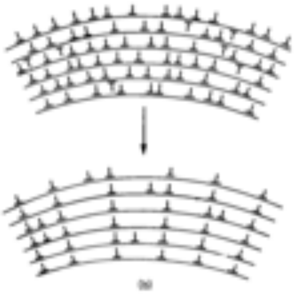
textureIndex: 4.9 (@ 10° hw)
83 % quartz

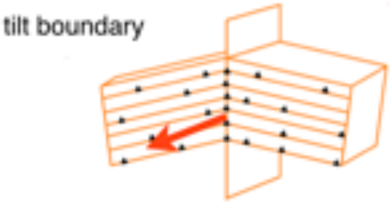
origin of CPO: new or inherited

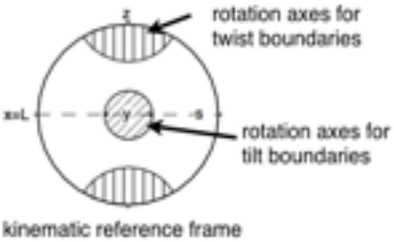
comparison with quartz-rich
parts of the shear zone: misorientation axes

misorientation axes 2-10°









kinematic reference frame

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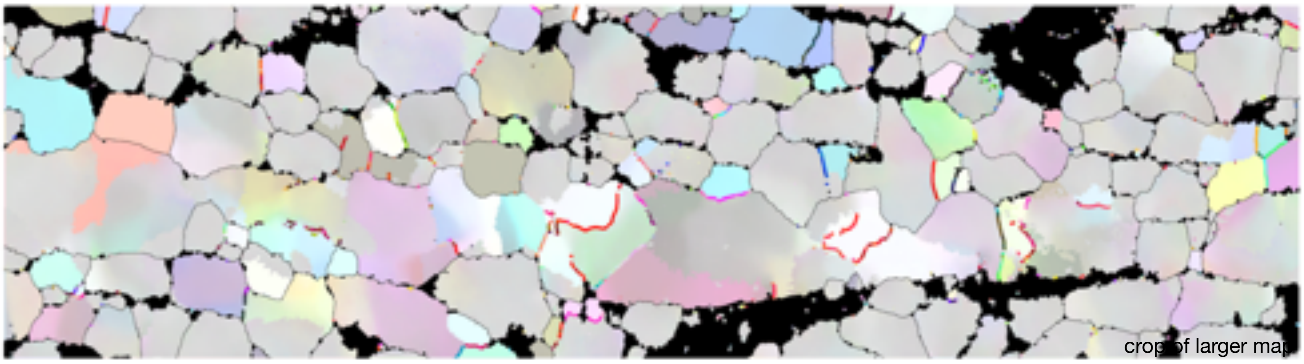
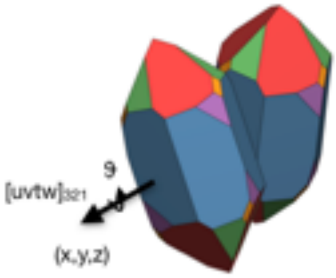
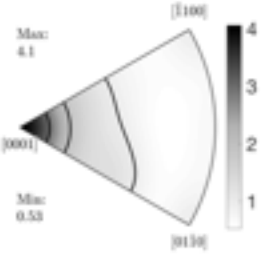
origin of CPO: new or inherited

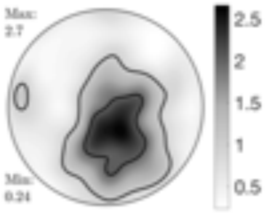
comparison with quartz-rich
parts of the shear zone: misorientation axes

misorientation axes 2-10°



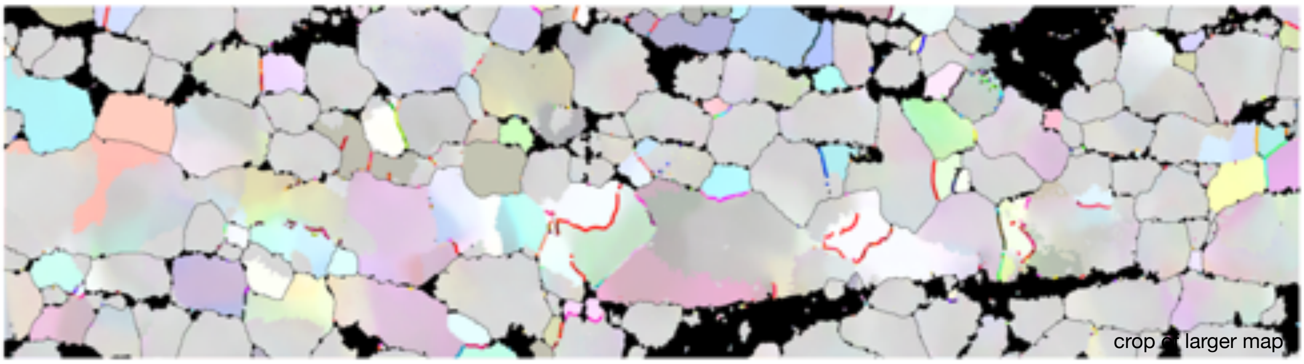






comparison with quartz-rich parts of the shear zone

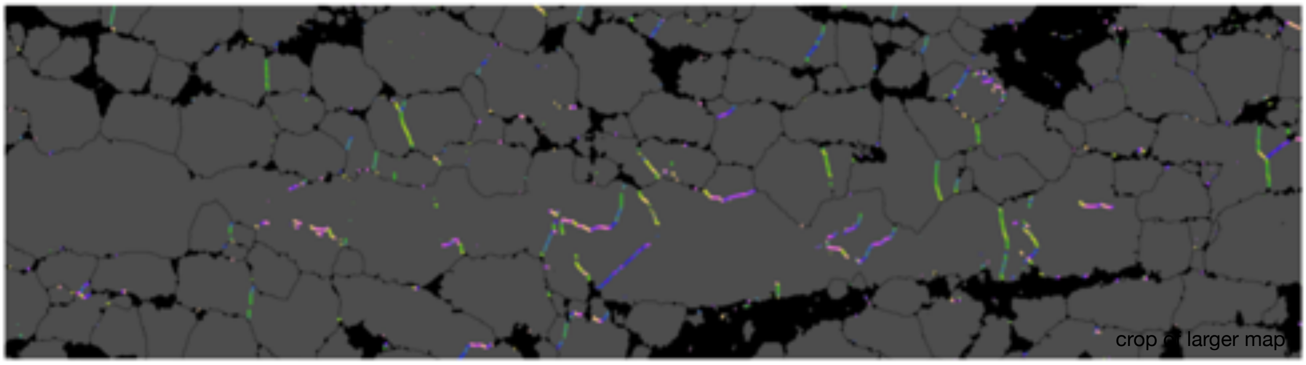
misorientation axes 2-10°

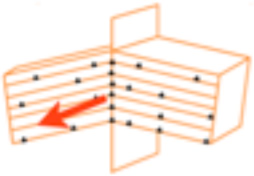


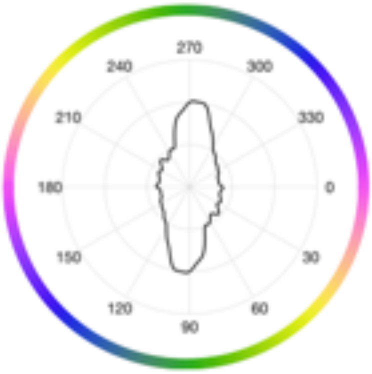
How to derive low angle boundaries in Mtex:

```
% calculate grains with a low threshold angle
[subgrains,ebsds.grainId]=ebsds.calcGrains('angle',1*degree)
% smooth grains (optional, only important for gb trend)
subgrains = subgrains.smooth(8);
% gather boundaries (closed) /  "internal" boundaries (non-closed)
sgb = [subgrains.boundary('q','q') ...
       subgrains.innerBoundary('q','q')]
% find some condition for low angle boundaries
LAB = sgb(sgb.misorientation.angle< 10*degree & ...
          sgb.misorientation.angle> 2*degree
```

comparison with quartz-rich parts of the shear zone: trend of LAB

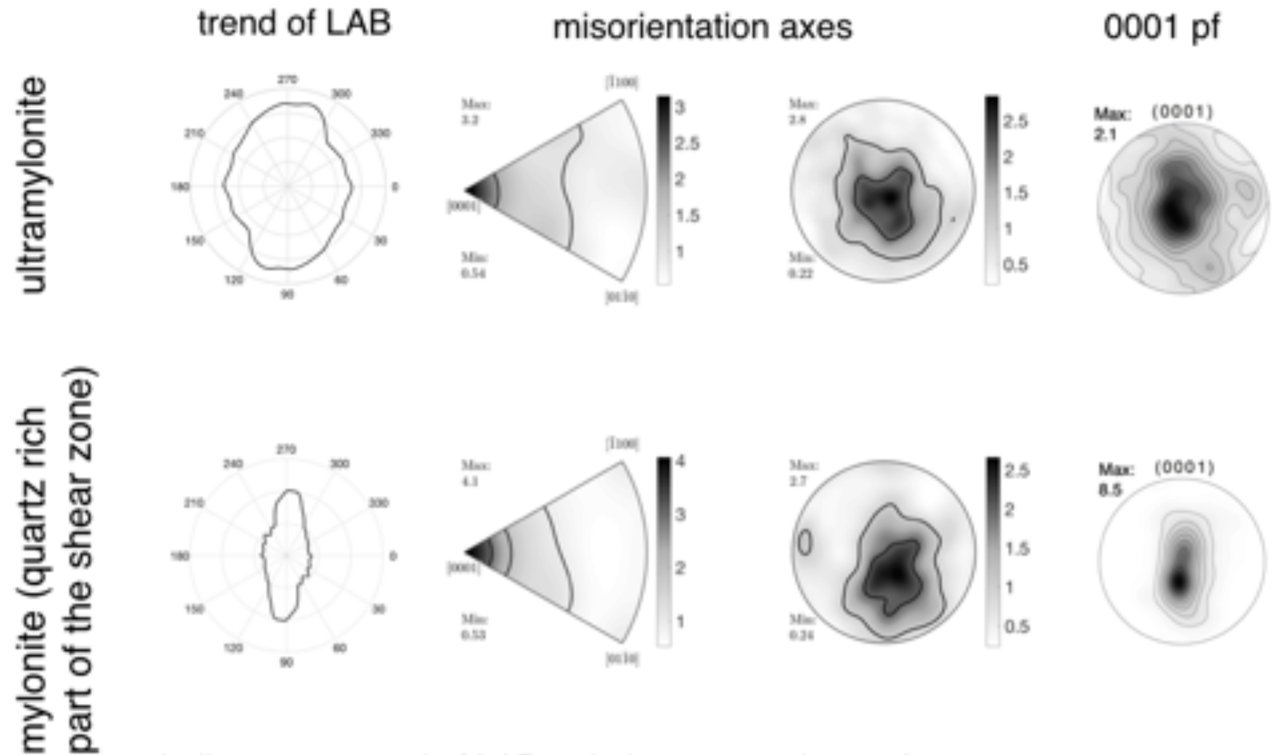



tilt boundary



```
% get the gb trend
gbdir = mod(LAB.direction.rho,pi);
```

Comparing properties of LAB



trend of LAB

misorientation axes

0001 pf

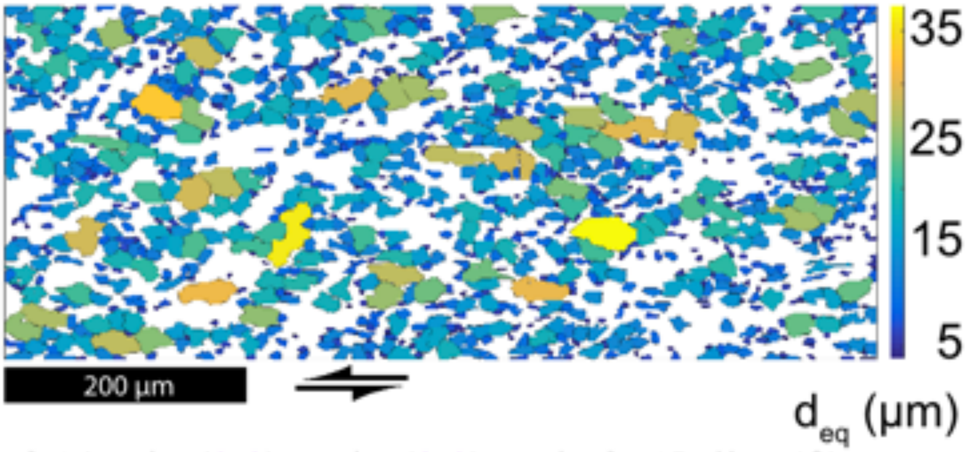
ultramylonite

mylonite (quartz rich part of the shear zone)

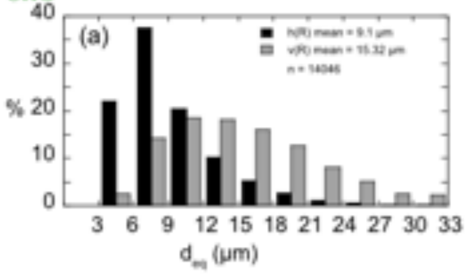
bulk texture, trend of LAB ordering are weakenend,
misorientation axes (specimen coordinates) remain surprisingly constant
-> texture might not be inherited?

Which grains contribute to the non-random texture?

With MTEX it is very easy to map grain properties and compare textures obtained from different subsets. e.g. grain size



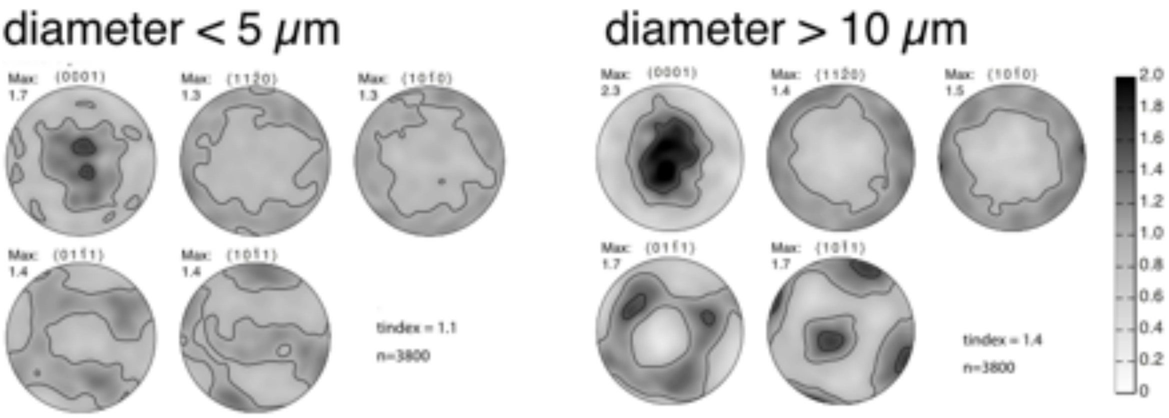
```
plot(grains('q'),grains('q').equivalentRadius.*2)
% equivalentRadius = radius of a circle with the
% same area (r =sqrt(A/pi))
```



example: grains size

Which grains contribute to the non-random texture?

With MTEX it is very easy to map grain properties and compare textures obtained from different subsets. e.g. grain size

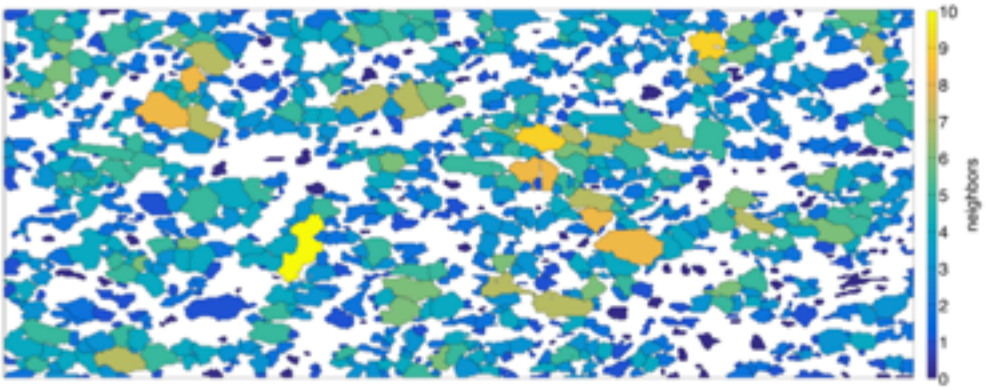


diameter < 5 μm

diameter > 10 μm

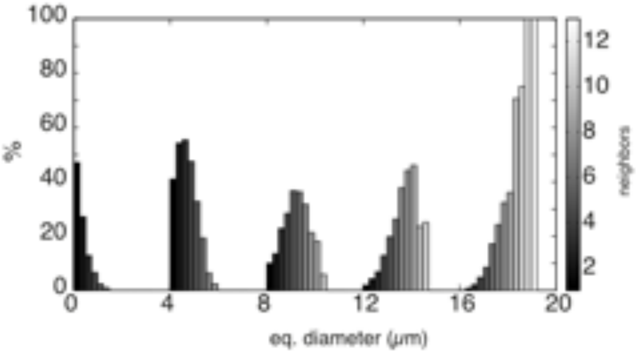
Which grains contribute to the non-random texture?

isolated grains vs. those grains with grain boundaries (in contrast to phase boundaries): neighbor count



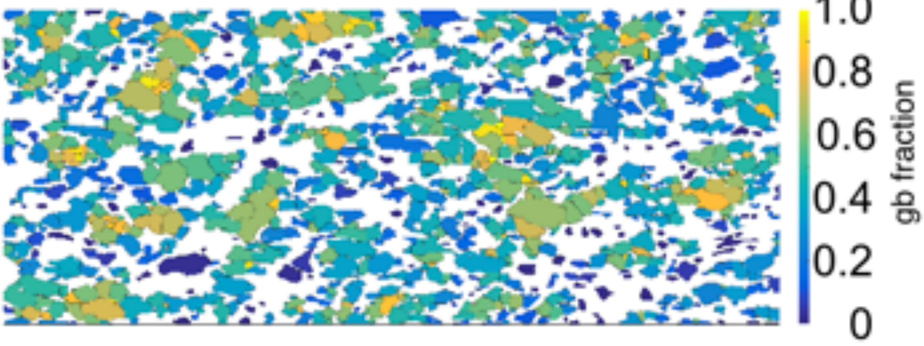
```
nb =   grains('q').neighbors
```

however, neighbor counts seem not to be independent from grain size

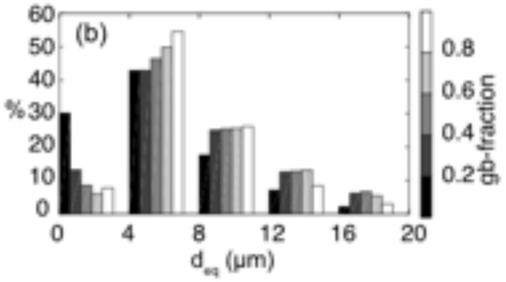


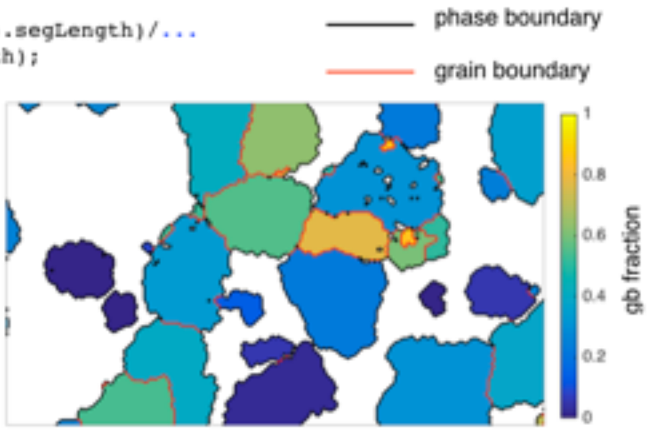
Which grains contribute to the non-random texture?

isolated grains vs. those grains with grain boundaries (in contrast to phase boundaries): grain boundary fraction



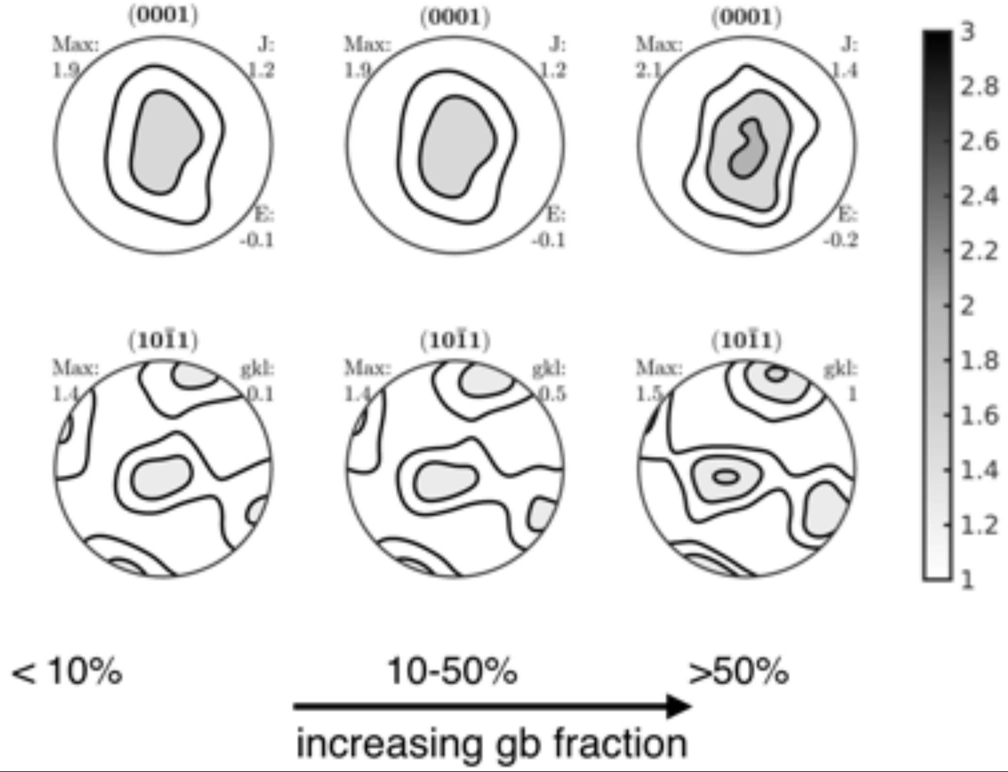
```
for j = 1:length(grains('q'))
gbfrac(j) = sum(grains('q',j).boundary('q','q').segLength)/...
            sum(grains('q',j).boundary.segLength);
end
plot(grains('q'),gbfrac)
```





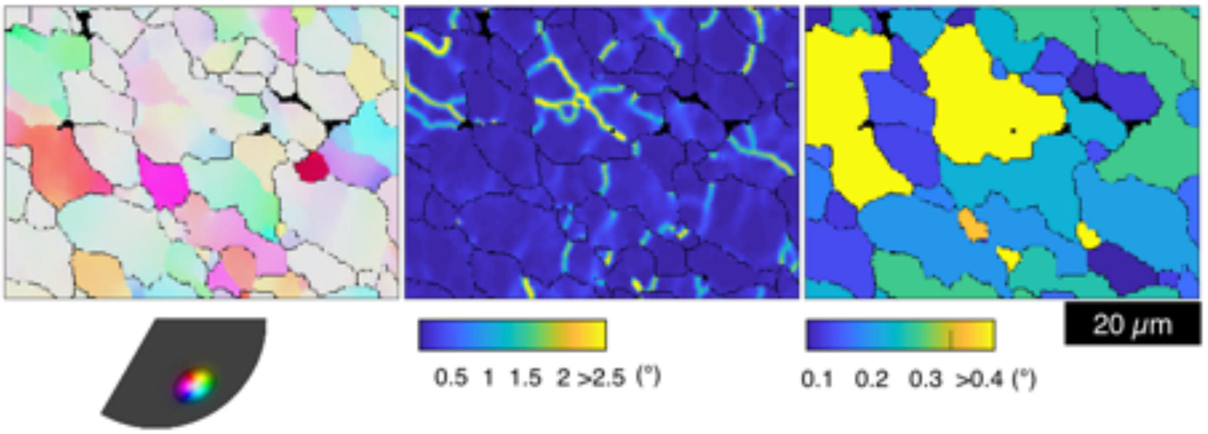
Which grains contribute to the non-random texture?

isolated grains vs. those grains with grain boundaries (in contrast to phase boundaries): grain boundary fraction



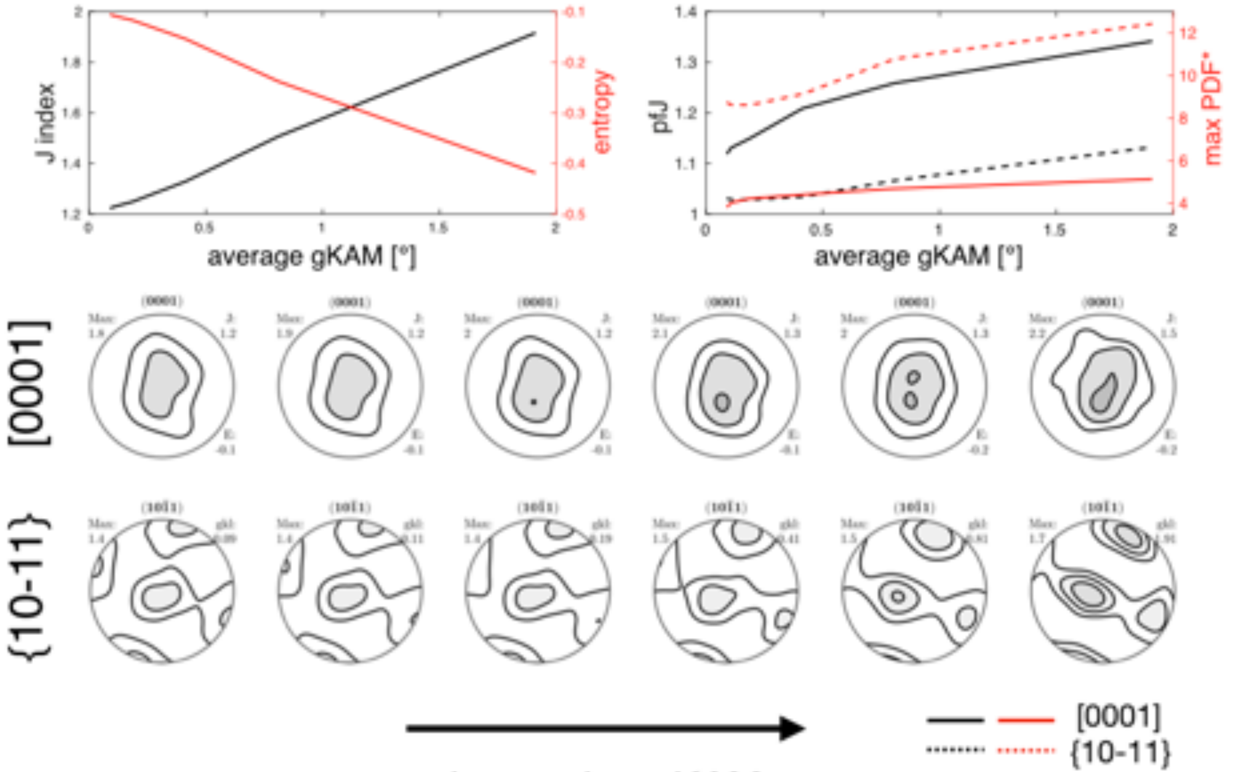
Which grains contribute to the non-random texture?

other measures potentially indicating dislocation creep: gkam



gKAM= grain averaged kernel average misorientation
- measure of local orientation gradient averaged over a grain
- measures density and angle of low angle (intragranular) boundaries
- indirect measure for the amount of recovery (and hence previous deformation)

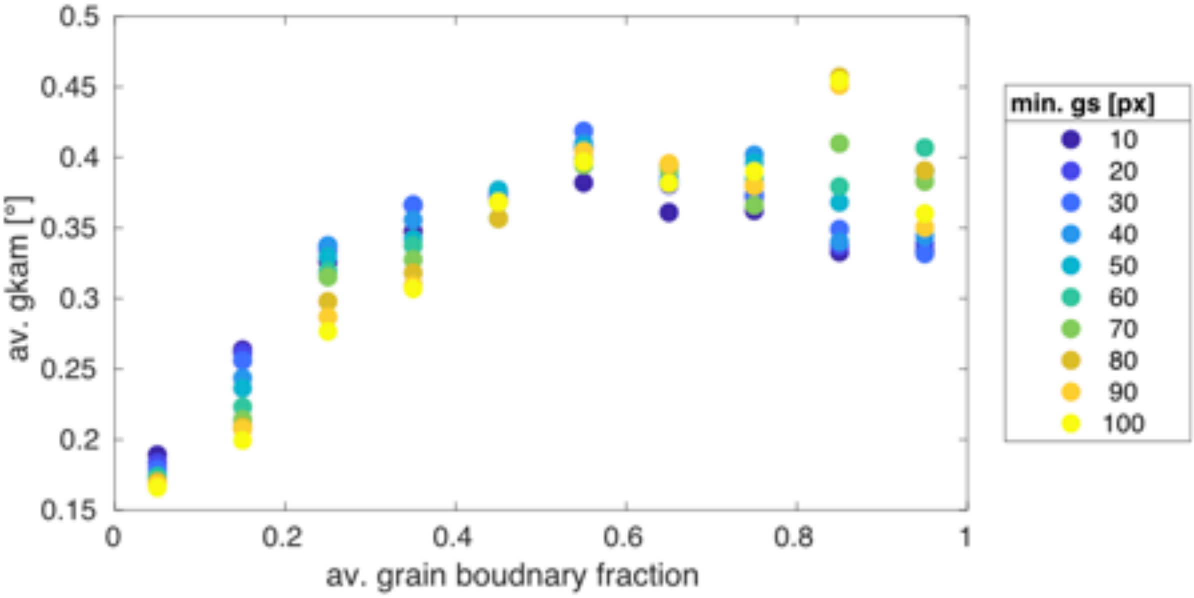
Texture strength and CPO as a function of gKAM



increasing gKAM

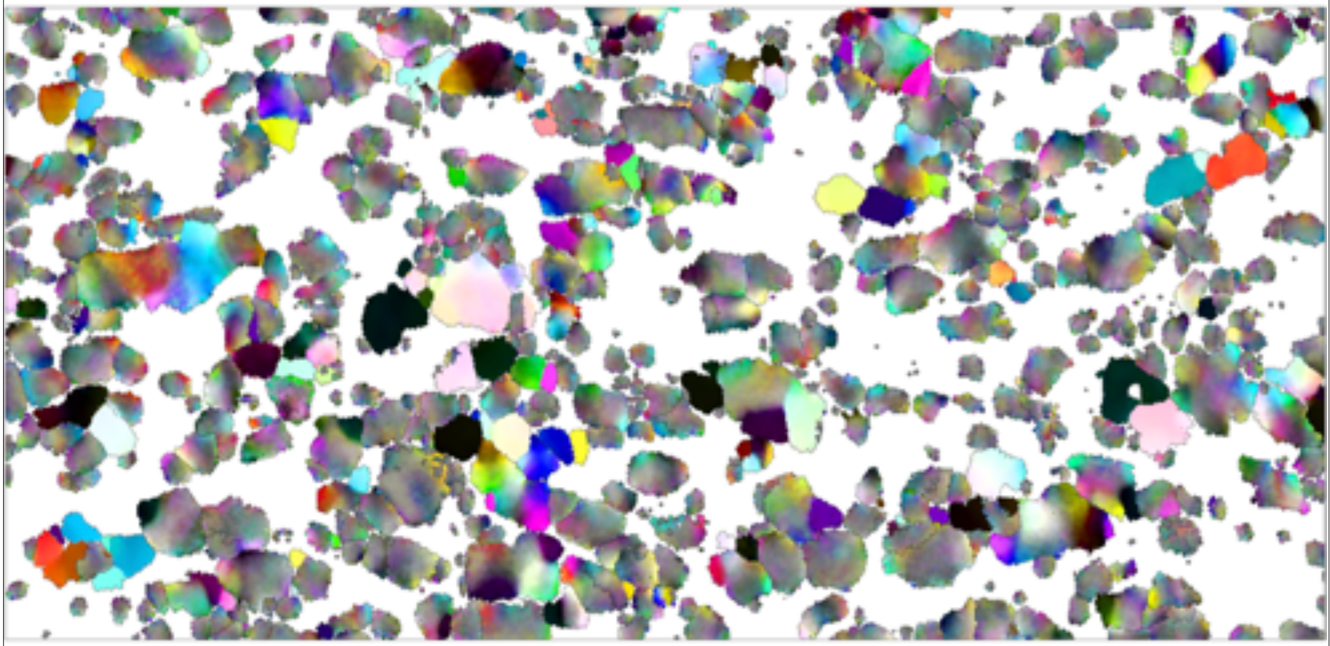
* times multiplicity of [c] = 2, {r} = 6

gkam and grain boundary fraction

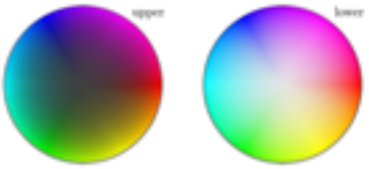


higher grain boundary fraction might allow for more dislocation creep

intragranular orientation deviations

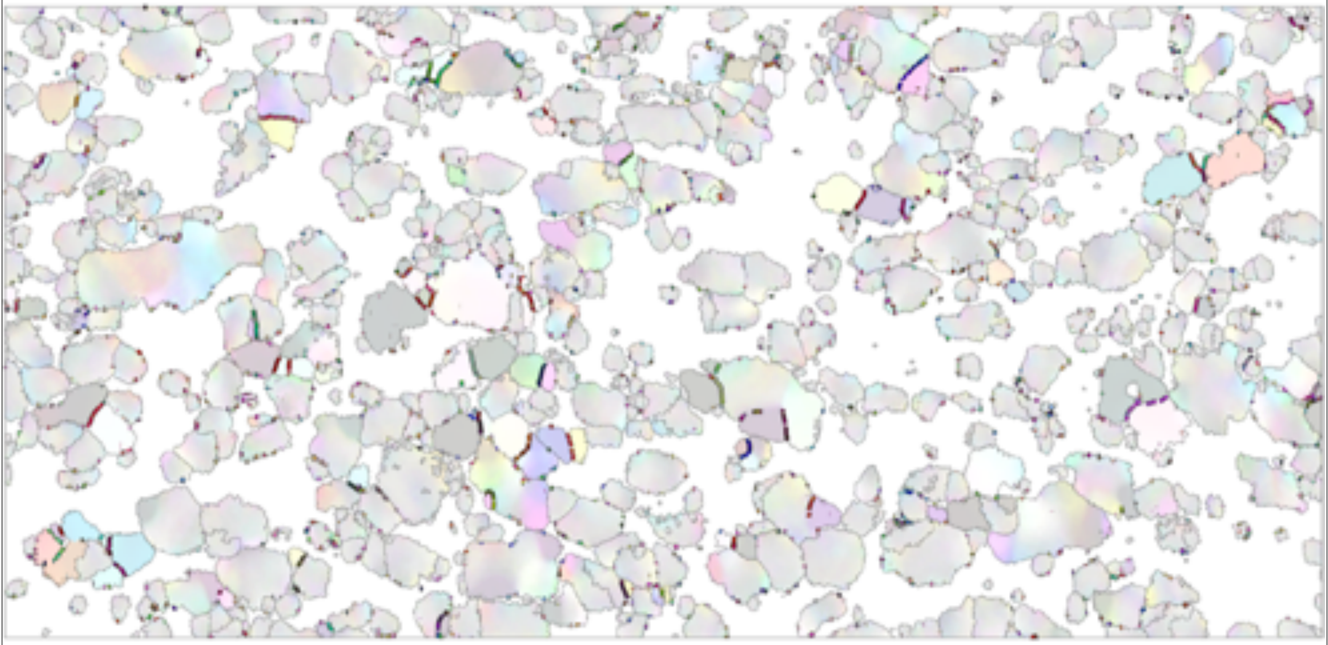


intragranular orientation deviation form areas
~size of smallest grains
-> subgrains, dynamic recrystallization ?



colorcoding:-> misorientation axis / angle wrt to grain mean orientation in specimen coordinates
(Thomsen et al.: Quaternion-based disorientation coloring of orientation maps, 2017)

intragranular orientation deviations

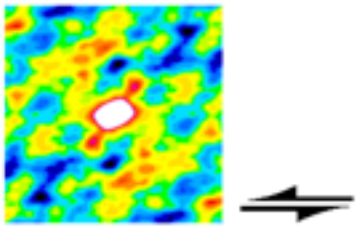


intragranular orientation deviation, some areas separated by discrete LAB
-> subgrains, dynamic recrystallization ?

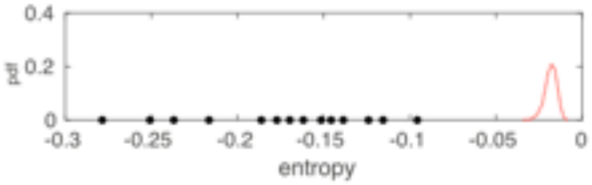
colorcoding for misorientation axes of LAB

Summary

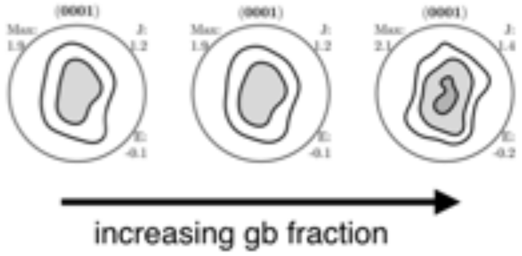
- Quartz grains in HT ultramylonite form columnar aggregates inclined against the sense of shear



- Texture is weak but distinct from random

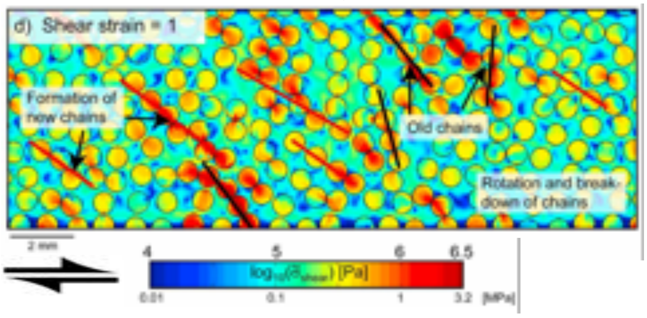


- Texture is supported by large grains with a high grain boundary fraction and a high gKam (those from within the columnar structures)

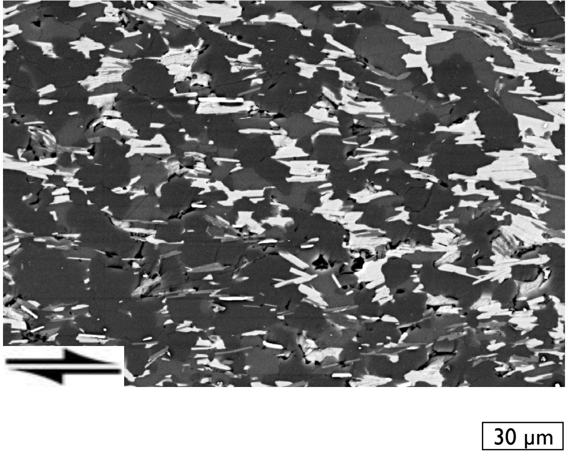


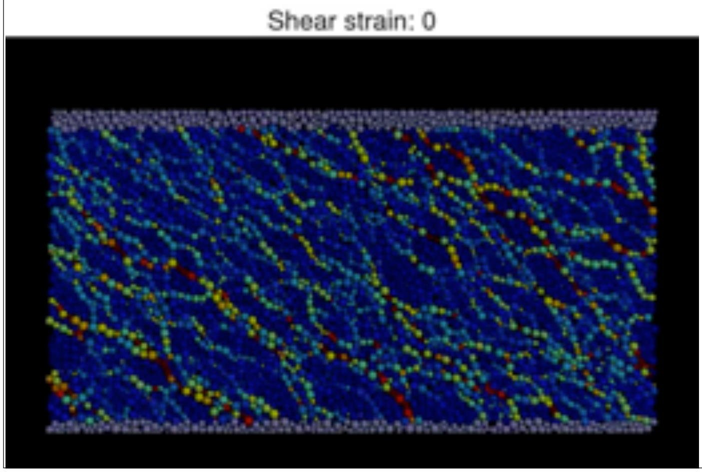
Columnar aggregates = jammed particles?

Deubelbeiss et al., 2011



this study

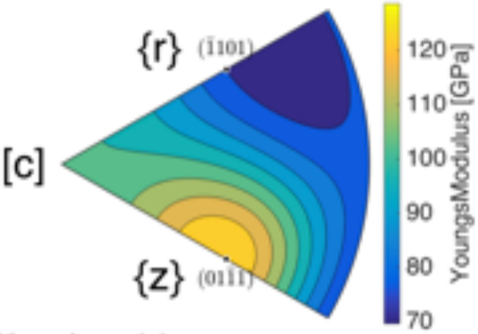




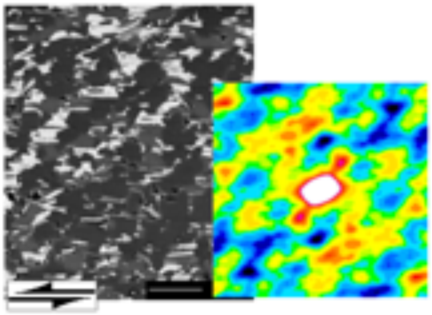
$\sum\sigma_{neff}$ in numerical simulation of frictional-viscous granular flow
Damsgaard et al. (2013)

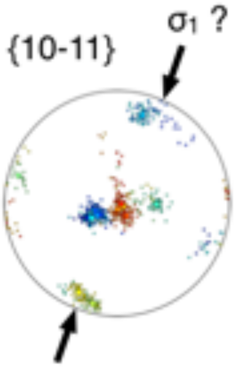
Interpretation of {10-11}-maxima

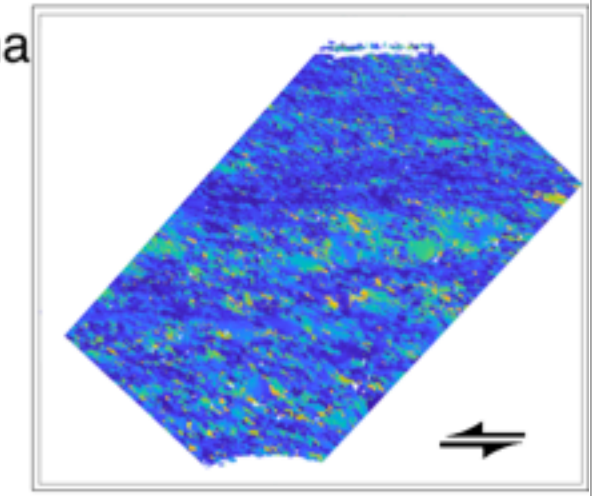
-> minimising elastic energy by Dauphiné twinning (60° around [c])



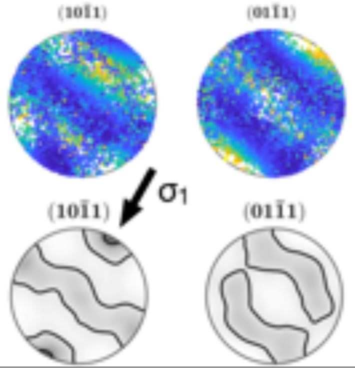
$E_{ij} = \sigma_{ij}/\varepsilon_{ij}$ Young's modulus
$U_e(\varepsilon)=\frac{1}{2}E\varepsilon^2$ ~elastic energy

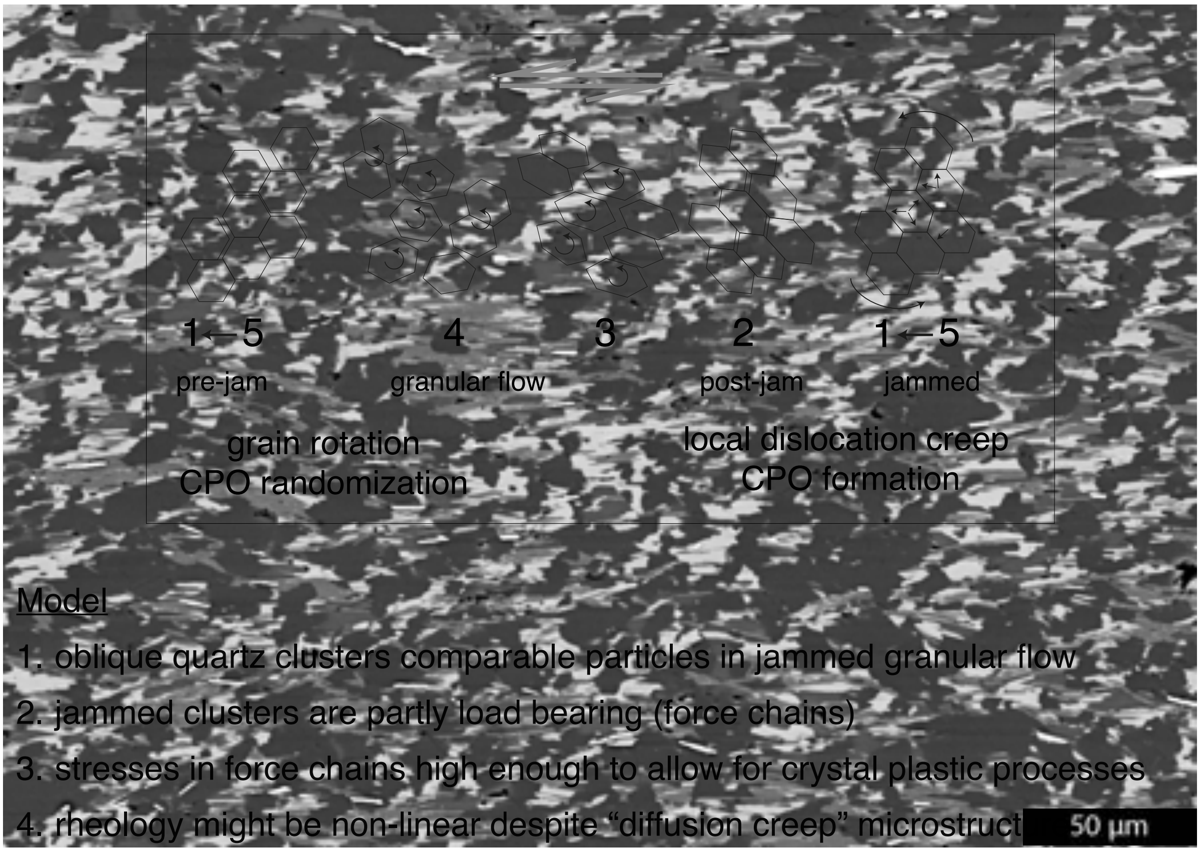






Young's modulus map of experimentally sheared quartzite
(see Kilian & Heilbronner, 2017)





<u>Model</u>

1. oblique quartz clusters comparable particles in jammed granular flow
2. jammed clusters are partly load bearing (force chains)
3. stresses in force chains high enough to allow for crystal plastic processes
4. rheology might be non-linear despite “diffusion creep” microstruct