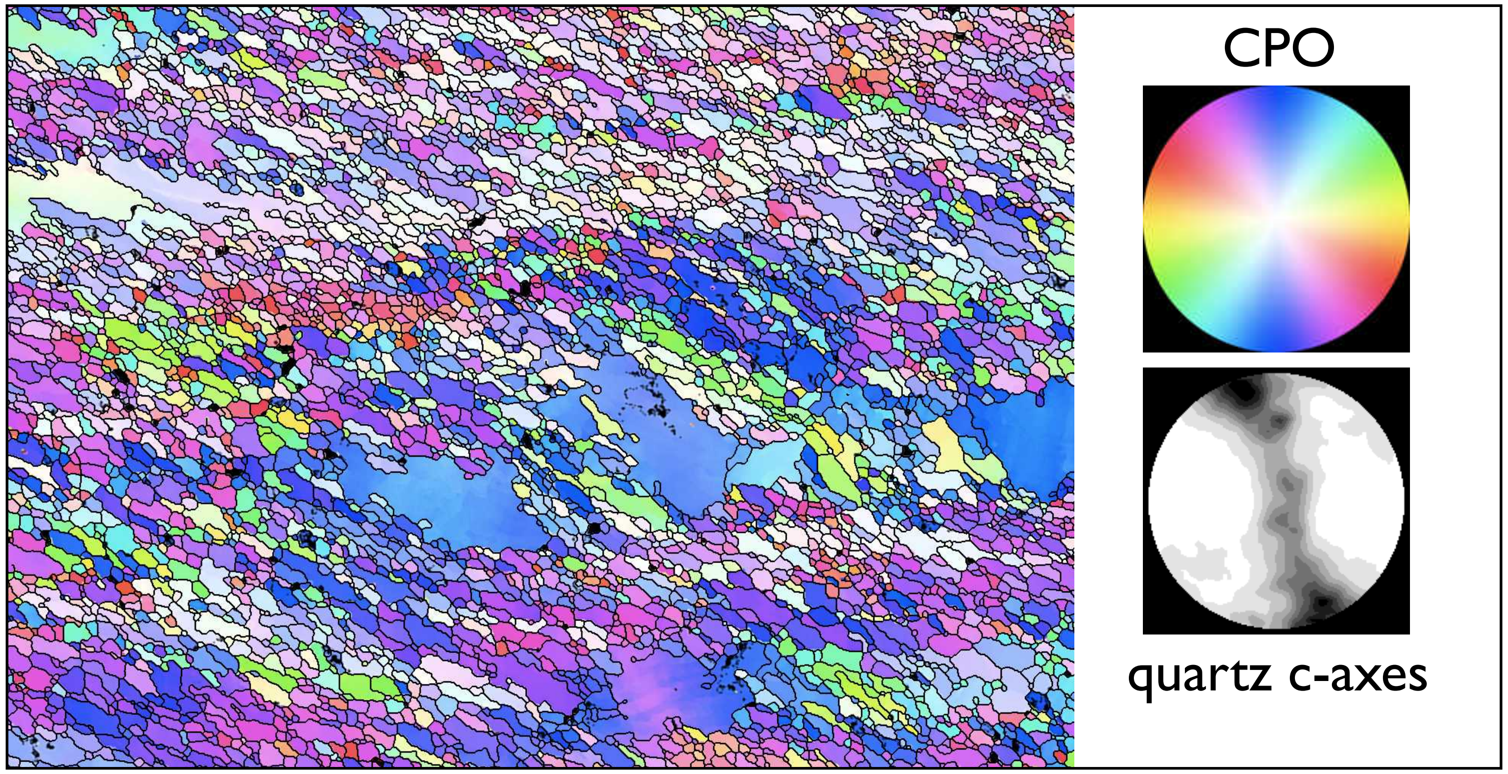
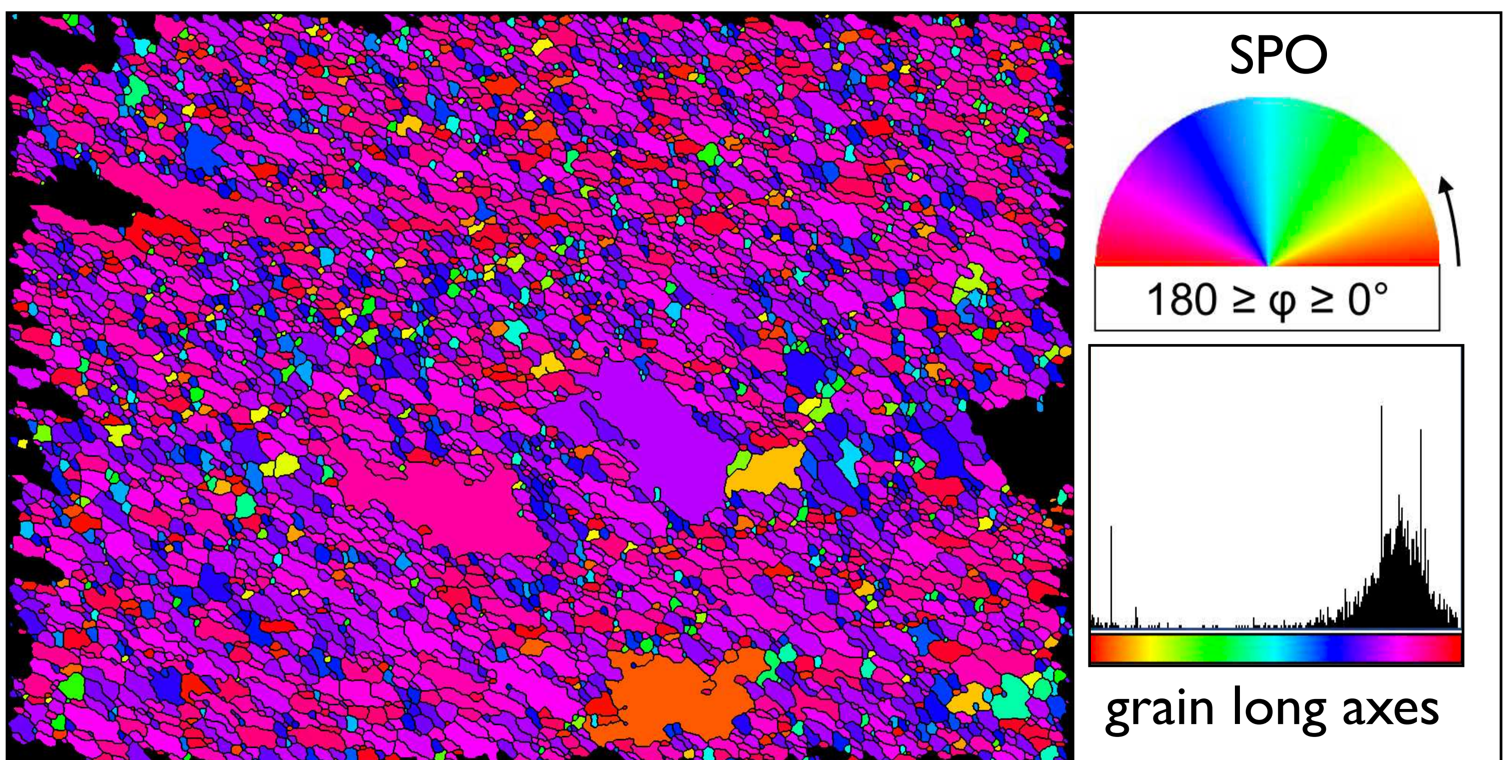
Three decades of Orientation Imaging in Structural Geology - Visualization and Analysis of Rock Properties

renee.heilbronner@unibas.ch

Abstract



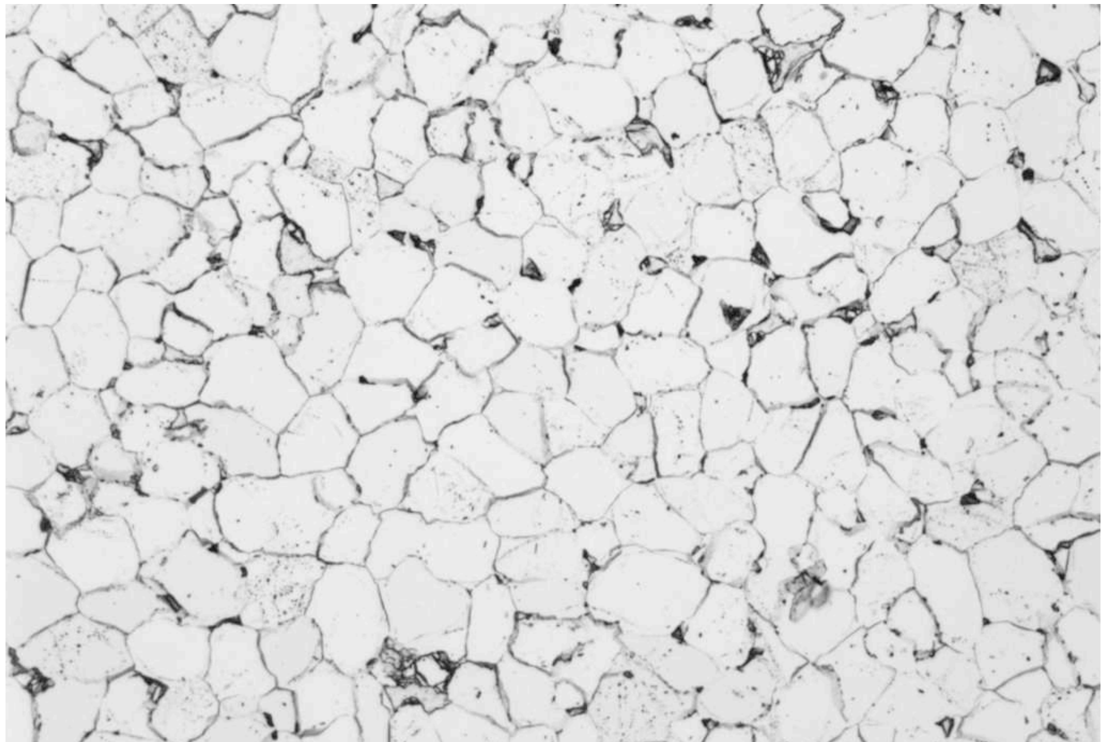


Three decades of Orientation Imaging in Structural Geology – Visualization and Analysis of Rock Properties...

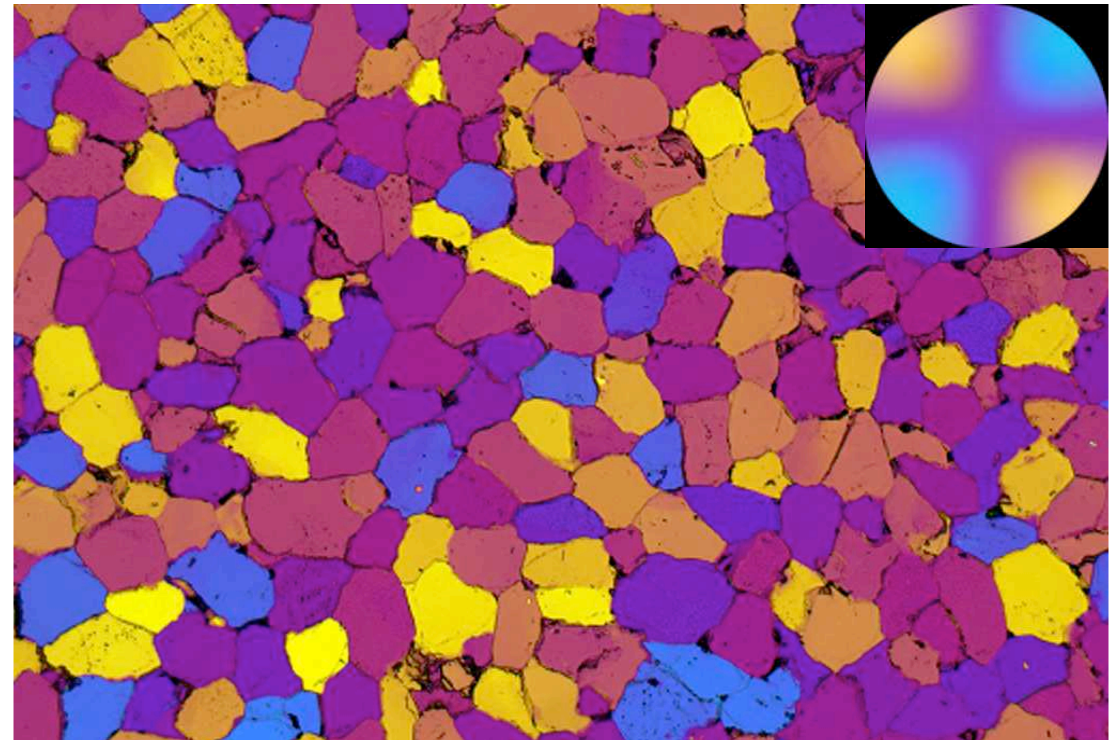
... and the problem of extrapolating from 2D to 3D

what is behind this talk ?

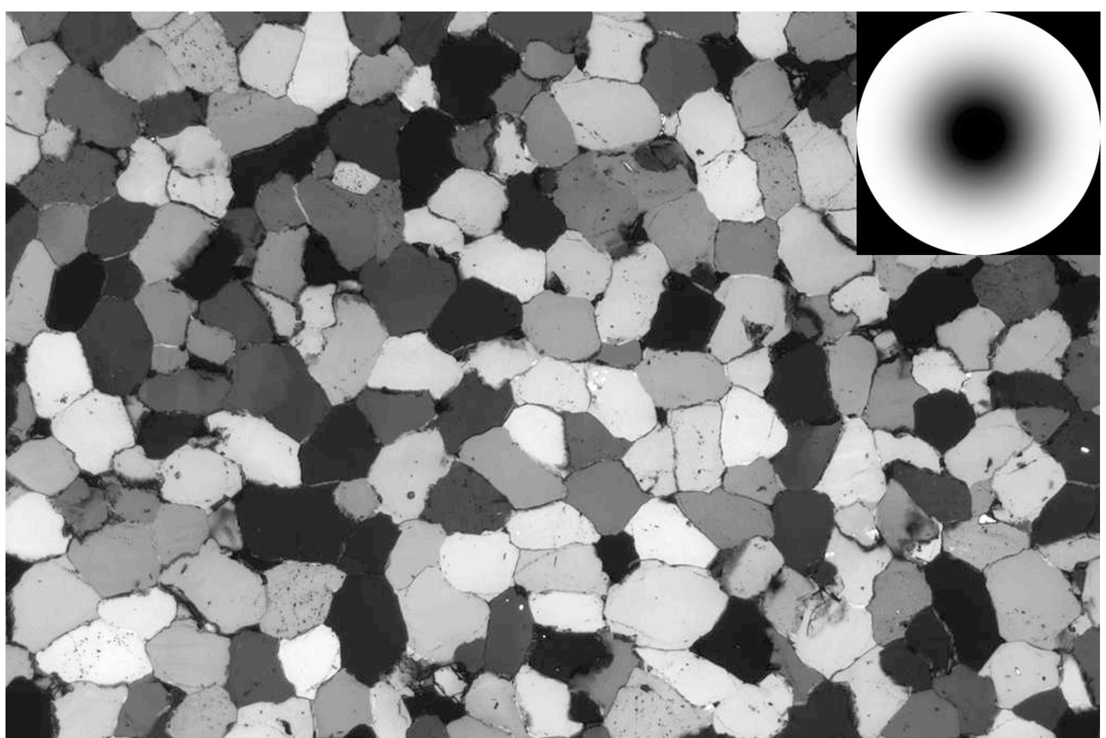
CIP – c-axis orientation imaging



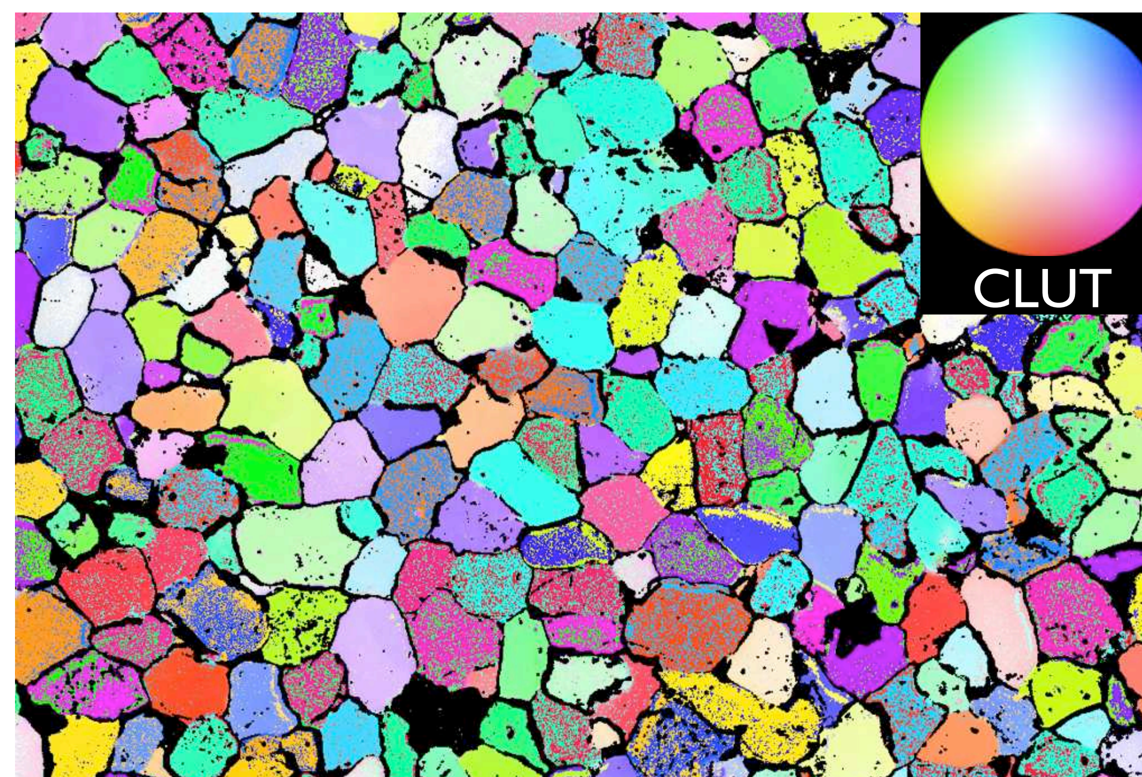
nopol ≠ Orientation Image



+PolLambda = Orientation Image

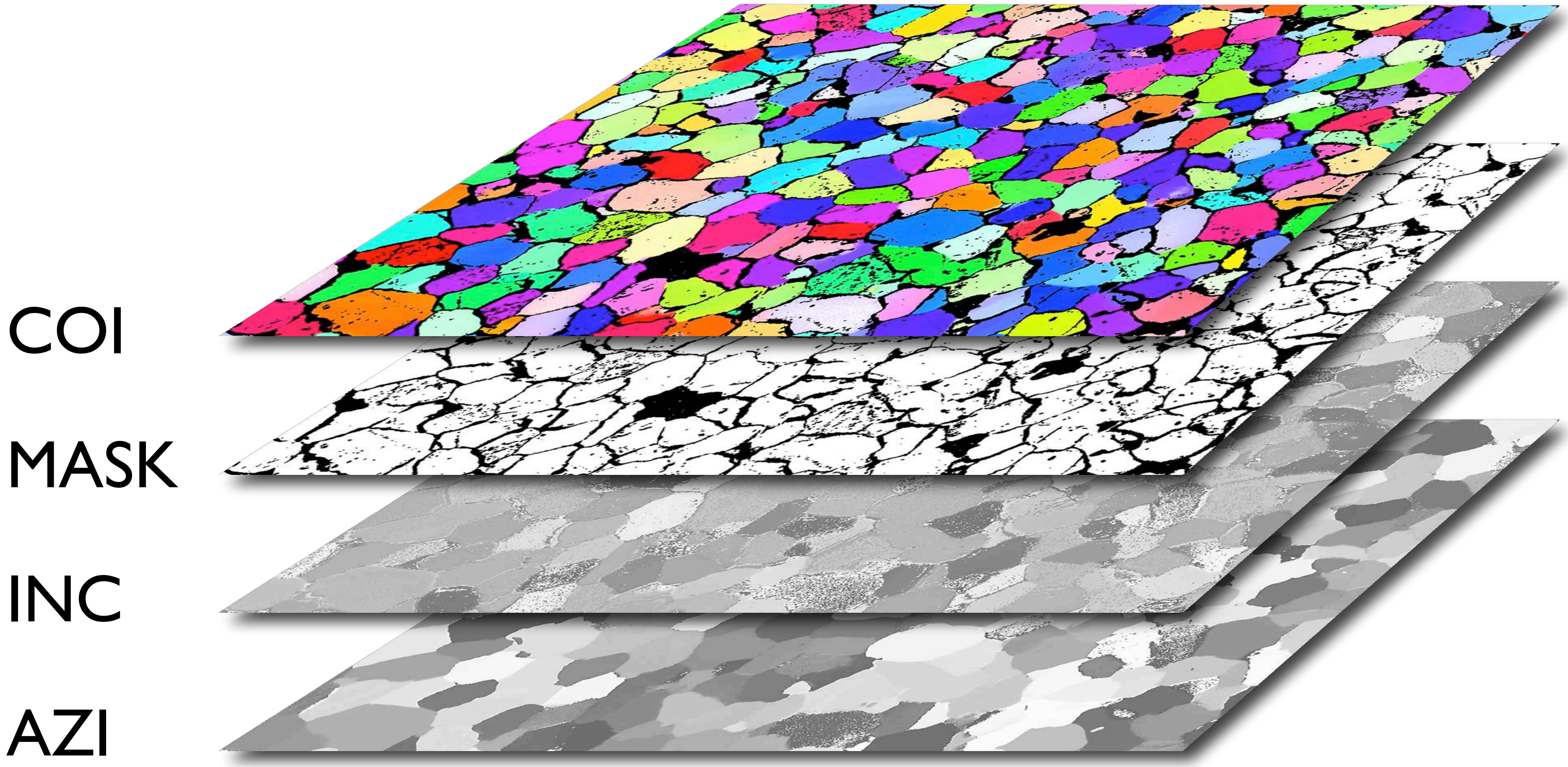


cirpol = Orientation Image

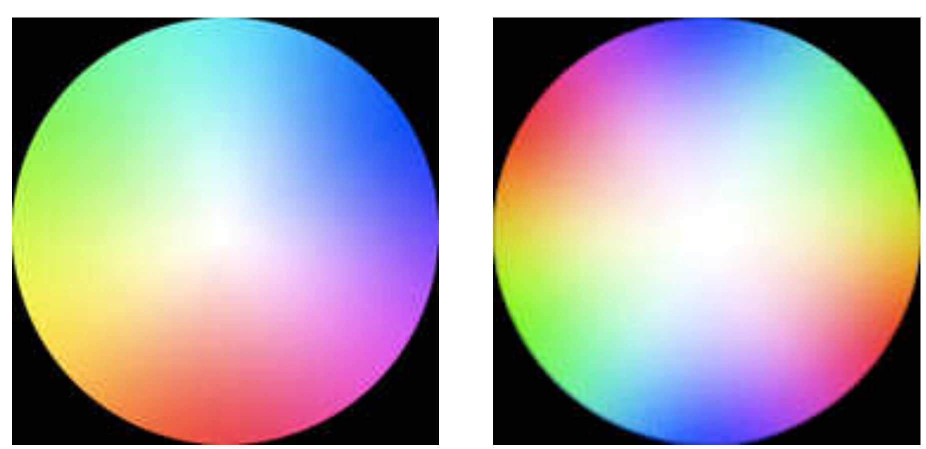


COI = Orientation Image

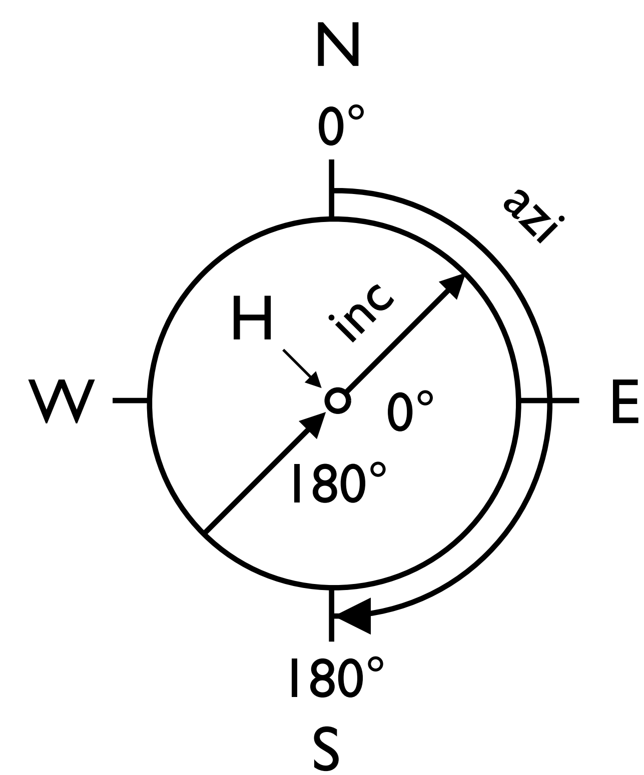
COI – c-axis orientation image



CLUT

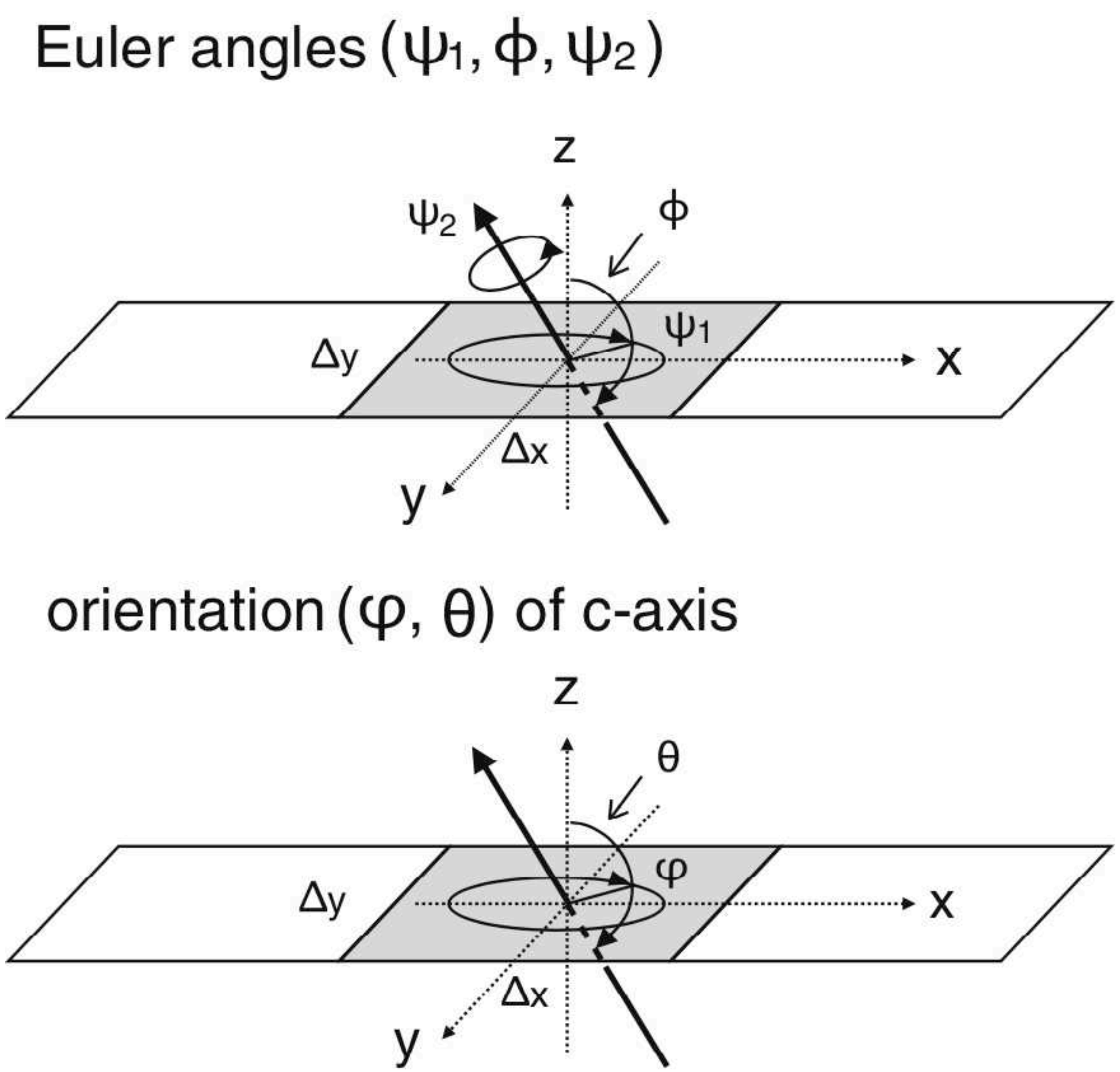


CIP-Standard CIP-Spectrum

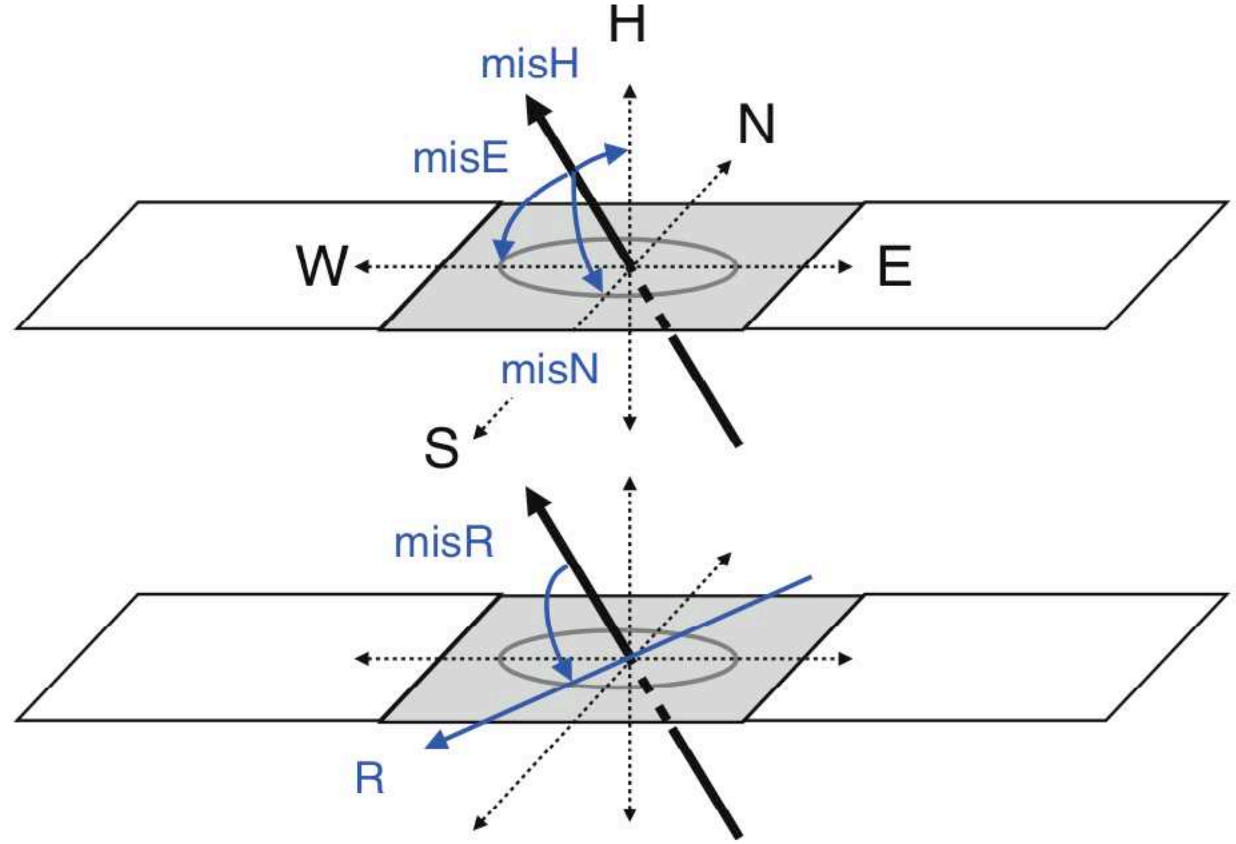


all kinds of orientations

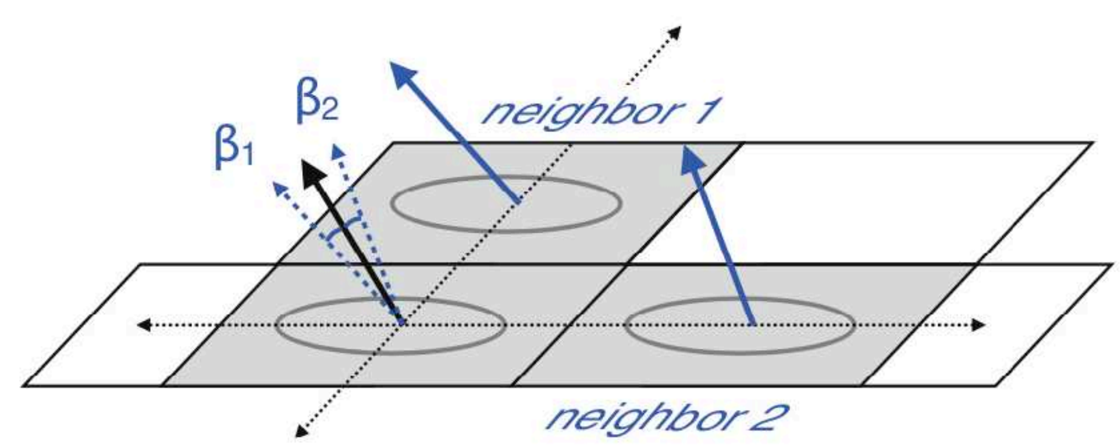
EBSD vs. CIP



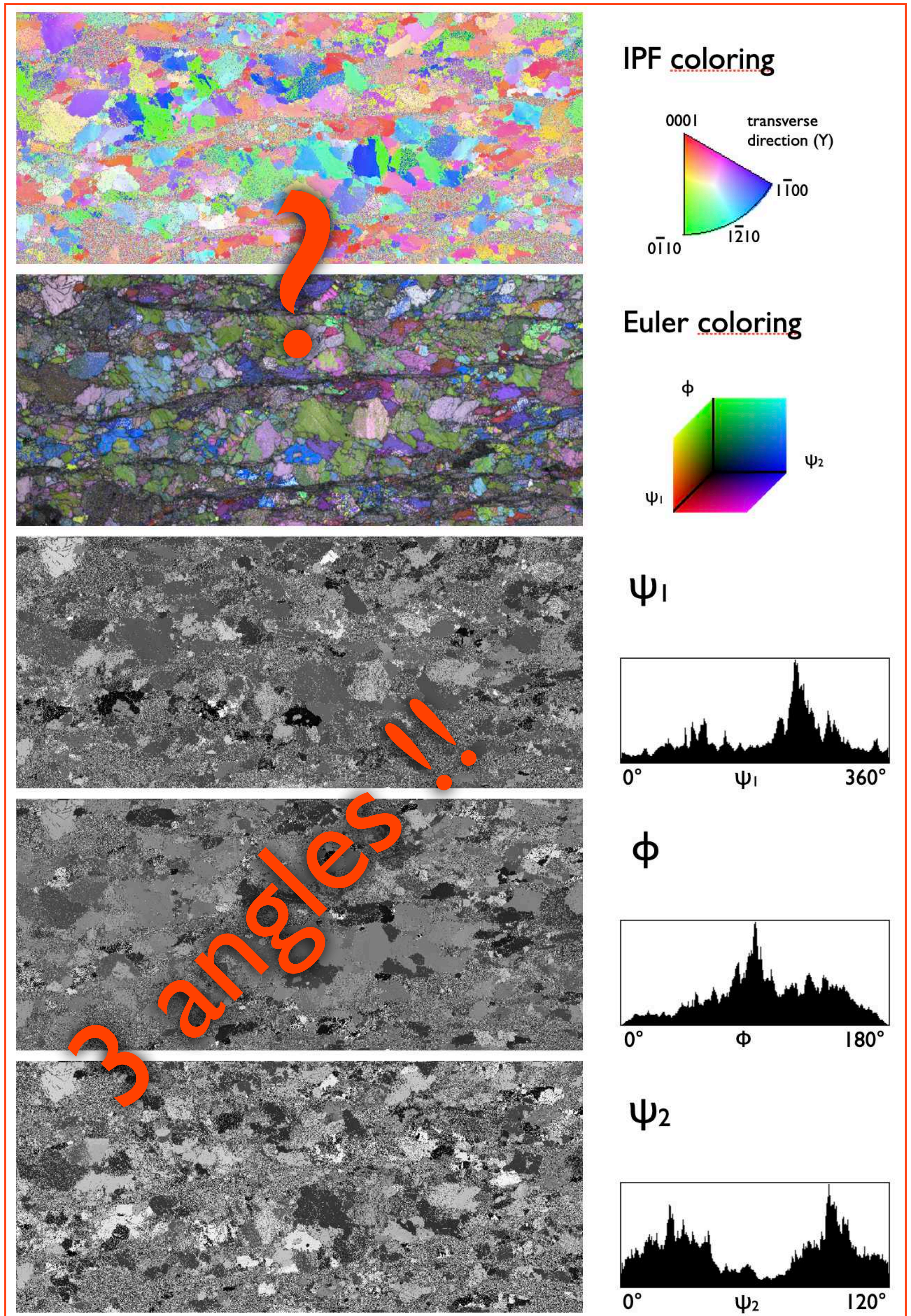
CIP misorientation

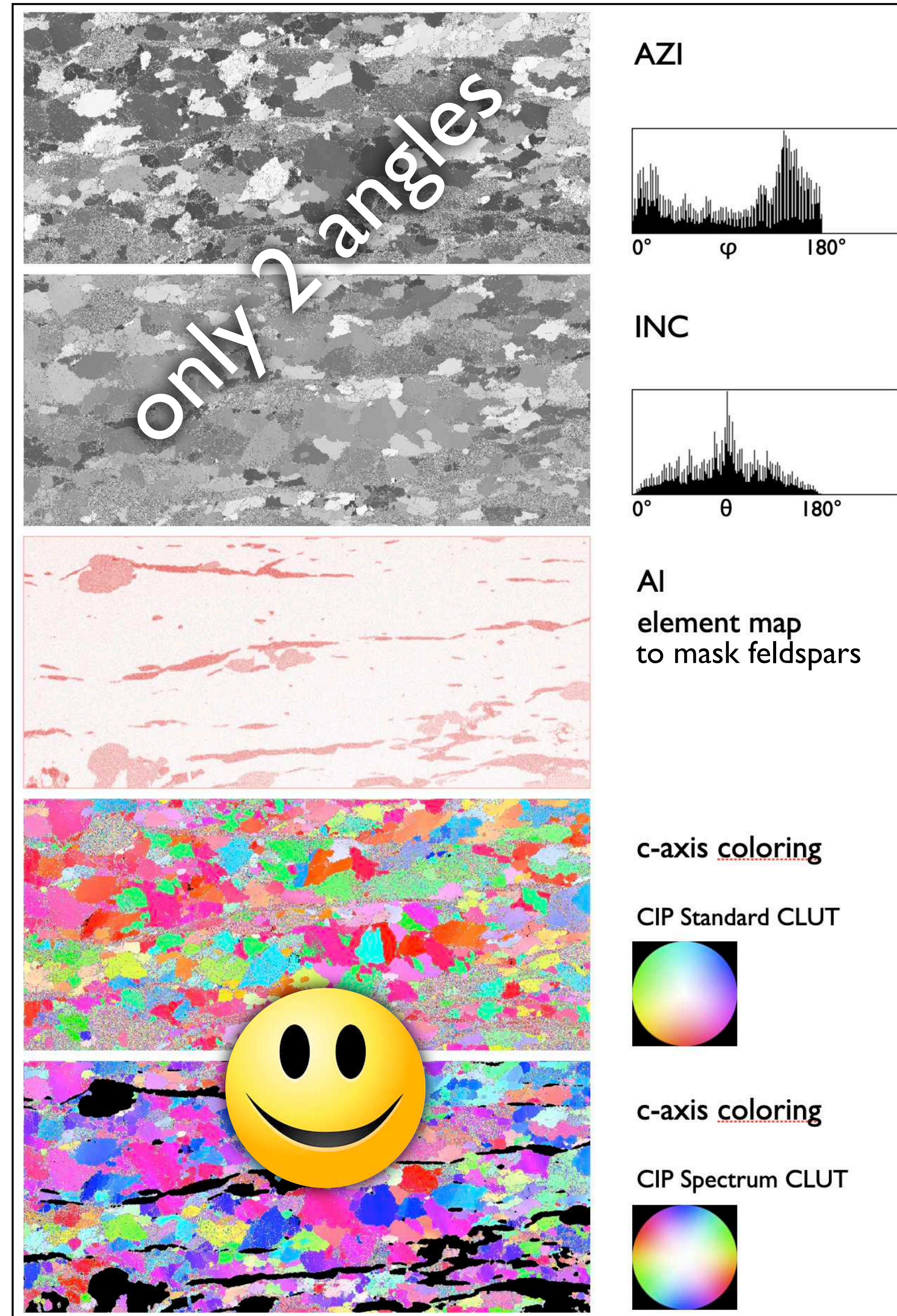


CIP orientation gradient



EBSD – full orientation imaging





history of orientation imaging ...
... as by the CIP method

1950 – Bruno Sander

Achsenverteilungsanalyse (AVA)

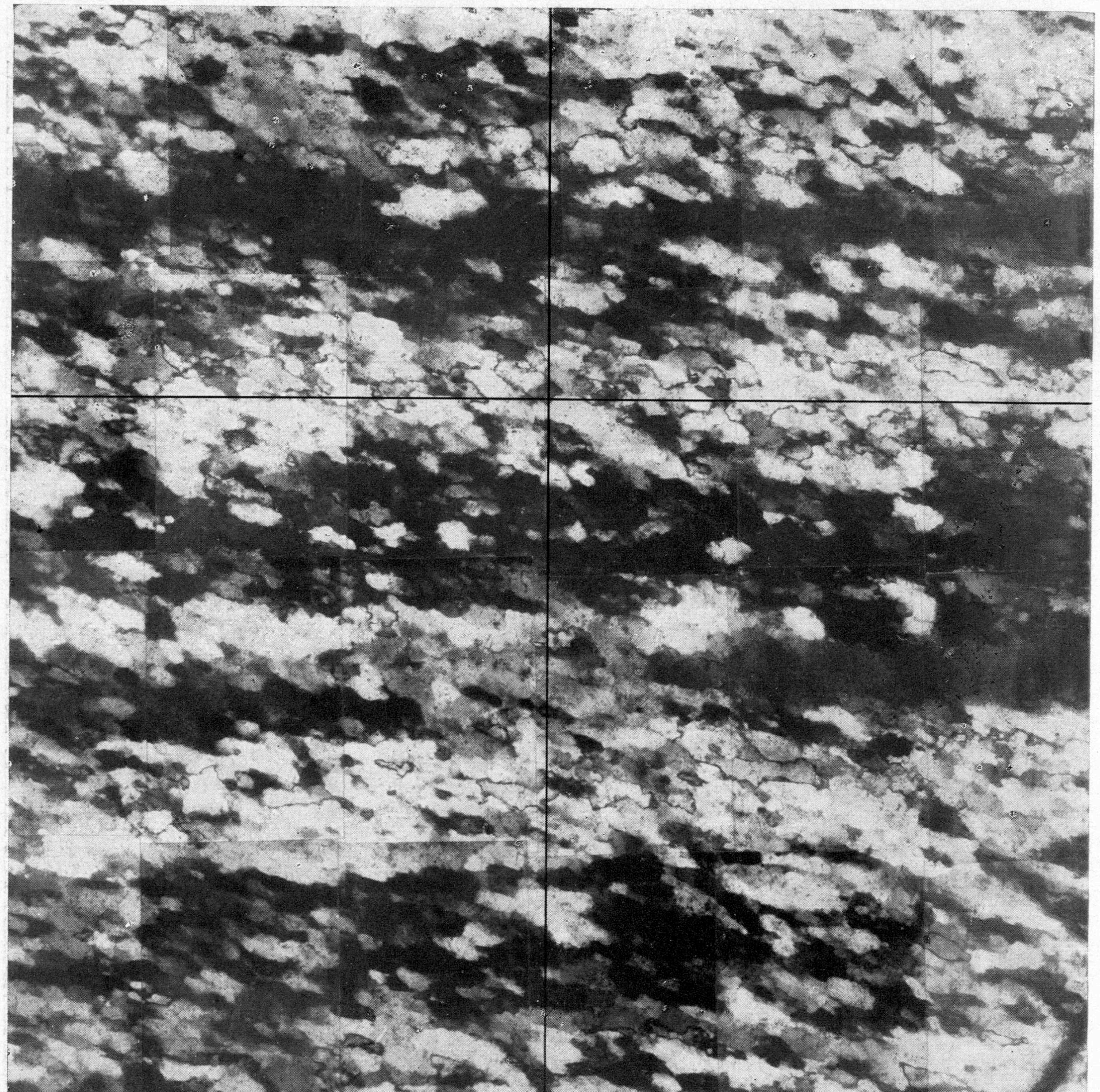
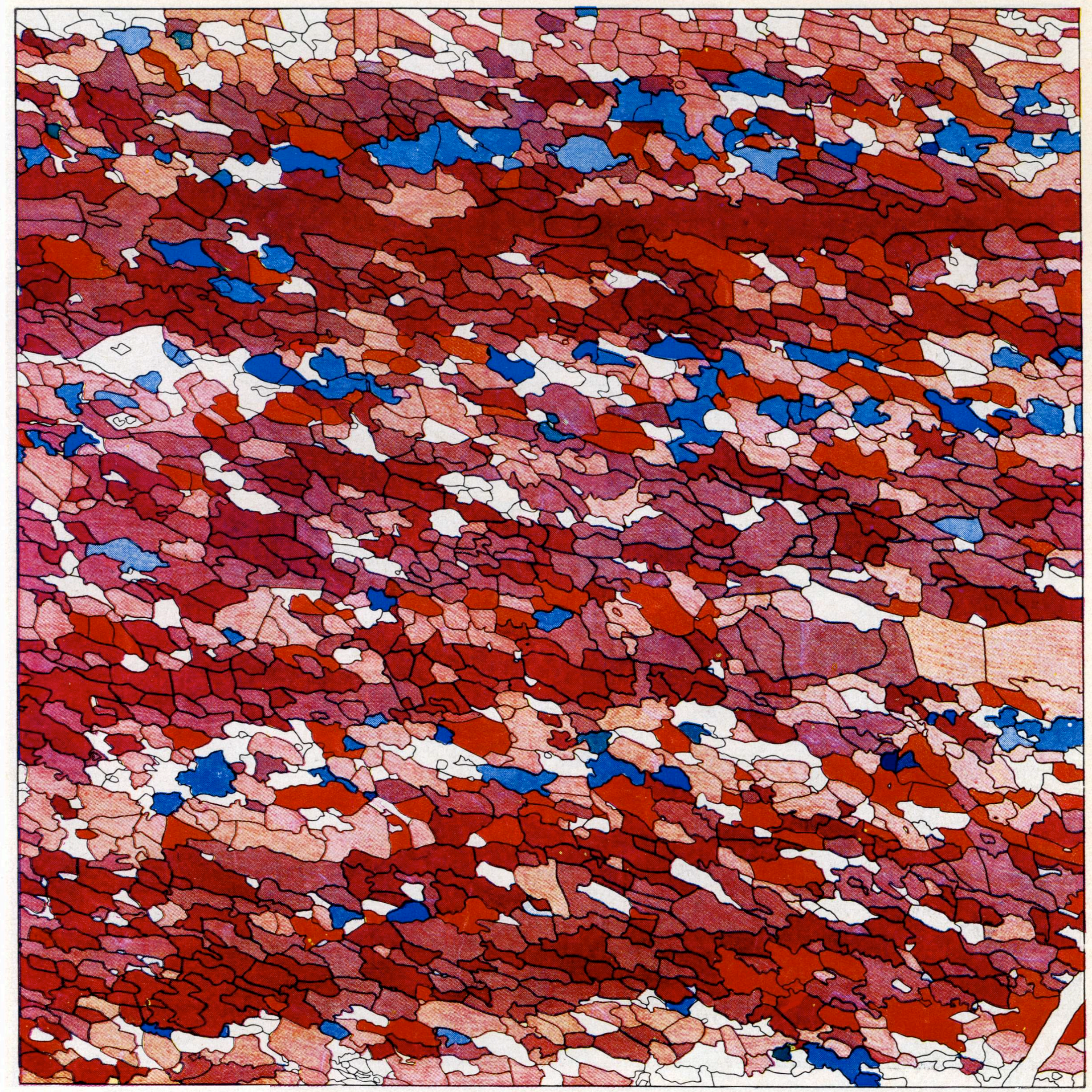


PLATE II.a. Quartzite, Rensenspitze, Bozen; section ⊥ a; crossed Nicols; ×90



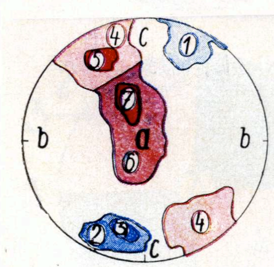


PLATE II.b. Quartzite, Rensenspitze, Bozen; section ⊥ r a; 1629 quartz-axes; ×90; A.V.A. (Ramsauer)

Sander, B. 1950. Einführung in die Gefügekunde der geologischen Körper, zweiter Teil: Die Korngefüge. Springer, Wien.

1991 – EUG VI, Strasbourg

QUARTZ C.P.O.

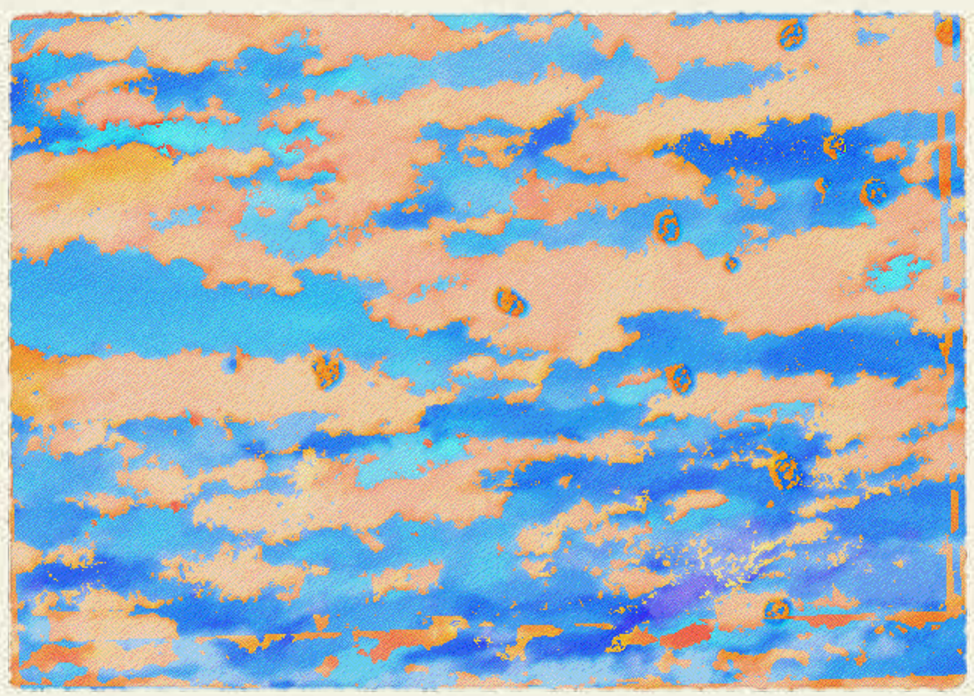
DERIVATION OF QUARTZ C.P.O. BY MEANS OF DIGITAL IMAGE ANALYSIS

C. PAULI, R. PANOZZO HEILBRONNER, and R. GSCHWIND

(Geol.-Paleontol. Institute & Dept. Scientific Photography, Basle University, Basle, Switzerland)

In cases where X-ray goniometry is inapplicable, quartz c-axis orientations are ususally determined by U-stage or photometric measurements. The latter method (Price, Am. J. Sci., 273, p.523-537, 1973) is based on light intensity variations that result from the rotation
polarizers. The proposed new method
significant ways: (a) the light intensity
digitized image matrices, and (b) the t
polarizers are rotated. In this manner,
is created, each image plane correspo
direction.
The white light intensity curve, I(α), c
values of a few selected quartz grains
of the form: A·sin2(2·α−2·B)+C, azim
grain can be derived. At low inclinatic
measurements is perfect, at higher inc
periodicity
order to rem
ence filters a

Christian Pauli



FIRST EVER CIP IMAGE

SEGMENTATION

QUARTZ C-AXIS ORIENTATION AS BASIS FOR IMAGE SEGMENTATION

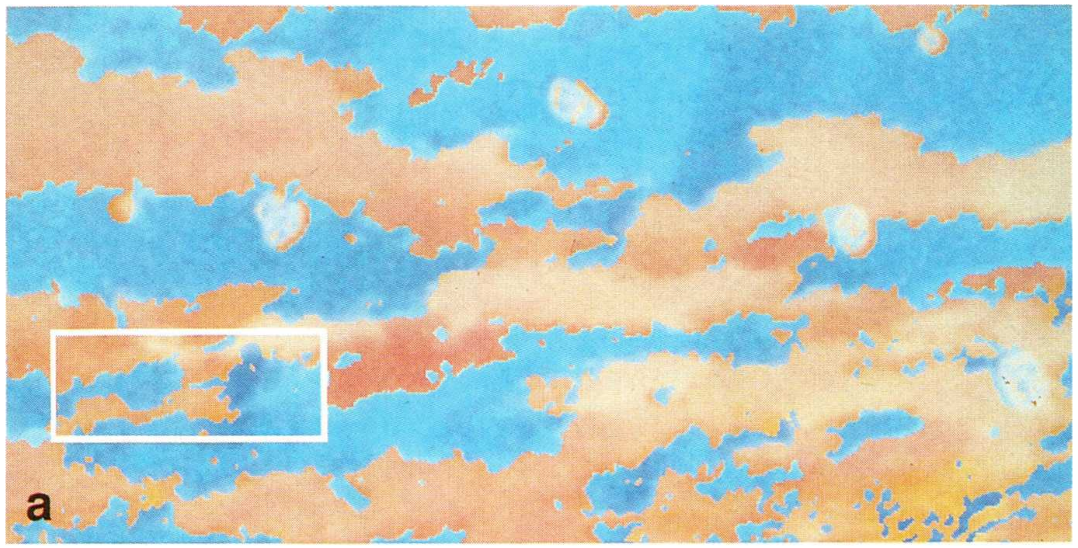
R. PANOZZO HEILBRONNER, R. GSCHWIND, and C. PAULI

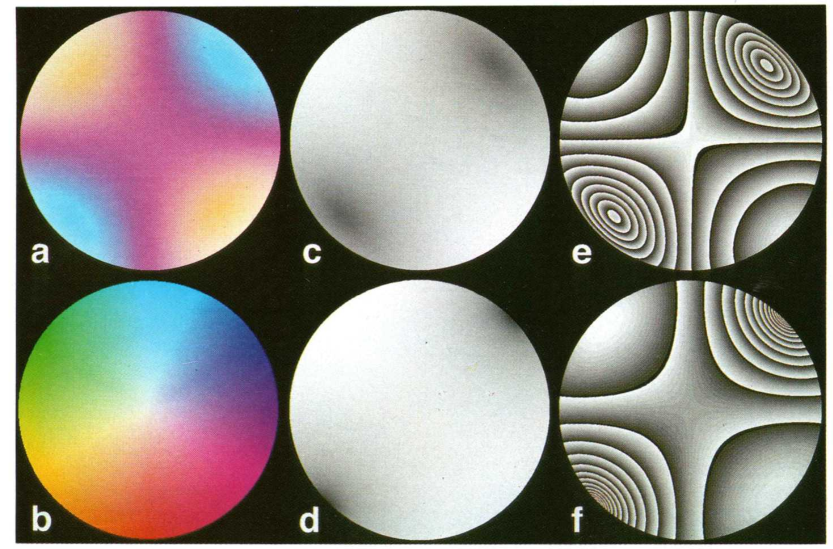
(Dept. Scientific Photography & Geol.-Paleontol.Institute, Basle University, Basle, Switzerland)

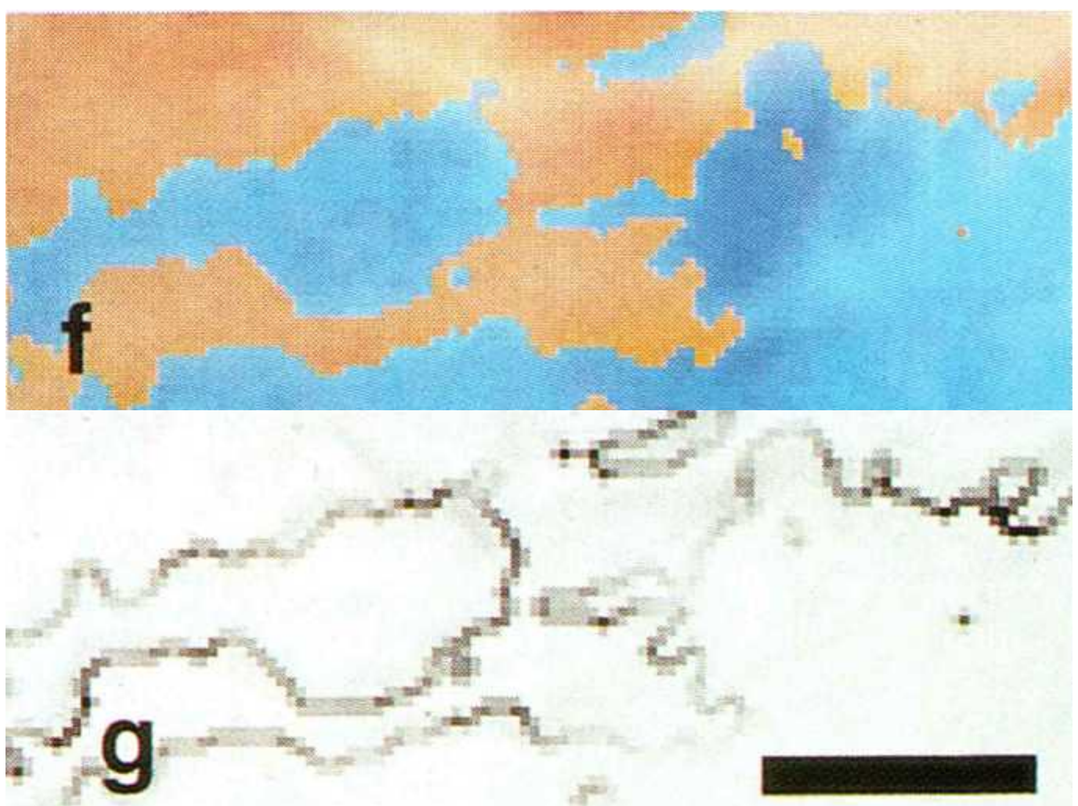
Conventional segmentation techniques are based on recognition of patterns or grey level differences that occur within an image. Constant grey level within a grain or sharp grey level differences at grain boundaries are the underlying
most successful segmentation algorithms.
the grey level that may be recorded for a given grain
ientation with respect to the crossed polarizers. Using
(i.e., digitization of a stationary image at incremental
is information is here proposed as basis for
nstead of first segmenting an image and then assigning
h segmented grain, first the orientation of each pixel is
nentation is based on orientation differences.
ecessary:
ionary thin section at various rotation angles, α, of
α of 20°, nine image planes are necessary).
) curve (see Pauli et al, this volume).
h and inclination from I(α) curve. This derivation
els exhibiting low correlation coefficients are rejected.
gion filtering: pixel areas with identical absolute
leviation) are interpreted as connected.
ge detection: sharp changes in absolute orientation are
daries. (Possibility of differentiating subgrain and grain
ing of azimuth, θ, and inclination, φ, such that close spatial orientation is expressed by close similarity of colour (high resolution A.V.A.).

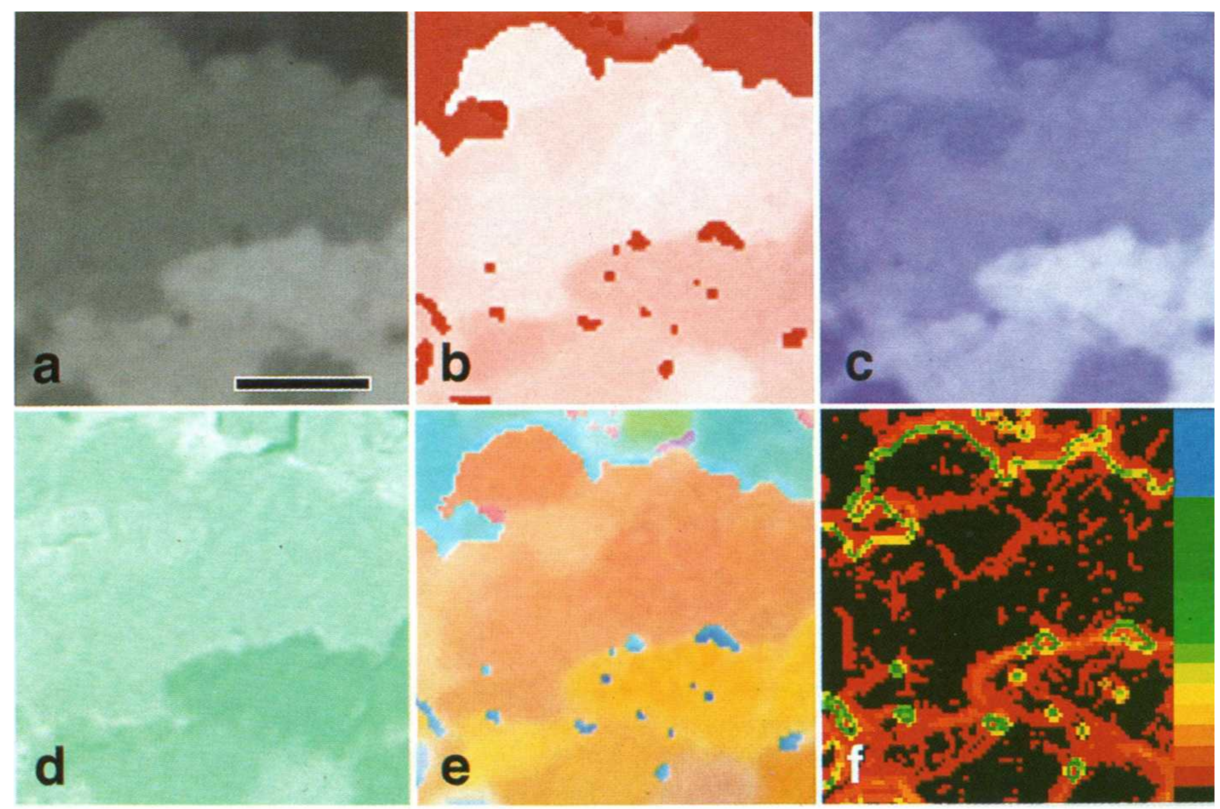
1993 – publication, JSG

(computer-integrated polarisation microscopy)



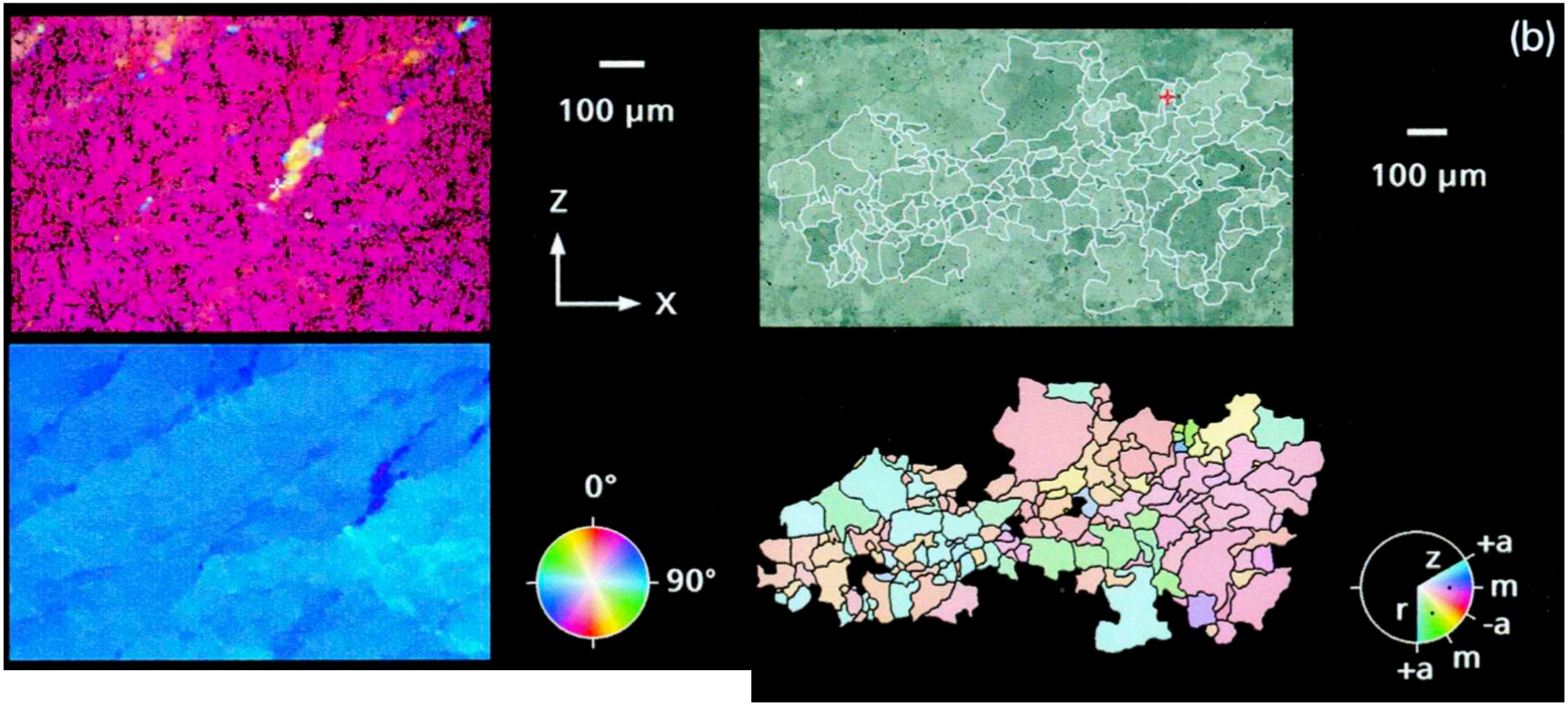






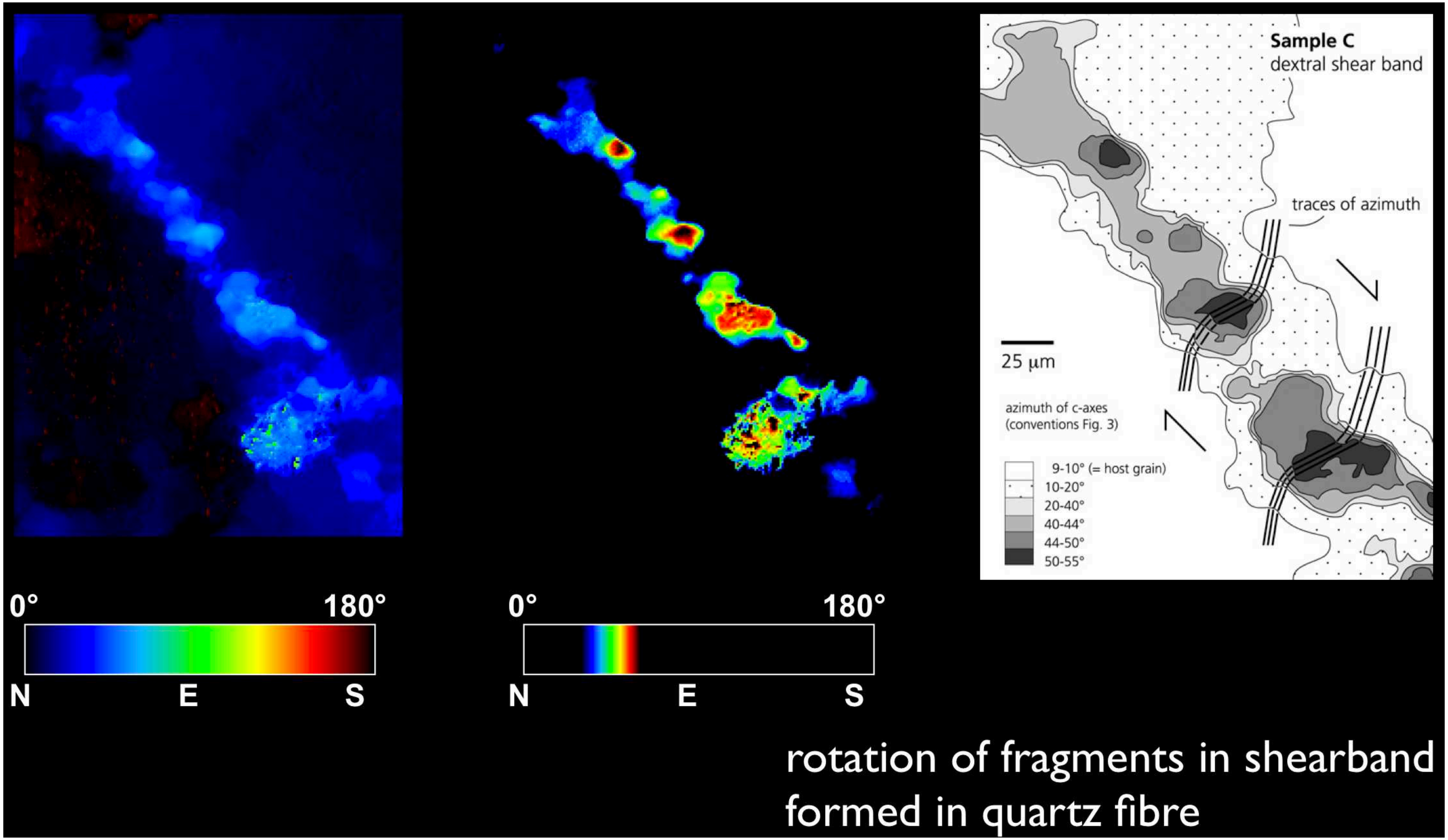
Heilbronner, R.P. & Pauli, C. (1993) Integrated spatial and orientation analysis of quartz c-axes by computer- aided microscopy, JSG, 15, p.369

1999 – publication Tectonophysics



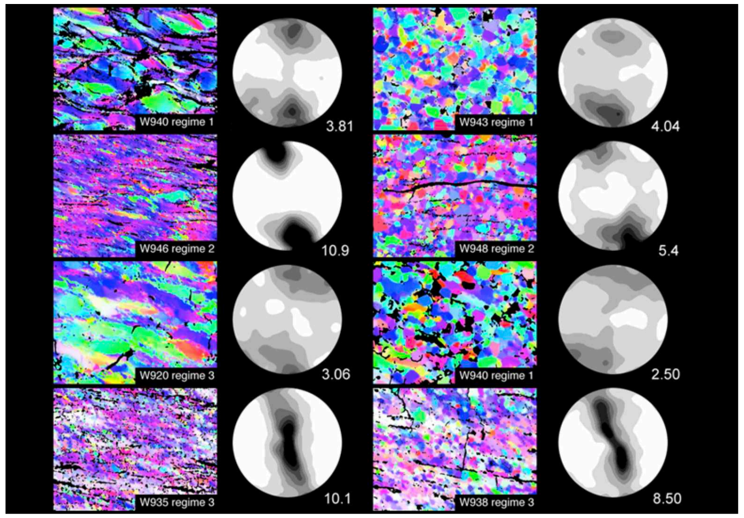
Mirjam van Daalen, Renée Heilbronner, Karsten Kunze (1999) Orientation analysis of localized shear deformation in quartz fibres at the brittle–ductile transition, Tectonophysics, 303, 83.

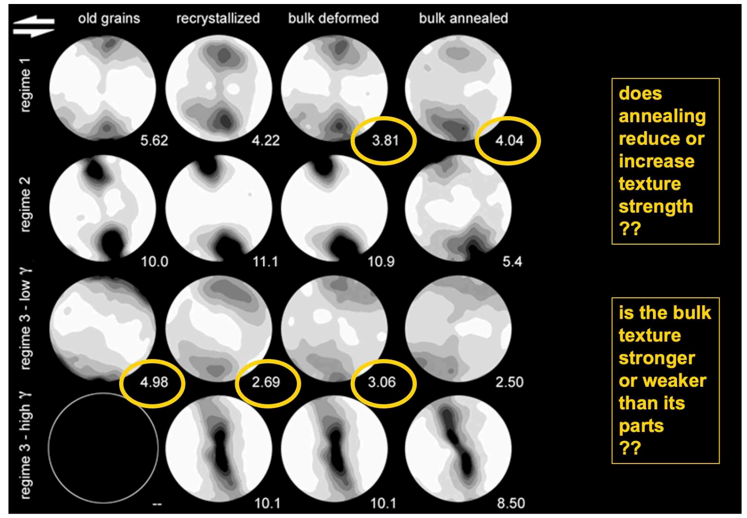
1999 – publication Tectonophysics

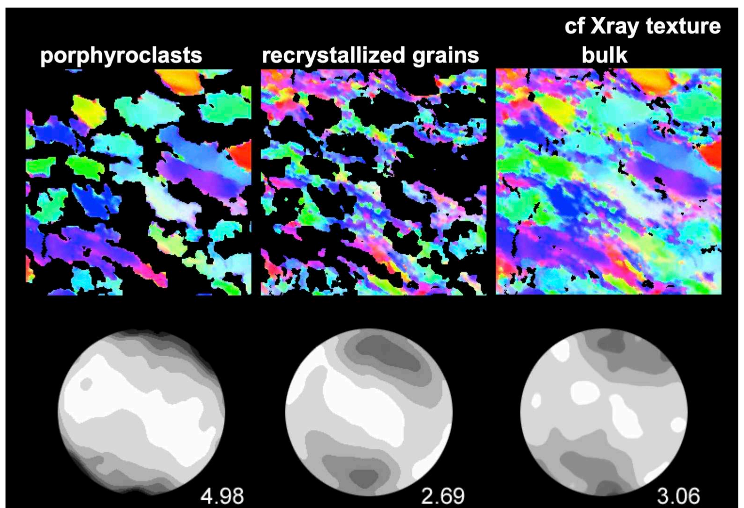


Mirjam van Daalen, Renée Heilbronner, Karsten Kunze (1999) Orientation analysis of localized shear deformation in quartz fibres at the brittle–ductile transition, Tectonophysics, 303, 83.

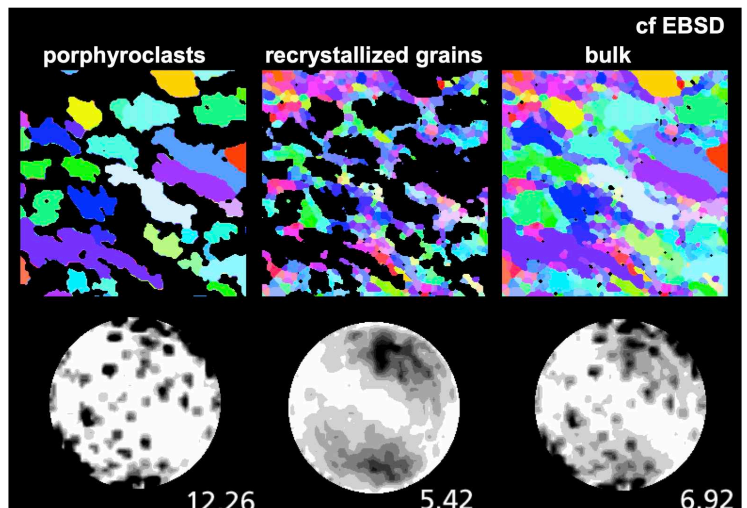
2002 – IAMG, Berlin







porphs - rexl - bulk



flat grains

mathematical definition of PDI

pole density index (PDI)

$$I[\hat{P}_{\mathbf{c}}(\circ)] = \oint \hat{P}^2_{\mathbf{c}}(\mathbf{r})\mathrm{d}\mathbf{r} = \oint \left(\frac{1}{n}\sum_{i=1}^{n} k(\mathbf{r}'_i\mathbf{r})\right)^2 \mathrm{d}\mathbf{r} = \frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n} V_{\mathbf{k}}(\mathbf{r}'_i\mathbf{r}_j)$$

expected value of PDI

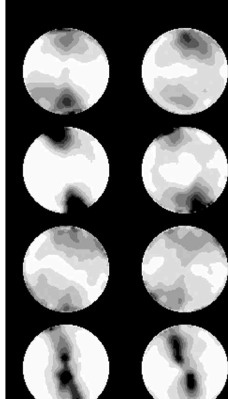
$$\mathrm{e}(I[\hat{P}_{\mathbf{c}}]) = \oint \mathrm{e}(\hat{P}_{\mathbf{c}}(\mathbf{r})^2)\mathrm{d}\mathbf{r} = \oint \mathrm{e}[\hat{P}_{\mathbf{c}}(\mathbf{r})]^2\mathrm{d}\mathbf{r} + \oint \mathrm{var}(\hat{P}_{\mathbf{c}}(\mathbf{r}))\mathrm{d}\mathbf{r}$$

second term depends on no. of c-axes and spatial dependencies

$$\mathrm{gvar}(\hat{P}_{\mathbf{c}}(\circ)) \underset{df}{=} \oint \mathrm{var}(\hat{P}_{\mathbf{c}}(\mathbf{r}))\mathrm{d}\mathbf{r} \propto n > 0$$

Unbiased estimator of I [P_c]

$$\hat{I}[P_{\mathbf{c}}] \quad = \quad I[\hat{P}_{\mathbf{c}}] - \hat{\mathrm{gvar}}(\hat{P}_{\mathbf{c}}(\circ))$$



max of CPO		pole density index (PDI)		different types of CPO
def.	ann.	def.	ann.	
3.86	3.84	5.042	3.771	•small circles
13.87	6.99	10.53	6.282	•single maximum
3.67	3.44	5.027	4.727	•small circles
6.77	5.74	2.290	2.400	•single girdle

COMPARISON OF COARSE- AND FINE-GRAINED QUARTZ TEXTURES USING THE POLE DENSITY INDEX (PDI)

Conclusions (of long abstract)

We therefore propose that new - grain s[...] independent - measures such as the P[...] introduced in this paper be adopte[...] quantification of the strengths [...] (and ultimately for texture).

With respect to assess[...] strength of c-axis pole figures be[...] annealing, for example, the PD[...]rforms the classical CPOmax mea[...]

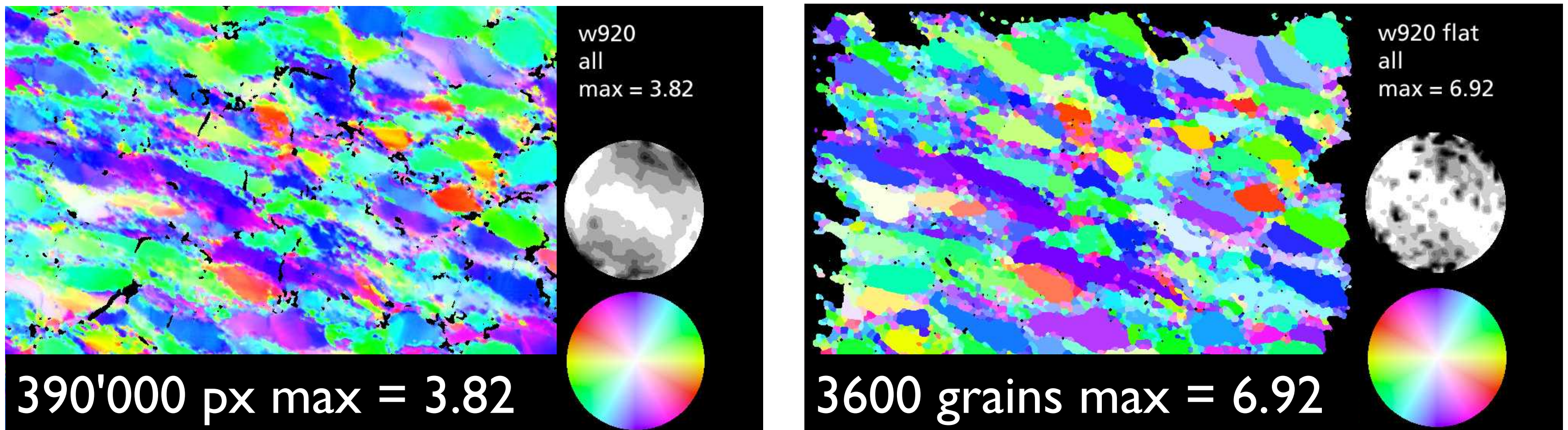
The the[...]n this paper is not restricted to CI[...]s (c-axis pole figures) but to all [...]hat are derived from any type of [...]aging. It also applies to incompletely [...]nage matrices. This is of particular [...]ce in the context of partial pole figures [...] are obtained by masking out certain parts of [...] orientation image.

strength of texture ?!

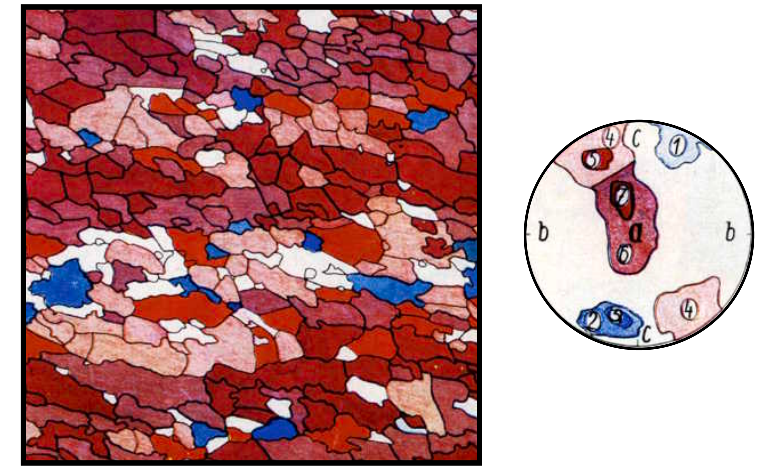
Renée Heilbronner, K. Gerald van den Boogaart, H. Schaeben: Comparison of coarse- and fine-grained quartz textures using the pole density index (PDI)

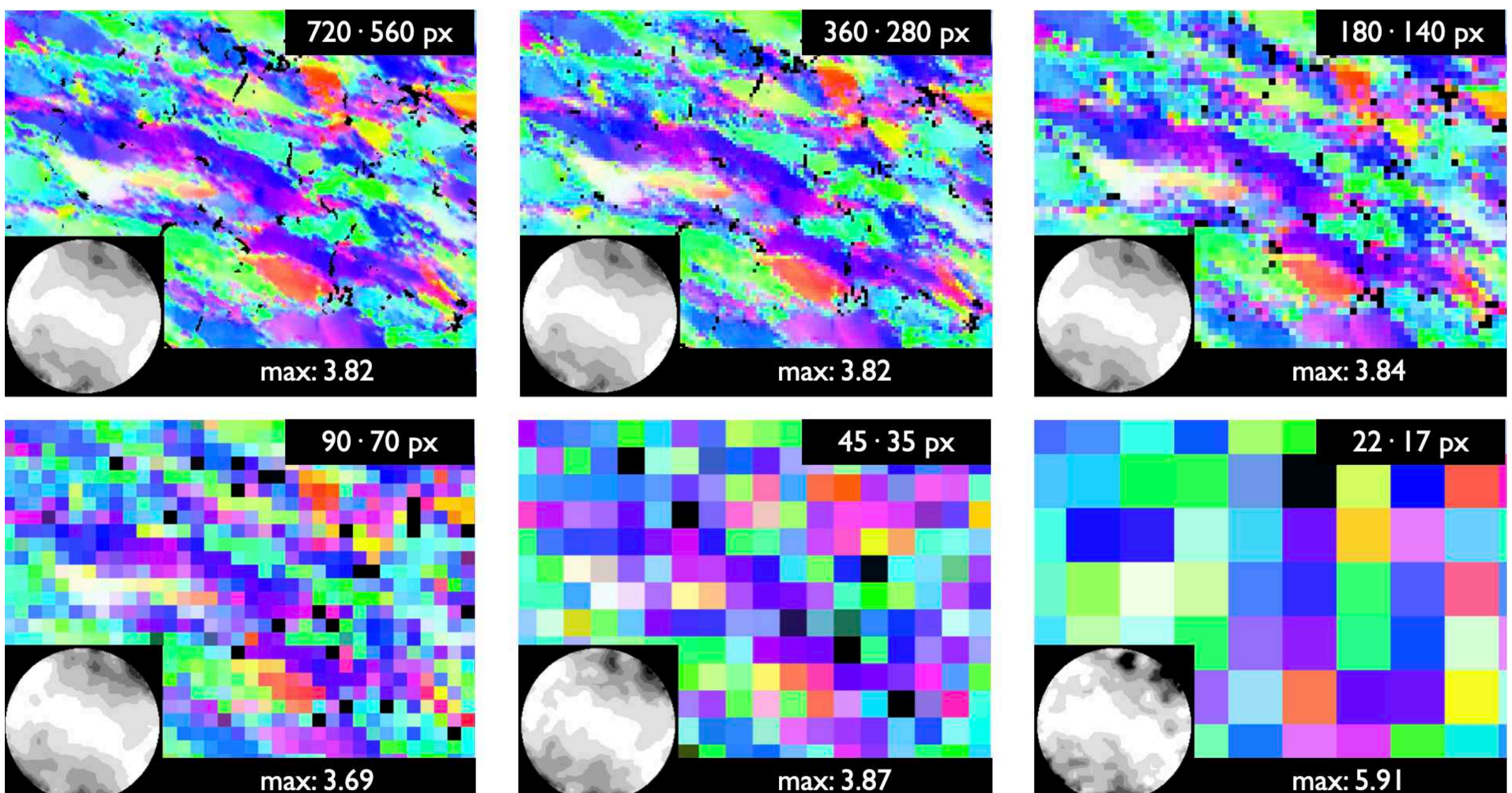
2002 – IAMG, Berlin

1 axis-orientation / pixel　　　1 axis-orientation / grain



pixels versus grains



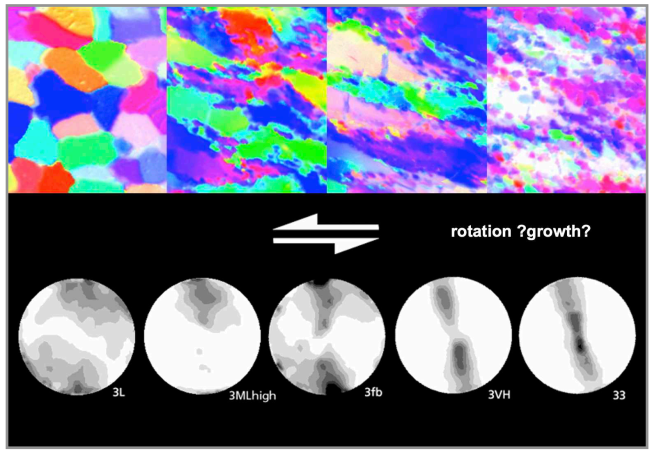


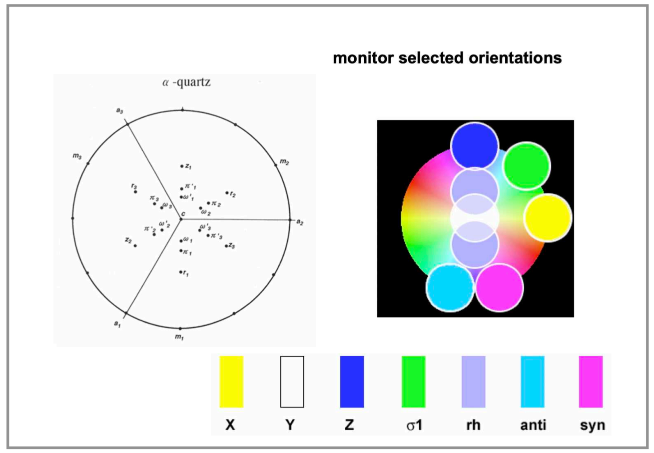
"enlarging the pixel" – increasing sampling steps

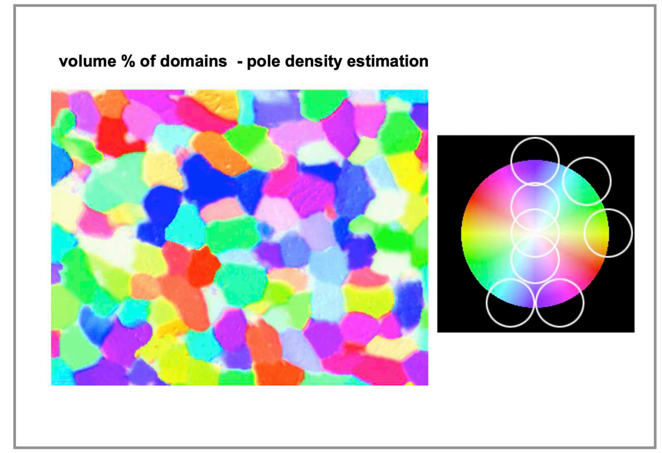
approaching the
"infinite texture"
of single crystals...

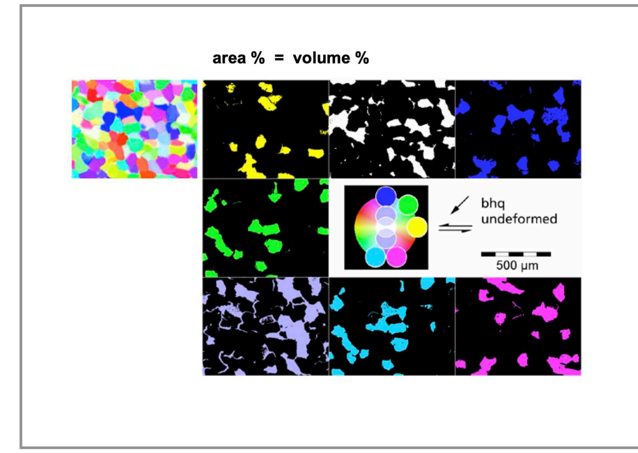
Renée Heilbronner, K. Gerald van den Boogaart, H. Schaeben: Comparison of coarse- and fine-grained quartz textures using the pole density index (PDI)

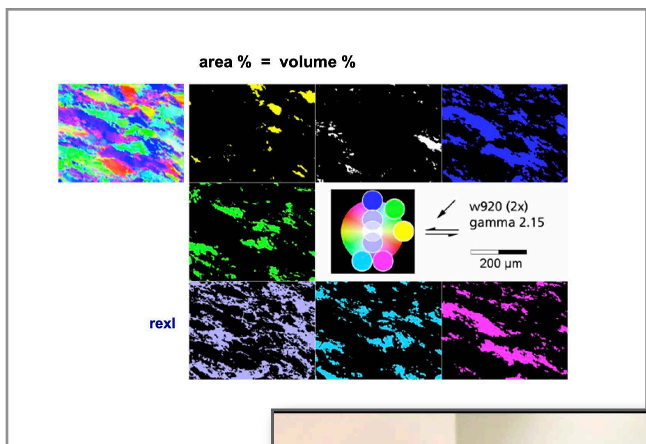
2002 – Penrose, Monte Verità

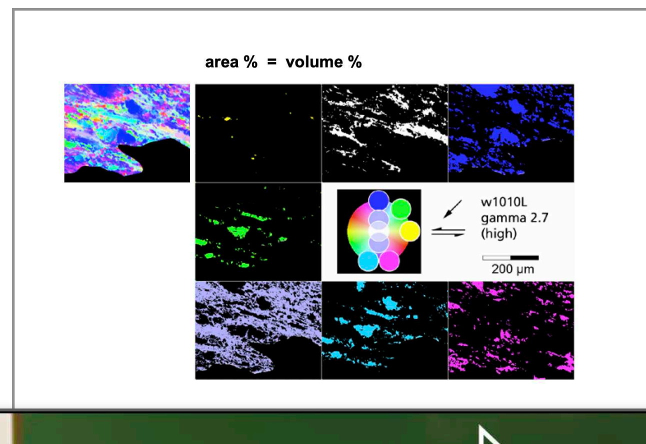


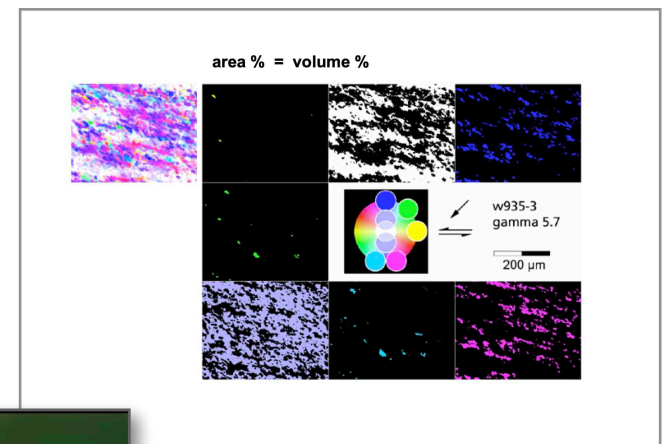


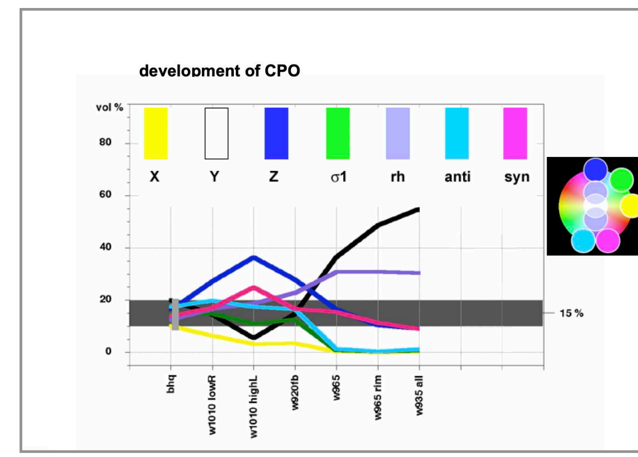


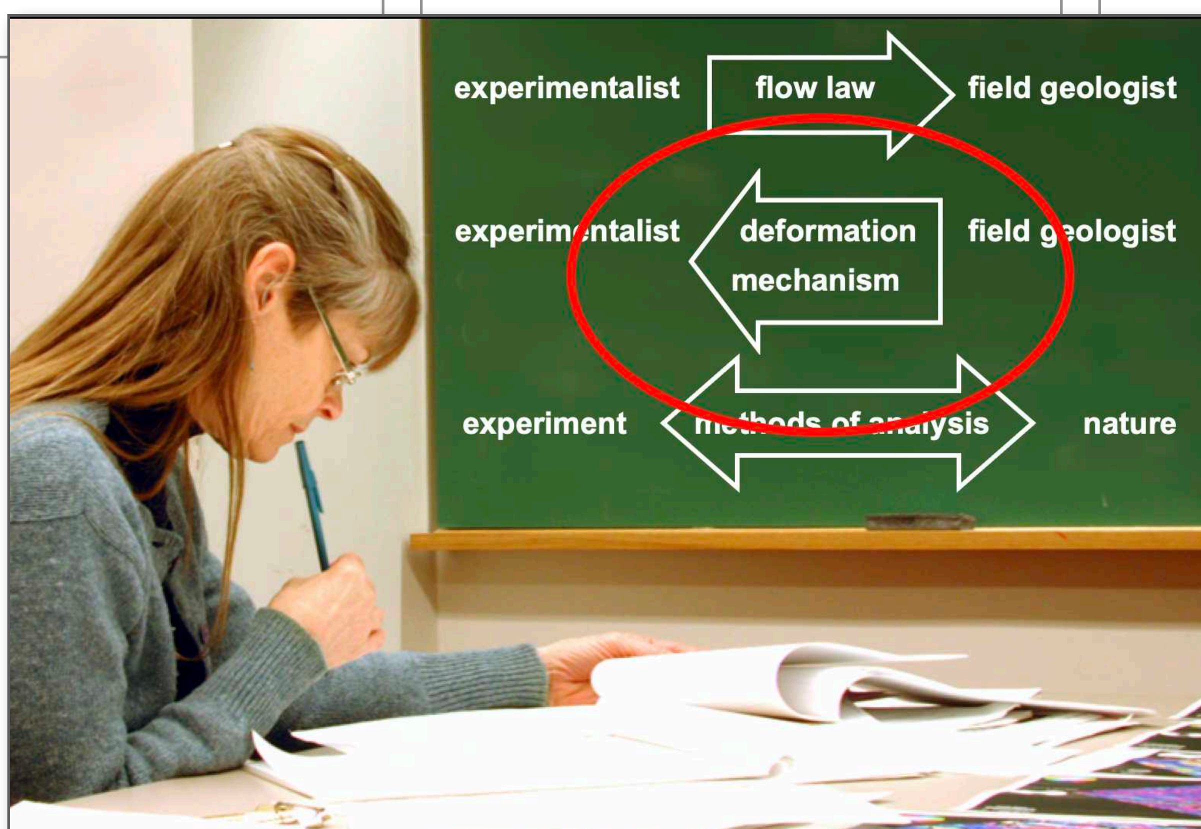






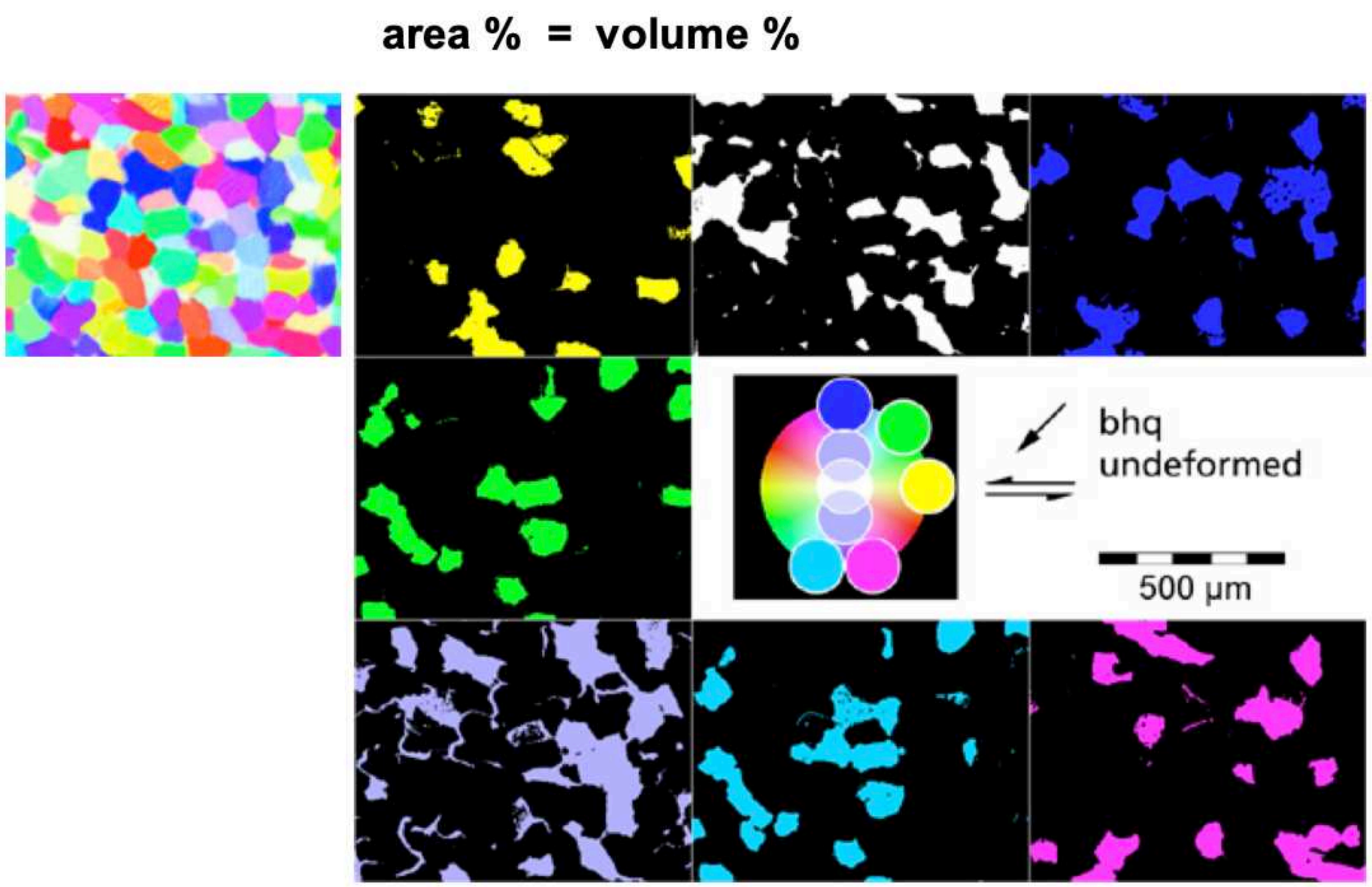




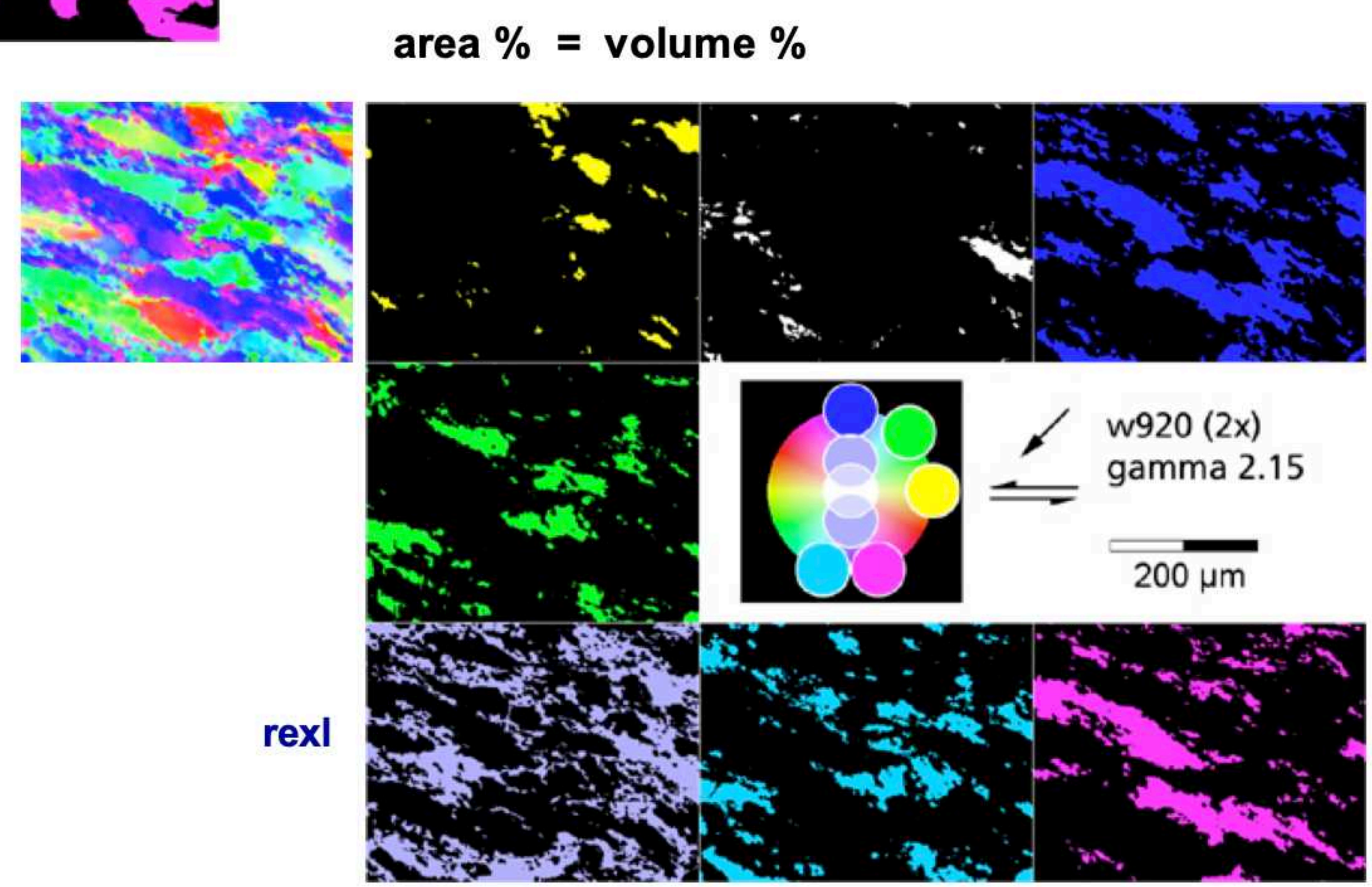


Renée Heilbronner (2002) Microfabric development in nature and experiment.

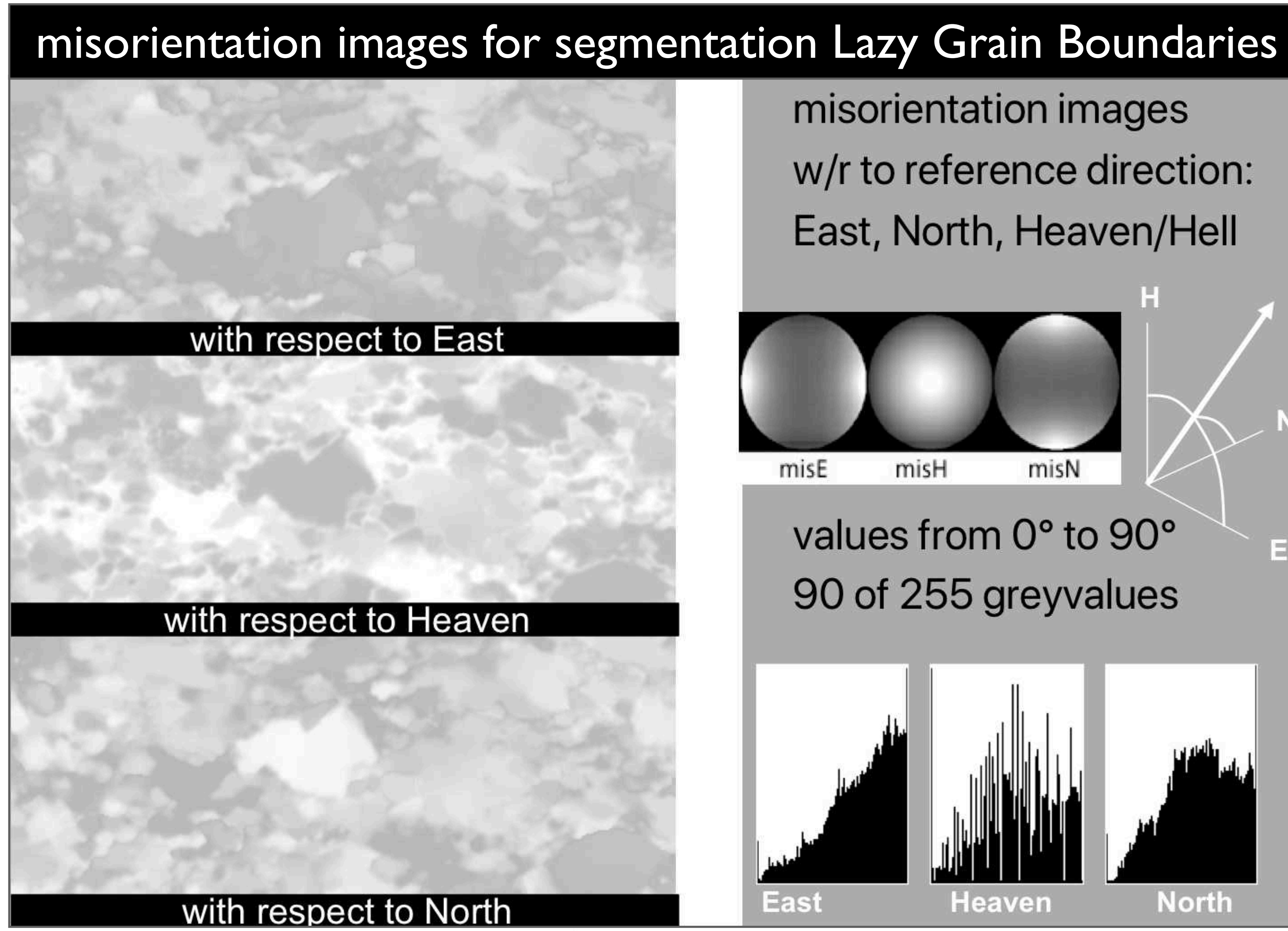
2002 – Penrose, Monte Verità

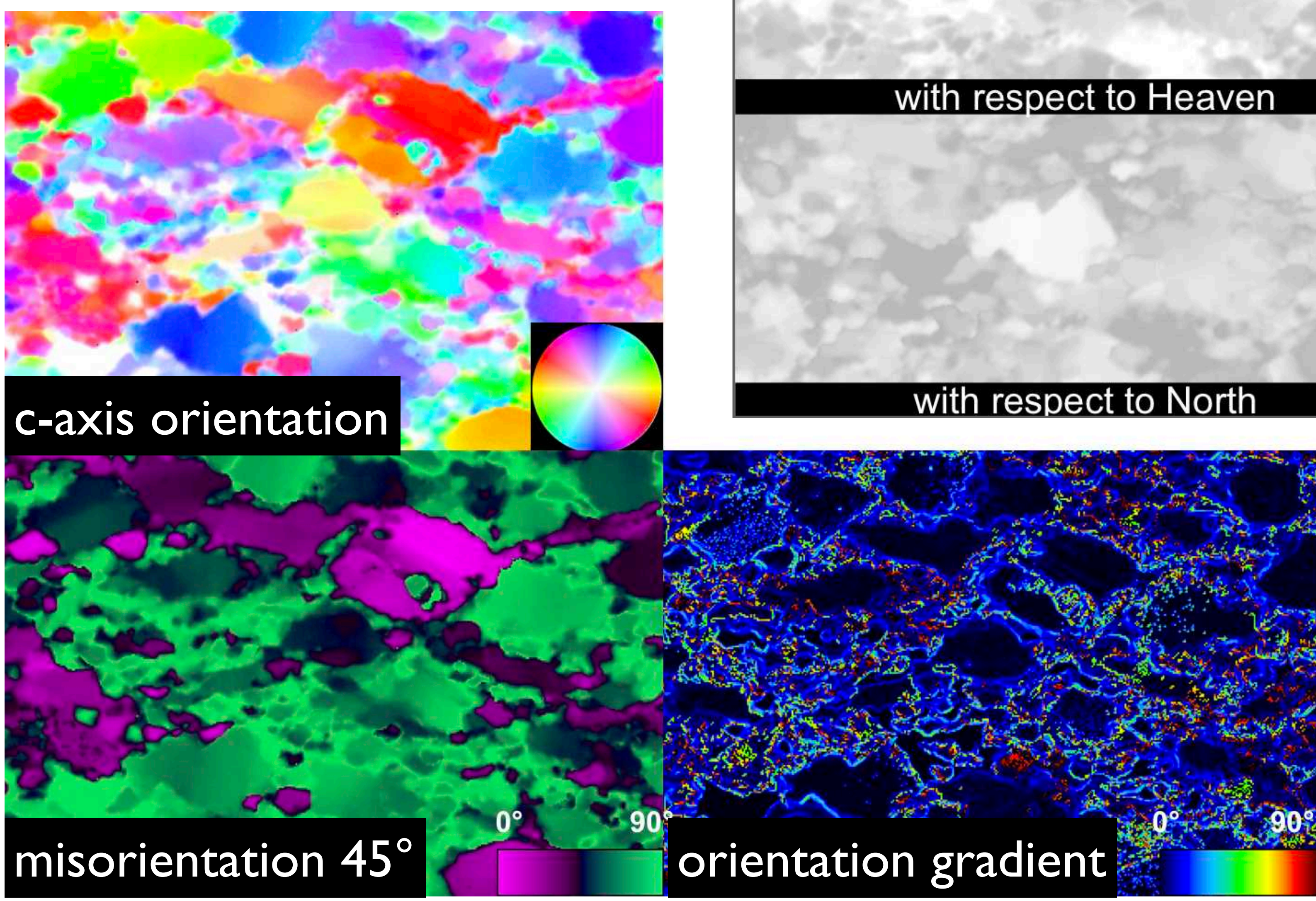


volume fraction and shape of texture domains



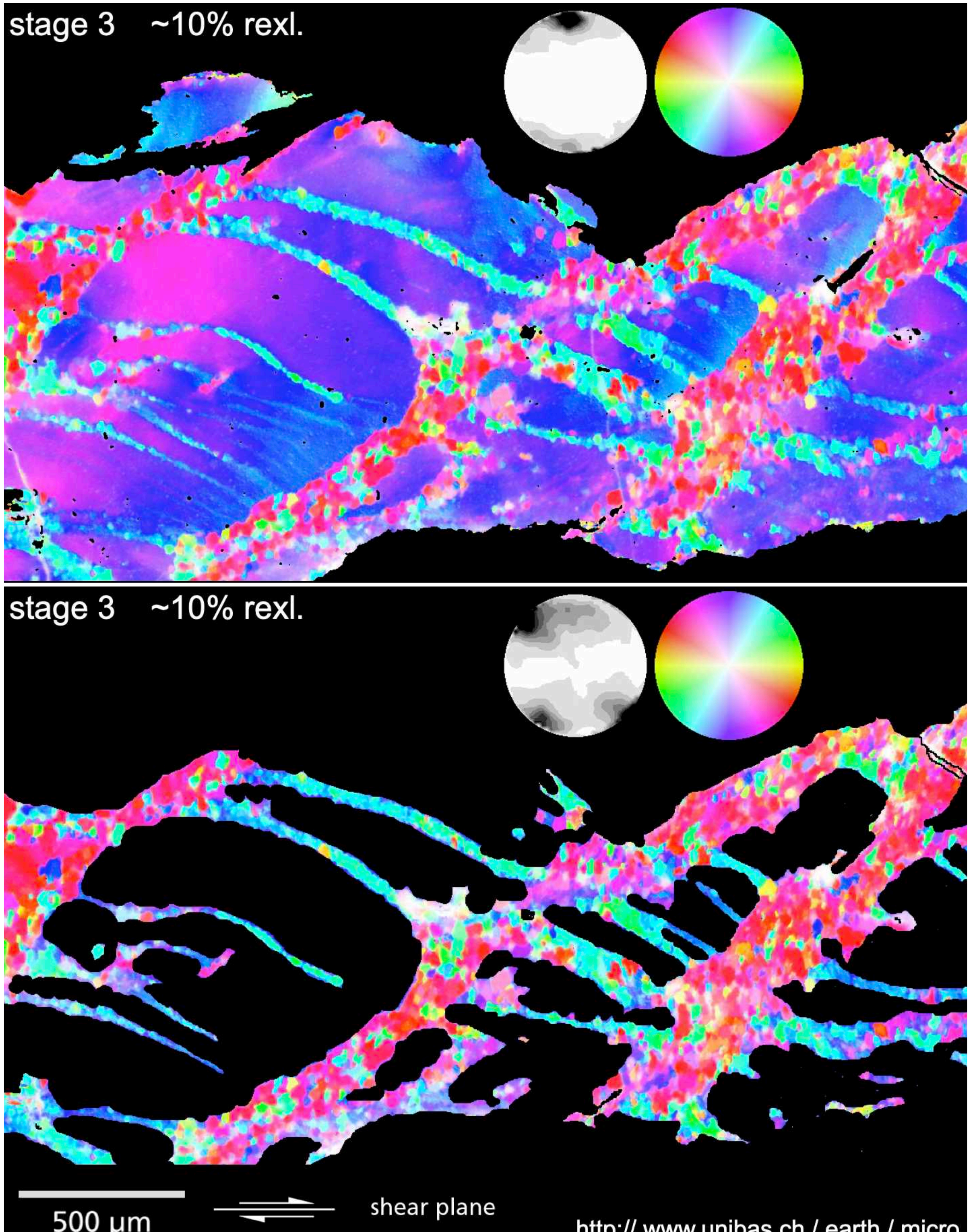
2003 – GSJ, Shizuoka

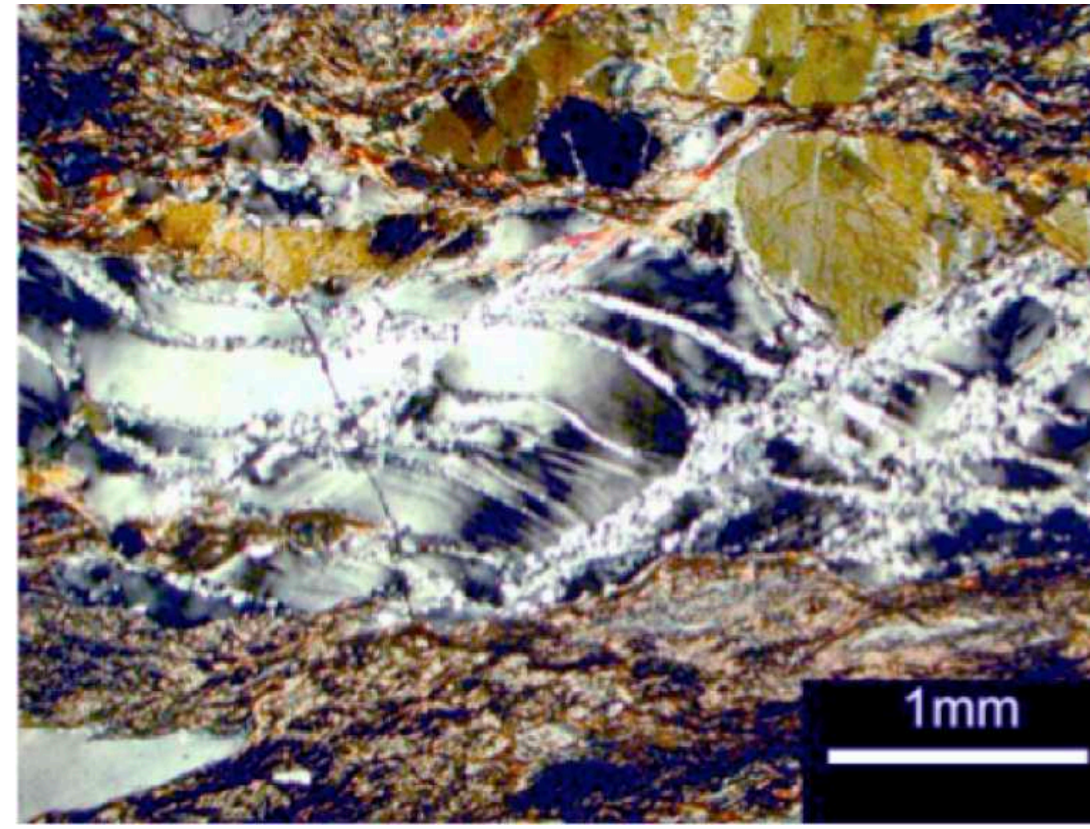


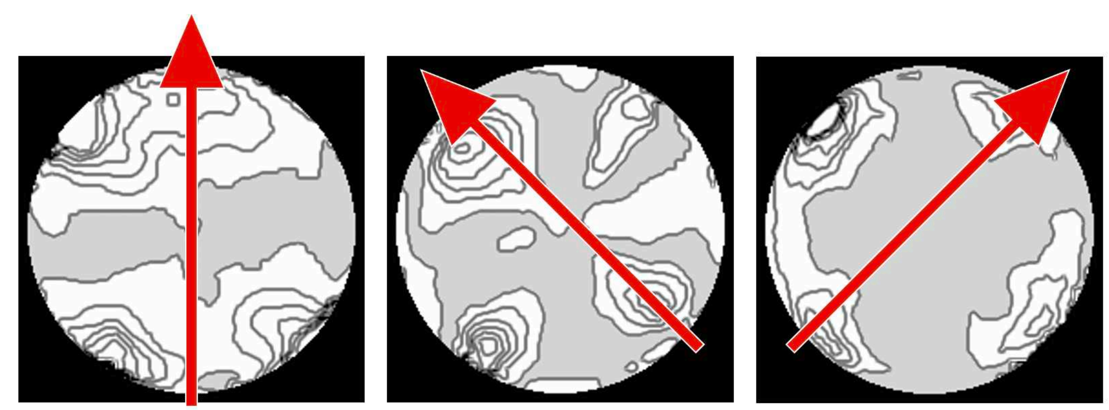


Renée Heilbronner (2003) Quantification of dislocation creep microstructures in quartz: comparison of experimental and natural deformation.

2005 – GSA, Salt Lake City

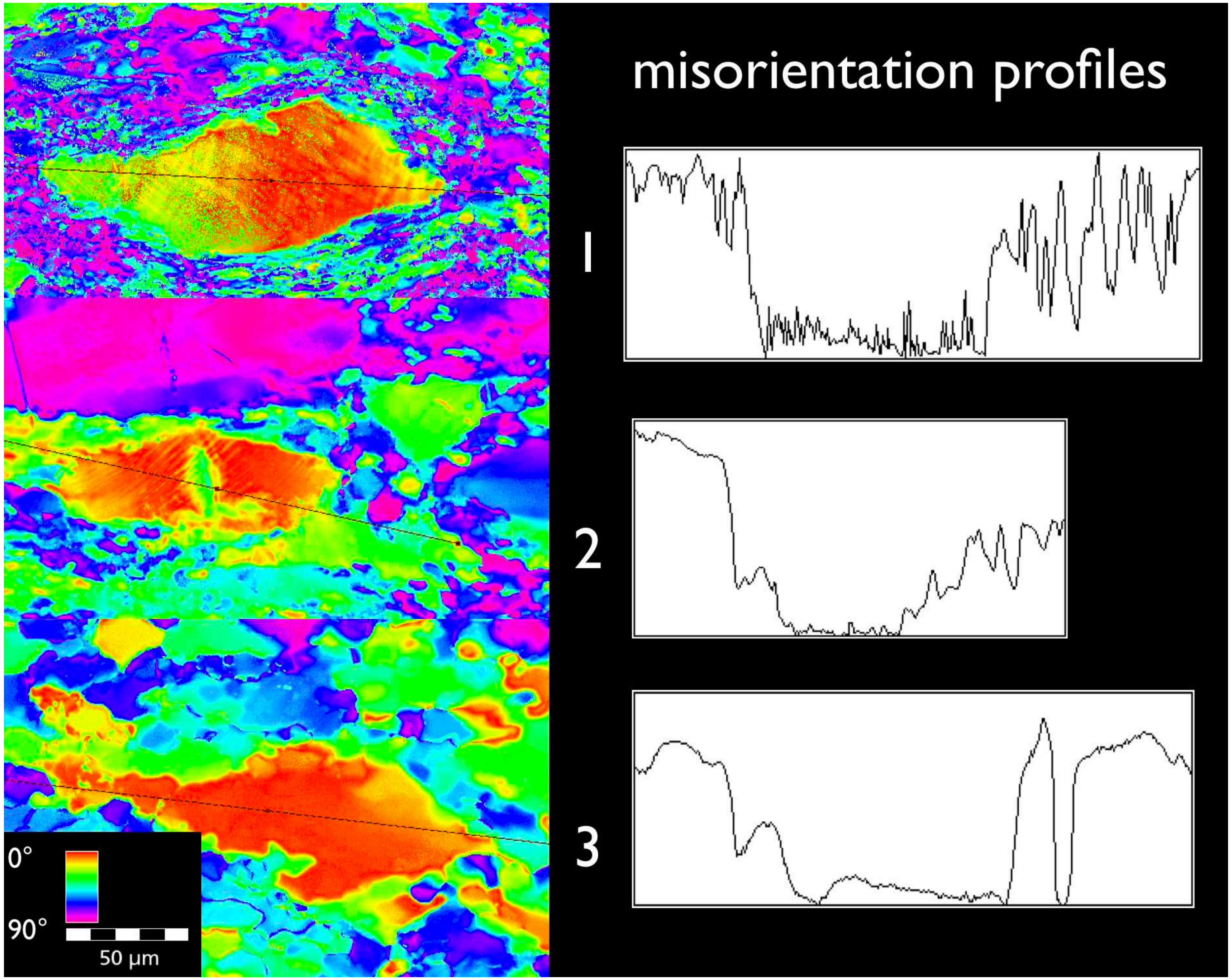






Renée Heilbronner, Luca Menegon (2003) The problem of deriving bulk rock behaviour of heterogeneously deforming crystalline aggregates.

2006 – IAfM, Liverpool



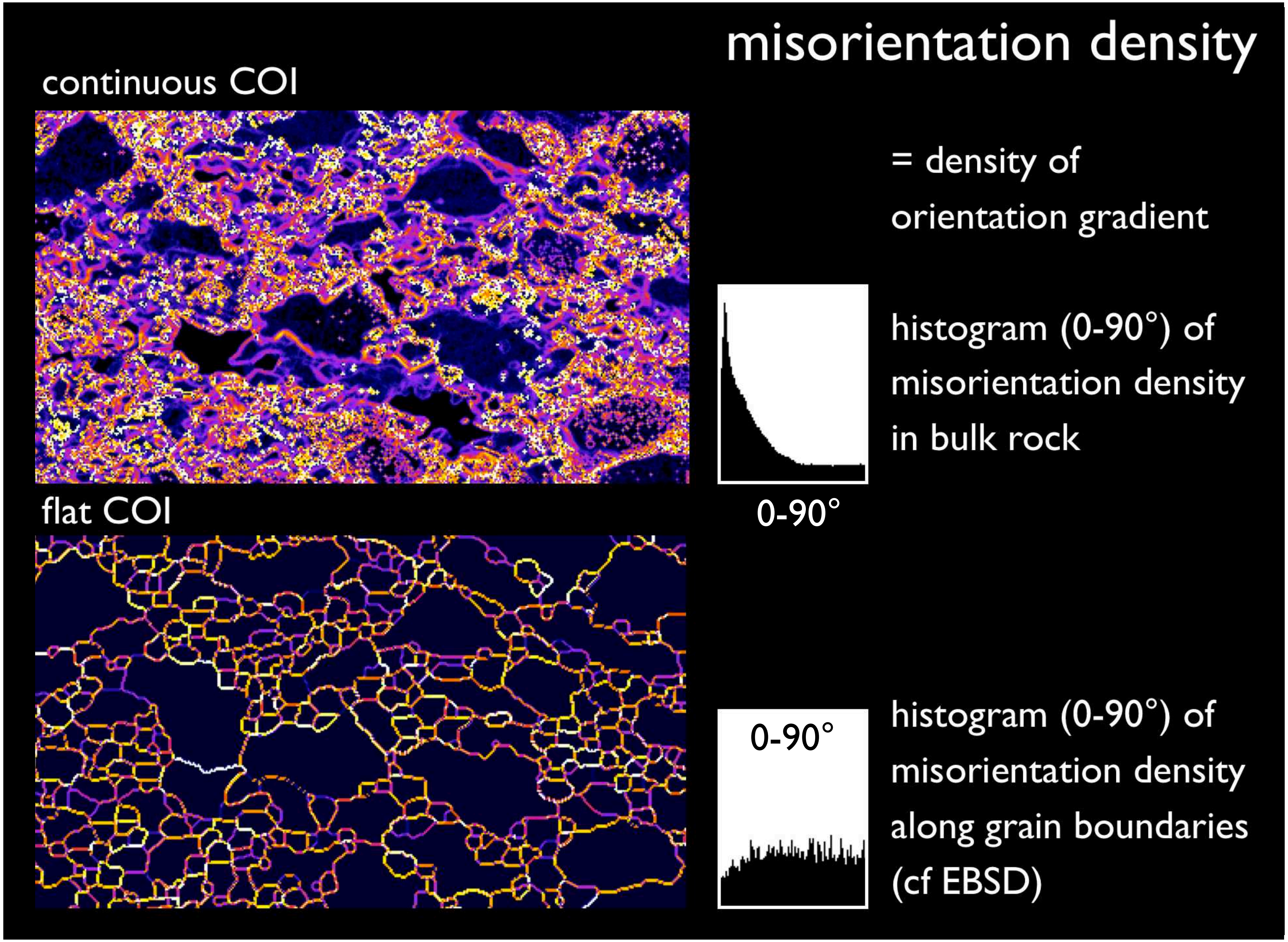
BULGING
inside: very high frequency
boundary: high gradient
outside: high frequency

SUBGRAIN
ROTATION
inside: medium frequency
boundary: medium gradient
outside: medium frequency

GRAINBOUNDARY
MIGRATION
inside: low frequency
boundary: high gradient
outside: low frequency

Renée Heilbronner (2006) ORIENTATION IMAGING: measuring and mapping crystallographic orientations

2006 – IAfM, Liverpool

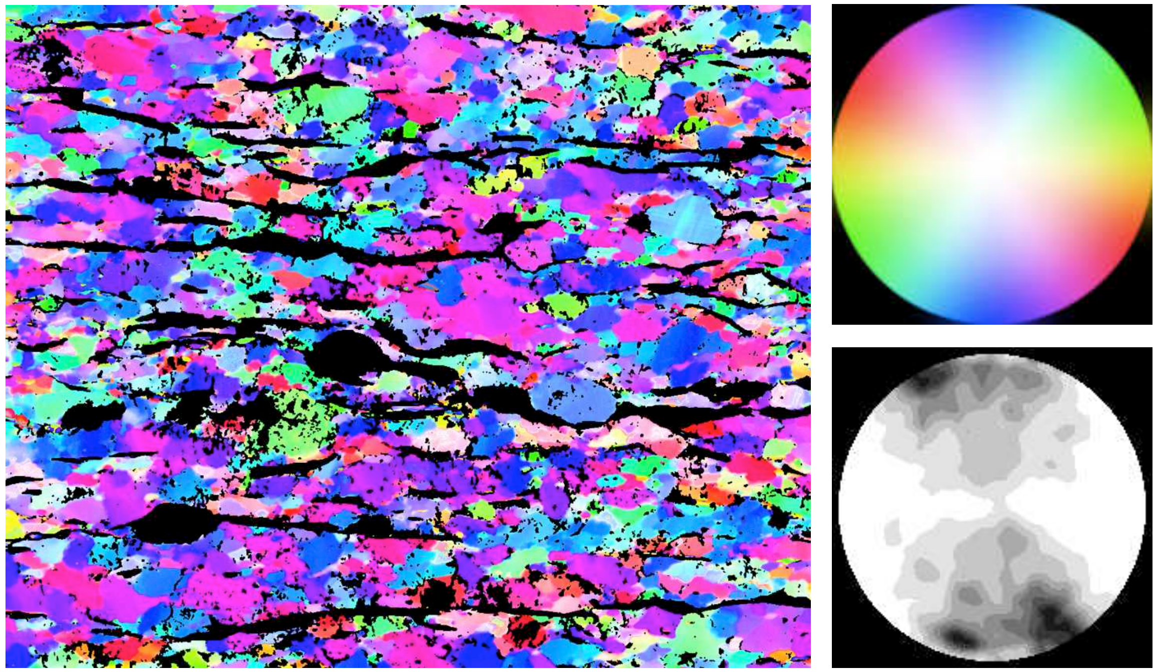


organizer of IAfM

Steve Barrett

Renée Heilbronner (2006) ORIENTATION IMAGING: measuring and mapping crystallographic orientations

2010 – publication JGSI

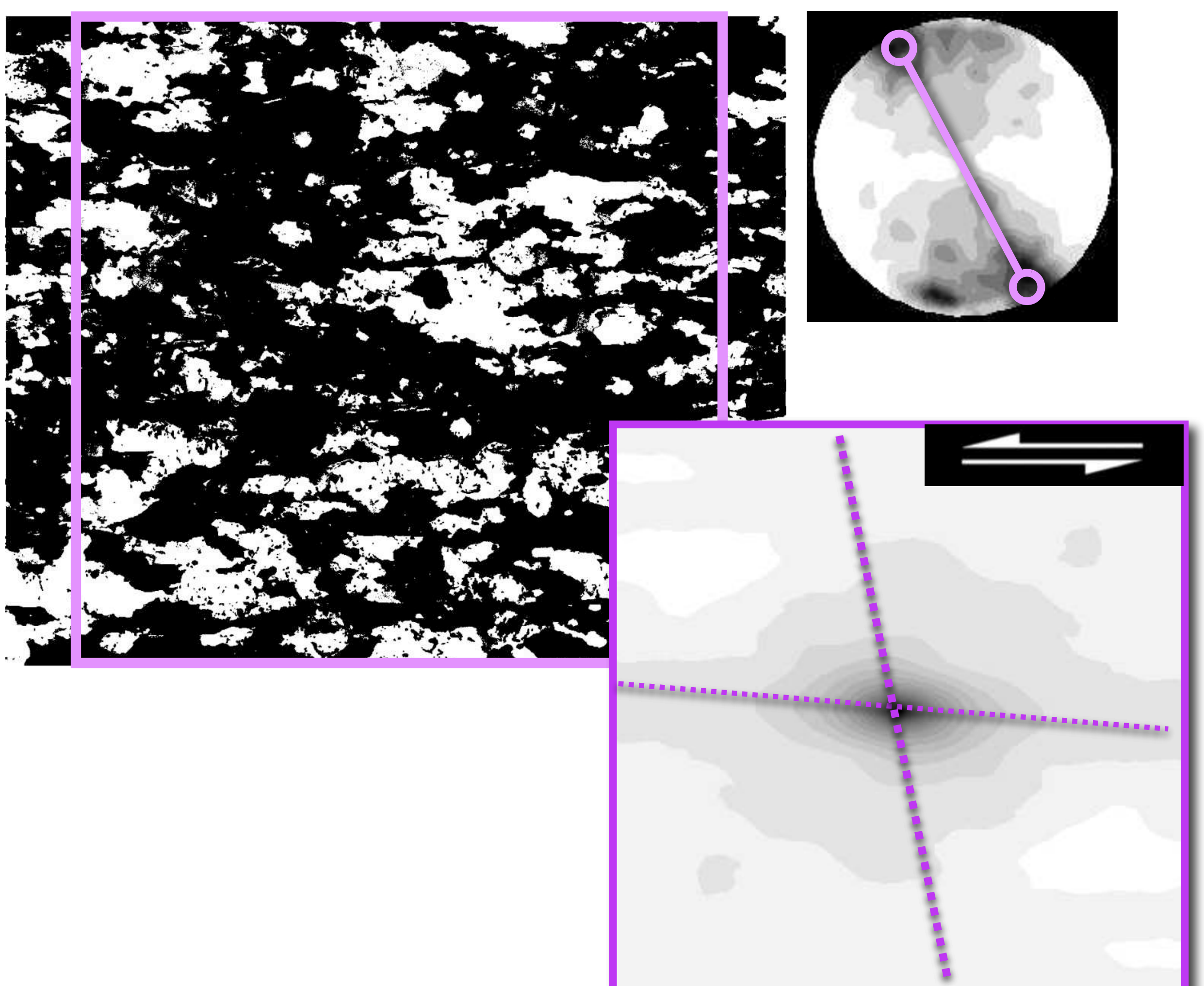


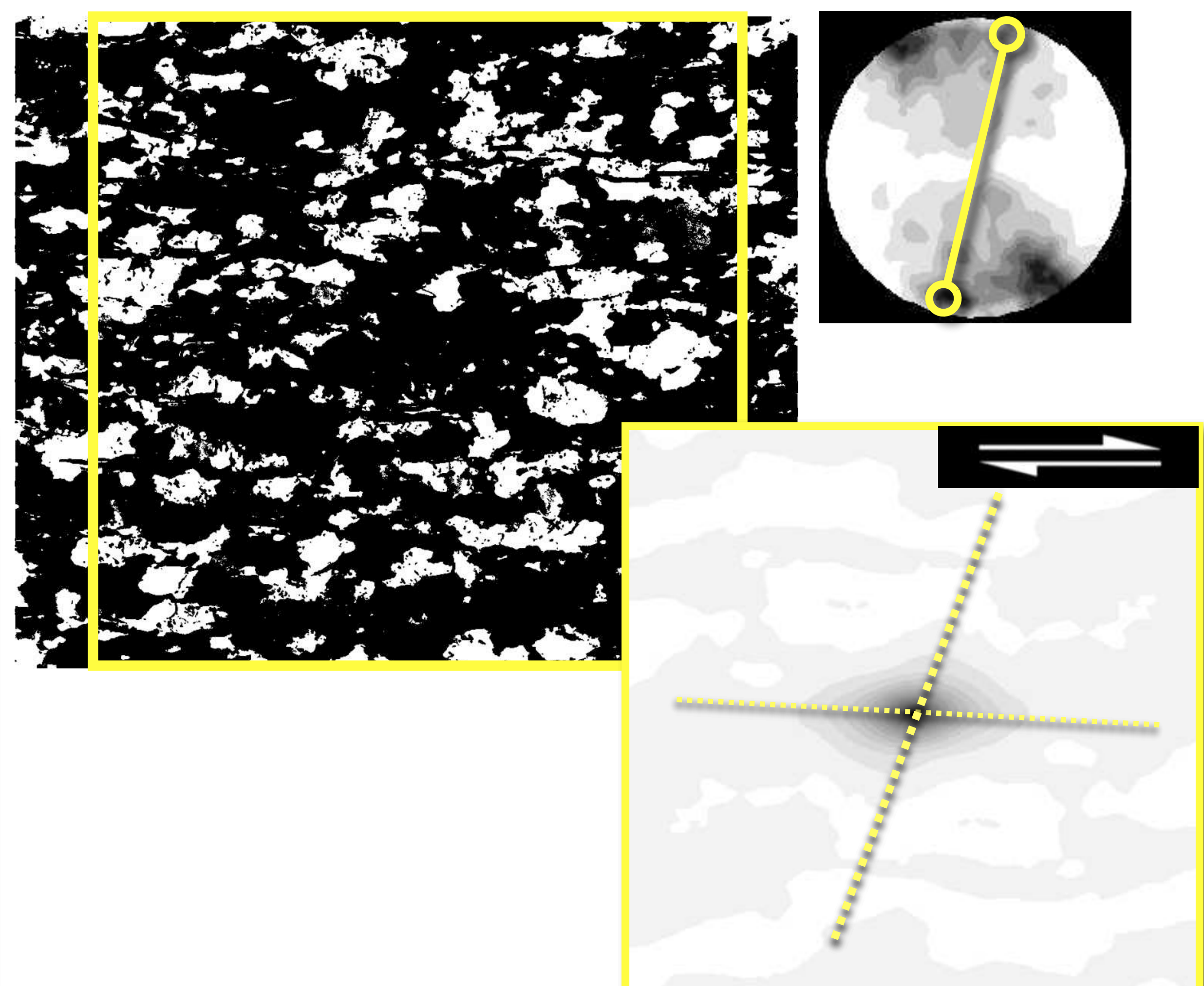
see IAES ...

Renée Heilbronner, Steve Barrett (2014): Image Analysis in Earth Sciences – Microstructures and textures of Earth Materials, Springer Verlag

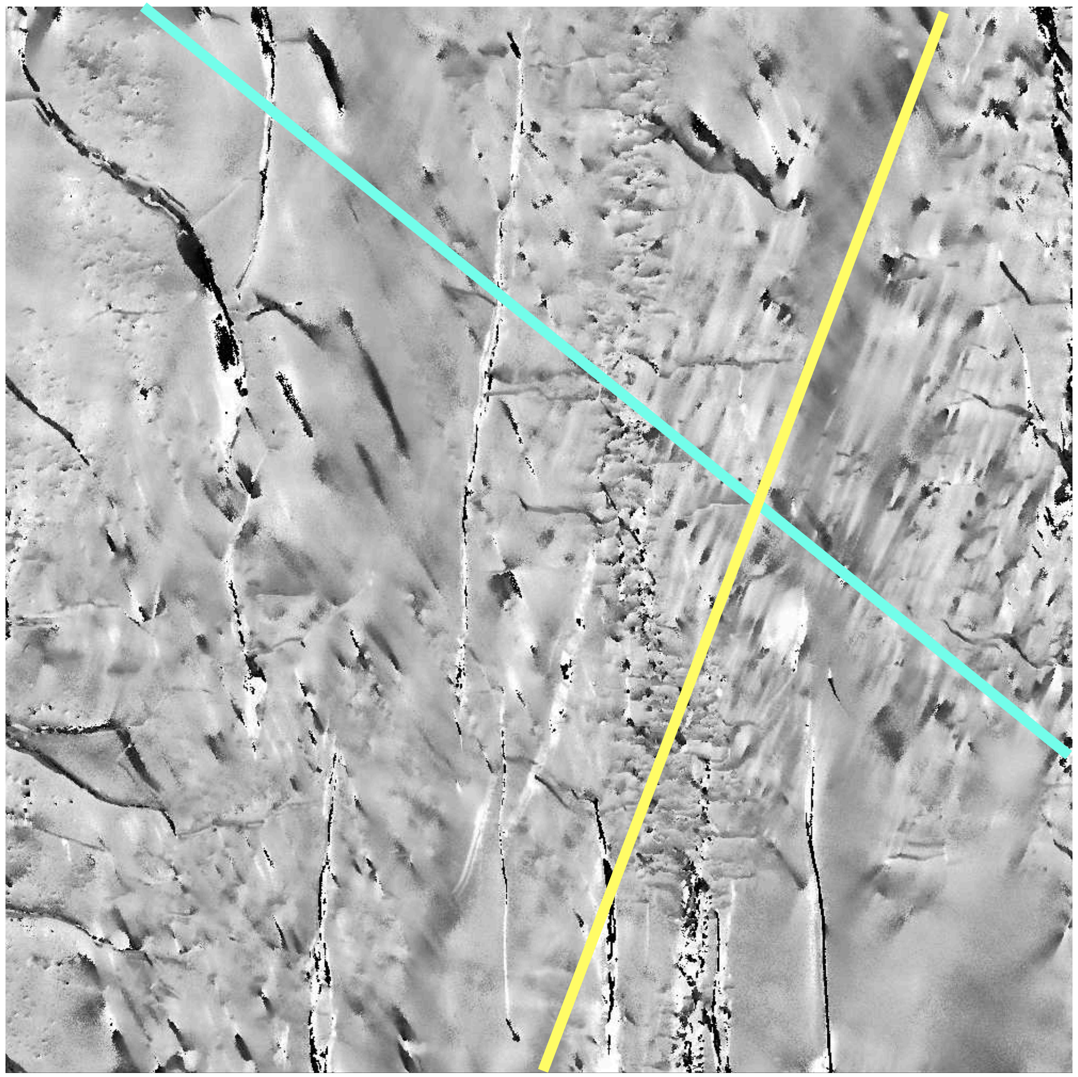
... and 2023 Torino workshop

Renée Heilbronner (2023): Microtectonics of Fault Rocks, Day 2 – The Ductile regime

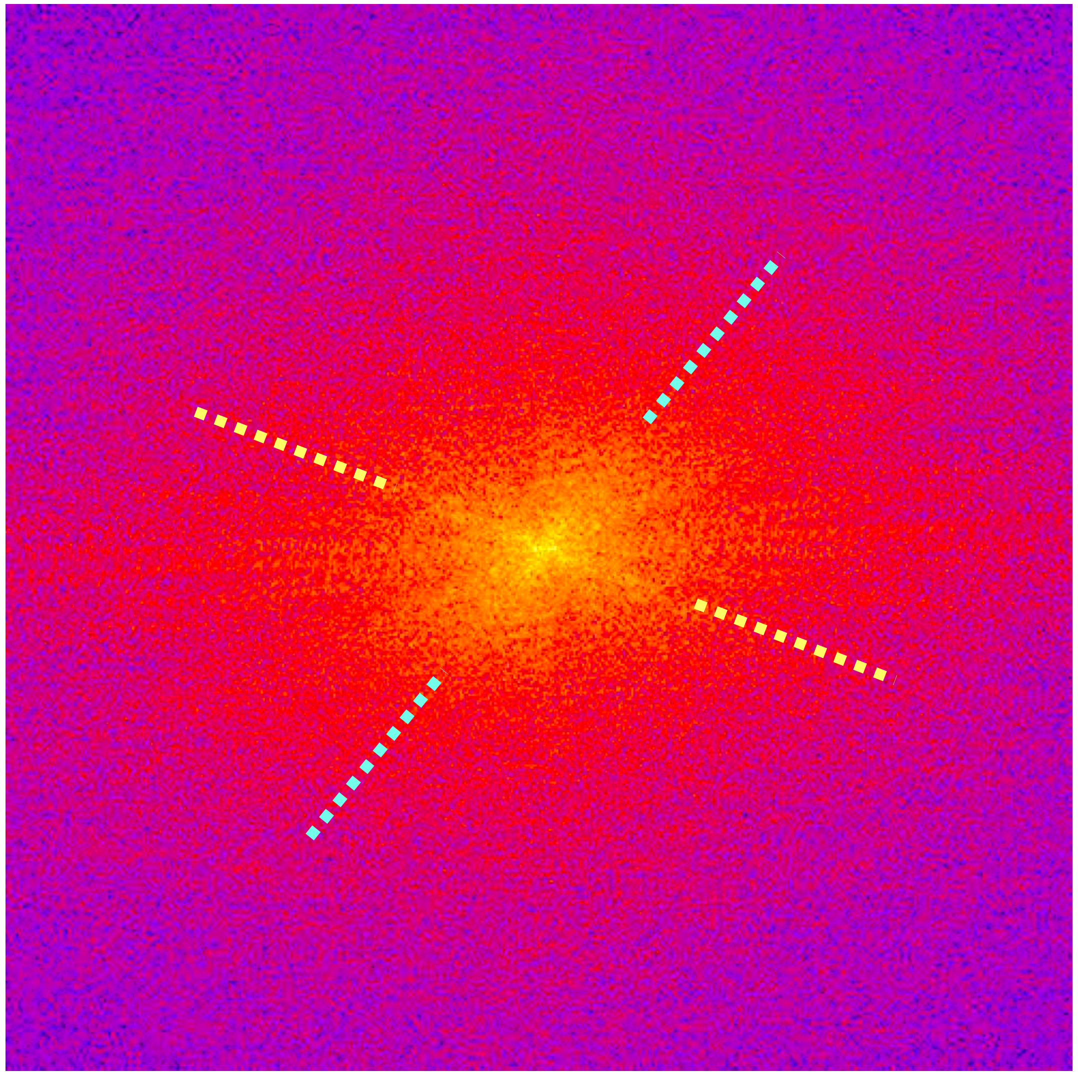




2011 – EGU, Vienna



azimuth image



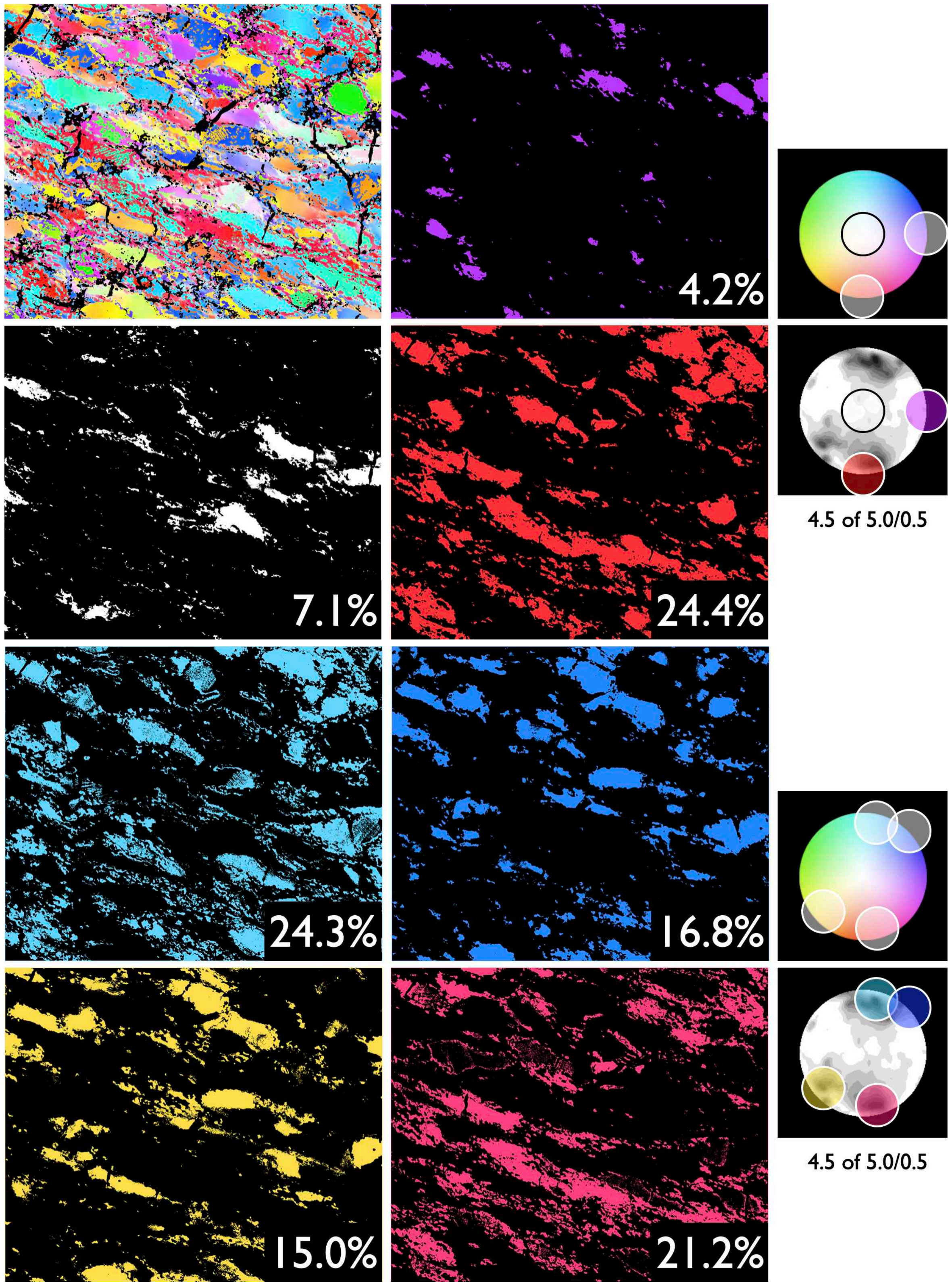
FFT of azimuth image, colorcoded

Renée Heilbronner, Anja Thust, Holger Stünitz:
Mapping Water and Misorientations in Experimentally Deformed Quartz

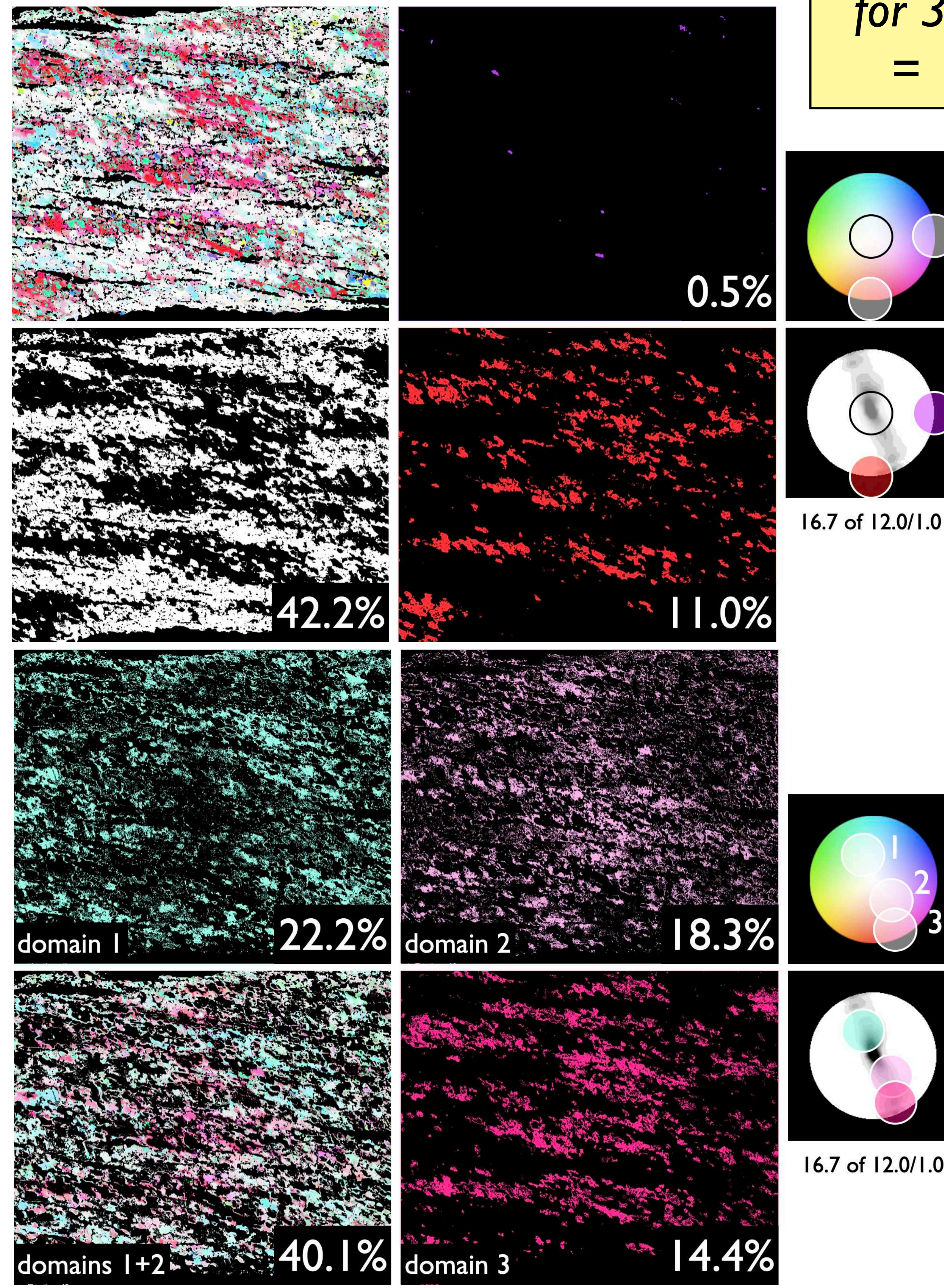
2014 – IAES

Renée Heilbronner, Steve Barrett (2014): Image Analysis in Earth Sciences – Microstructures and textures of Earth Materials, Springer Verlag

w920 γ~2 30° circular cone



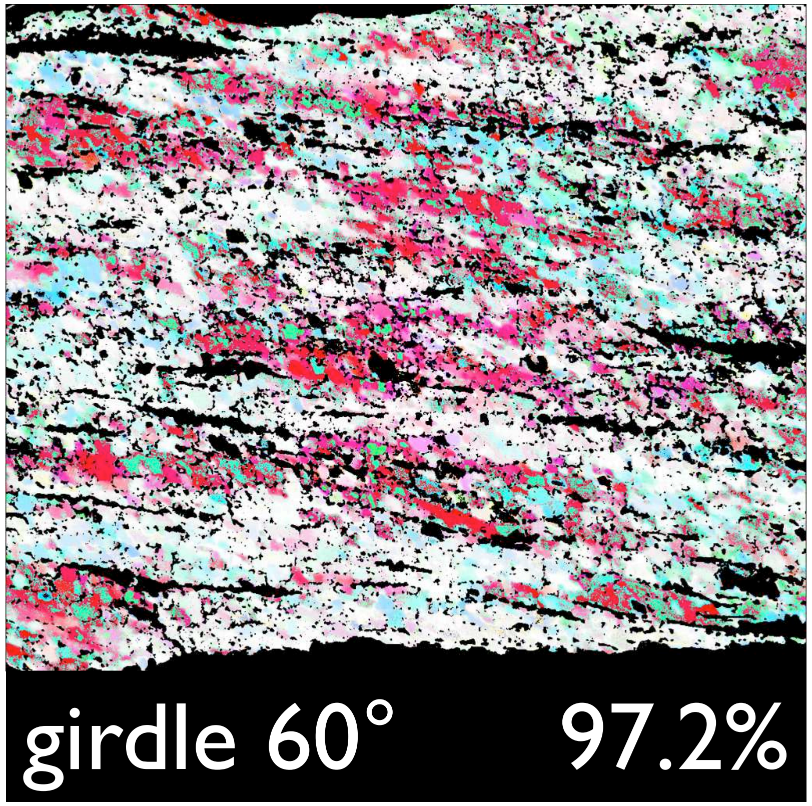
w935 γ~6 30° circular cone

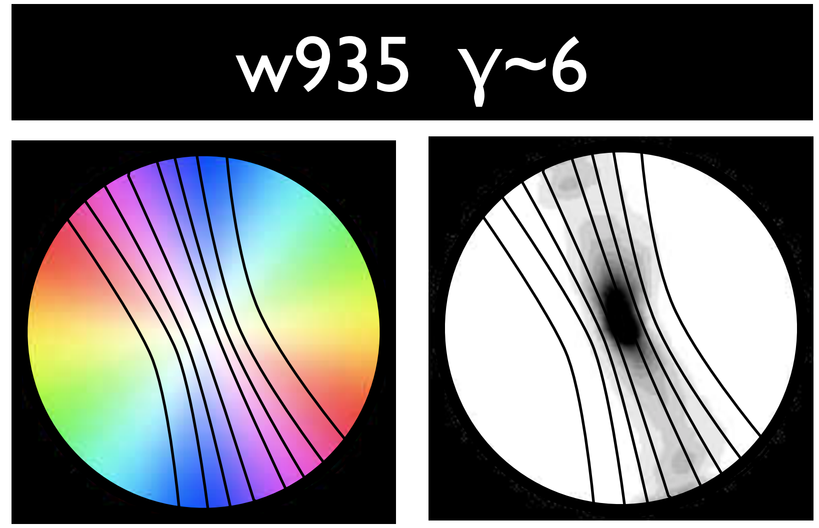


uniform density for 30° cone = 11.7%

2014 – IAES

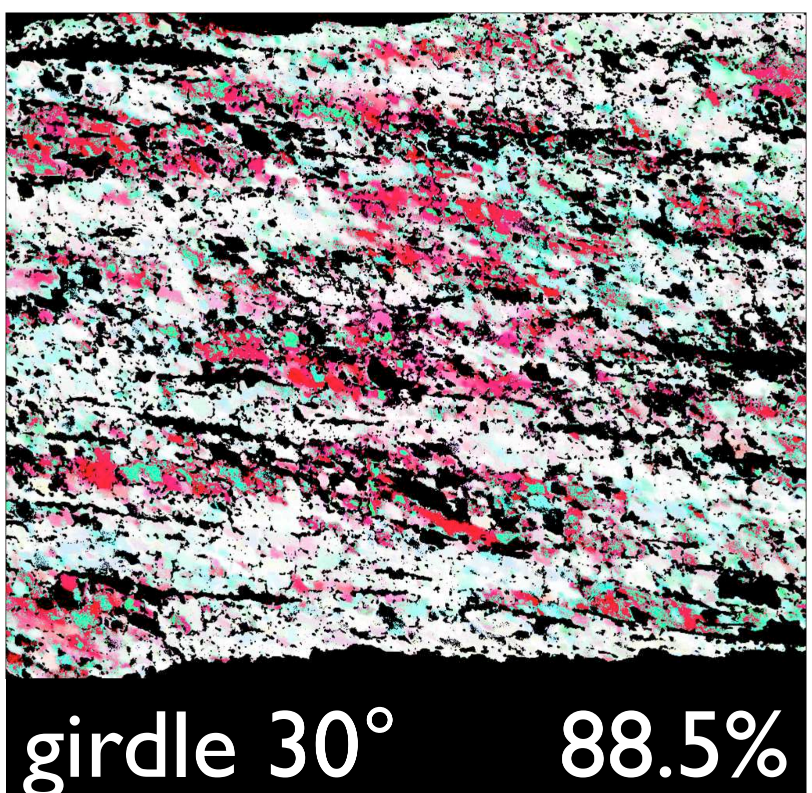
Renée Heilbronner, Steve Barrett (2014): Image Analysis in Earth Sciences – Microstructures and textures of Earth Materials, Springer Verlag

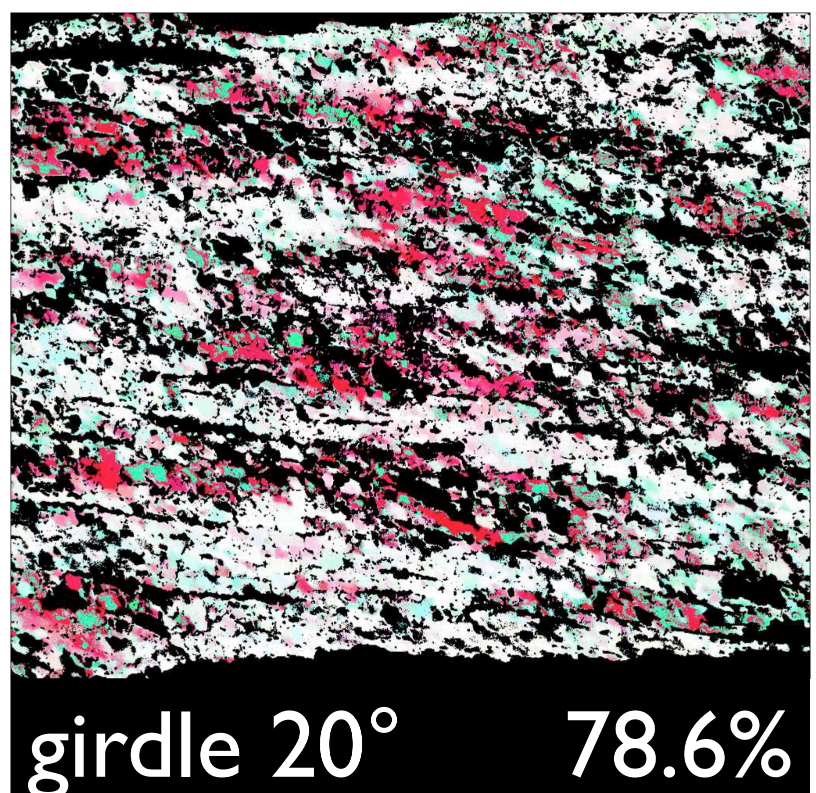


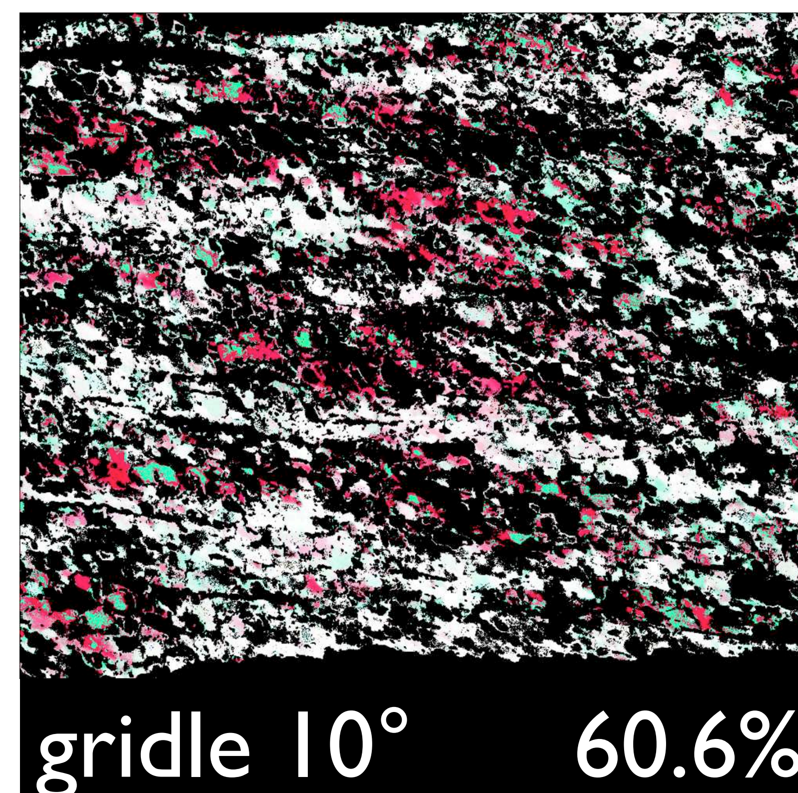


16.7 of 12.0/1.0

uniform density
for girdle width
60° = 54.3%
30° = 29.5%
20° = 20.1%
10° = 10.3%



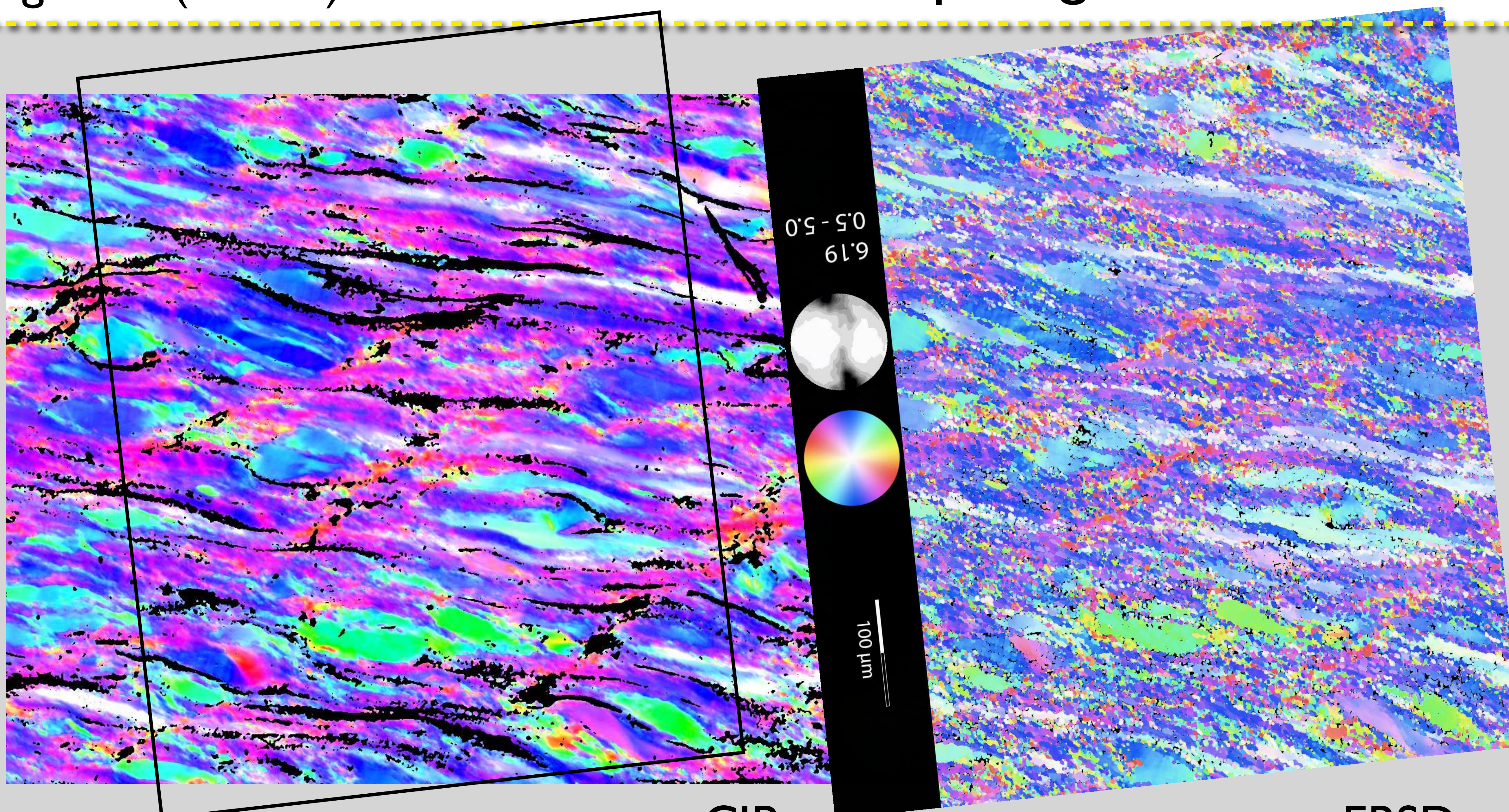




2016 – EGU, Vienna

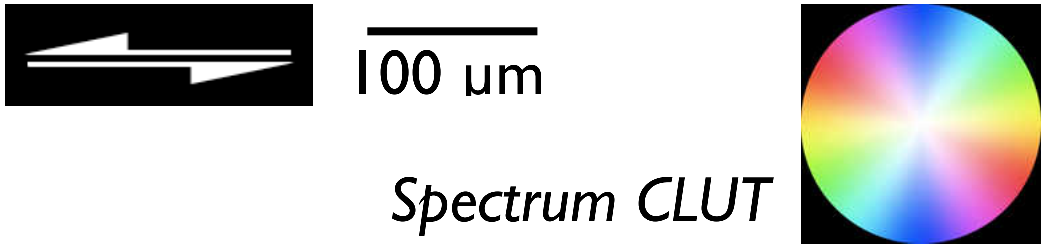
regime 1 (w1092)

comparing CIP and EBSD



CIP

EBSD

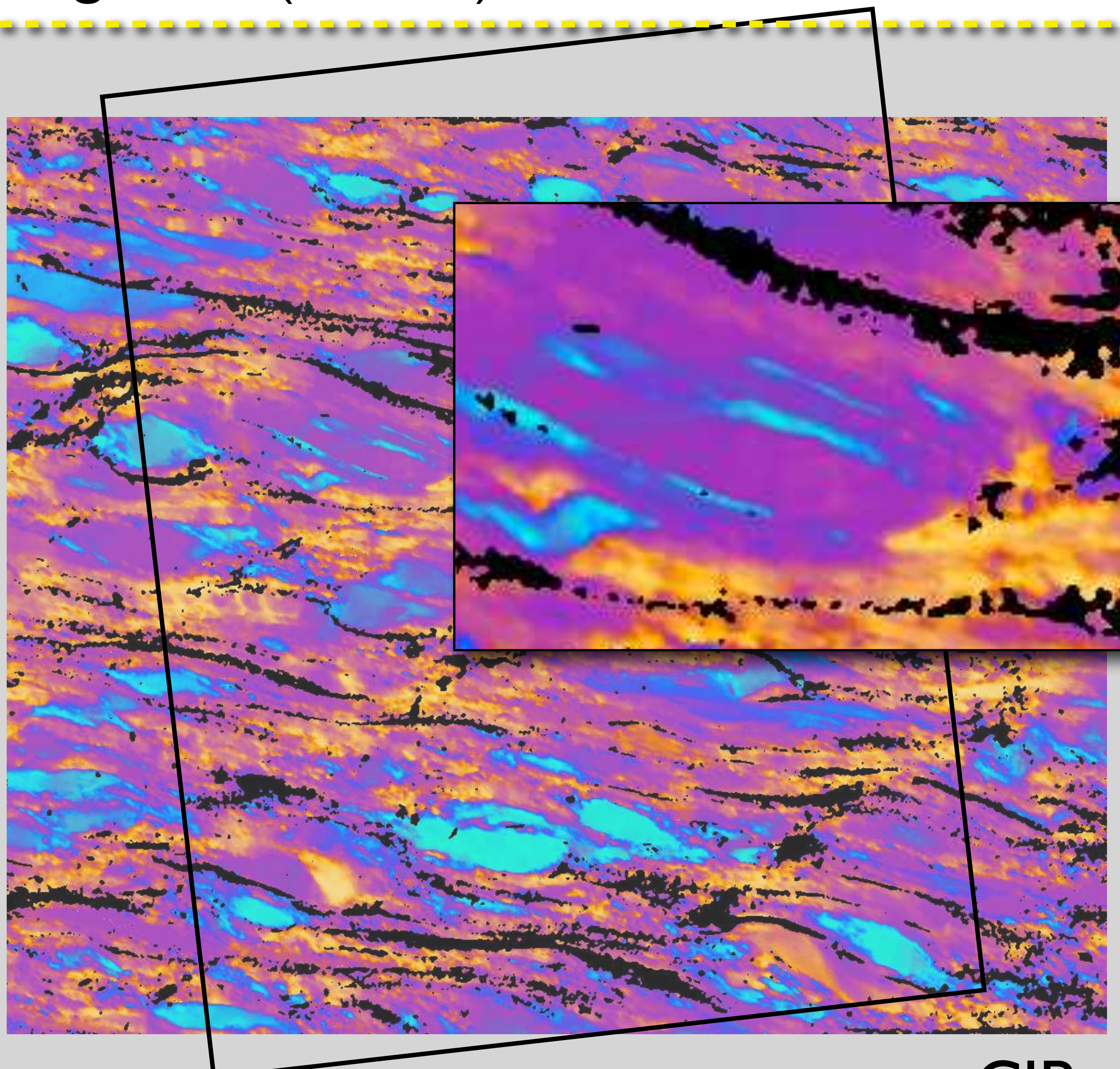


Renée Heilbronner (2016): Deformation of the lithosphere and what microstructures can tell you about it

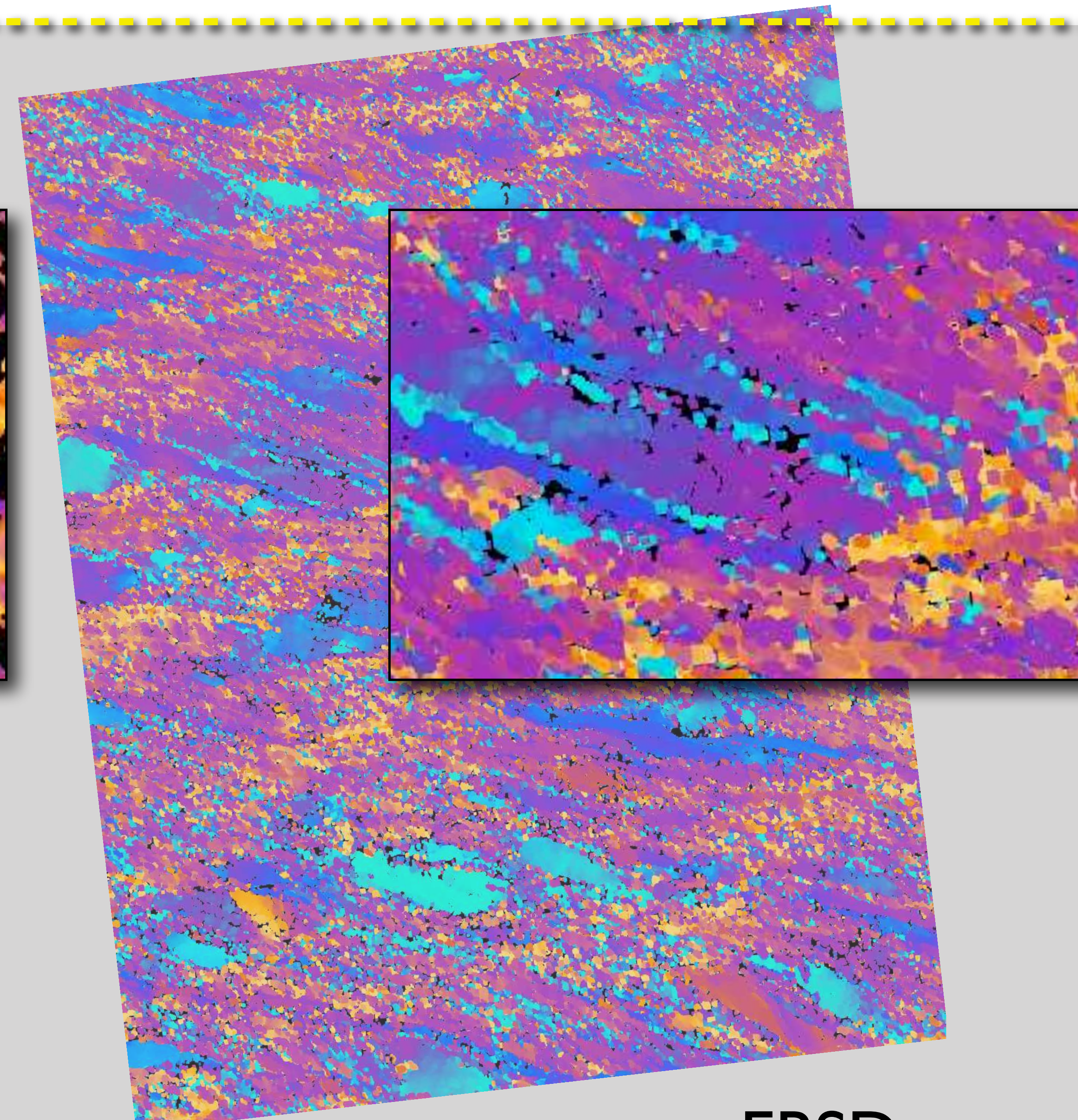
2016 – EGU, Vienna

regime 1 (w1092)

optical microscopy in the SEM



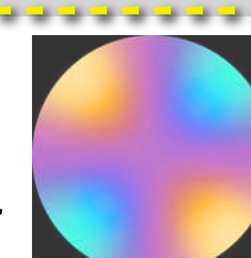
CIP



EBSD

100 µm

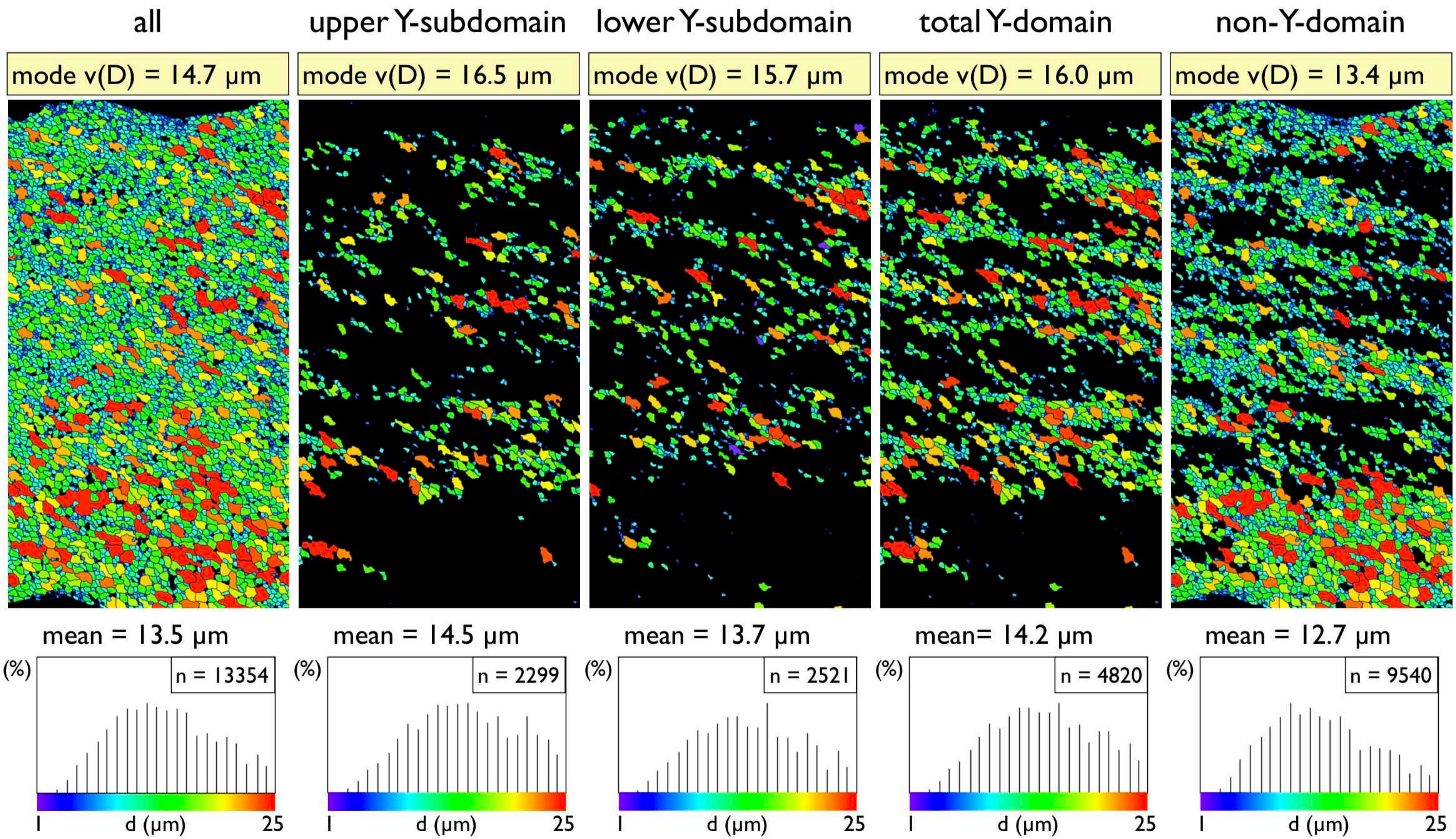
positive CLUT



Renée Heilbronner (2016): Deformation of the lithosphere and what microstructures can tell you about it

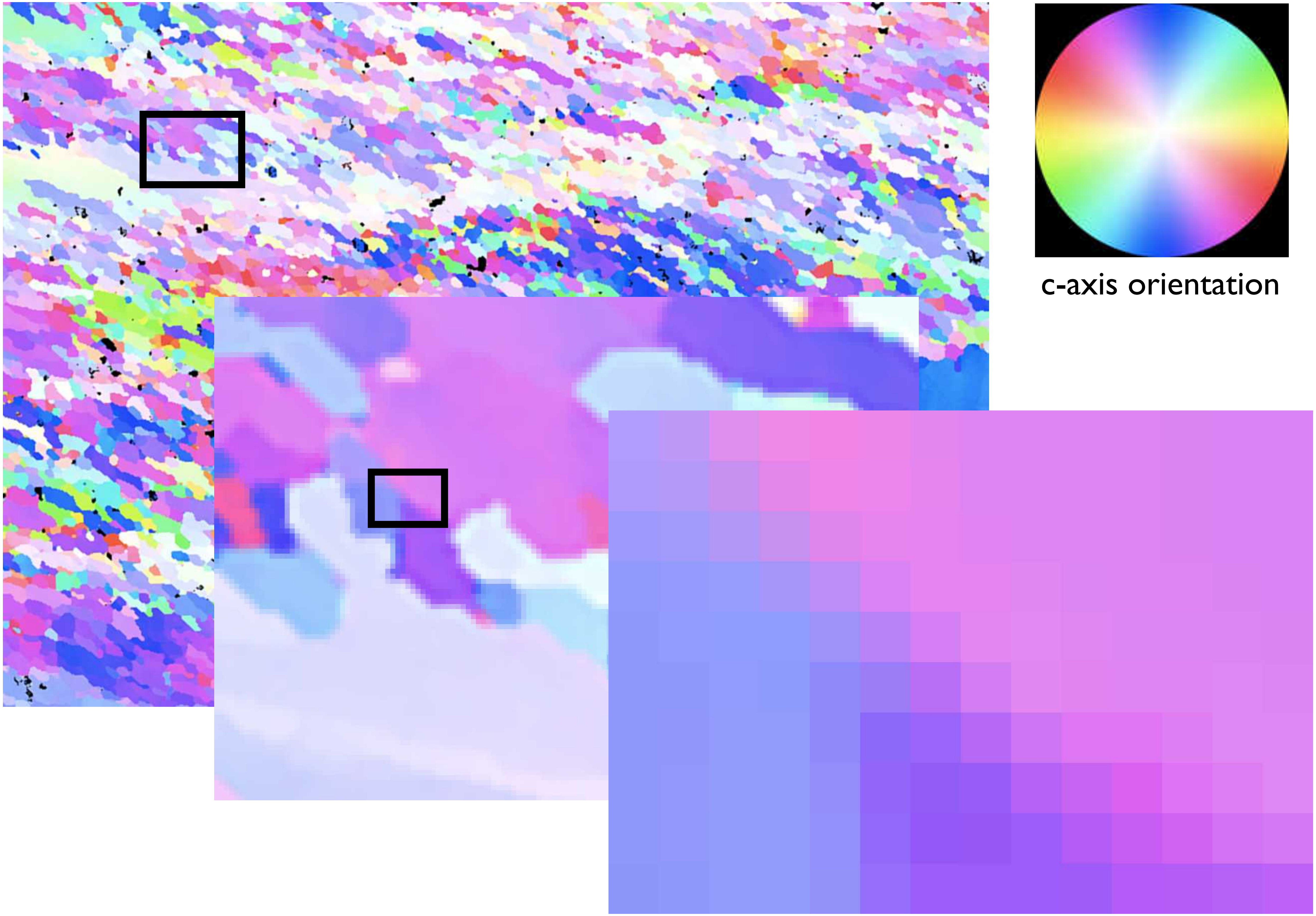
2017 – EGU, Vienna (PICO)

Renée Heilbronner and Rüdiger Kilian (2017): Complete grain boundaries from incomplete EBSD maps: the influence of segmentation on grain size determinations



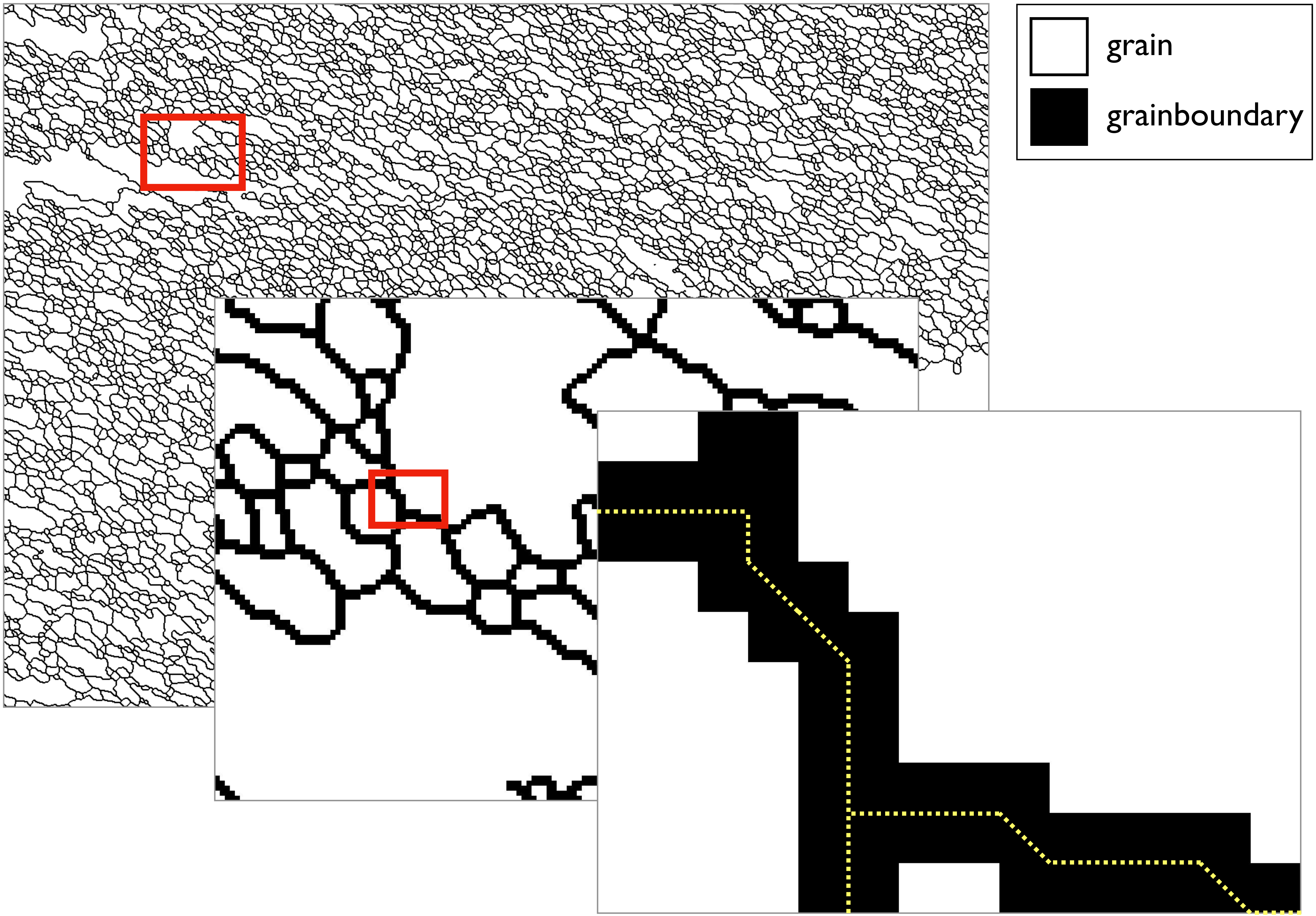
step back

the orientation image



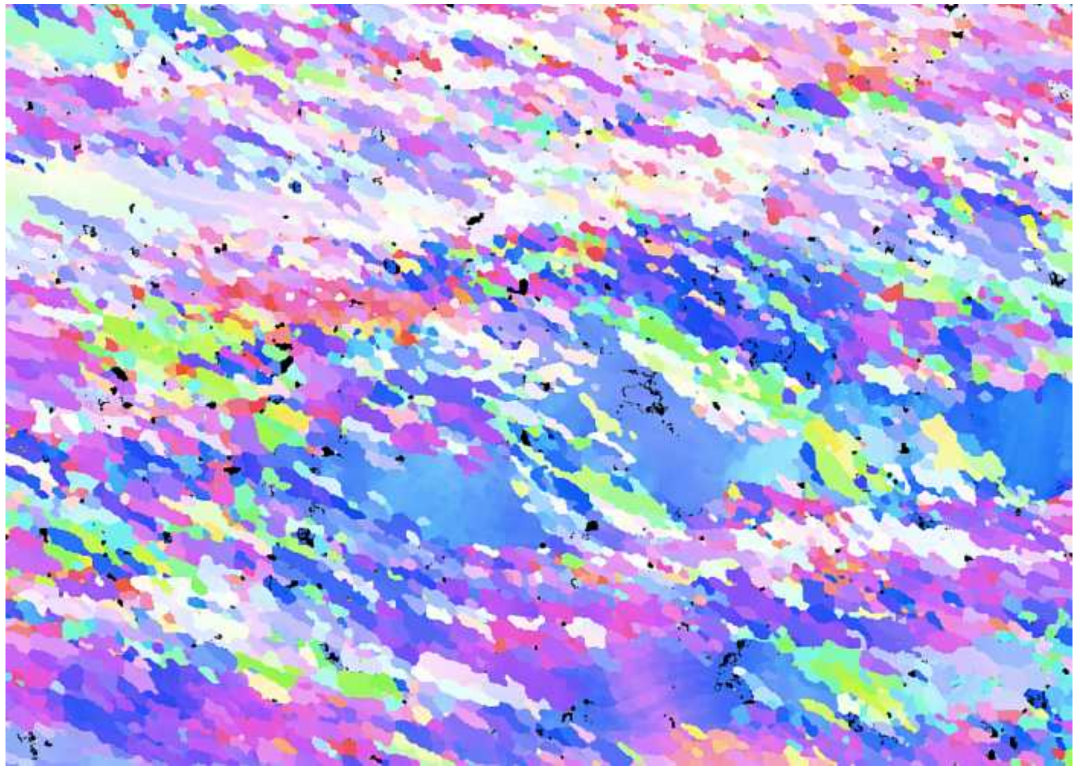
c-axis orientation

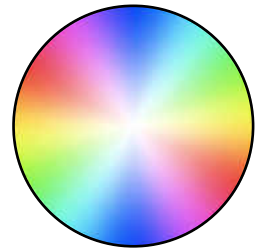
segmentation

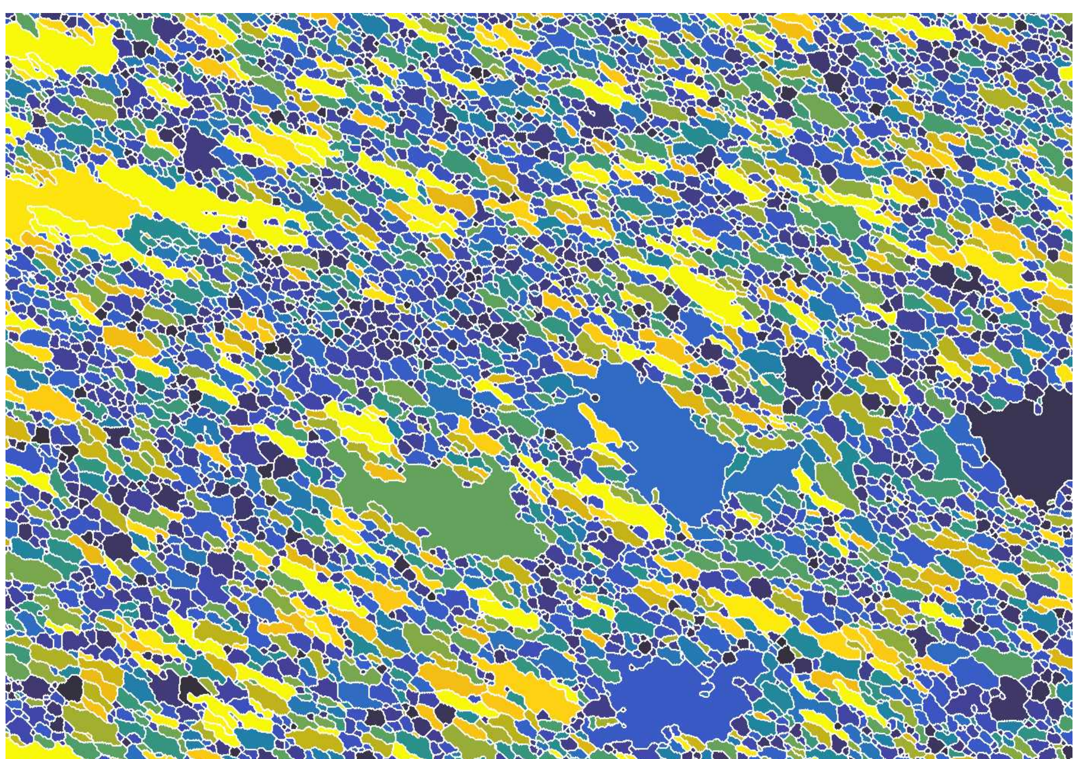


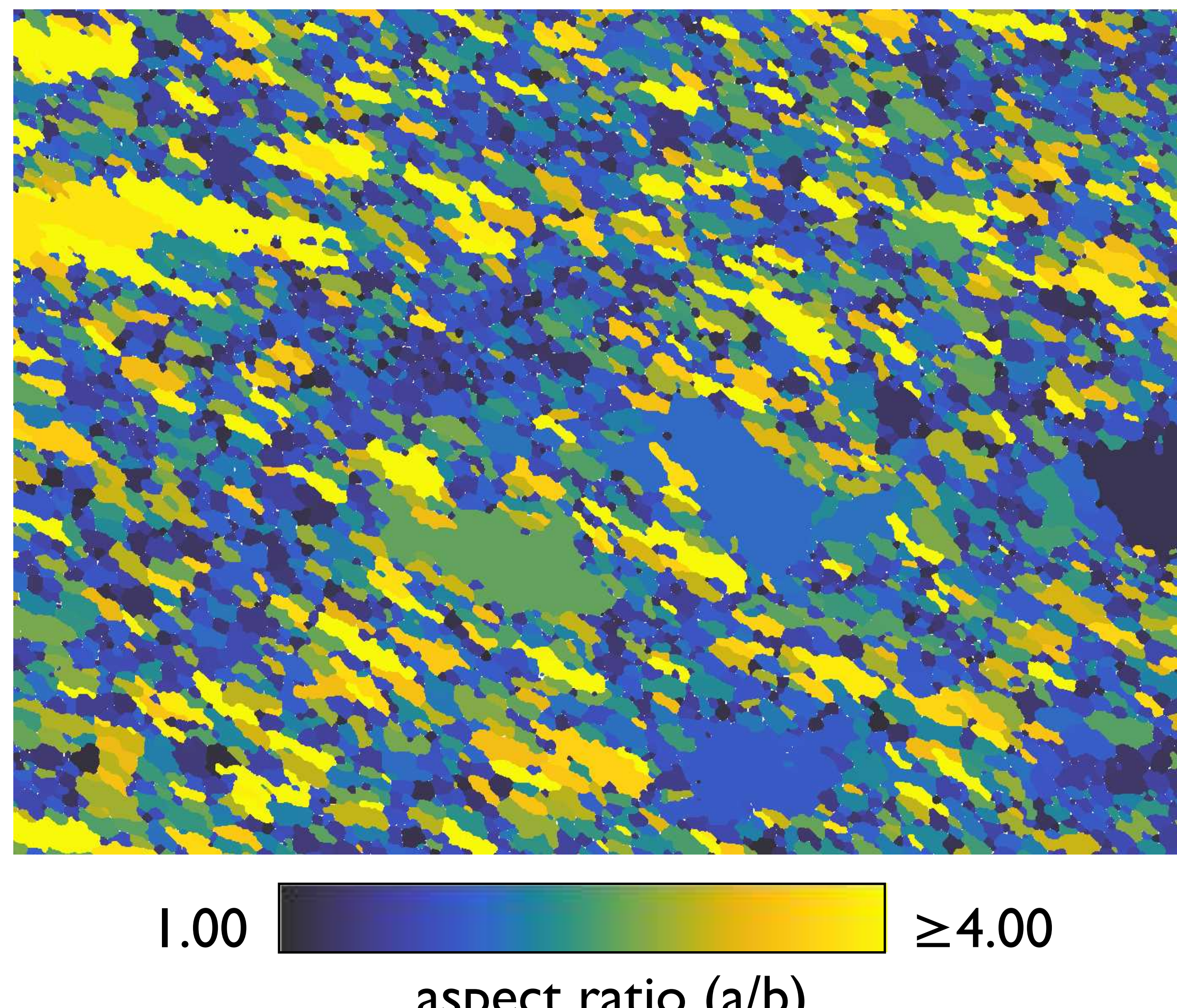
property mapping

property mapping – aspect ratio

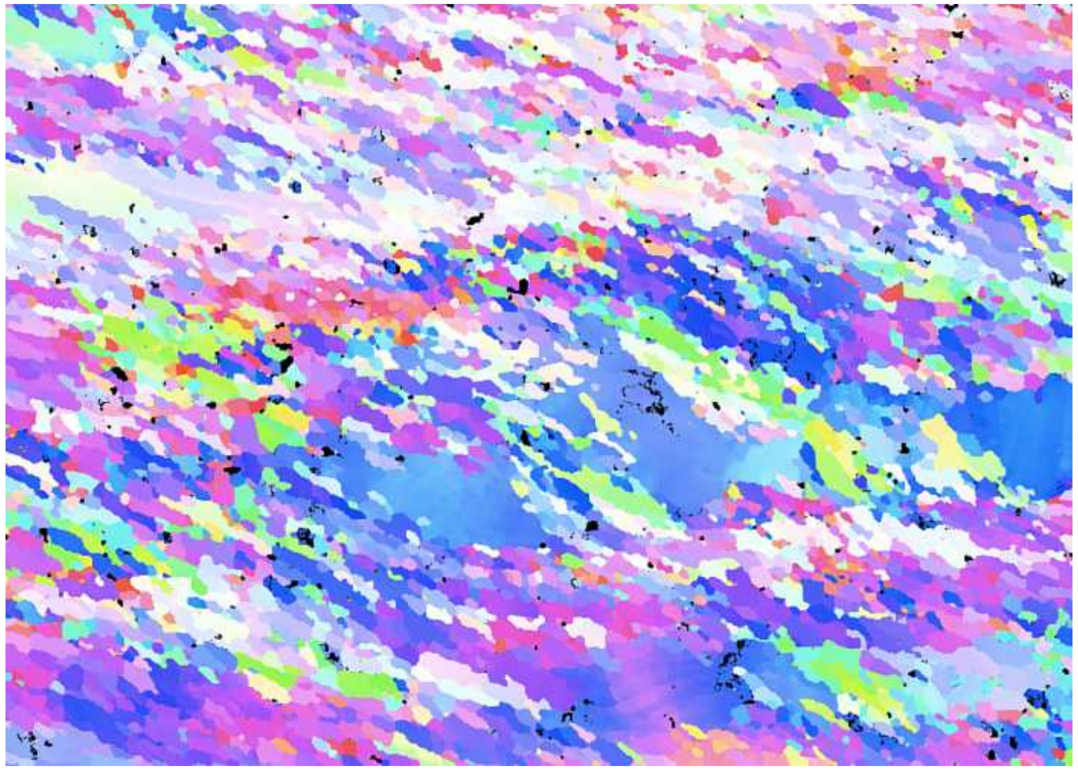


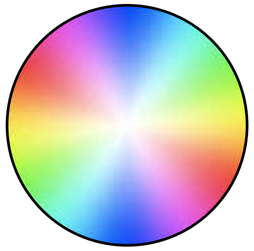


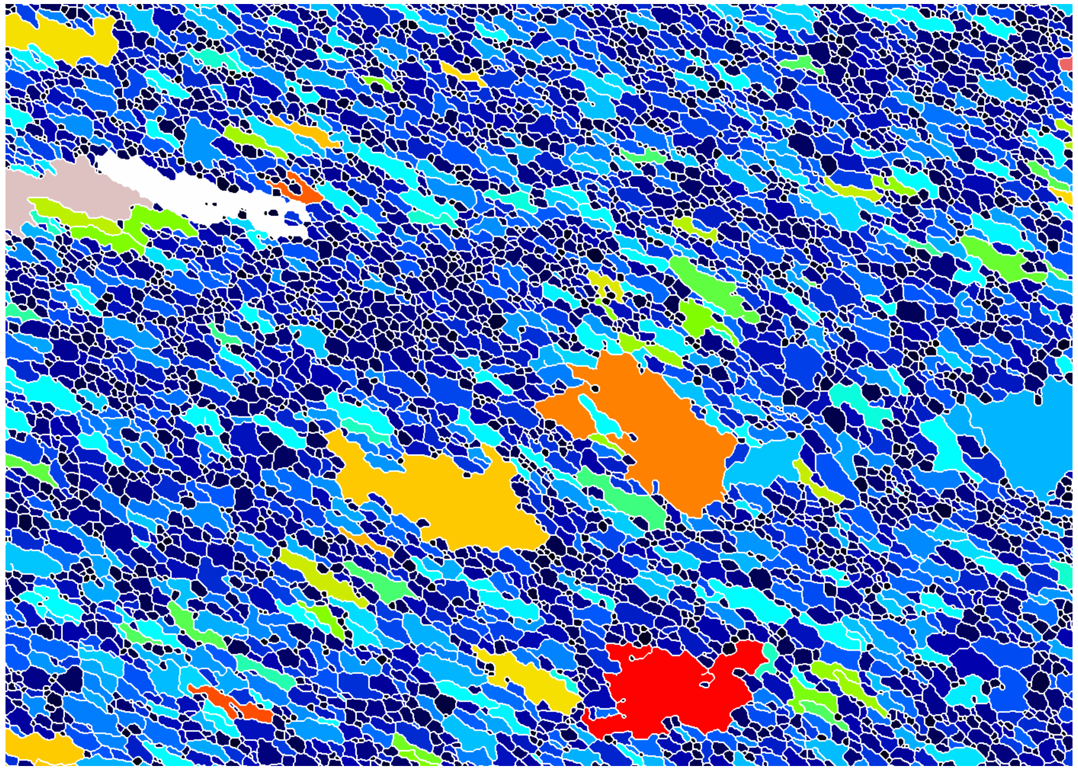


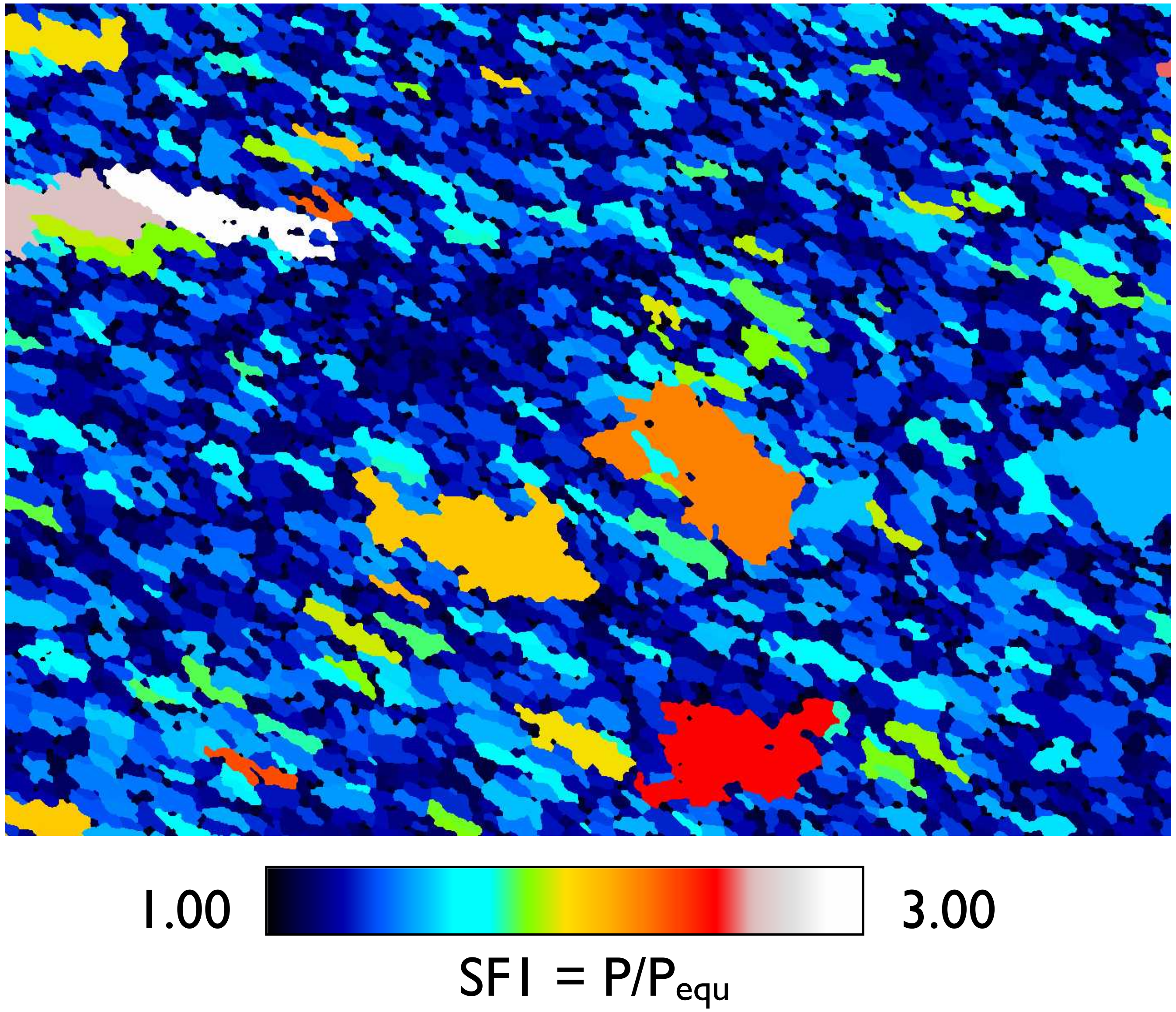


property mapping – shape factor

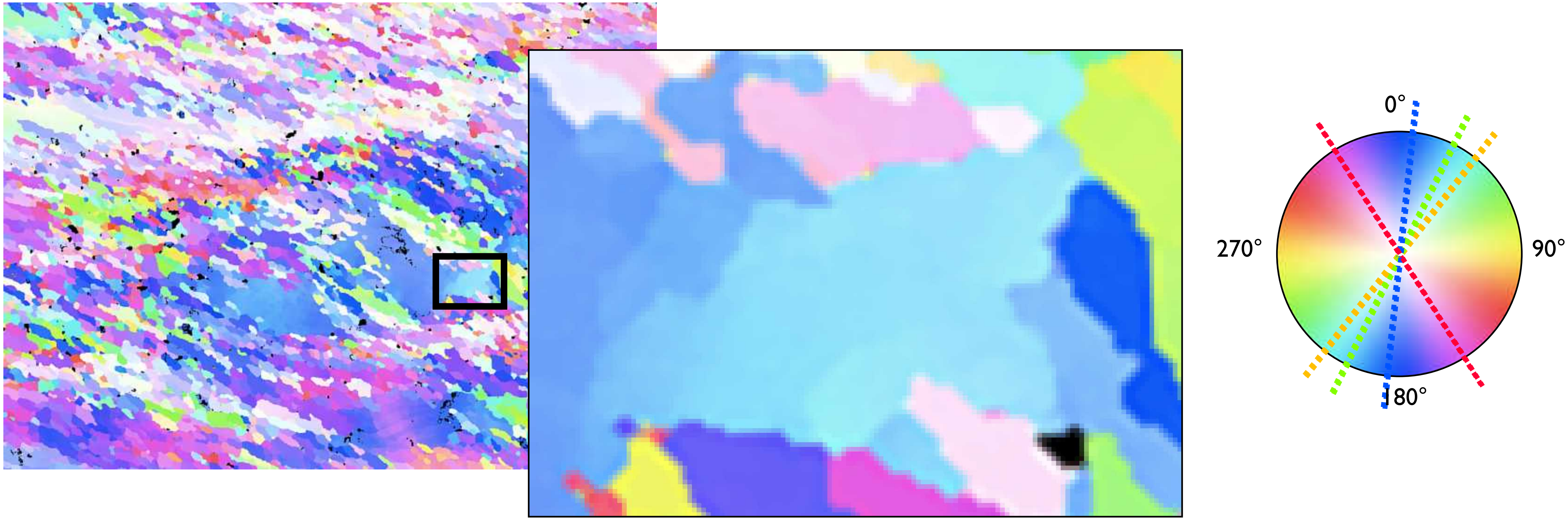


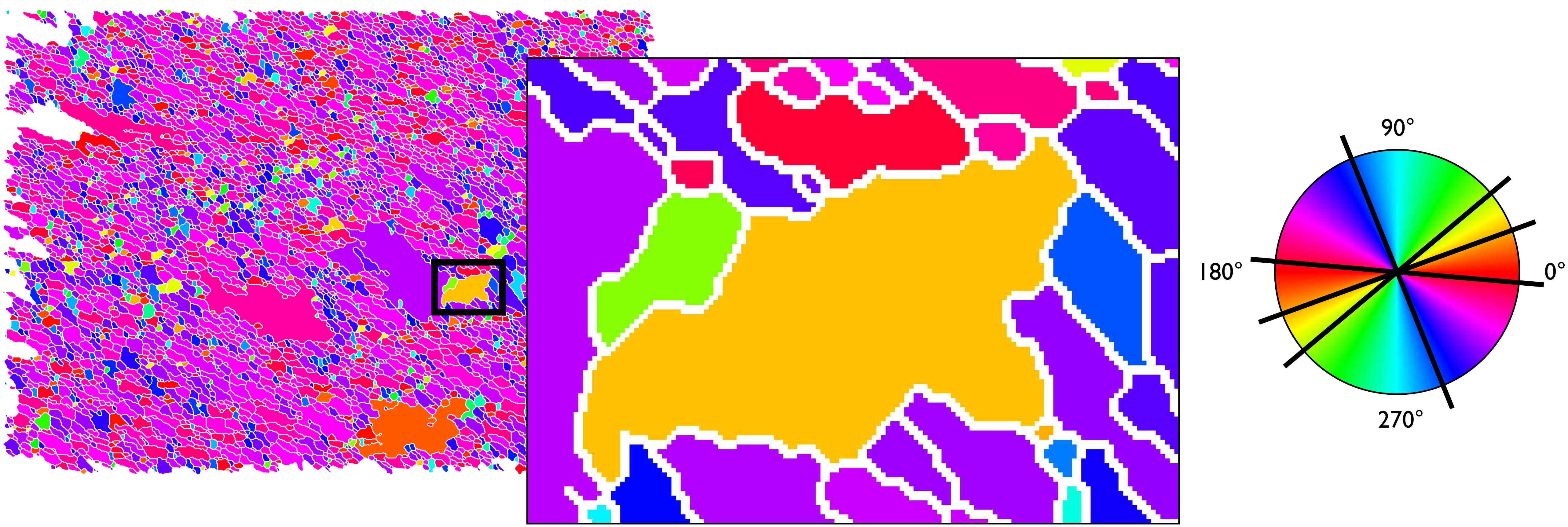






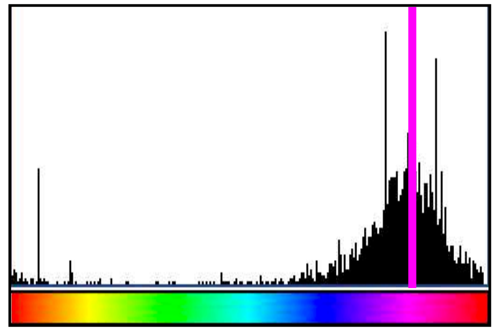
property mapping – LA orientation



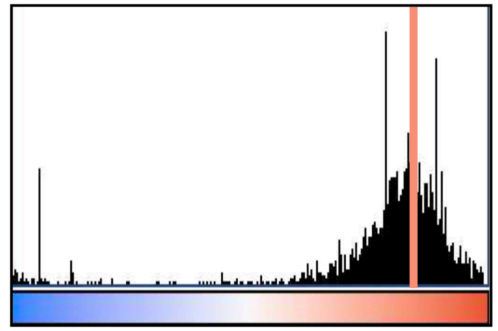


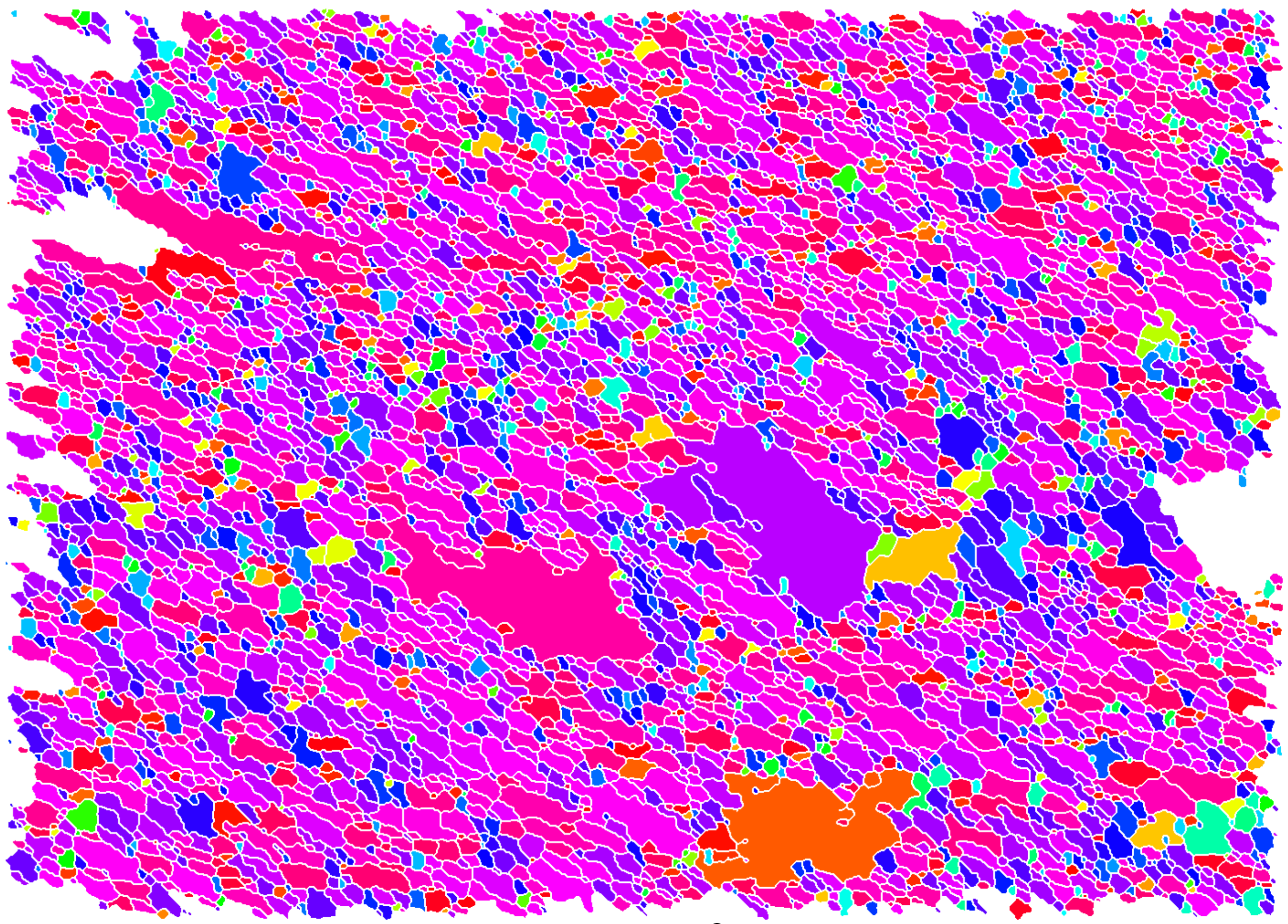
choice of LUT

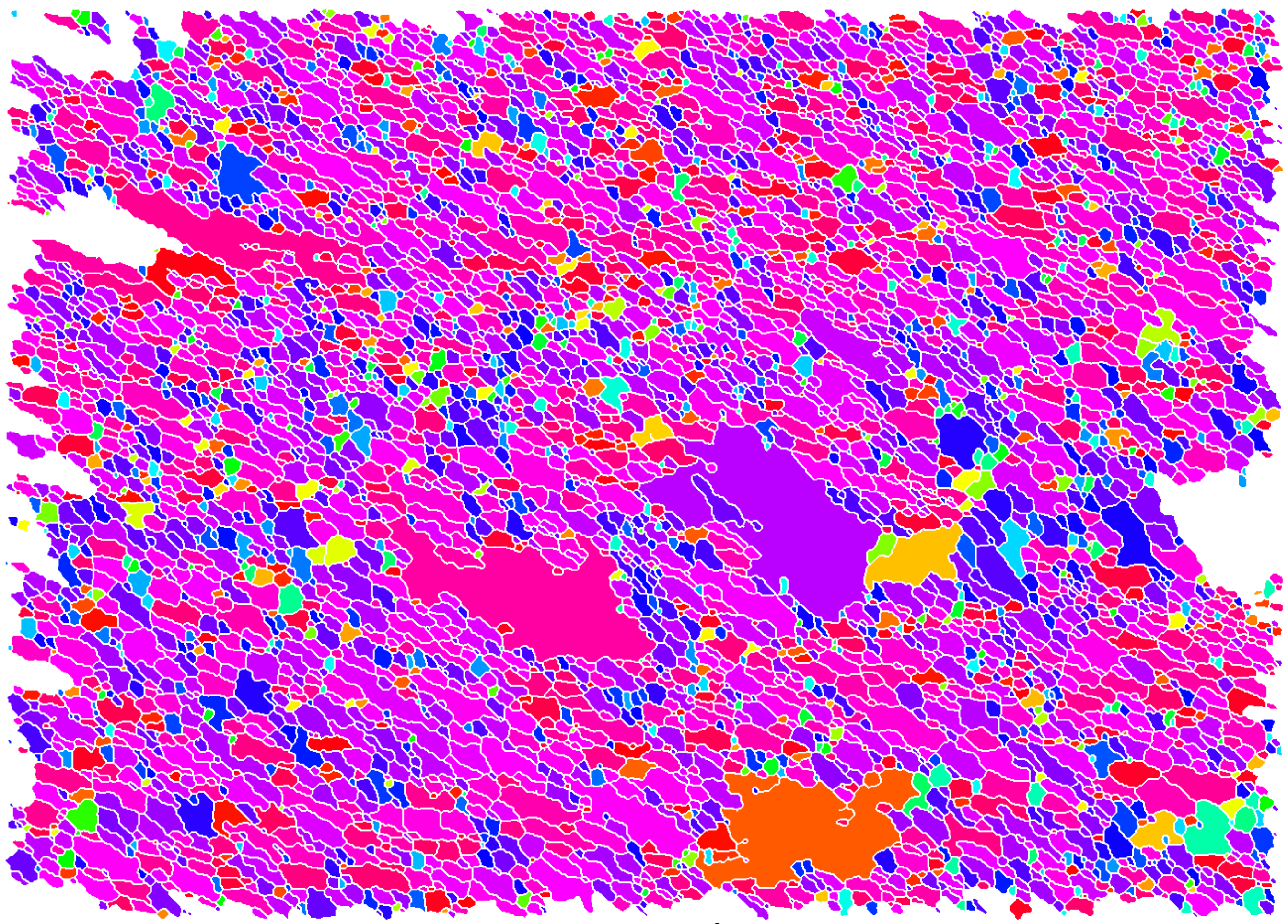
Spectrum
(circular LUT)
red = horizontal

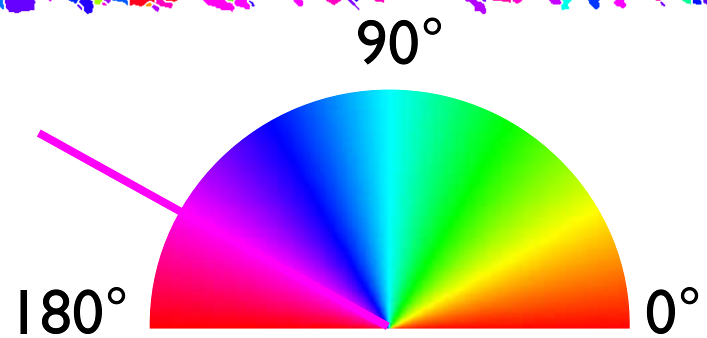


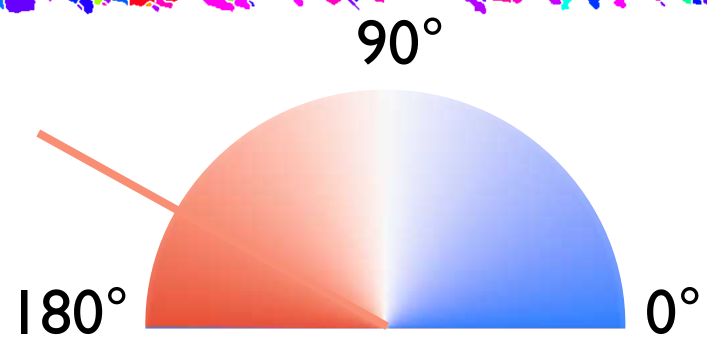
Blue-Red
white = horizontal
bluish = right-leaning
reddish = left-leaning





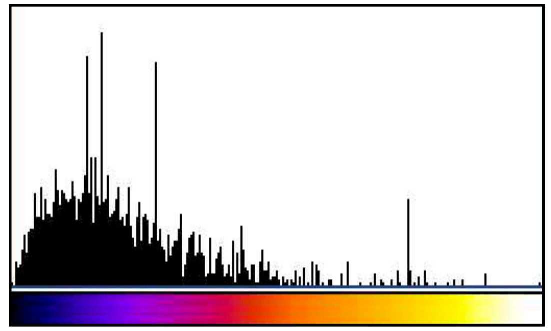


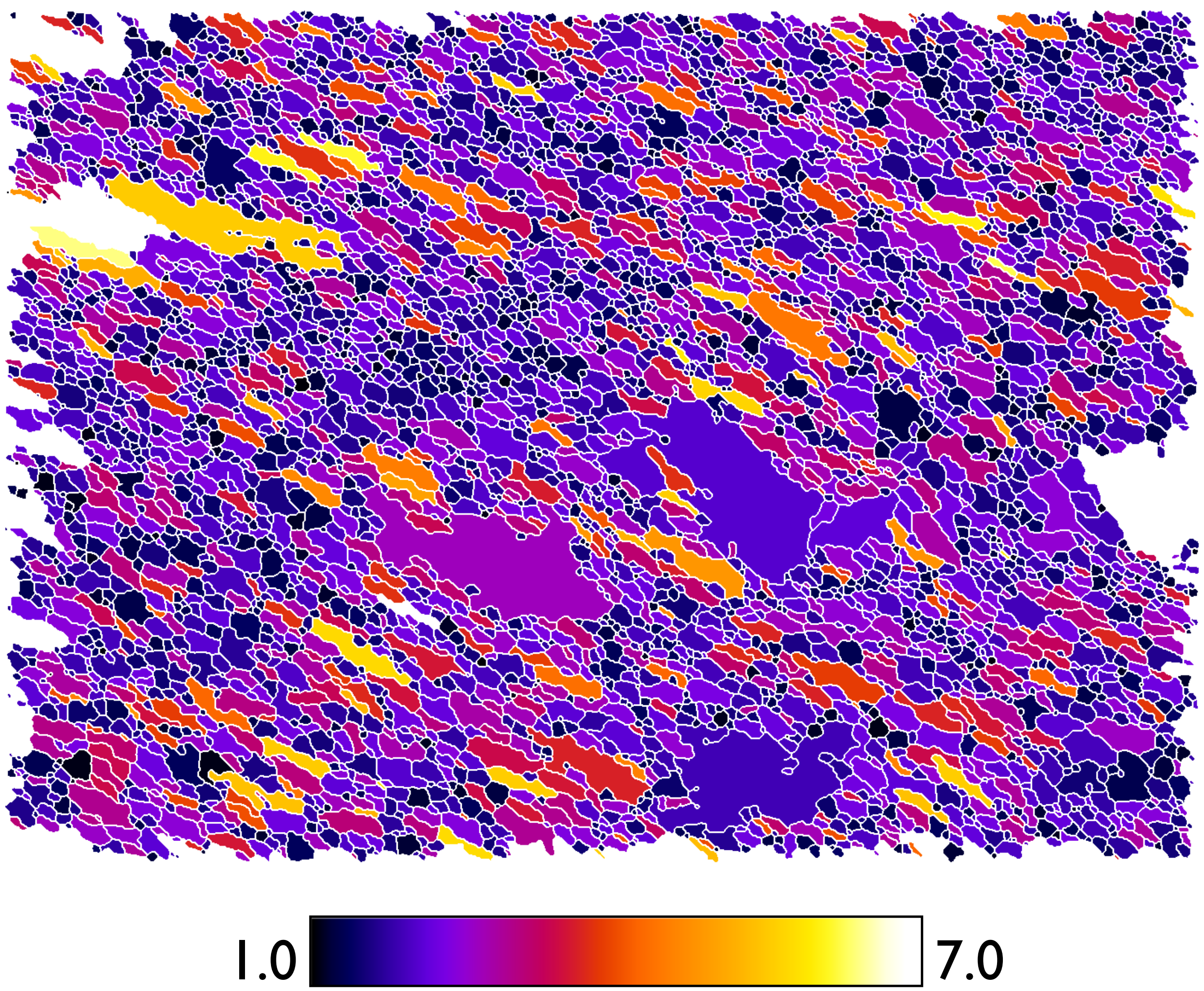




choice of property a/b versus b/a

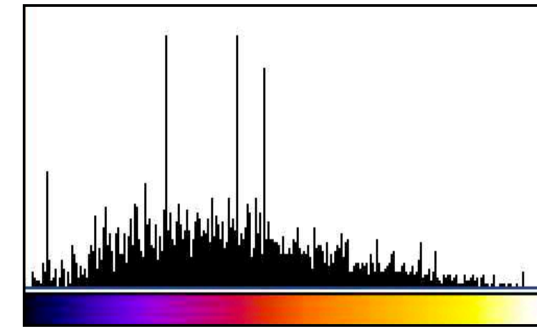
Fire
purple = round
yellow = elongate

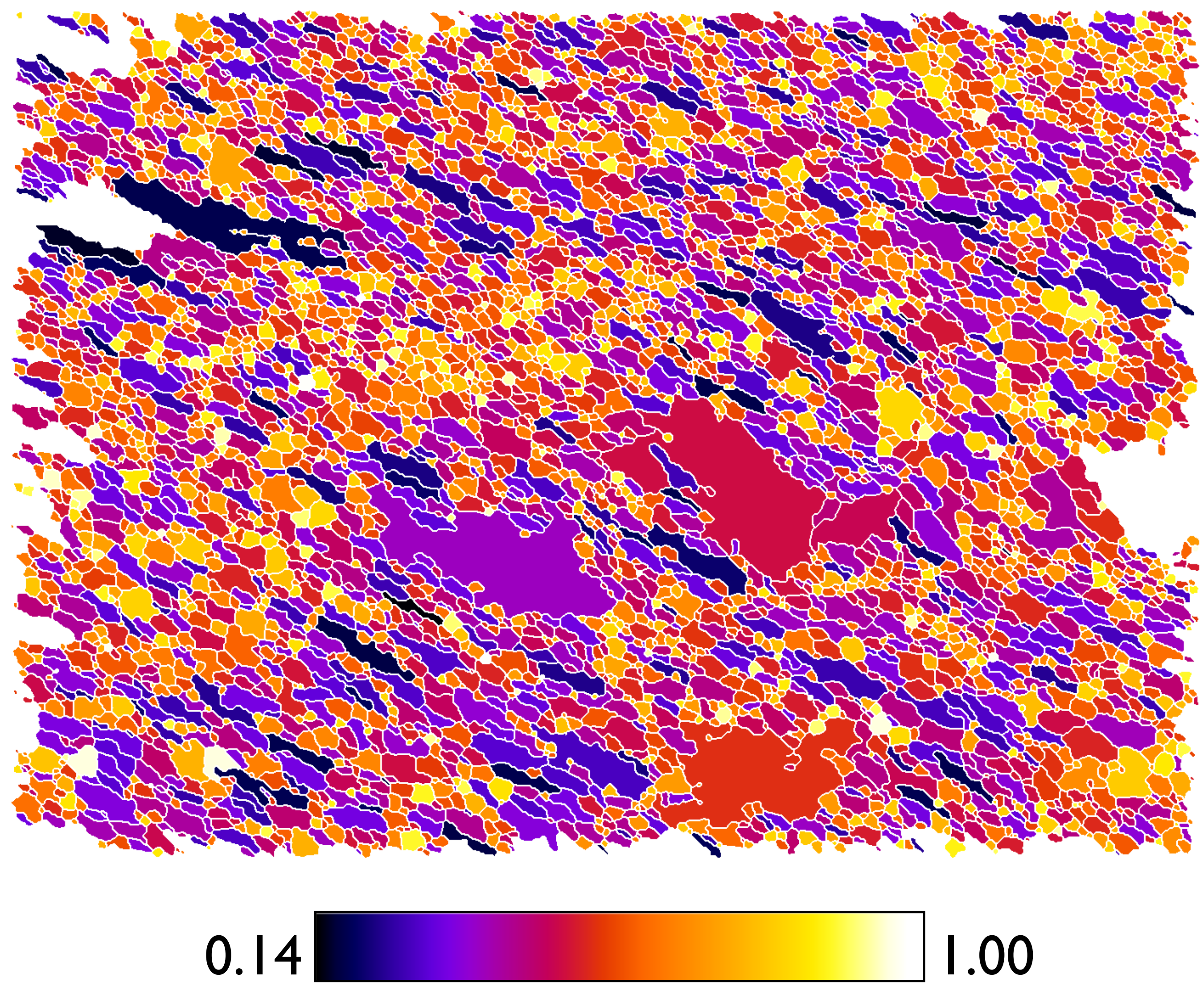




aspect ratio = long / short

Fire
purple = elongate
yellow = round





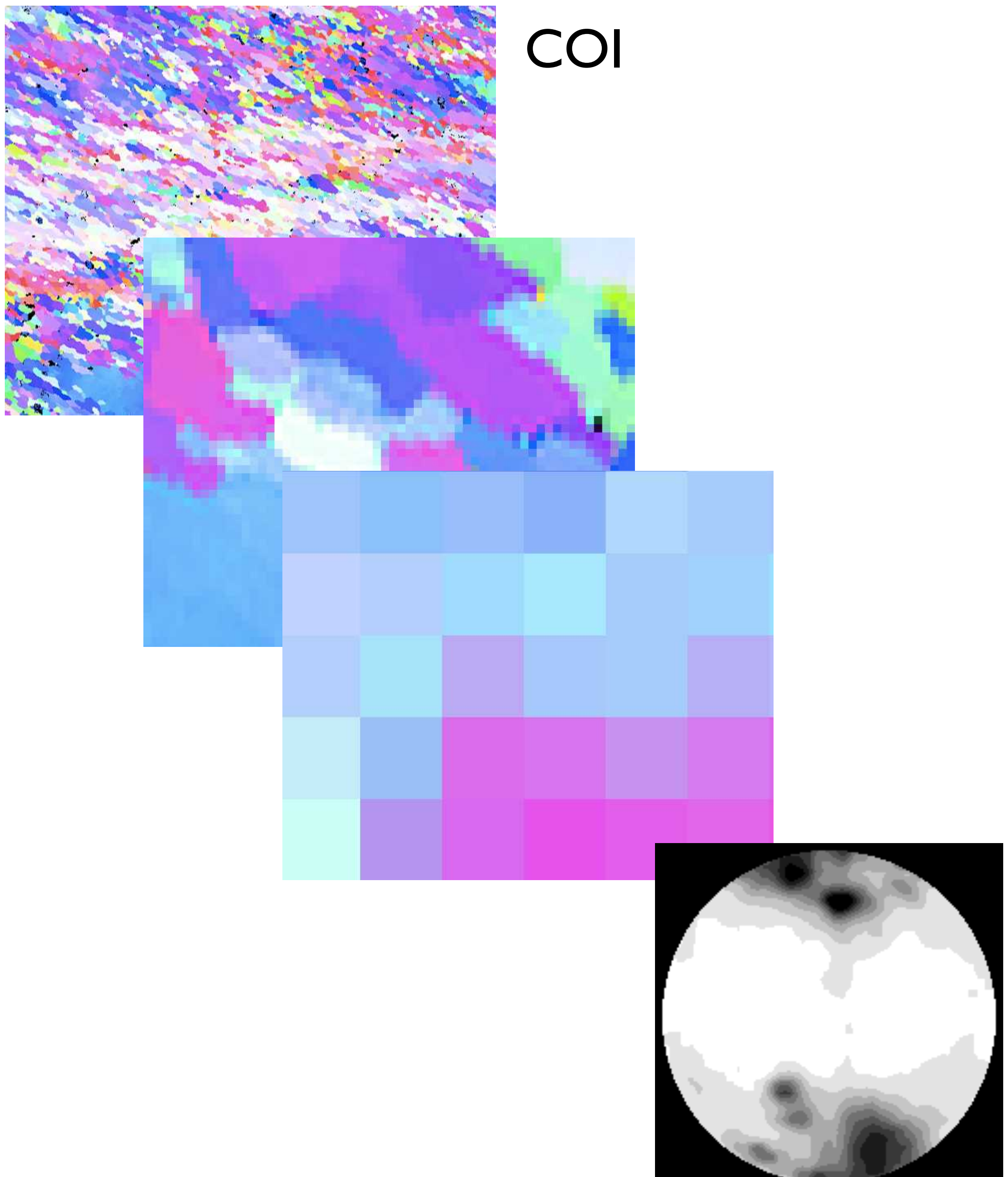
axial ratio = short / long

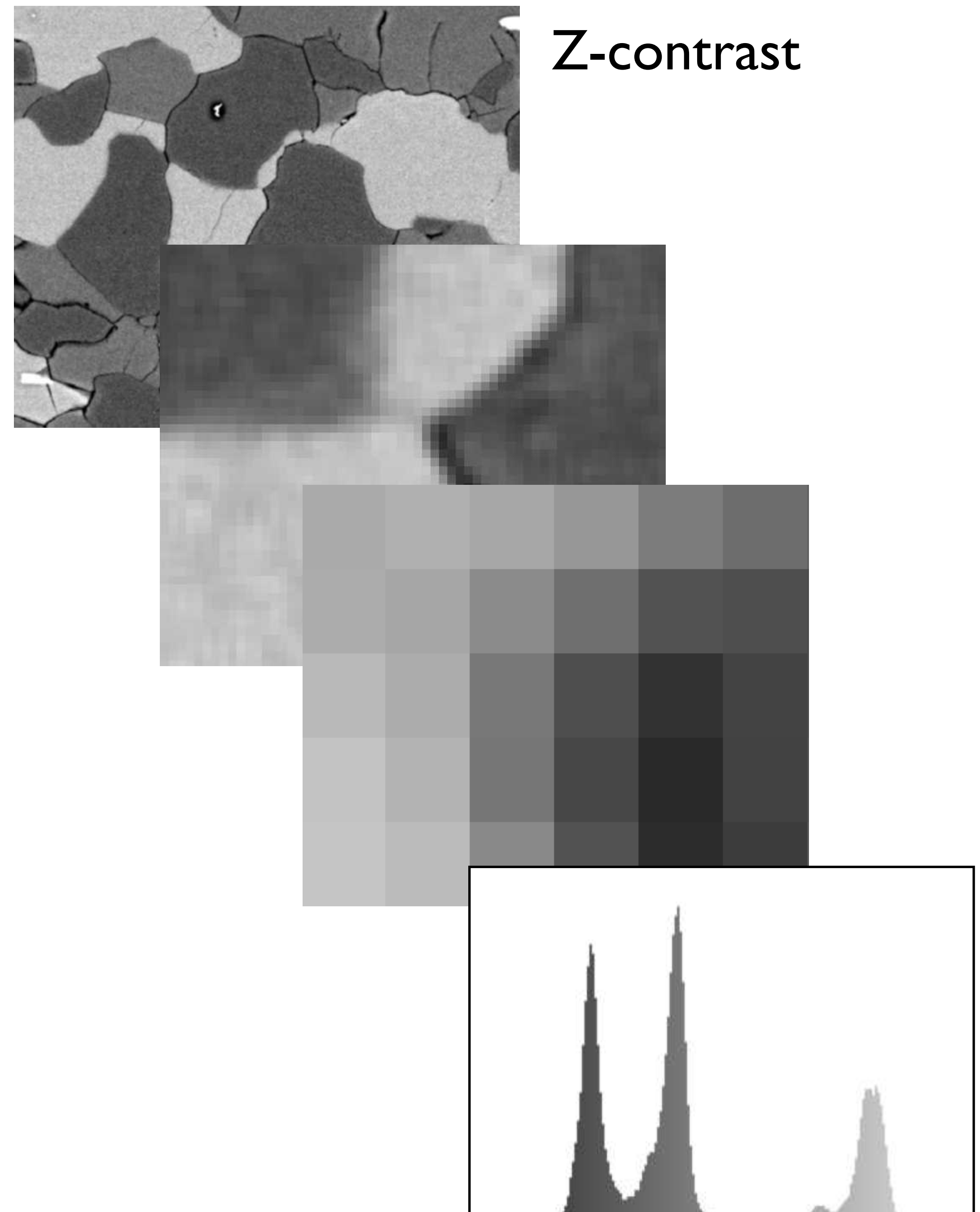
extrapolating to 3D

properties – defined at each pixel

$A_{phase}/A_{total} = V_{phase}/V_{total}$

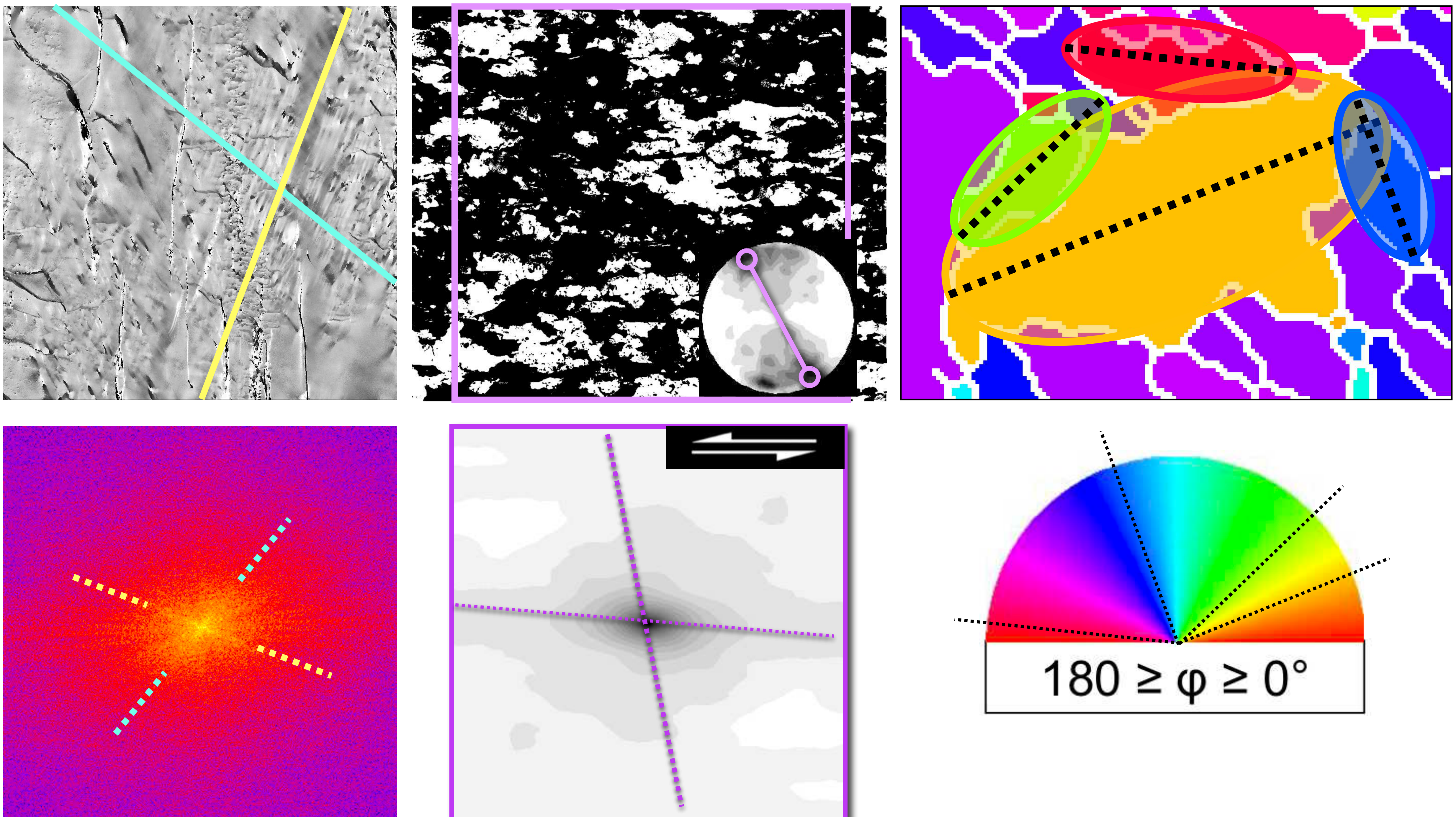
$A_{phase}/A_{total} = V_{phase}/V_{total}$





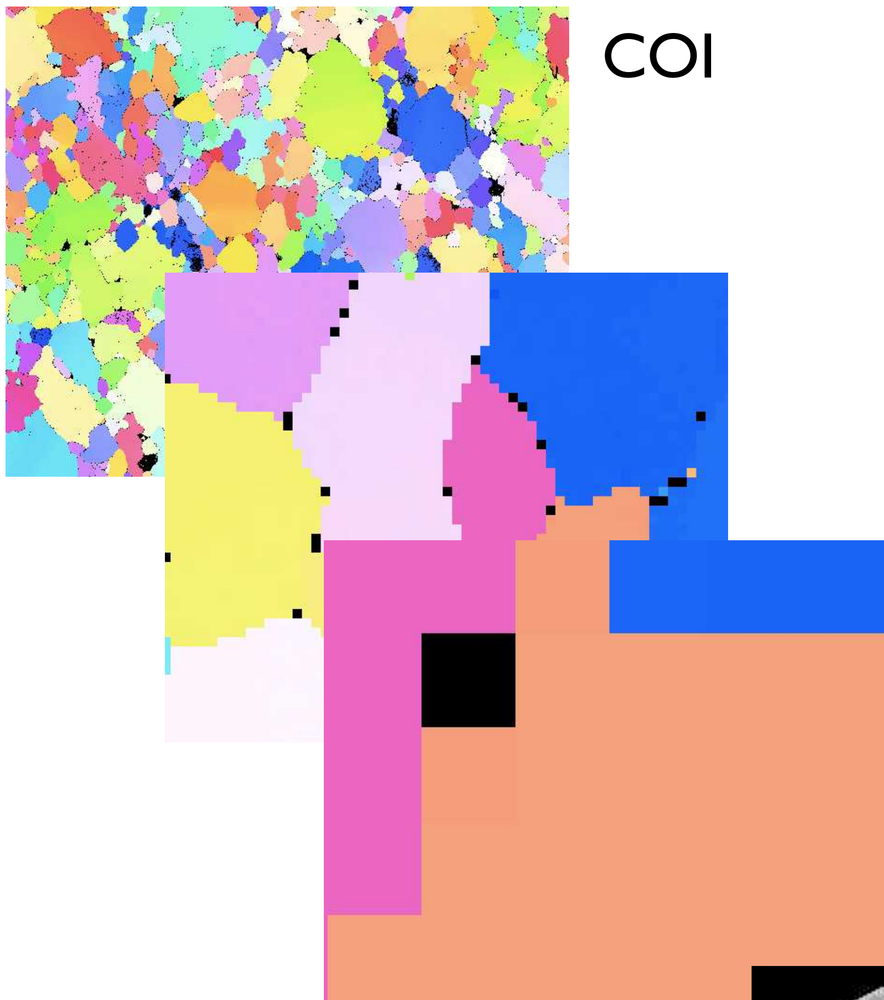
properties – defined in 2D ...

orientation in 2D does not define orientation in 3D



properties – defined at each grain

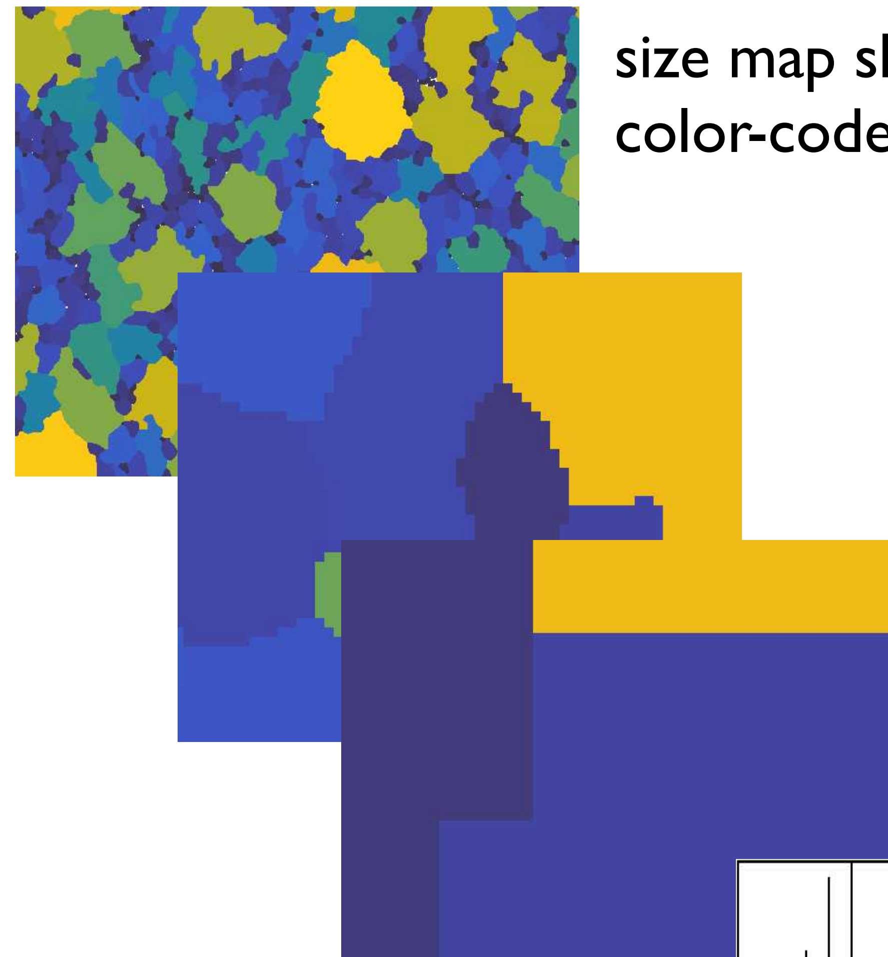
$$A_{phase}/A_{total} = V_{phase}/V_{total}$$



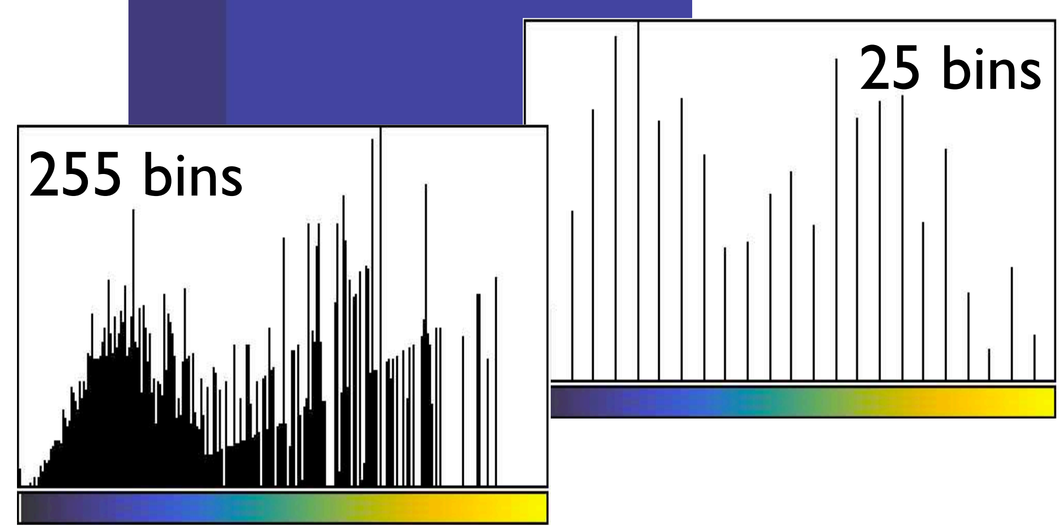
COI

quartz (0001)

$$A_{grainsize}/A_{total} \neq V_{grainsize}/V_{total}$$



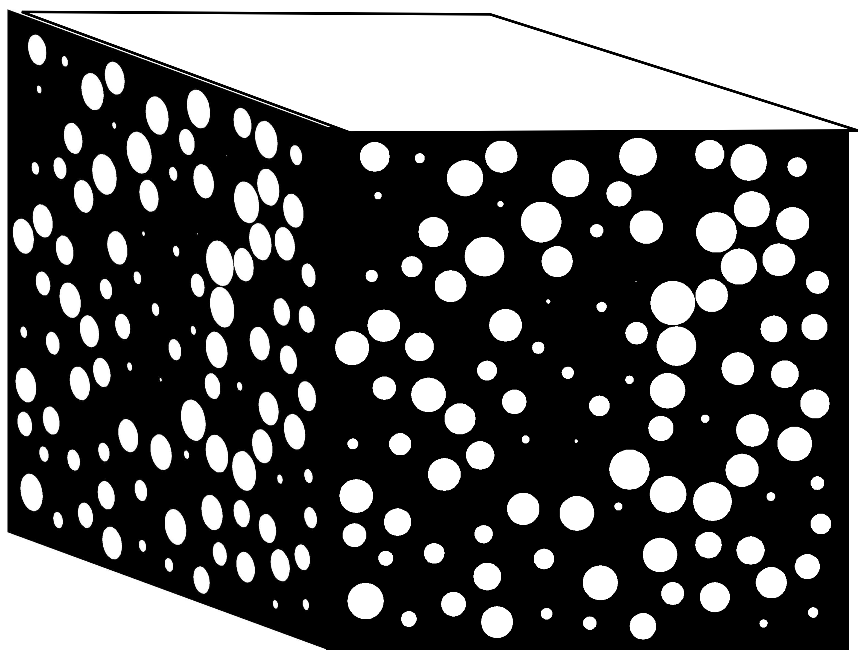
size map showing
color-coded diameters



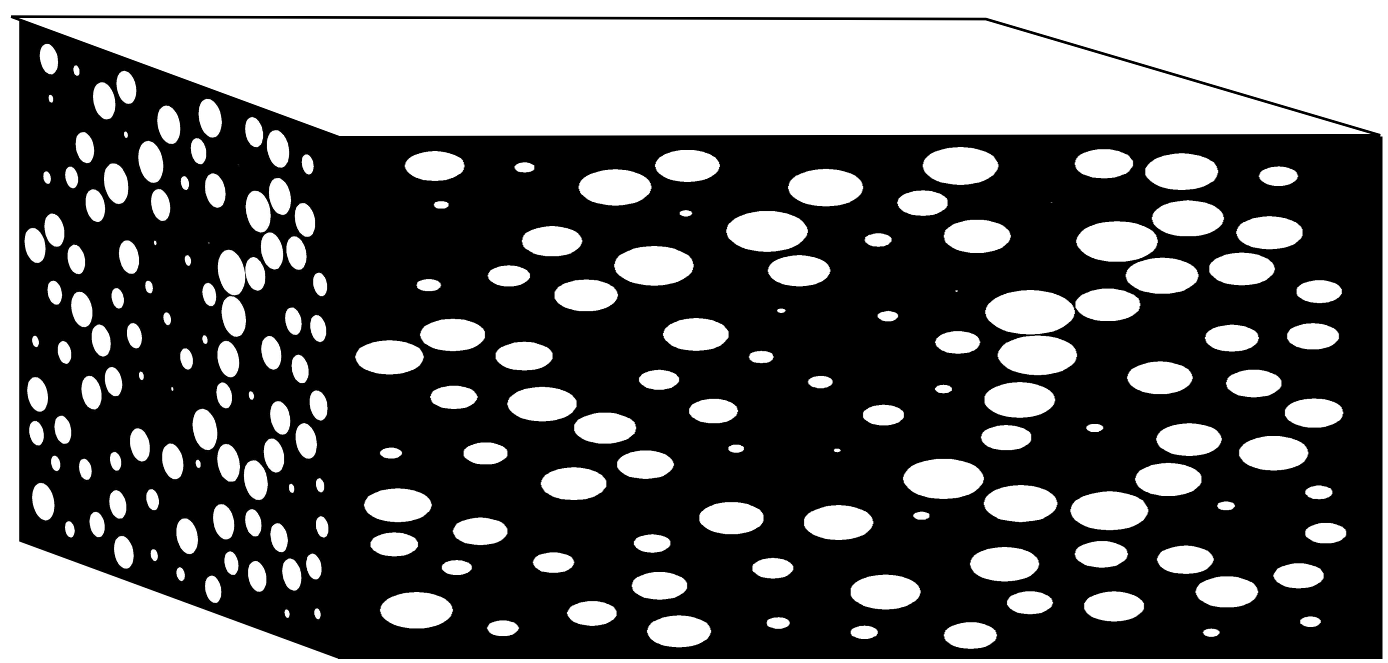
area-weighted histogram of diameters

problems of anisotropy ...

... when estimating
... volume fractions
... 3D grain size

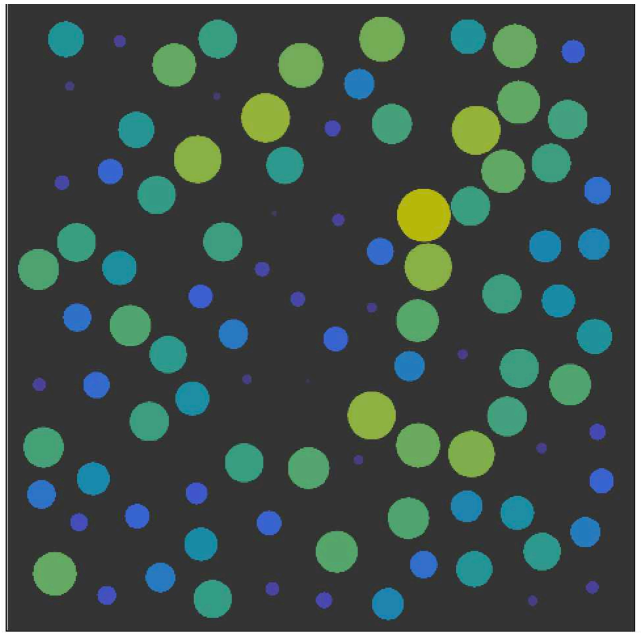


isotropic

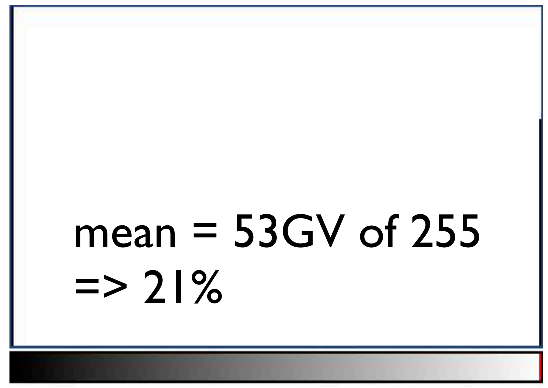


anisotropic

problem ? vol(%) NO, grainsize YES

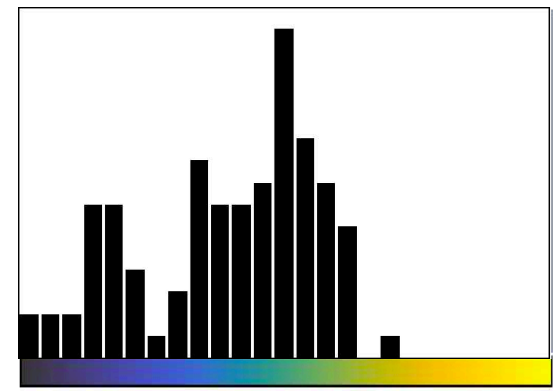


yz section

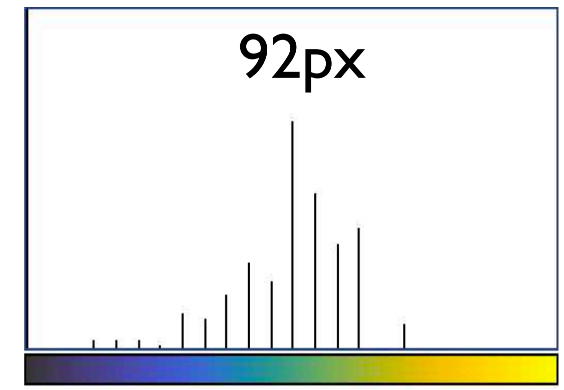


A/A_{tot} of grains = 21%
V/V_{tot} of grains = 21%

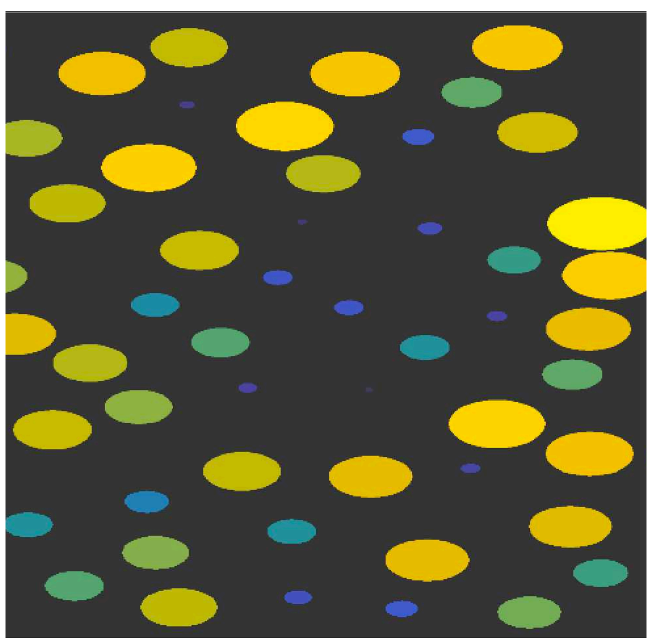
mean = 69



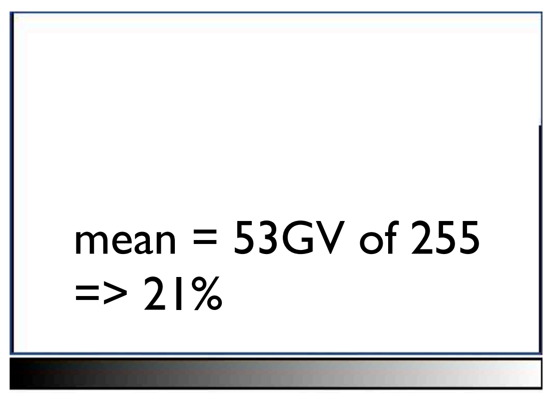
h(d)



area-weighted h(d)

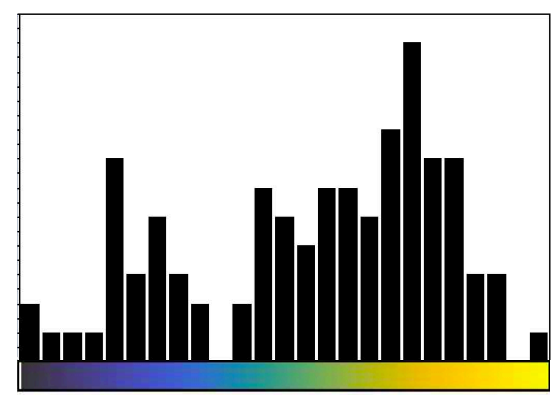


xz section

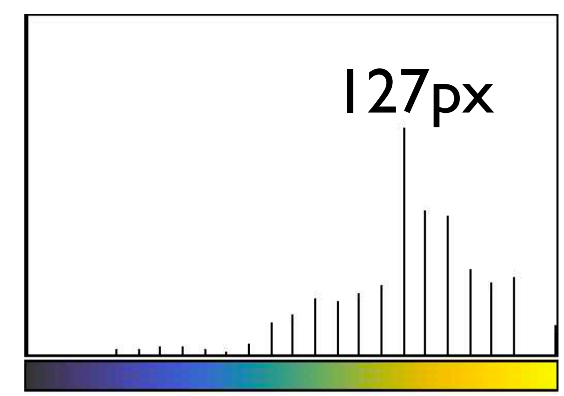


A/A_{tot} of grains = 21%
V/V_{tot} of grains = 21%

mean = 97



h(d)



area-weighted h(d)

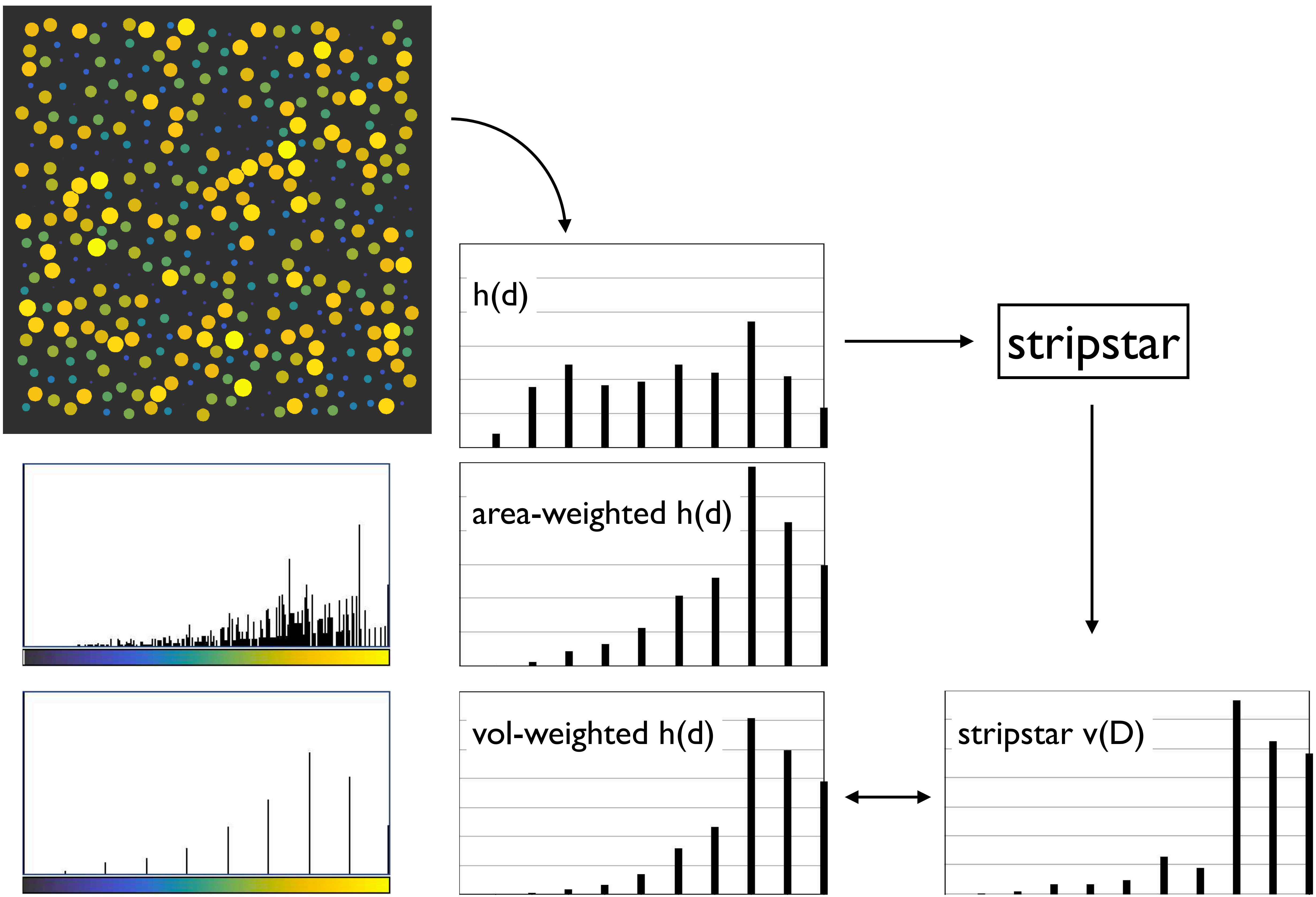
0  180px

equivalent diameter

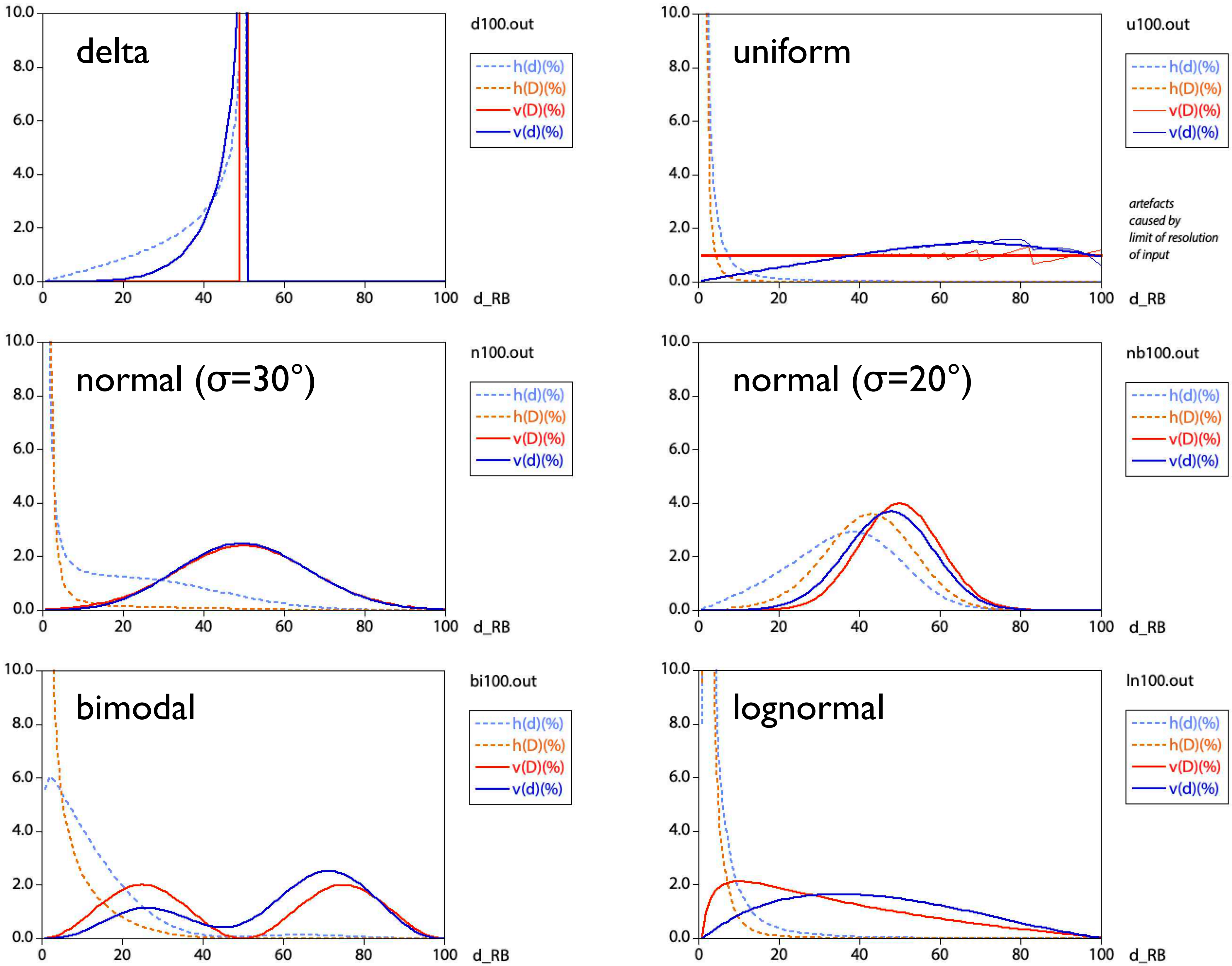
$V(\%)_{aniso} = V(\%)_{iso}$

$D_{aniso} : D_{iso} = \sqrt{2} : 1$

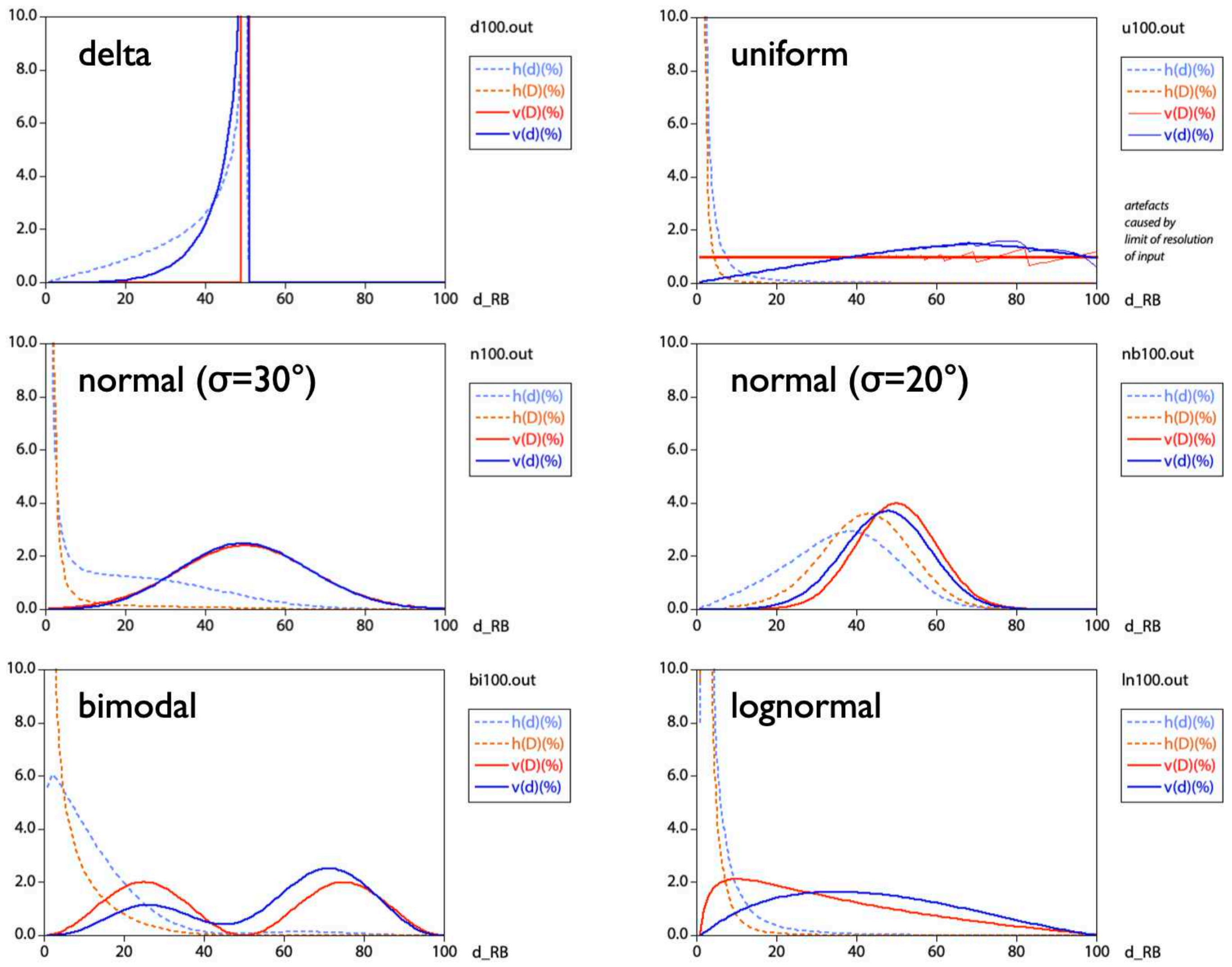
estimating 3D size from 2D sections

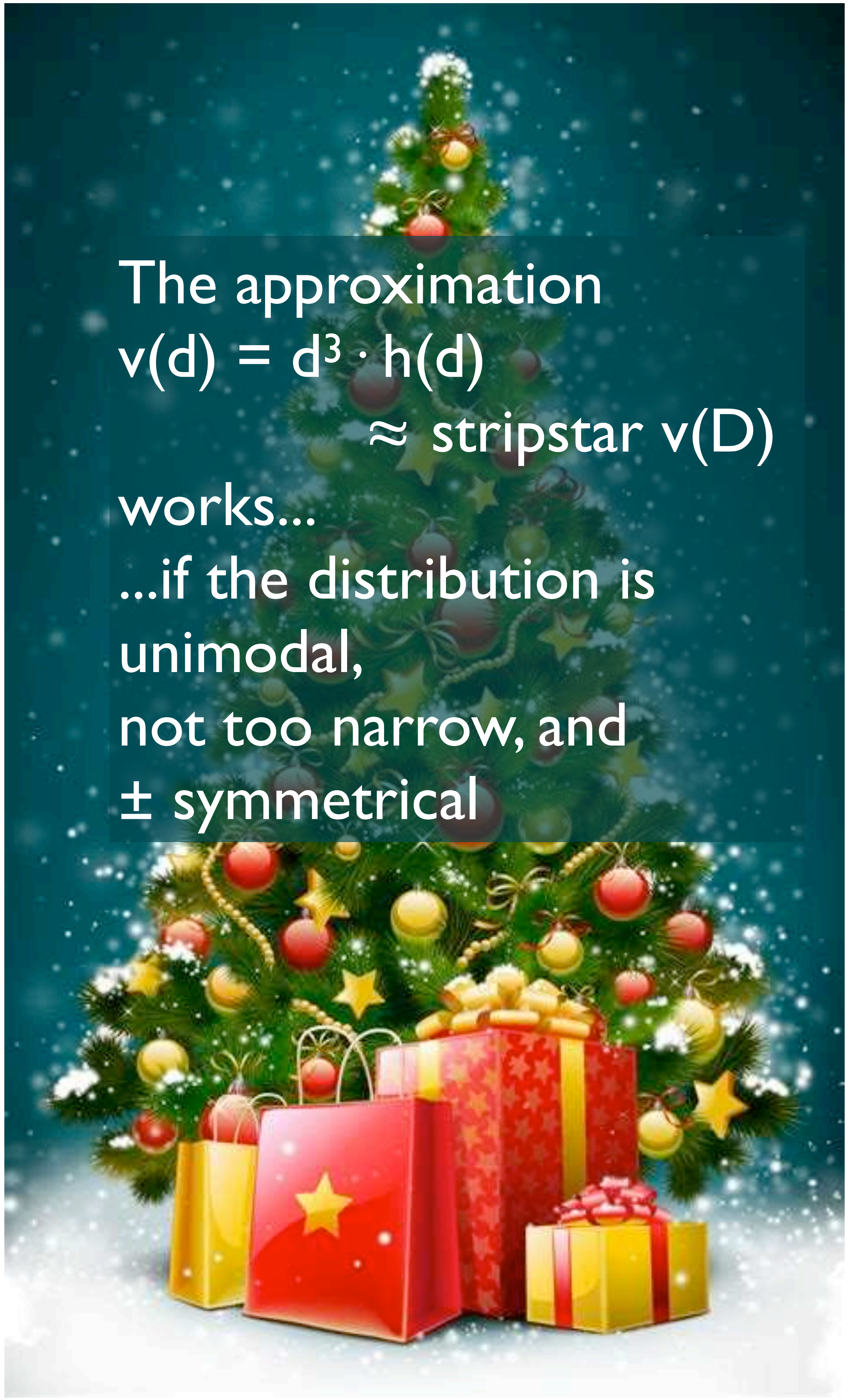


vol(d) ≠ stripstar v(D)



a Christmas present ...





The approximation
$v(d) = d^3 \cdot h(d)$
≈ stripstar v(D)
works...
...if the distribution is unimodal,
not too narrow, and
± symmetrical

summary

the CIP method...

- is useful for quartz, calcite, ice, especially if coaarse grained
- is based on regular polarisation microscopy and open source imageJ
- allows prototyping of analysis of orientation images
- provides insight in general concepts of orientation imaging
- is an ideal complement to EBSD
- is ... inspiring ...!