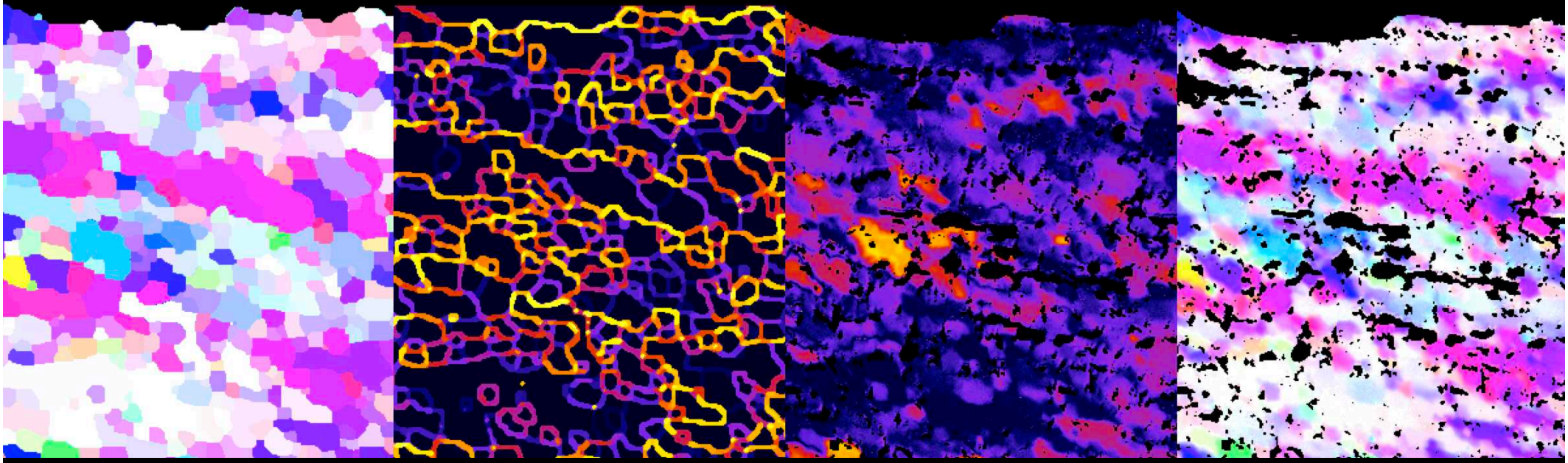
DRT 2022 Catania, July 5-7, 2015

from c-axis to grainsize – my last 50 years of image analysis

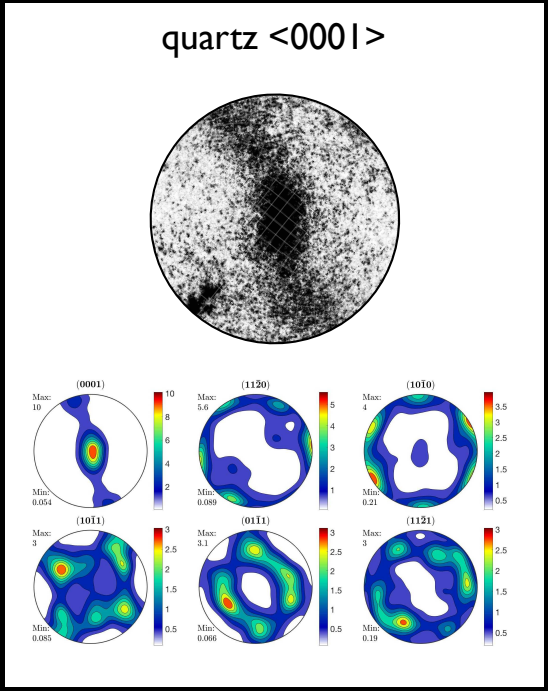


renee.heilbronner@unibas.ch

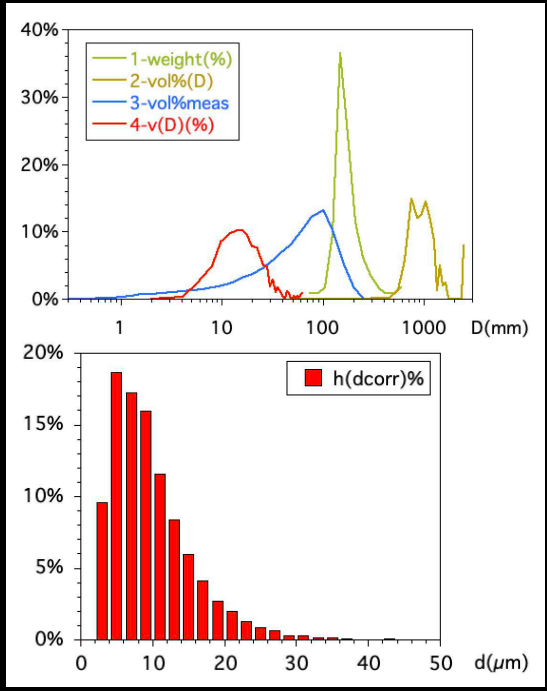
"The Deformation of Mountains Must Indeed Be Examined With the Microscope"

this talk will be about ...

c-axis



grain size



... and the use of image analysis

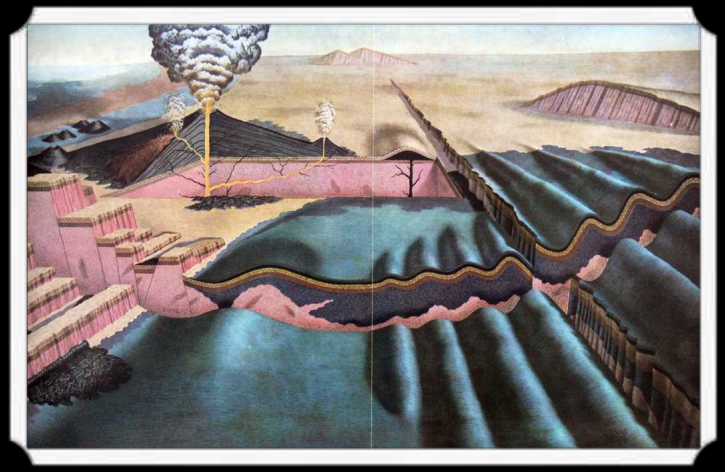
I

decades ago –

before microstructure and

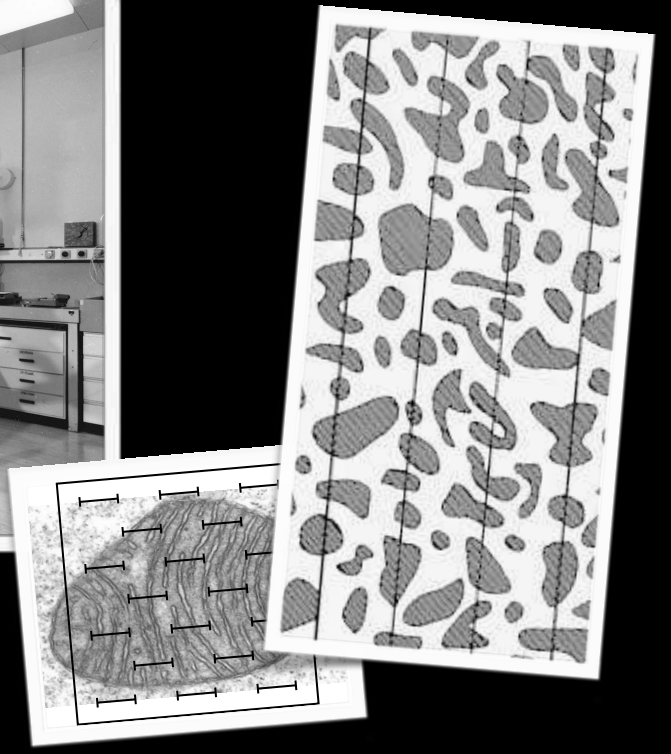
texture analysis went digital

when I was young ...



my view of geology

my start in geology



stereology and point counting ...

... or how to go from 2D to 3D

find volume density:

Achille Ernest Oscar Joseph Delesse
(1817-1881)

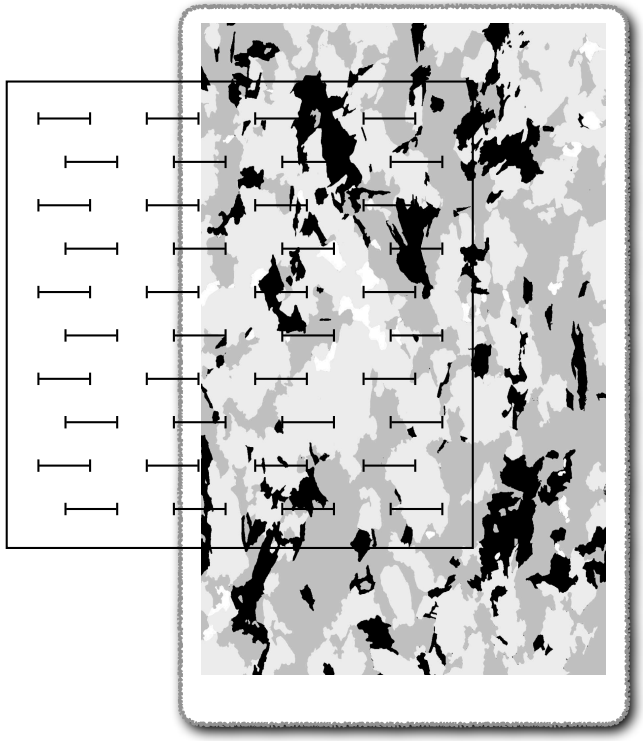
$$V_V = A_A$$

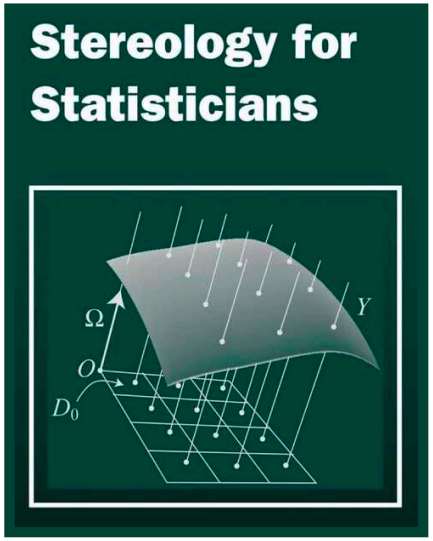
August Karl Rosiwal
(1860-1923)

$$V_V = A_A = L_L$$

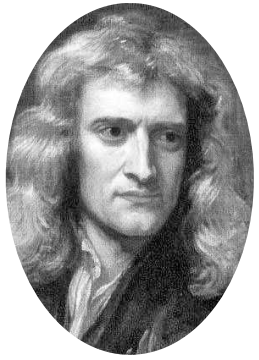
Andrei Aleksandrovich Glagolev
(1894-1969)

$$V_V = A_A = L_L = P_P$$

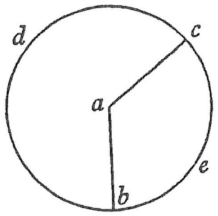


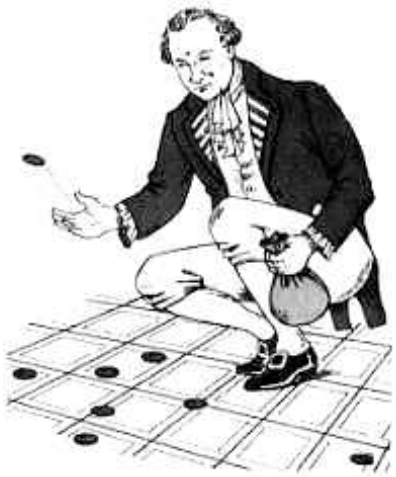


which is all about probabilities ...



I. Newton





Comte de Buffon

"Mémoire sur le jeu du franc-carreau"

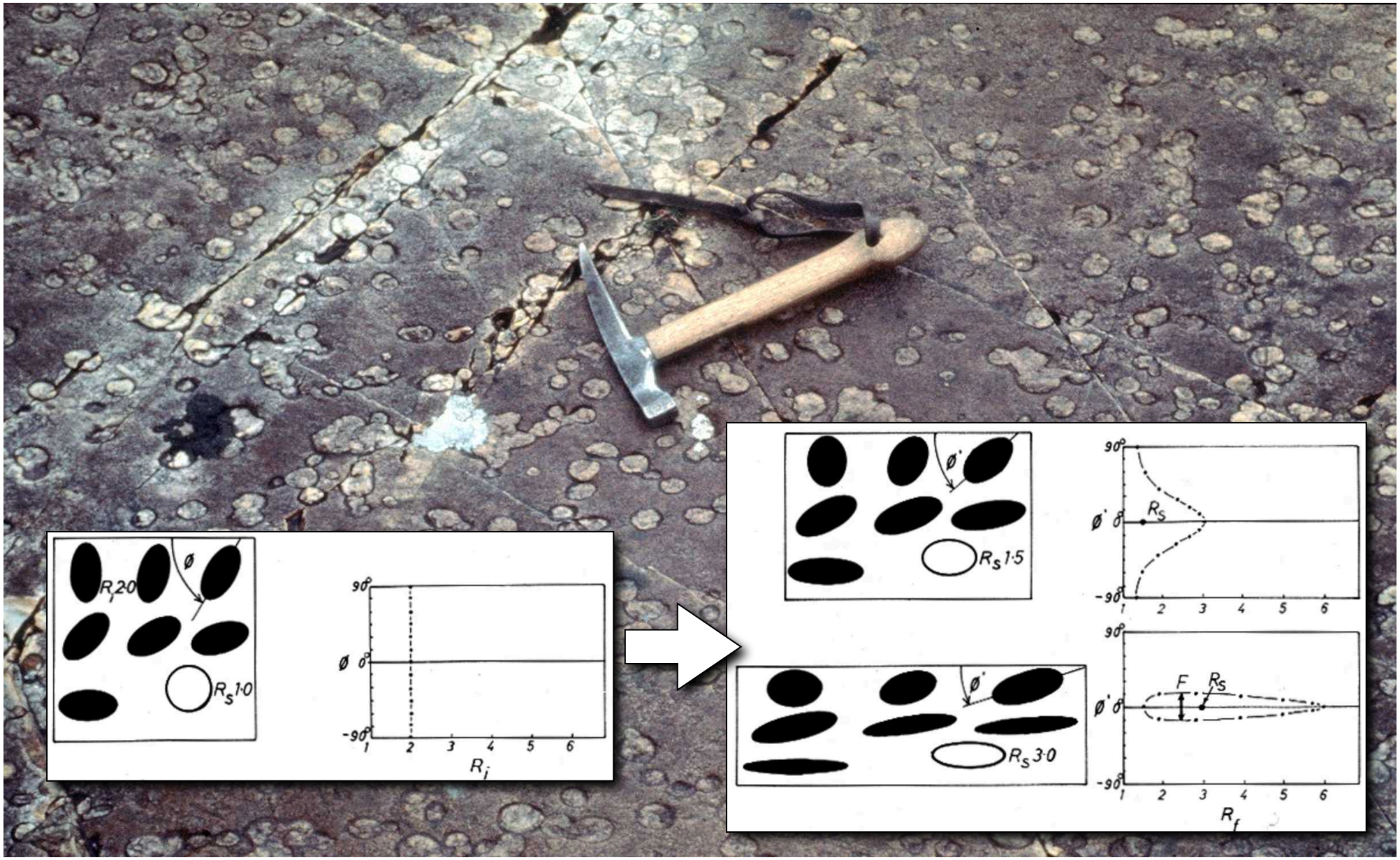
Blaise Pascal

Laplace

A.-L. Cauchy

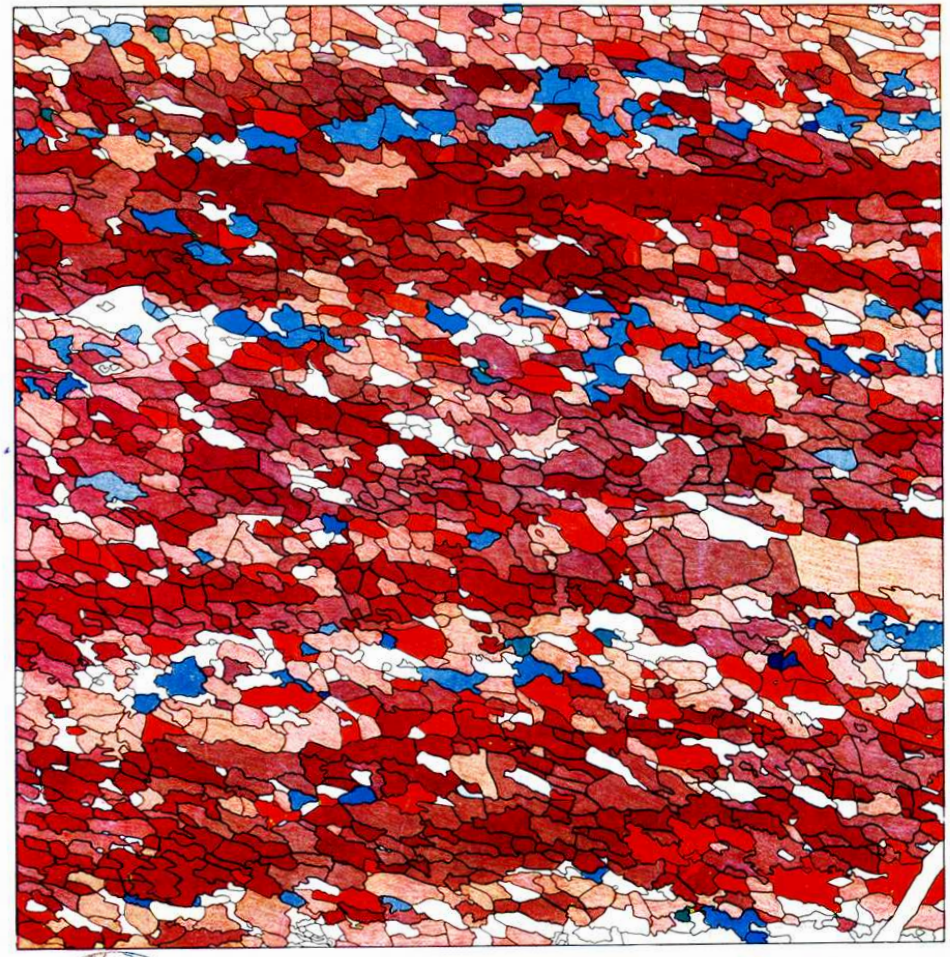
John Ramsay: R_f / φ ...

... or how to measure strain



Bruno Sander: AVA*) ...

... or how to map c-axis orientations



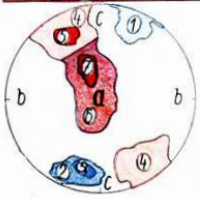
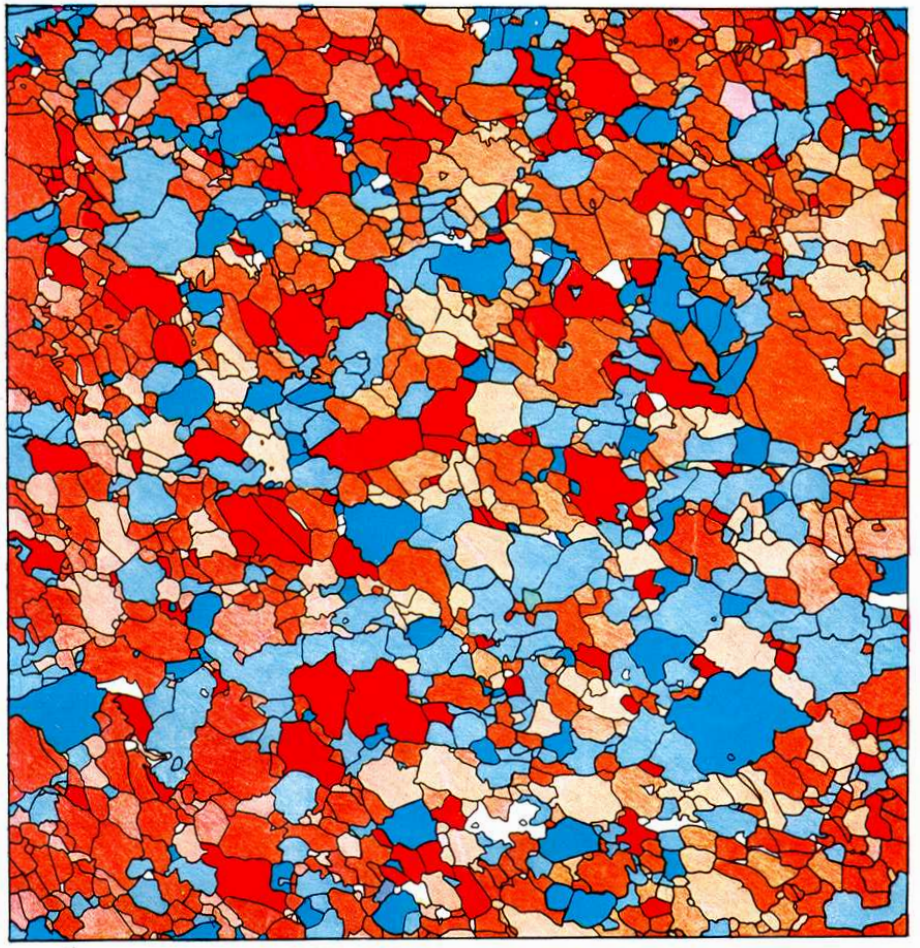


PLATE II.b. Quartzite, Rensenspitze, Bozen; section ⊥ r *a*;
1629 quartz-axes; ×90; A.V.A. (Ramsauer)

*) Achsenverteilungsanalyse



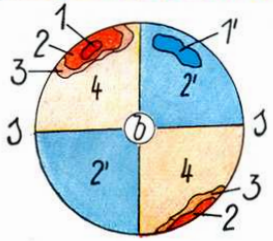
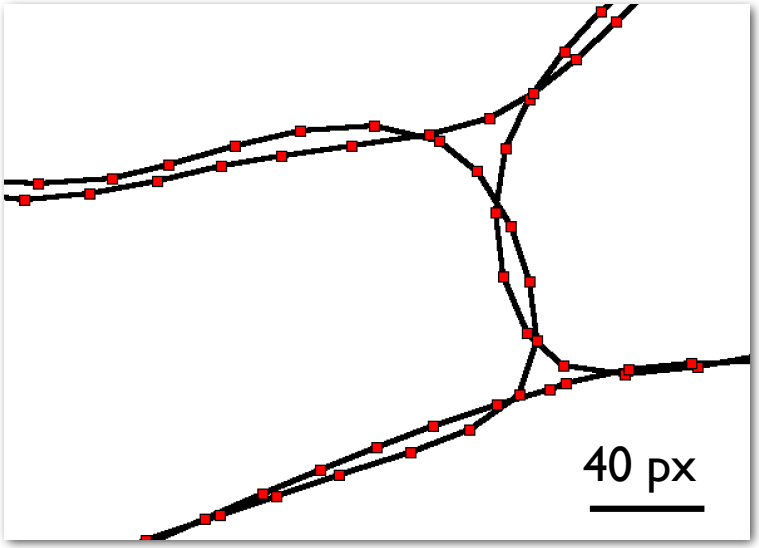


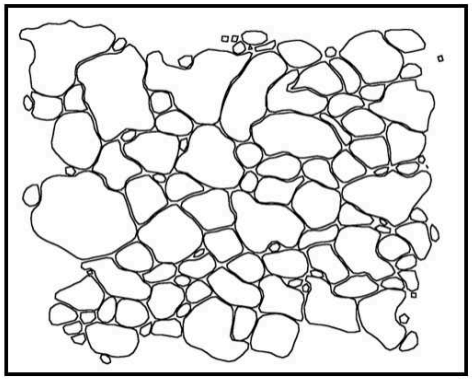
PLATE III.b. Quartzite, Vikarspitze, Innsbruck; section ⊥ *b*;
1484 quartz-axes; ×25; A.V.A. (Ramsauer)

2
early 'digital image analysis'
(vector graphics)

manual digitisation

boundaries on tablet

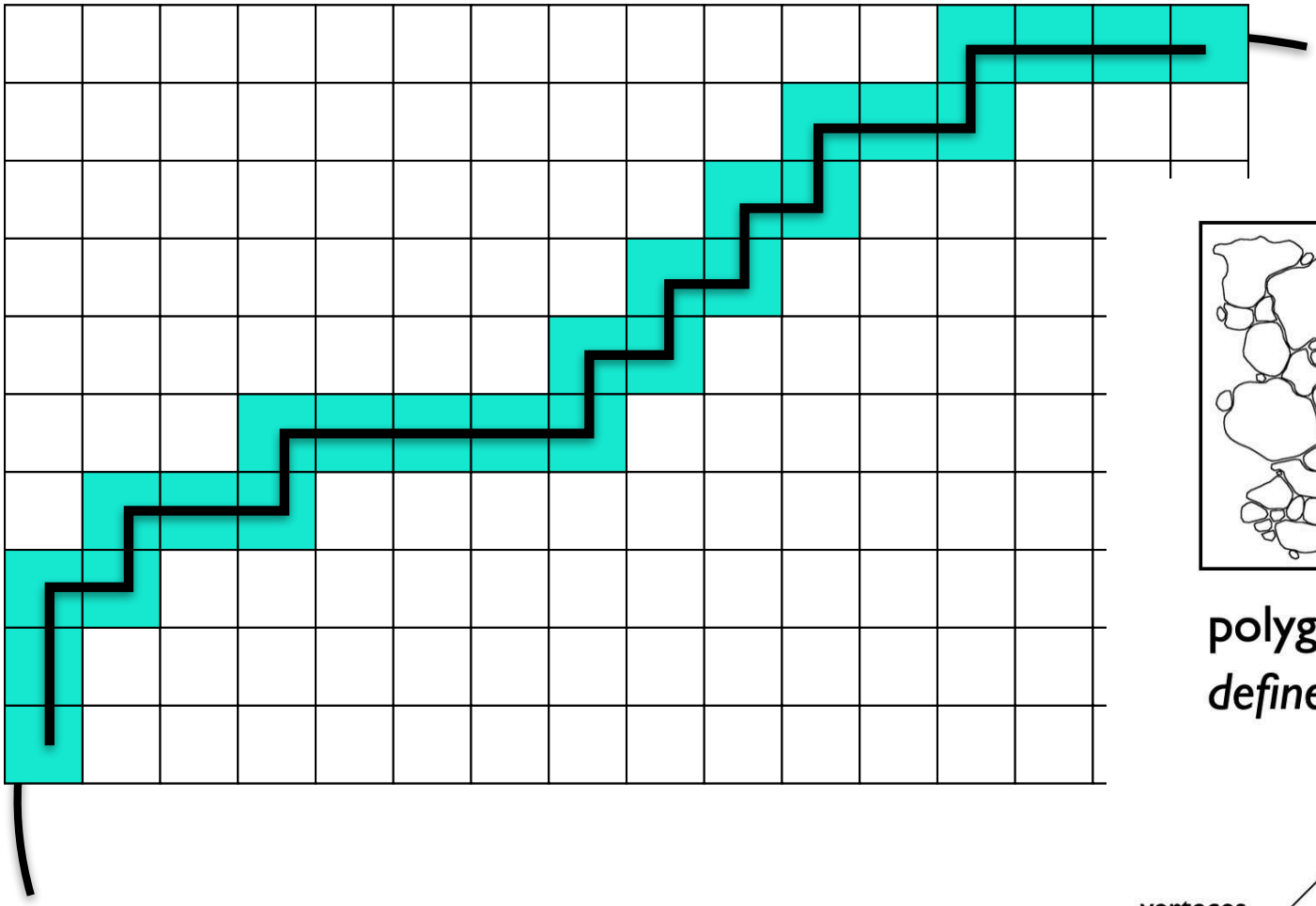


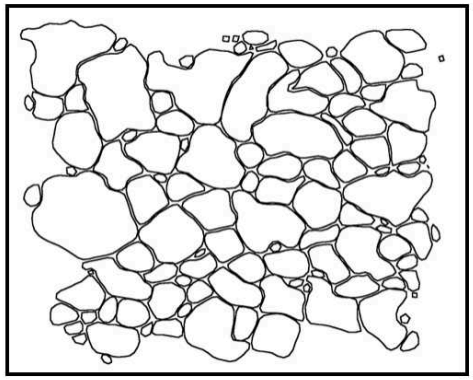


polygonal outline (polyline)
defined by:

	#	x	y
	1.	457	11
	2.	446	16
verteces of polyline →	3.	432	36
	4.	427	49
	5.	443	66
	6.	484	77
	7.	503	68
	8.	470	15
	9.	457	11
delimiter →	10.	9999	9999
	...	etc.	...

putting the curve on the grid



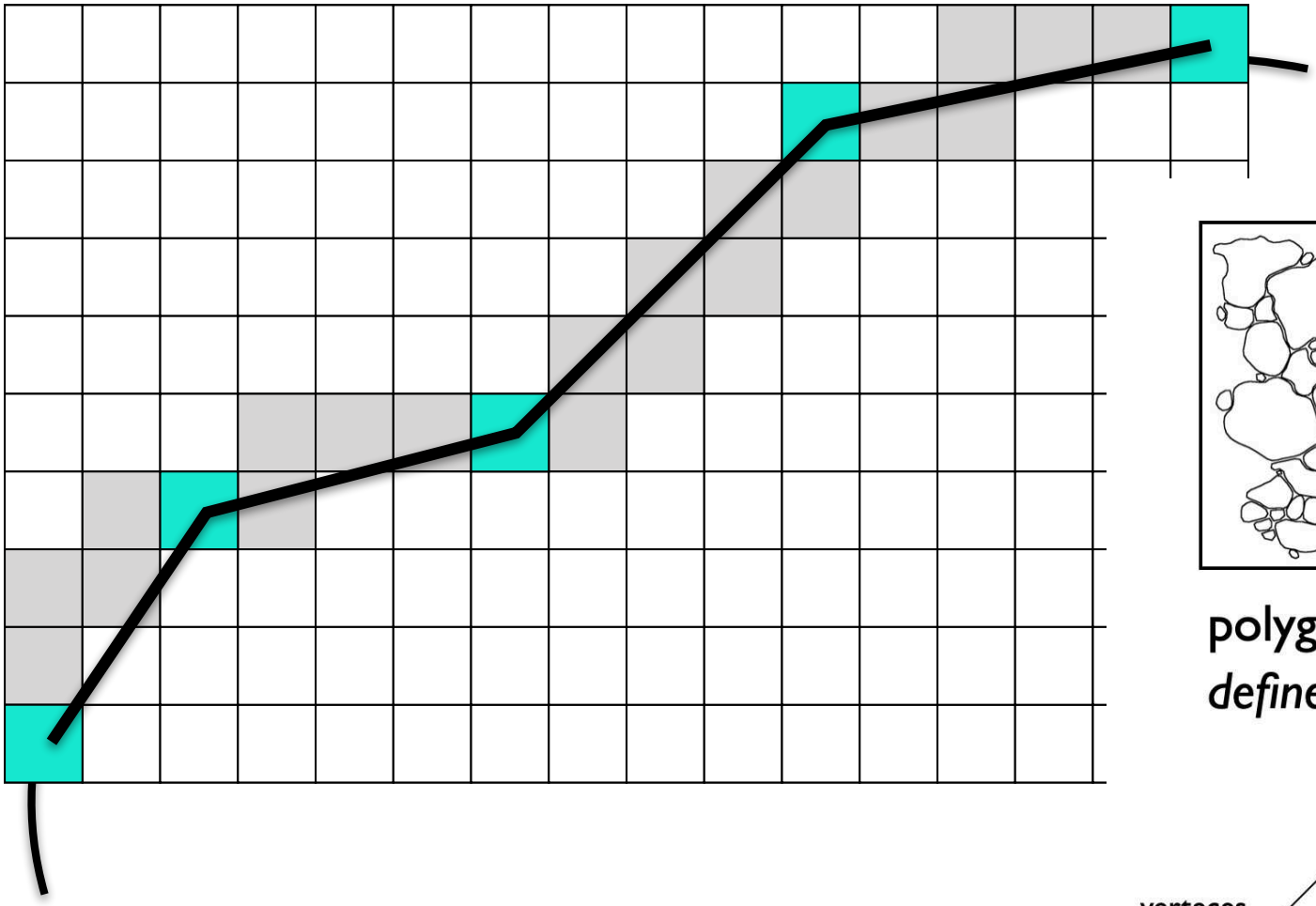


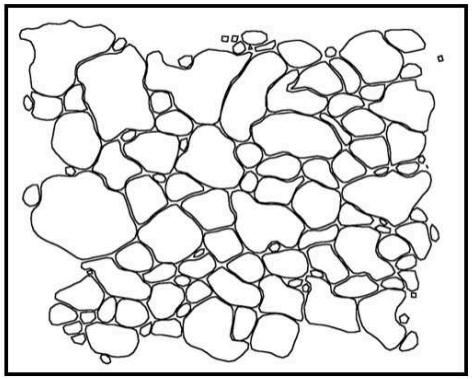
polygonal outline (polyline)

defined by:

	#	x	y
	1.	457	11
	2.	446	16
verteces of polyline →	3.	432	36
	4.	427	49
	5.	443	66
	6.	484	77
	7.	503	68
	8.	470	15
	9.	457	11
delimiter →	10.	9999	9999
	...	etc.	...

try again





polygonal outline (polyline)

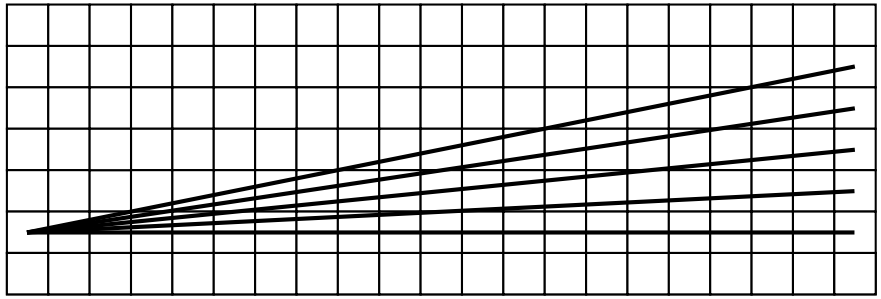
defined by:

verteces of polyline

delimiter

#	x	y
1.	457	11
2.	446	16
3.	432	36
4.	427	49
5.	443	66
6.	484	77
7.	503	68
8.	470	15
9.	457	11
10.	9999	9999
...	etc.	...

"Houston – we have a problem ...

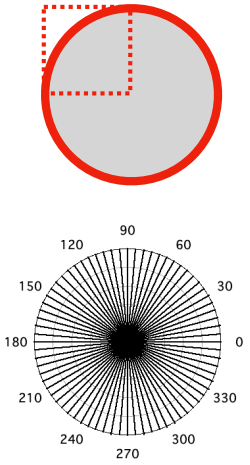


ΔL_x = 20 px

ΔL_y	tan:	angle:
4	4/20	11.3°
3	3/20	8.5°
2	2/20	5.7°
1	1/20	2.9°
0	0	0°

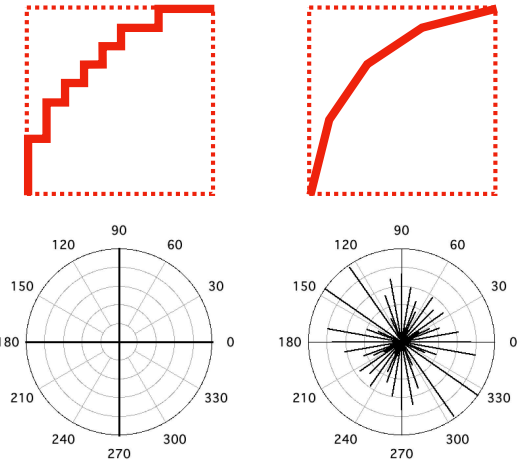
slope = $\tan^{-1}(\Delta Y/\Delta X)$
where X, Y = integer

continuous coordinates



on a square grid

d_{min} = 1px d_{min} = 5px

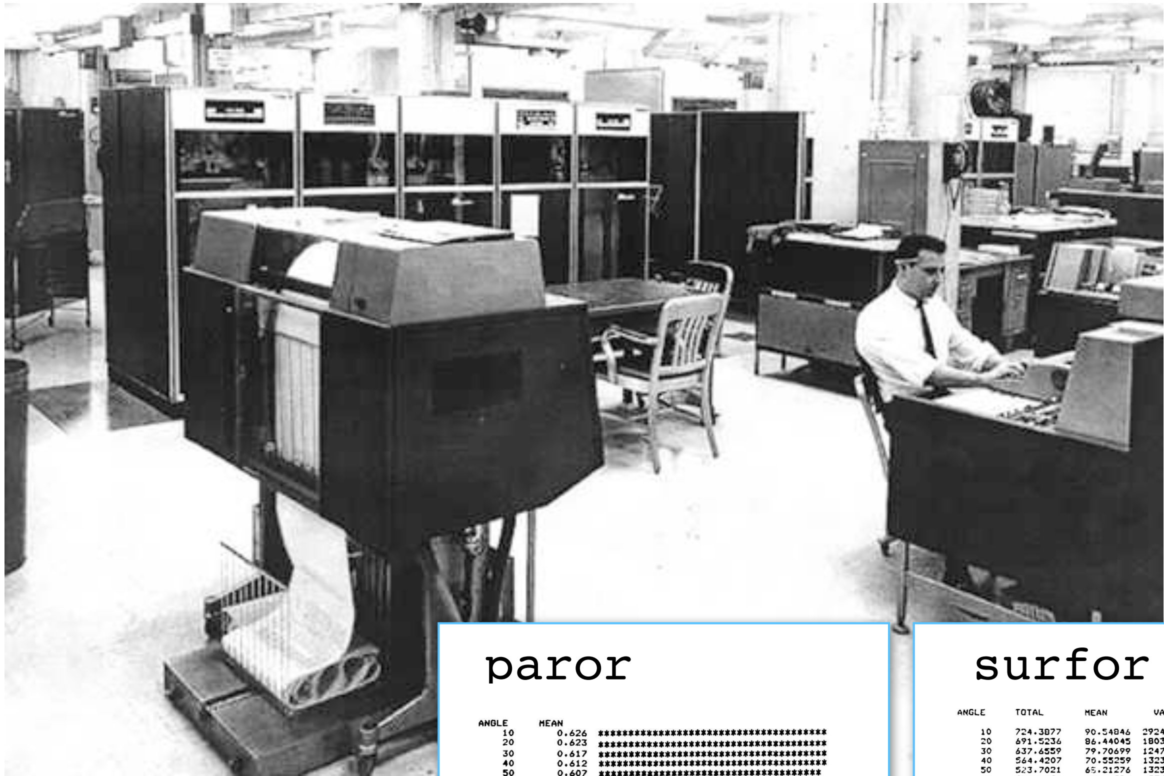


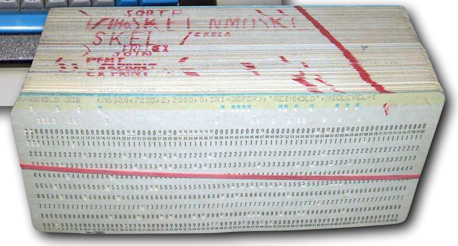
"Stand by, 13,
.... we are looking at it"

scasmo

```
-------------------------------------------------------------
***  scasmo  (full version)**                2010-10-25, rh
-------------------------------------------------------------
converts digitized files to formatted input files
plus optional: scaling, smoothing, closing of outlines
plus optional: reduction of number of coordinate points
maximum number of points per particle =  4000
particles with less than 3 points are discarded
-------------------------------------------------------------
input file:
   for each particle: X,Y          integer x-y coordinates
   |                  ...          ...etc.
   |                  XE,YE        end coordinate (XE=YE)
output file:
   line 1:            bti          title
   line 2:            n            total number of points
   for each particle: x,y          floating x-y coordinates
   |                  ...          ...etc.
   |                  xe,ye        end coordinates
-------------------------------------------------------------
```

small data sets – huge computers ...





... and Fortran

paror

ANGLE	MEAN
10	0.626
20	0.623
30	0.617
40	0.612
50	0.607
60	0.604
70	0.601
80	0.601
90	0.603
100	0.609
110	0.620
120	0.630
130	0.638
140	0.642
150	0.643
160	0.640
170	0.634
180	0.629

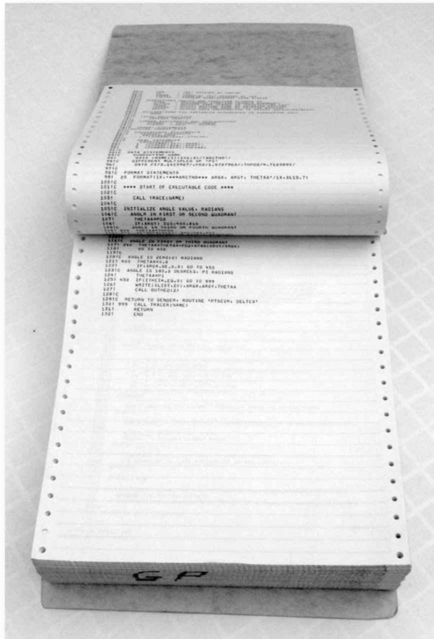
ANGLE	MEAN
10	0.212
20	0.204
30	0.192
40	0.177
50	0.161
60	0.144
70	0.133
80	0.130
90	0.128
100	0.132
110	0.141
120	0.153
130	0.168
140	0.183
150	0.197
160	0.207
170	0.214
180	0.216

surfor

ANGLE	TOTAL	MEAN	VARIANCE	ST.DEV.
10	724.3877	90.54846	2924.01562	54.07417
20	691.5236	86.44045	1803.02283	42.46202
30	637.6559	79.70699	1247.18213	35.31547
40	564.4207	70.55259	1323.50964	36.38007
50	523.7021	65.21276	1323.27502	36.37685
60	521.7486	65.21857	834.60577	28.88954
70	523.9480	65.24350	1316.75964	36.28718
80	564.1365	70.51707	1325.47253	36.40704
90	637.5422	79.69278	1244.69861	35.28028
100	691.5839	86.44798	1795.76782	42.37650
110	724.6199	90.57749	2912.23950	53.96517
120	778.9187	97.36484	3289.18237	57.35139
130	845.3282	105.66603	2859.47021	53.47401
140	886.0625	110.75781	2577.74292	50.77148
150	899.8844	112.48555	2477.96436	49.77916
160	886.3740	110.79675	2572.16577	50.71653
170	845.9417	105.74271	2848.98999	53.37593
180	779.8156	97.47695	3275.06006	57.22814

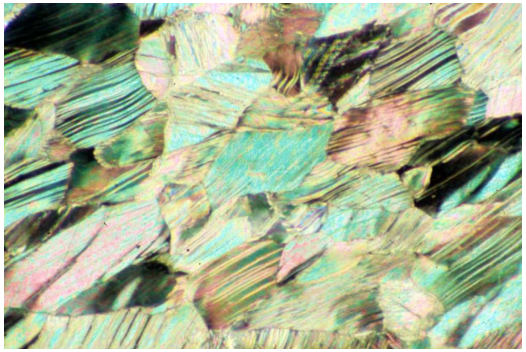
HISTOGRAM: TOTAL LENGTH OF PROJECTION VERSUS ANGLE OF ROTATION

900 MM

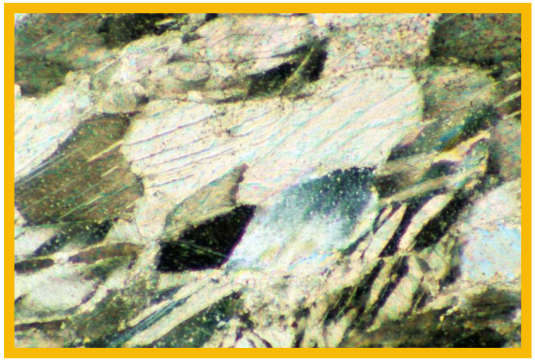


from Rf / φ ... when grains were elliptical

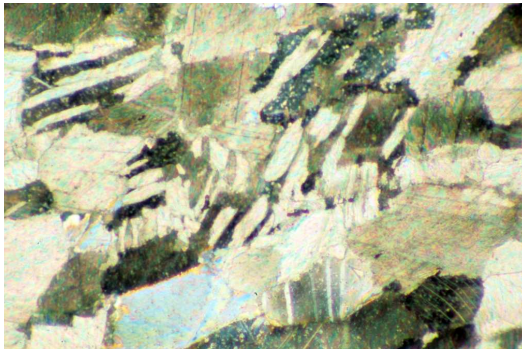
CT1 600°C

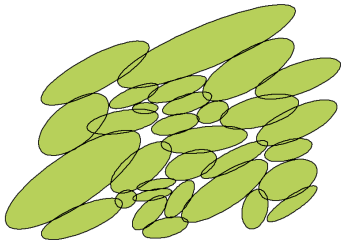


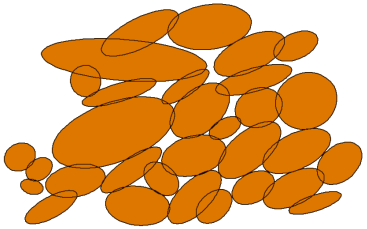
CT3 700°C

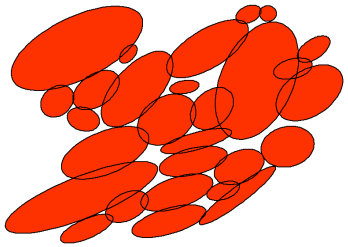


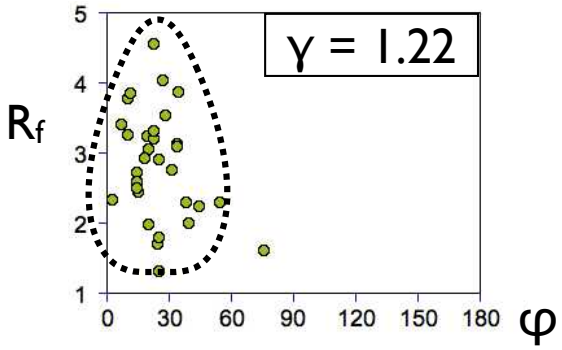
CT2 800°C

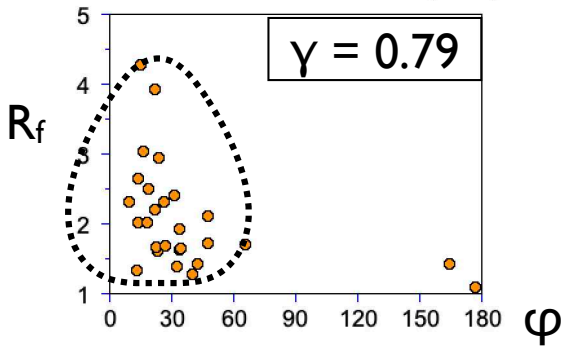


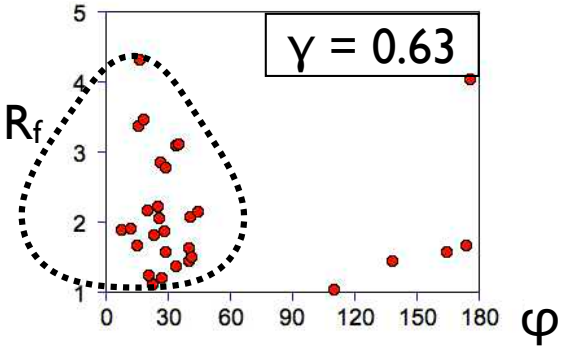




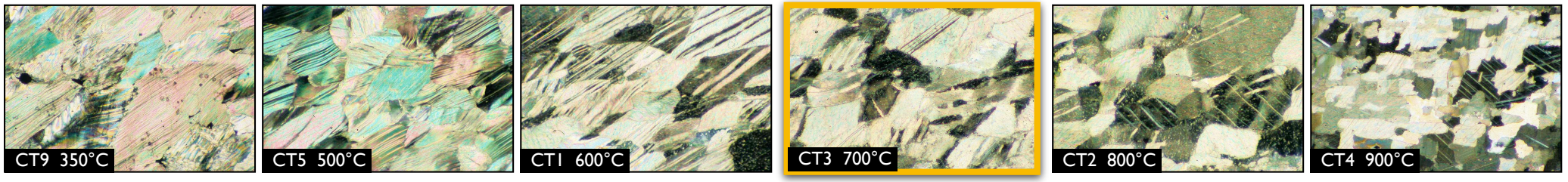




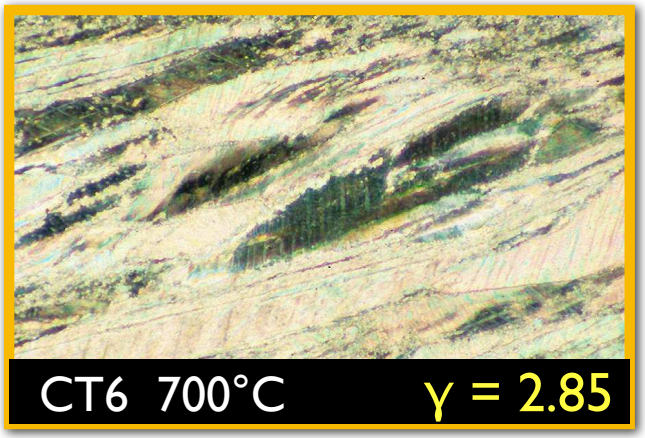


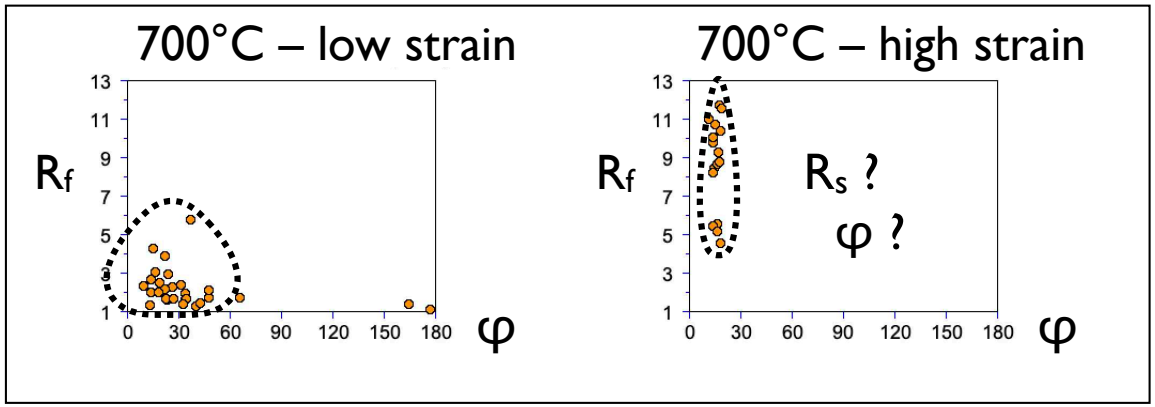


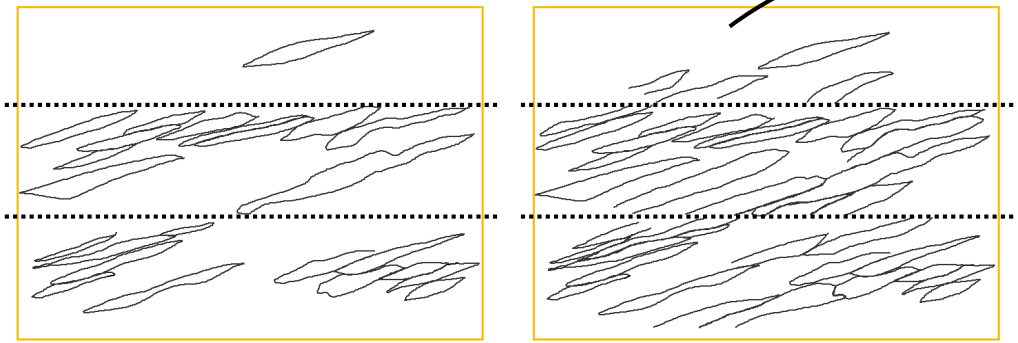
... to SURFOR ... when outlines counted



500 µm





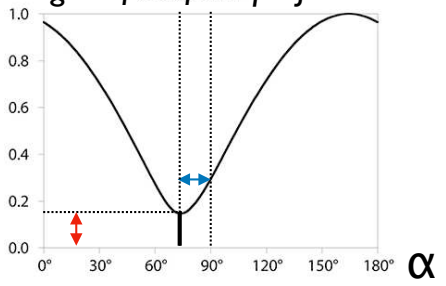


closed outlines only

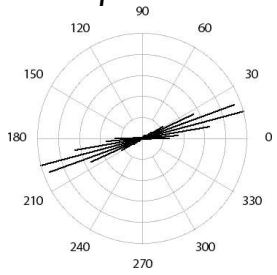
open and closed outlines

700°C – high strain

length of surface projection



surface ODF

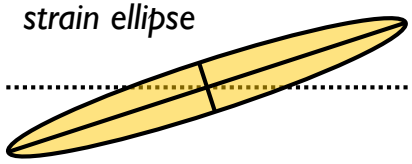


b/a = 0.146

R_s = 6.85

φ = 18°

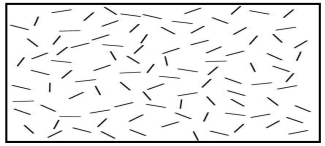
strain ellipse

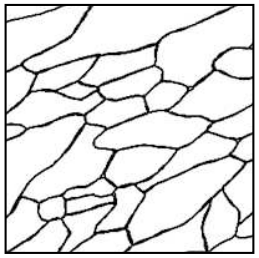


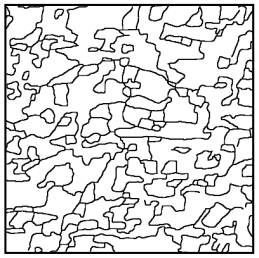
strain – no strain ? ... "fact or fiction ?"

strain – affine transformation

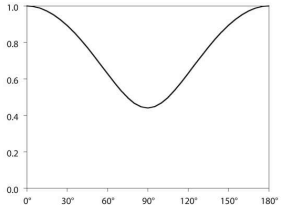
fabric



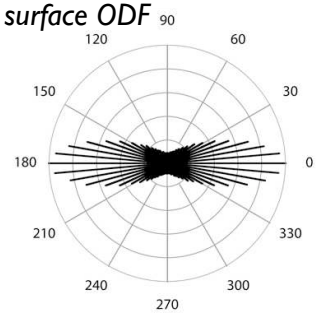


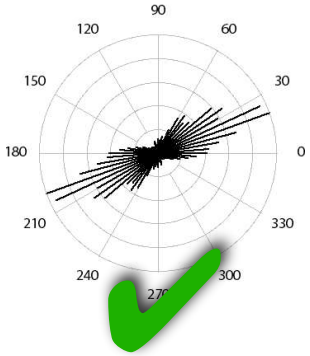


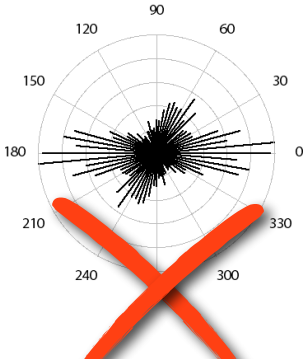
projection of outlines



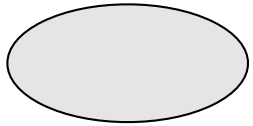
surface ODF

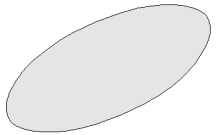


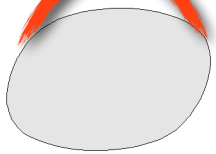




characteristic shape





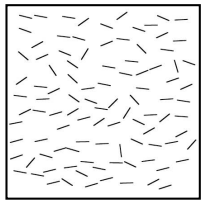


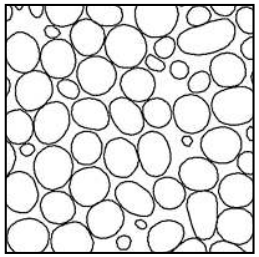
deformation recrystallization

≠

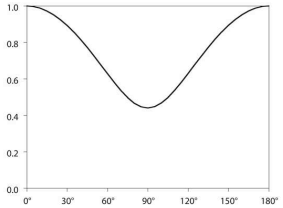
dispersion about mean

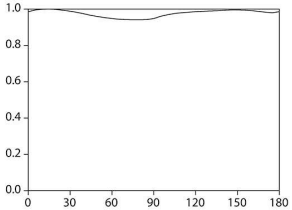
fabric



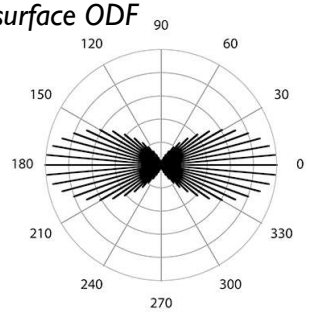


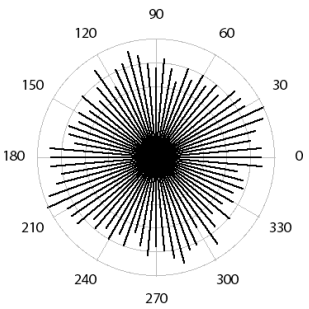
projection of outlines



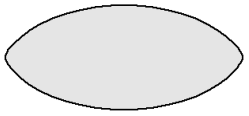


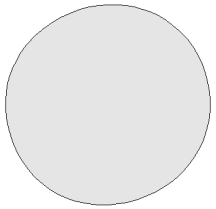
surface ODF





characteristic shape





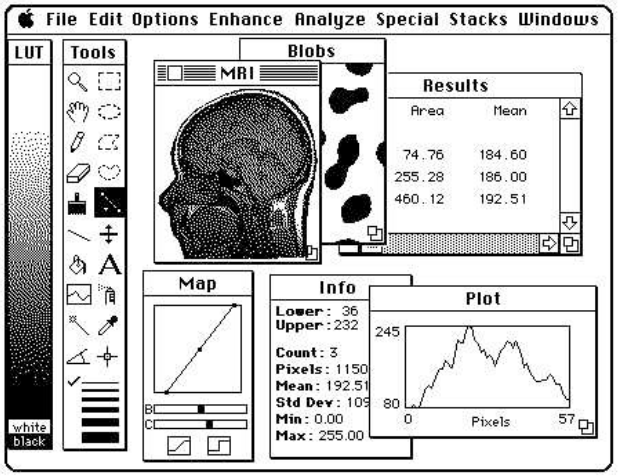
deposition

3
the beginning of digital image analysis (raster graphics)

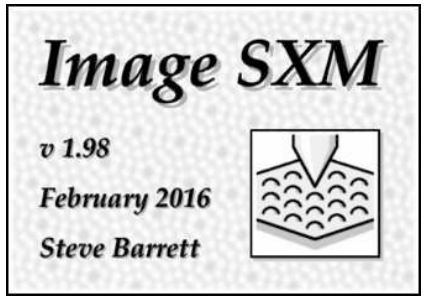
time moves on ...

Wayne Rasband

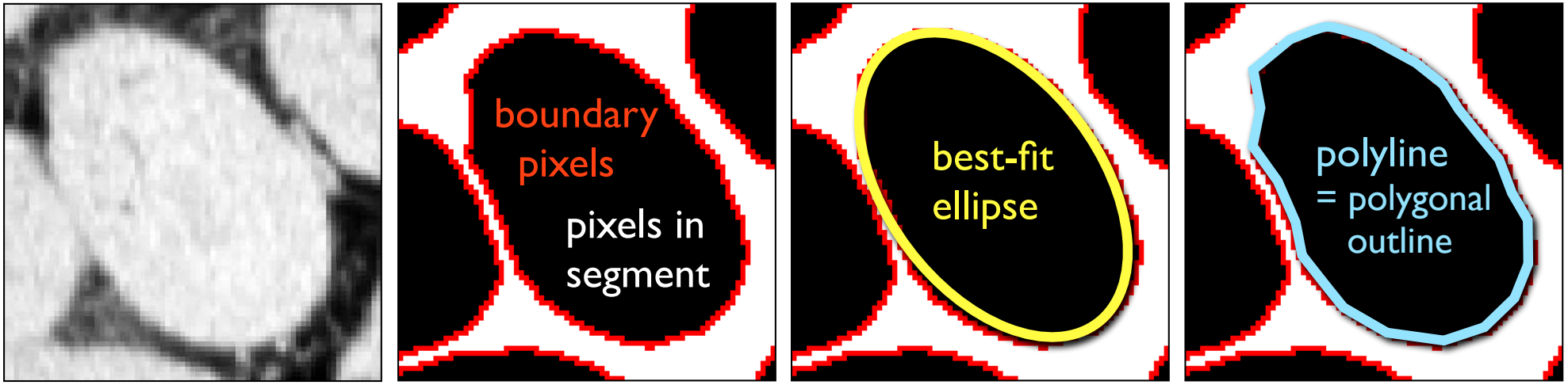
NIH Image



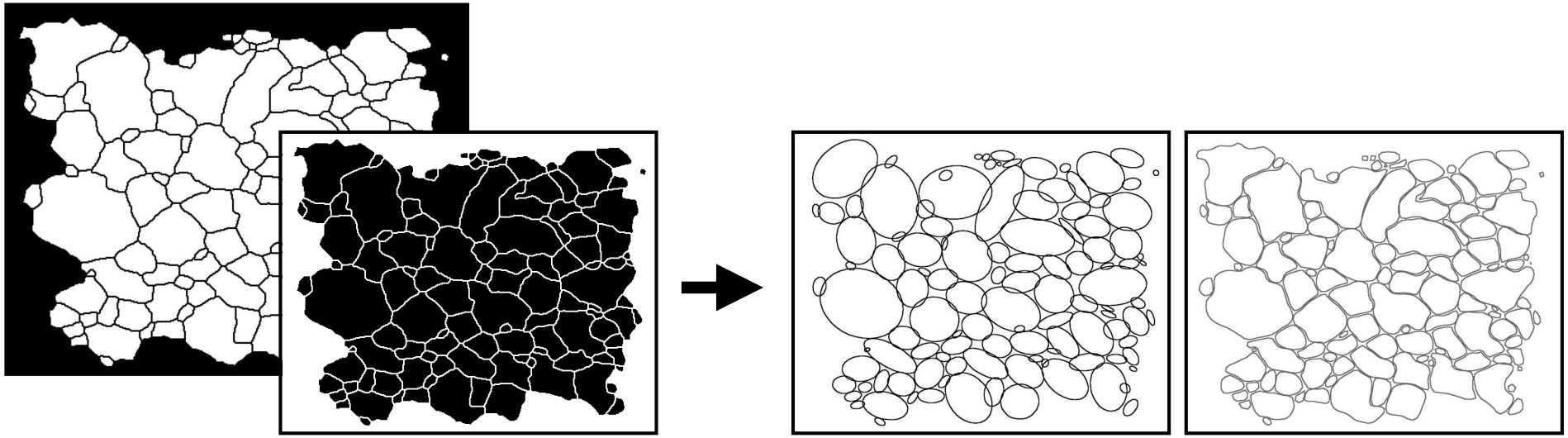
Steve Barrett



types of image analysis



segments best-fit ellipse outlines



pixels mathematical objects

image processing vs. image analysis

image processing

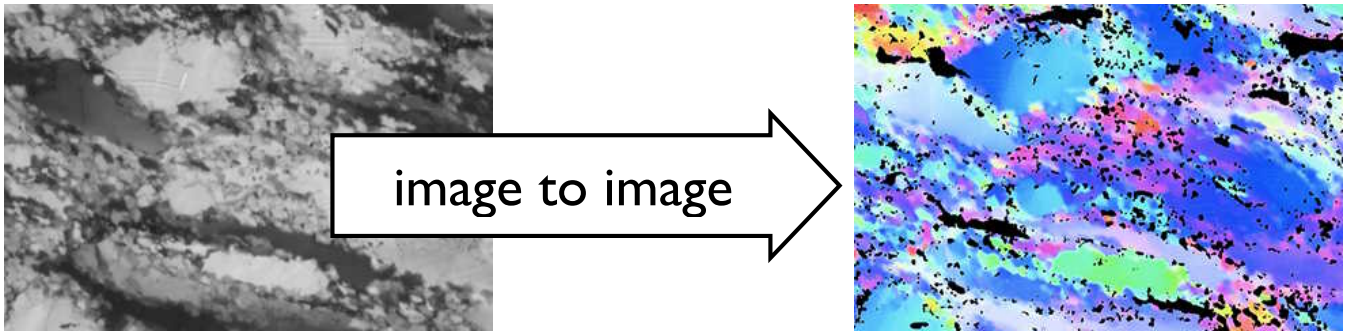
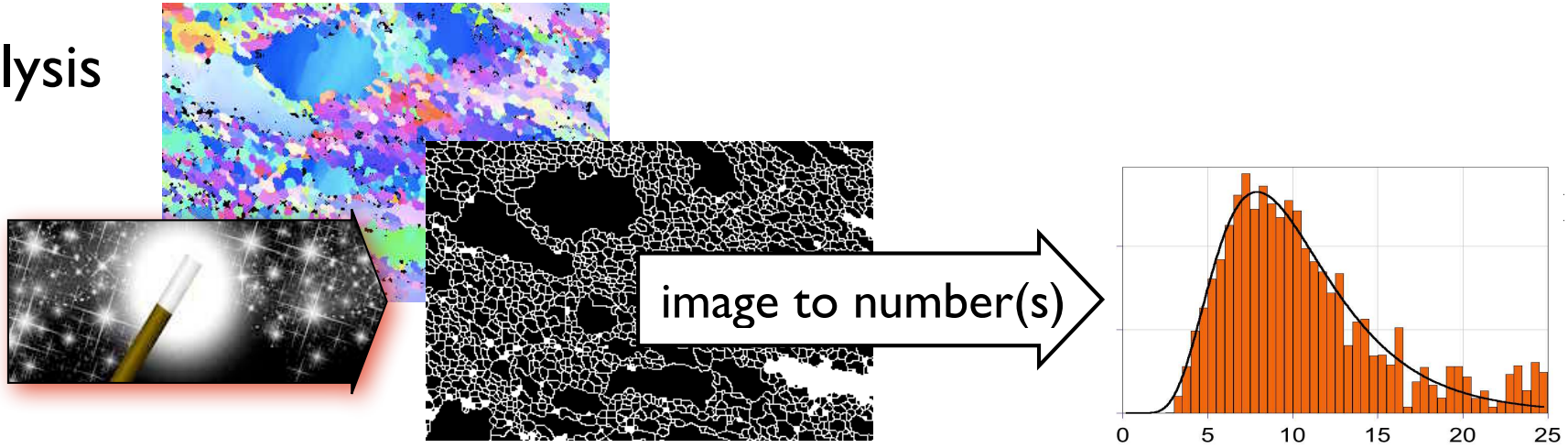
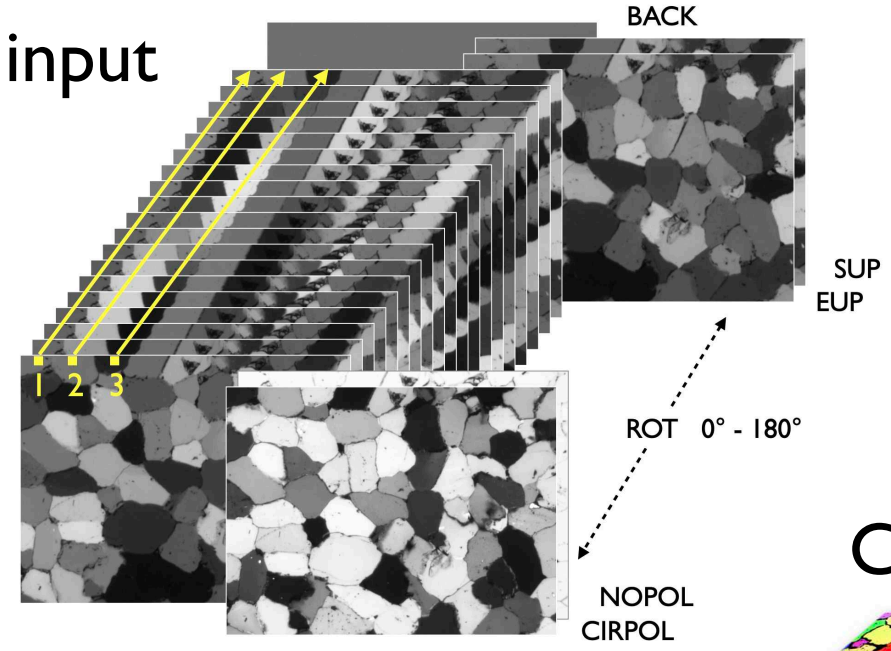
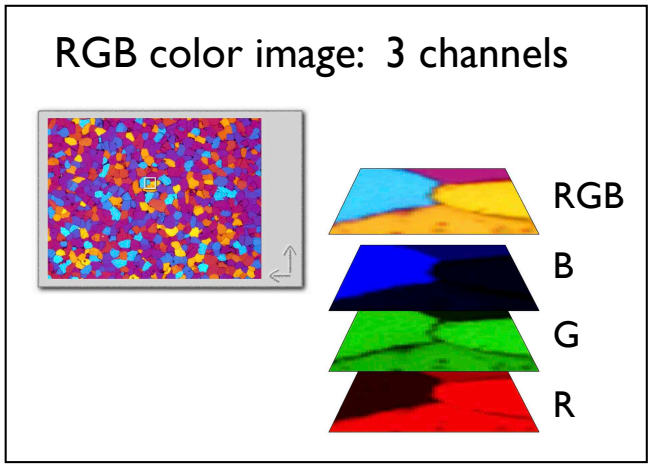


image analysis

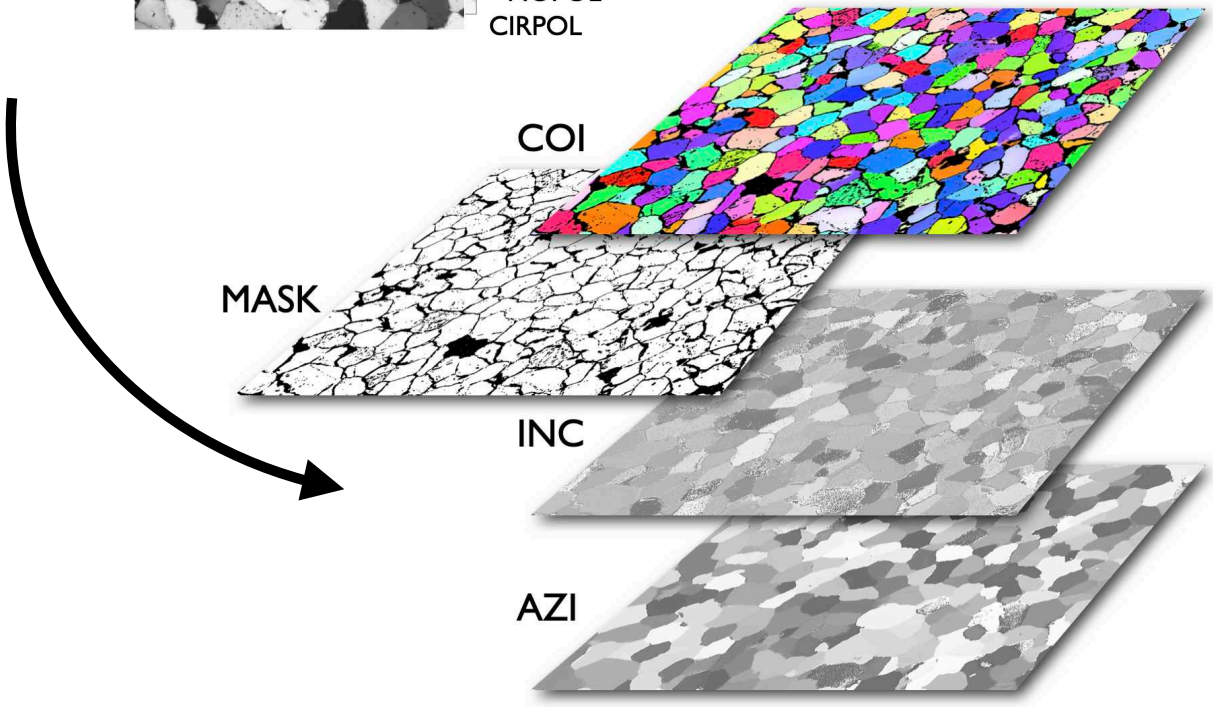


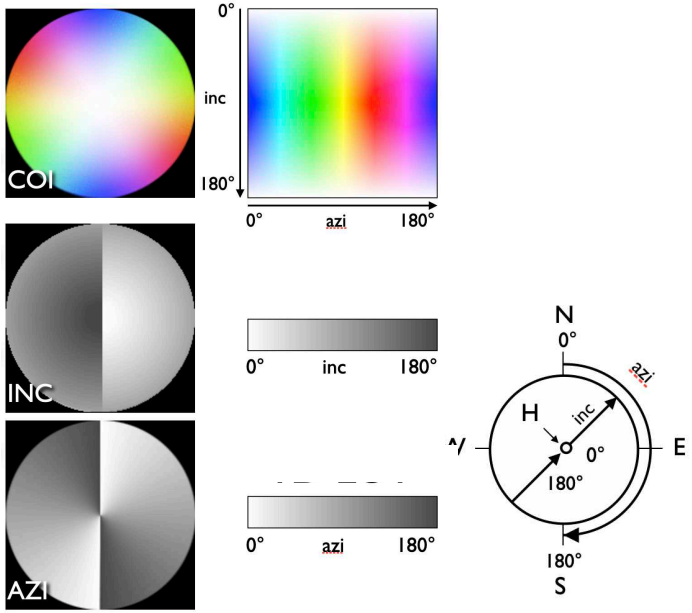
some heavy duty image processing



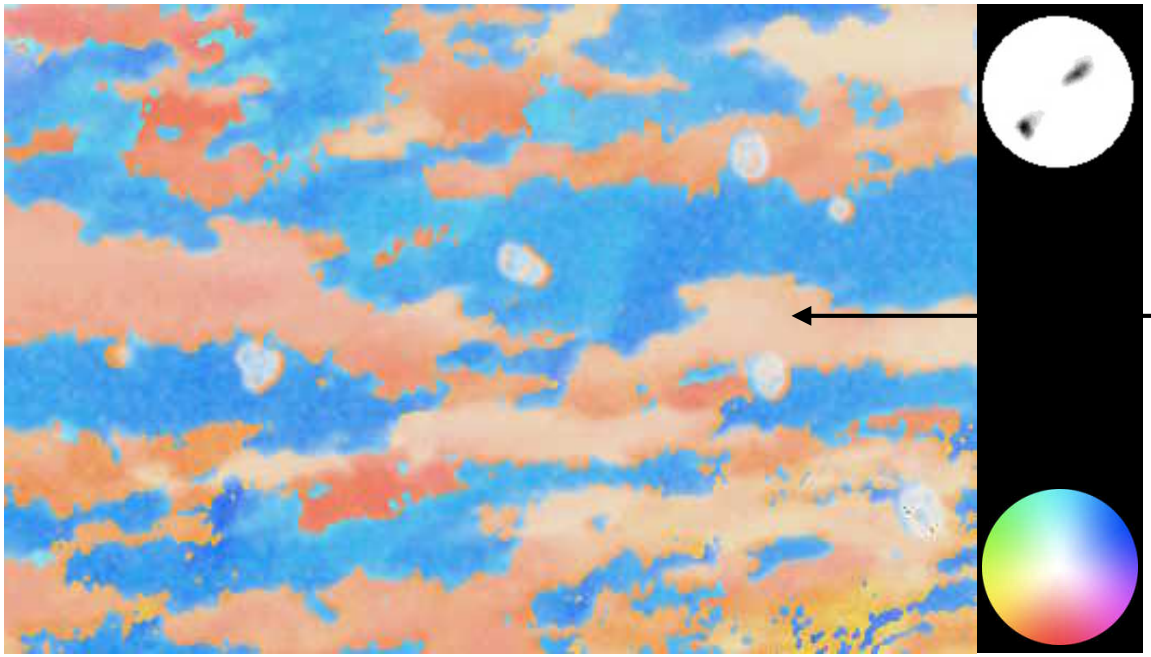


COI image: 2 channels (azi/inc)





from AVA to CIP

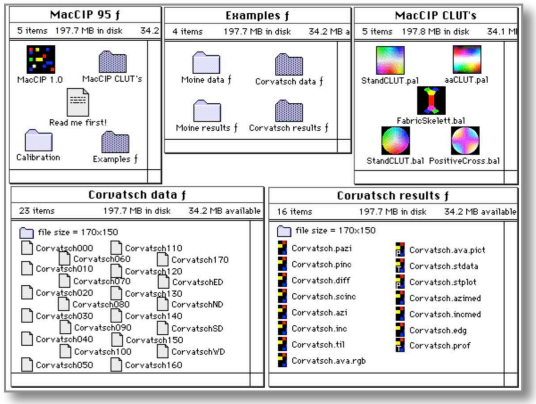


this is the 'number'

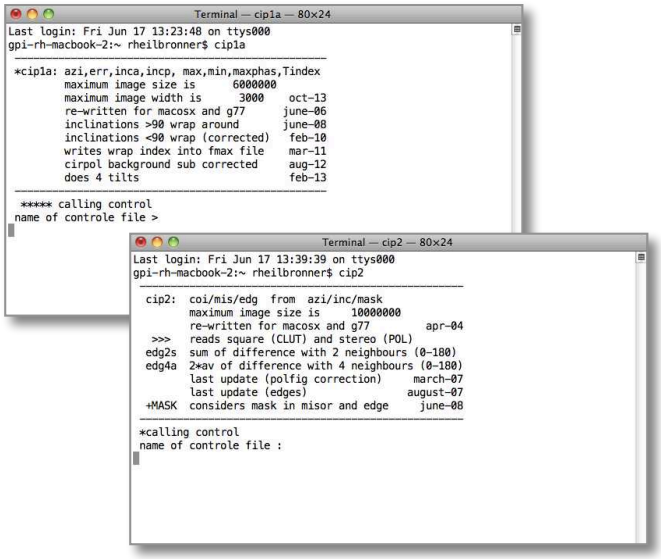
this is the image

the first ever CIP image shown at EUGVI (1991)

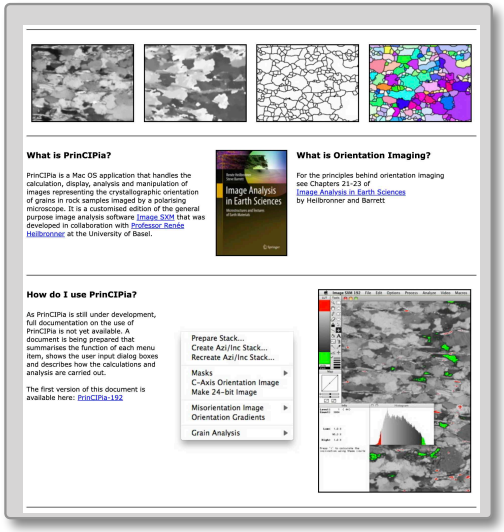
MacCIP (Pascal)



CIP (Fortran)



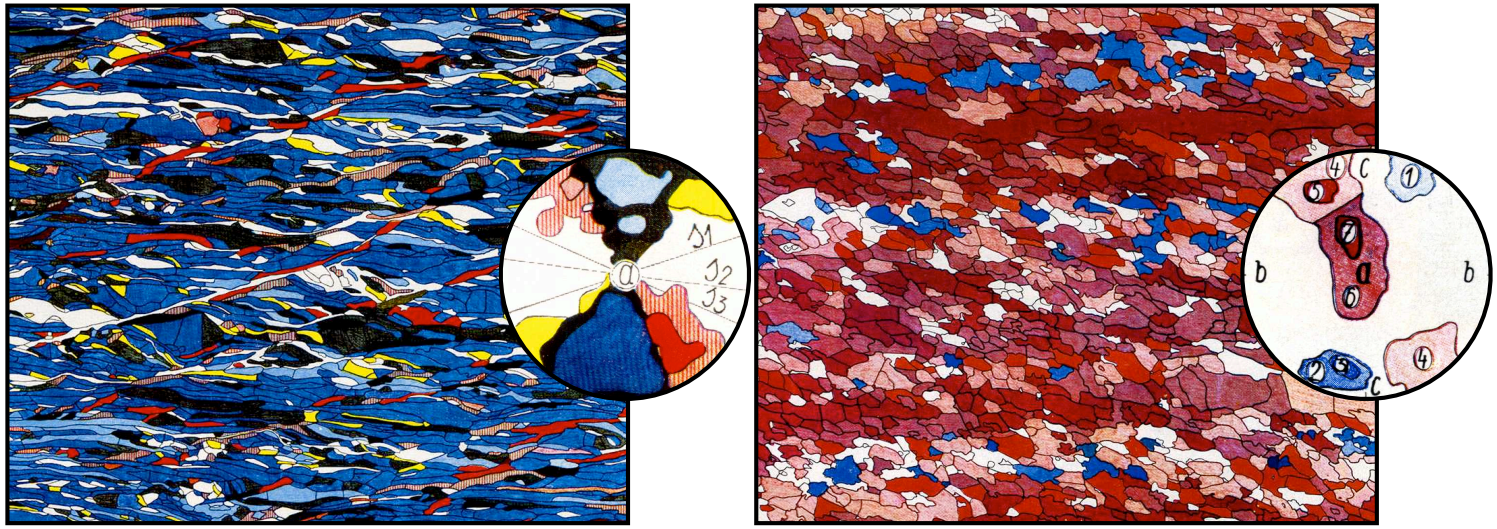
PrinCIPia / Image SXM



CIP versus AVA

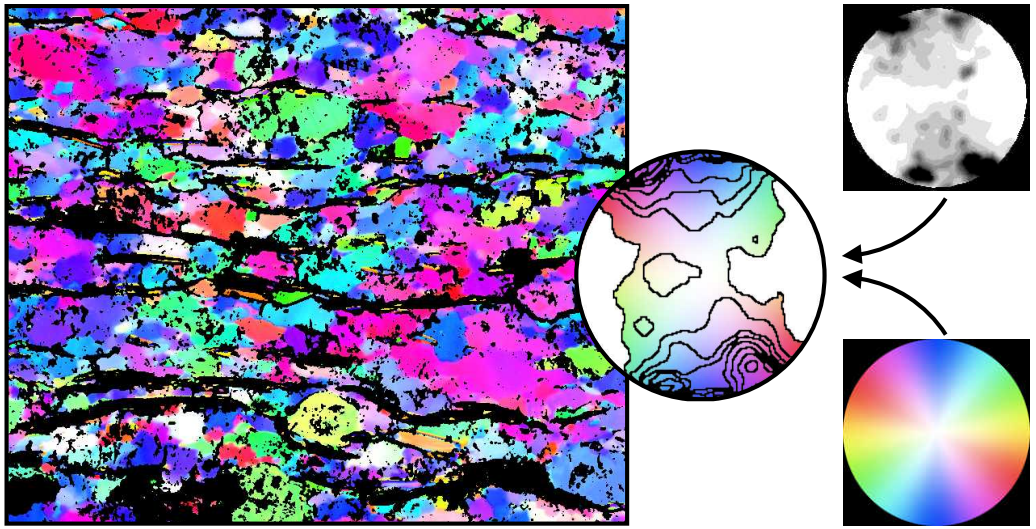
one grain – one c-axis orientation

procedure:
first segment
then color-code



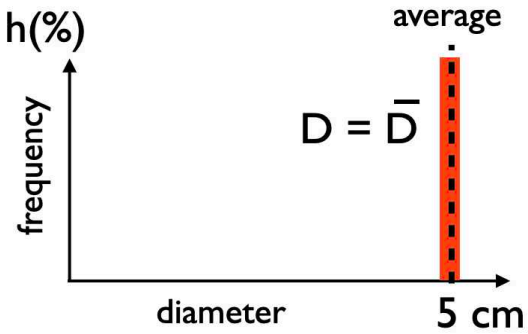
one pixel – one c-axis orientation

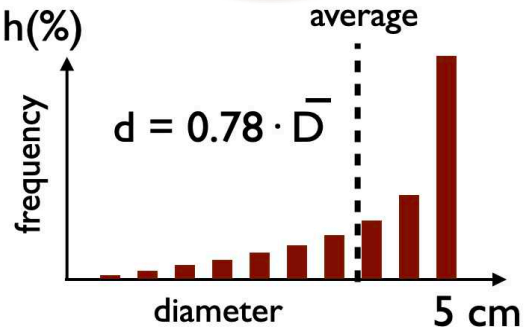
procedure:
first color-code
then segment

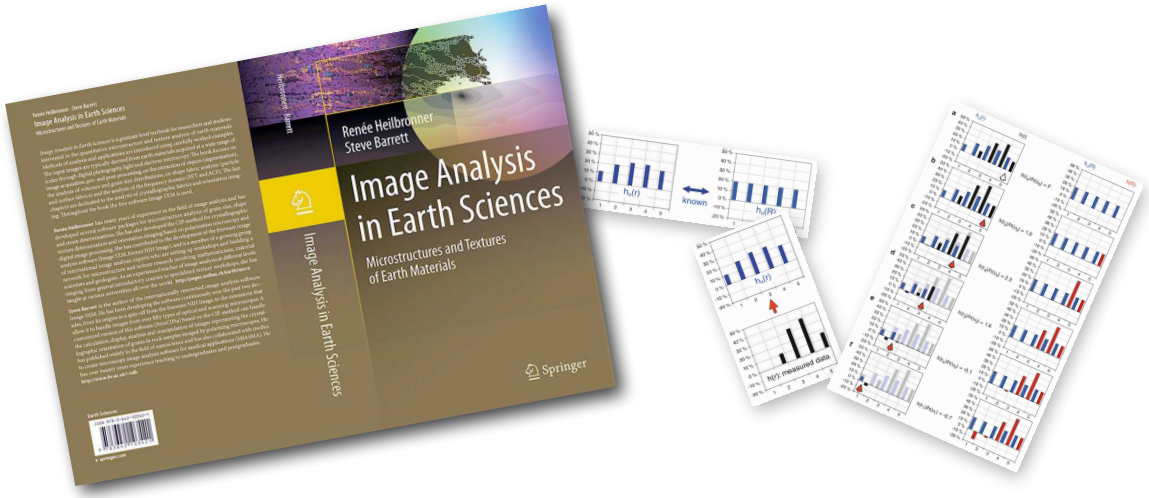


4
3D grain size
– an ongoing project

short intro: the tomato salad problem



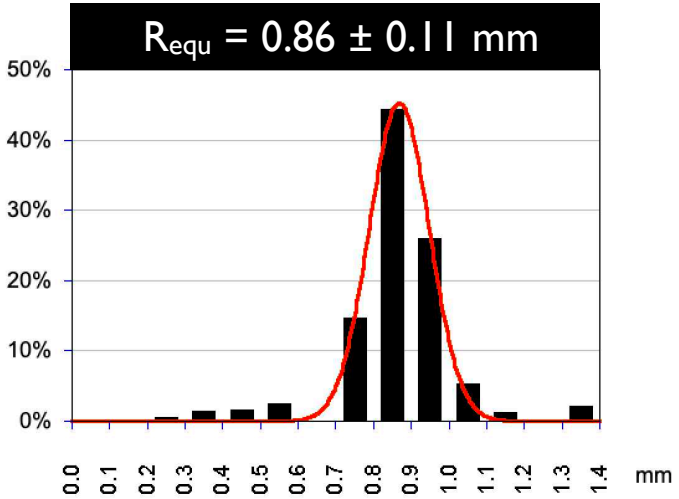




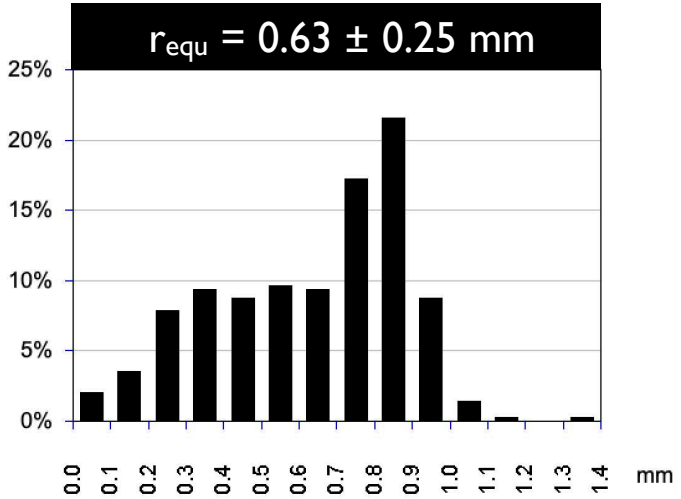
the effect of using 3D vs. 2D means

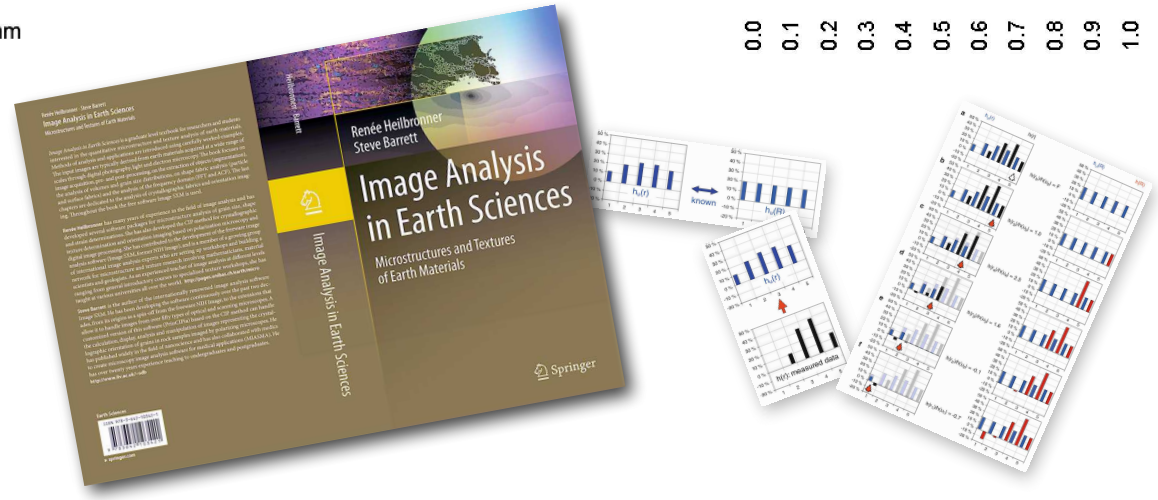
STRIPSTAR
calculates the mode of the volume weighted 3D diameters

vol%

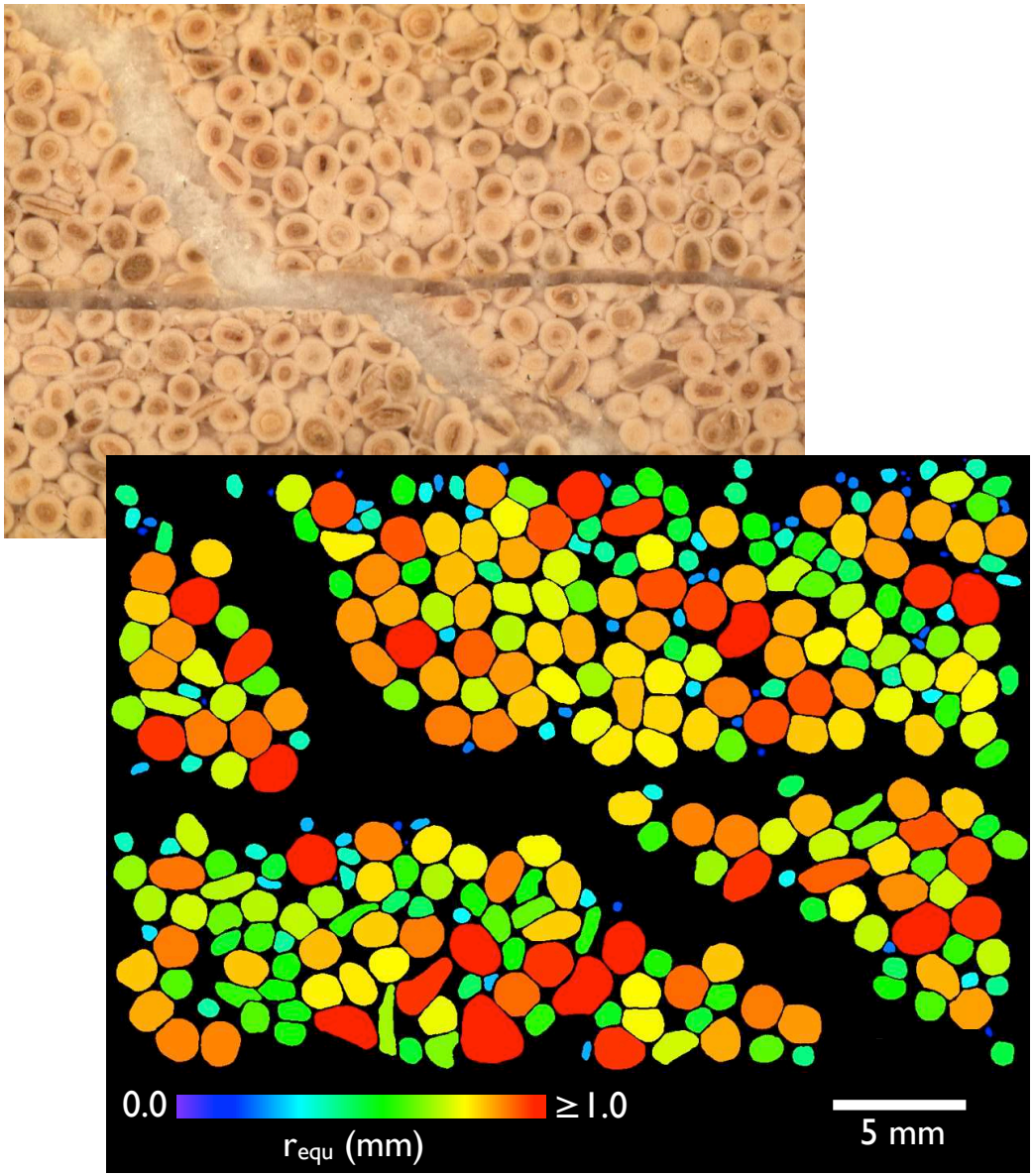


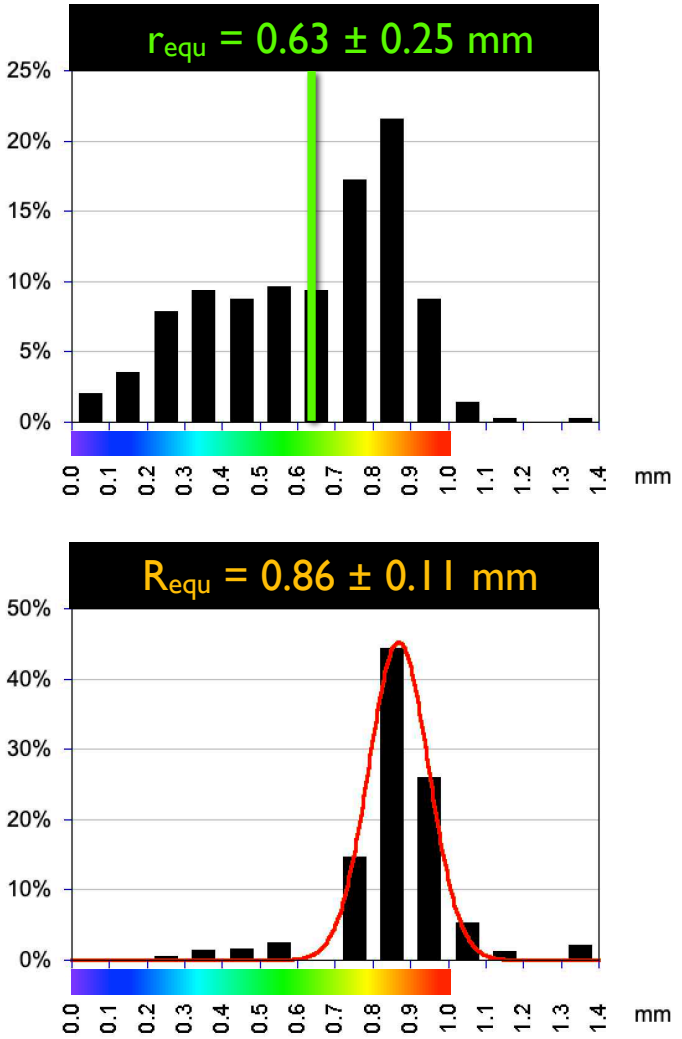
frequency





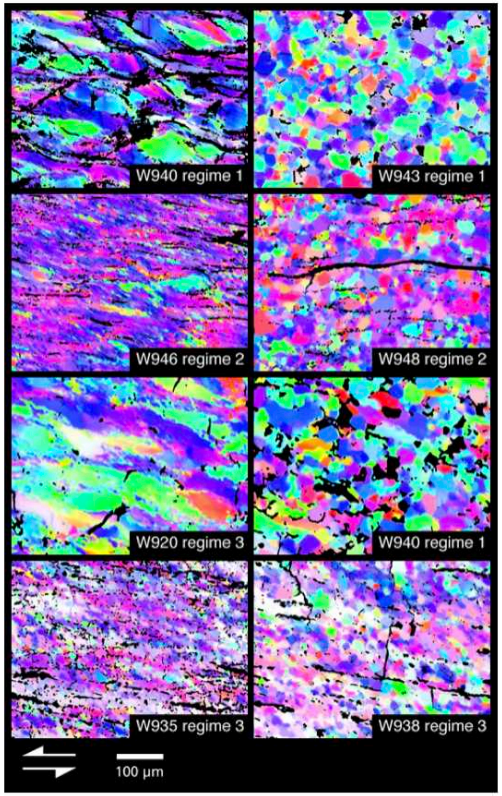
... have a look

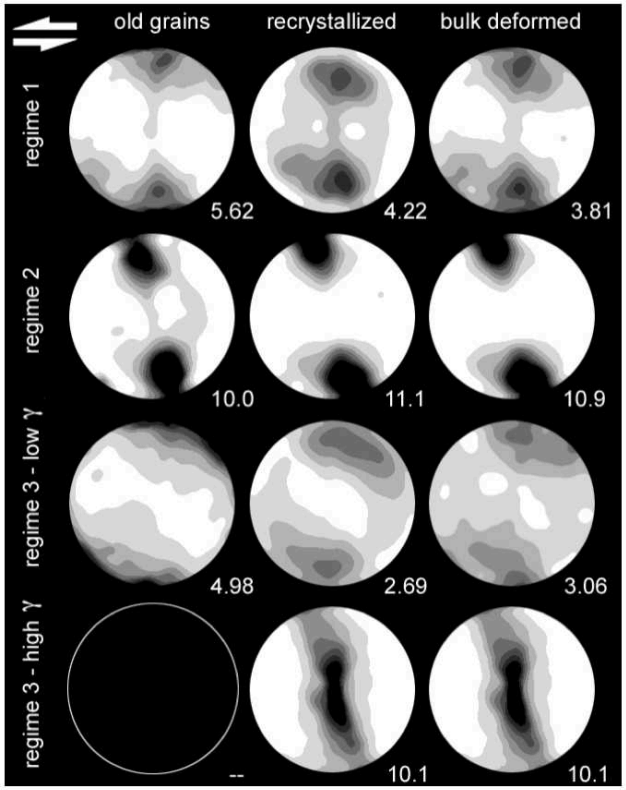

0.0
≥ 1.0
r_{equ} (mm)
5 mm

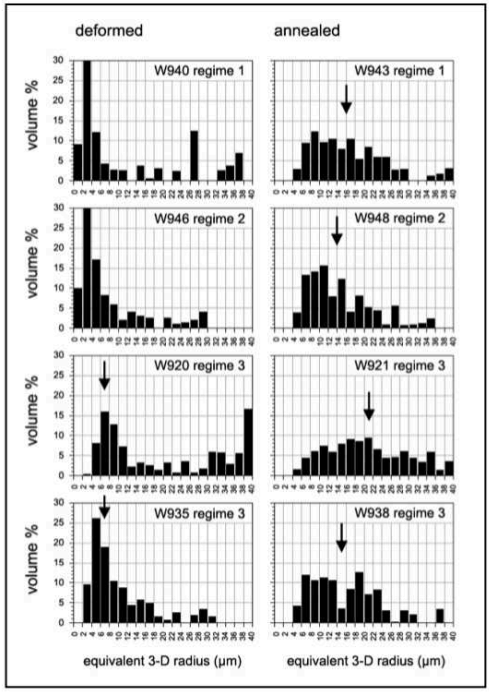

r_{equ} = 0.63 ± 0.25 mm
25%
20%
15%
10%
5%
0%
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4
mm
R_{equ} = 0.86 ± 0.11 mm
50%
40%
30%
20%
10%
0%
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4
mm

5
image analysis today
... by way of an example

looking at deformation experiments ...







Heilbronner, R. and Tullis, J. (2002). Geol. Soc. Lond., Spec. Publ.

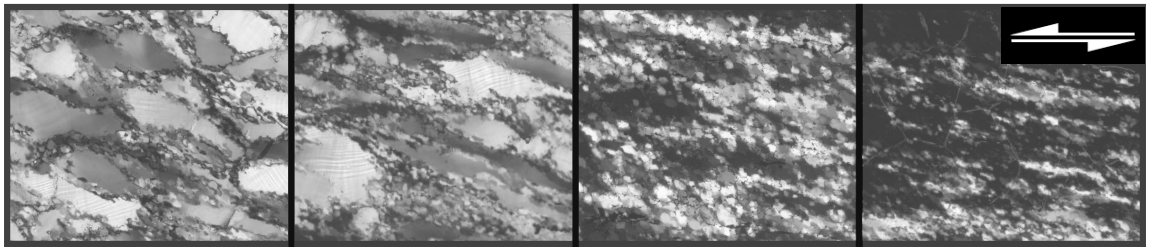
shearing in dislocation creep regimes 1, 2, and 3 ... and annealing

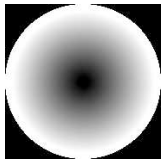
Sample # (regime)	Vol % recryst.	Vol % annealed	Mode grain diameter (µm)	CPO max. density (bulk texture)	CPO max. density of recryst. fraction	Mode of orient. gradient distrib. (°)	Measured perimeter/ perimeter of equivalent circle	PARIS factor (%)	Grain boundary surface per volume (μm^{-1})
w871 (1)	50		5	3.76					
w872 (2)	40		7	4.12					
w858 (3)	85		20	4.48					
w875 (1 ann.)		100	20	2.04					
w874 (2 ann.)		100	36	3.21					
w860 (3 ann.)		100	50	3.52					
w940 (1)	50		7	3.81					
w946 (2)	90		8	10.9					
w920 (3)	45		14	3.06					
w935 (3)	100		14	10.1					
w943 (1 ann.)		100	32	4.04					
w948 (2 ann.)		100	28	5.40					
w921 (3 ann.)		100	42	2.50					
w938 (3 ann.)		100	30	8.50					

mode D(µm)	
reg.1	~7
reg.2	~8
reg.3	~14

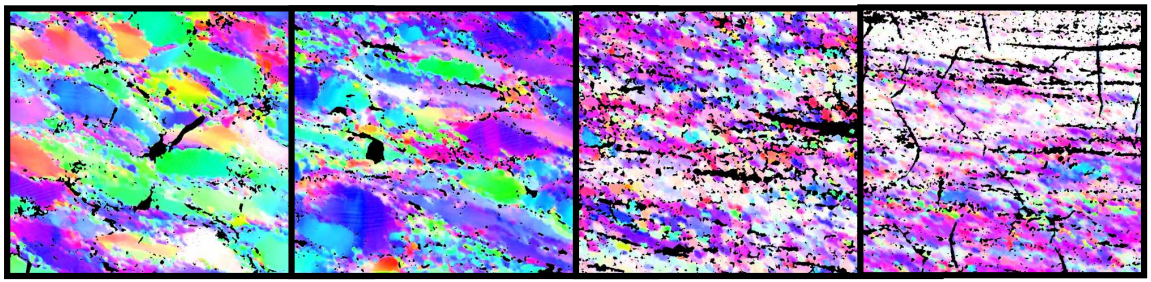
bulk CPO_{max}	
reg.1	3.8
reg.2	10.9
reg.3	10.1

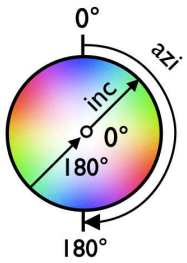
... of Black Hills Quartzite (BHQ)



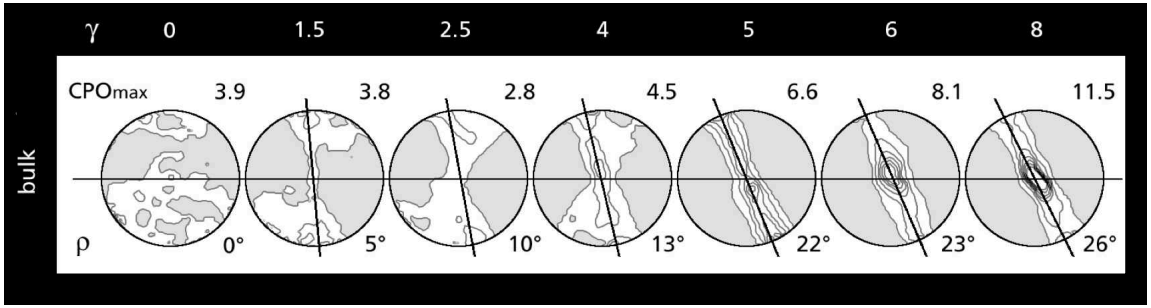


circular polarization



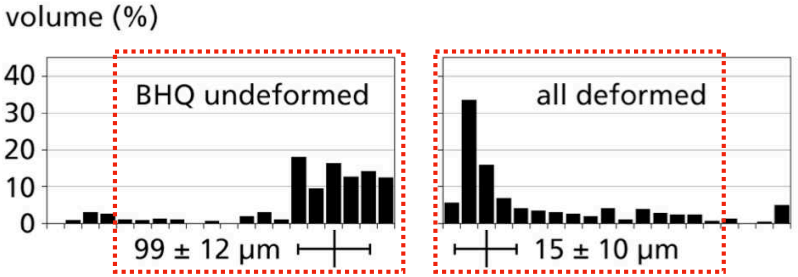


c-axis coloring



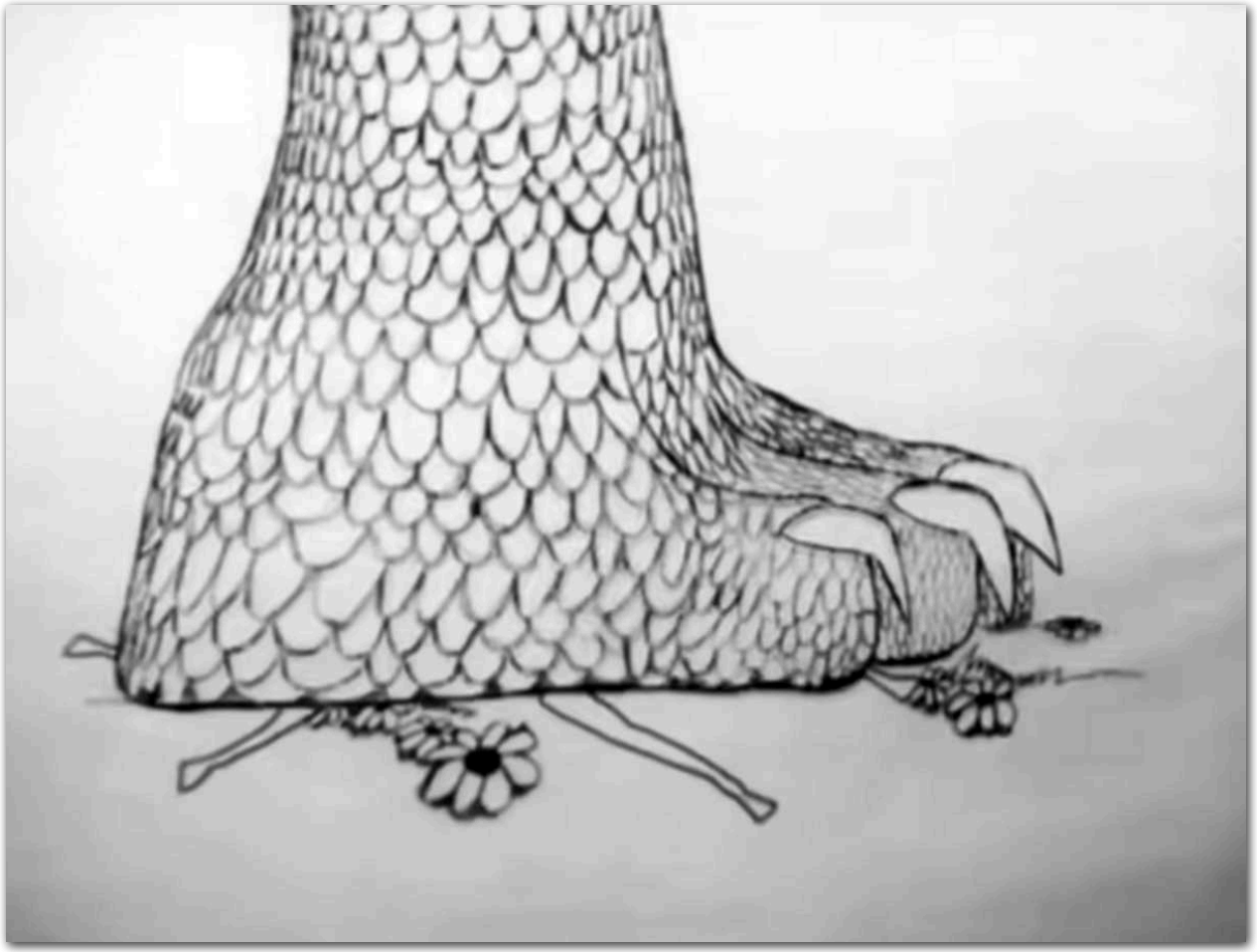
Heilbronner, R. and Tullis, J. (2006) JGR

shearing
in regime 3 only
to high strains

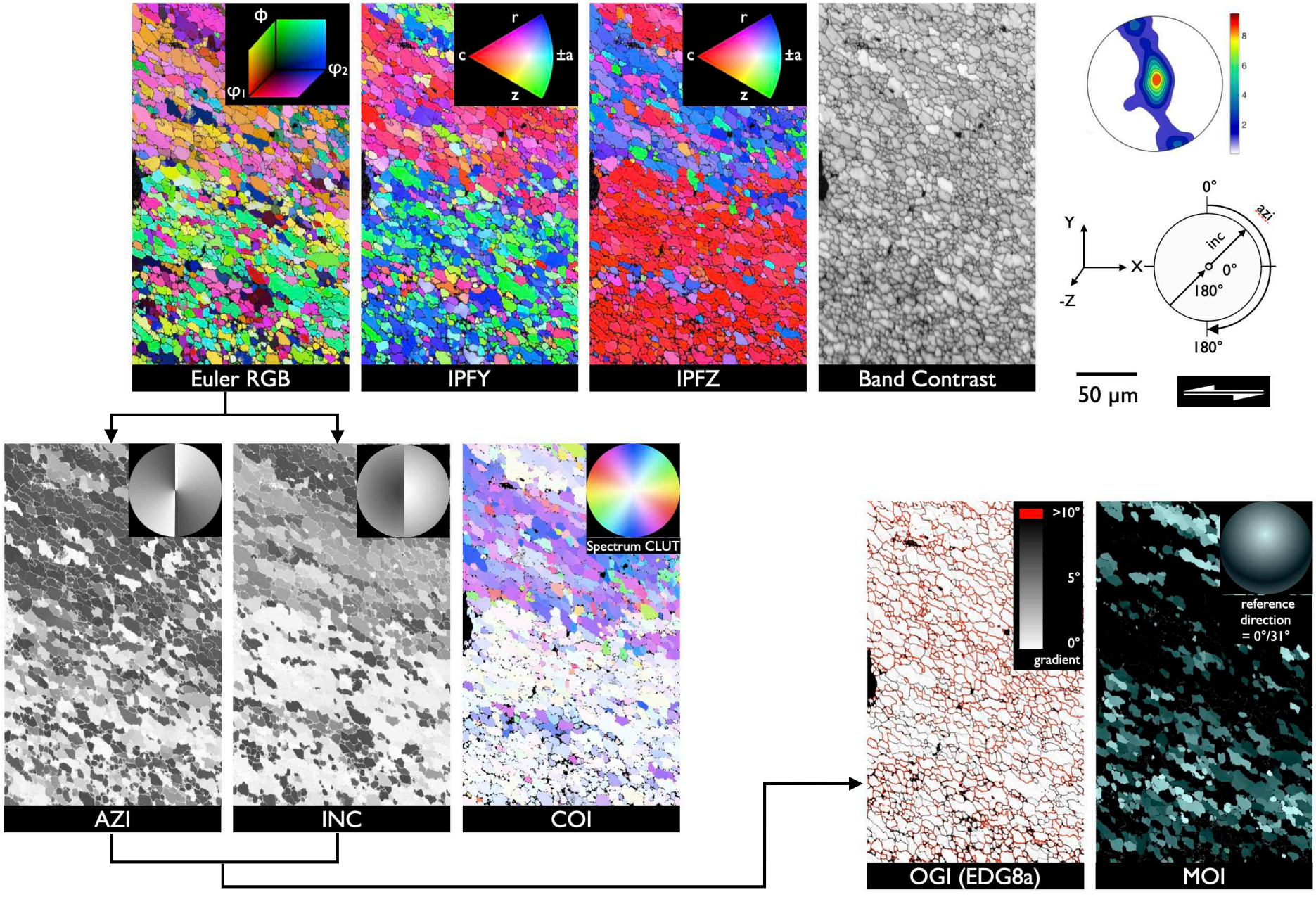


mode D(µm)	
undef.	99±12
reg.3	15±10

in the meantime, CIP meets EBSD ...

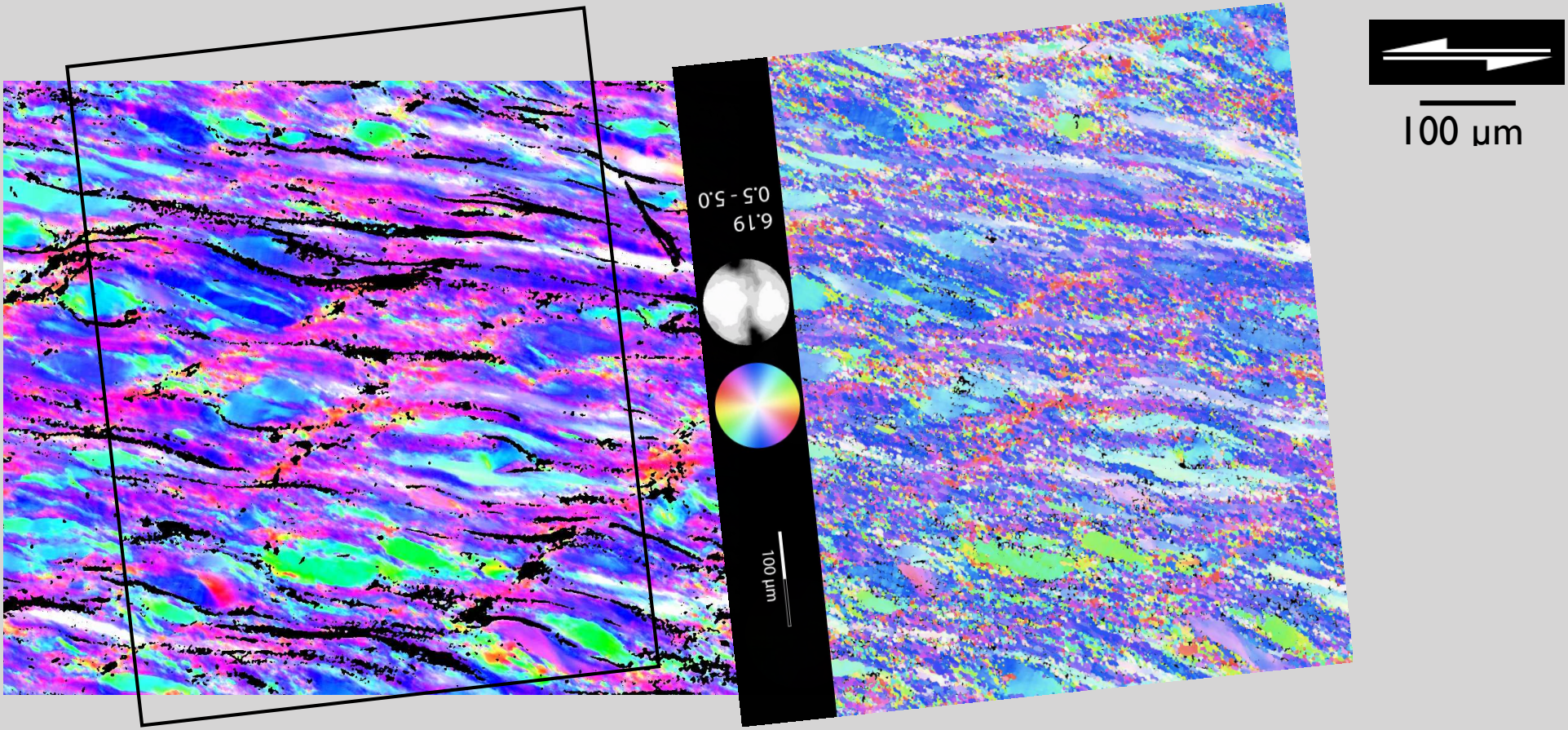


CIP images from EBSD data



comparing CIP and EBSD

regime 1 (w1092) – shearing



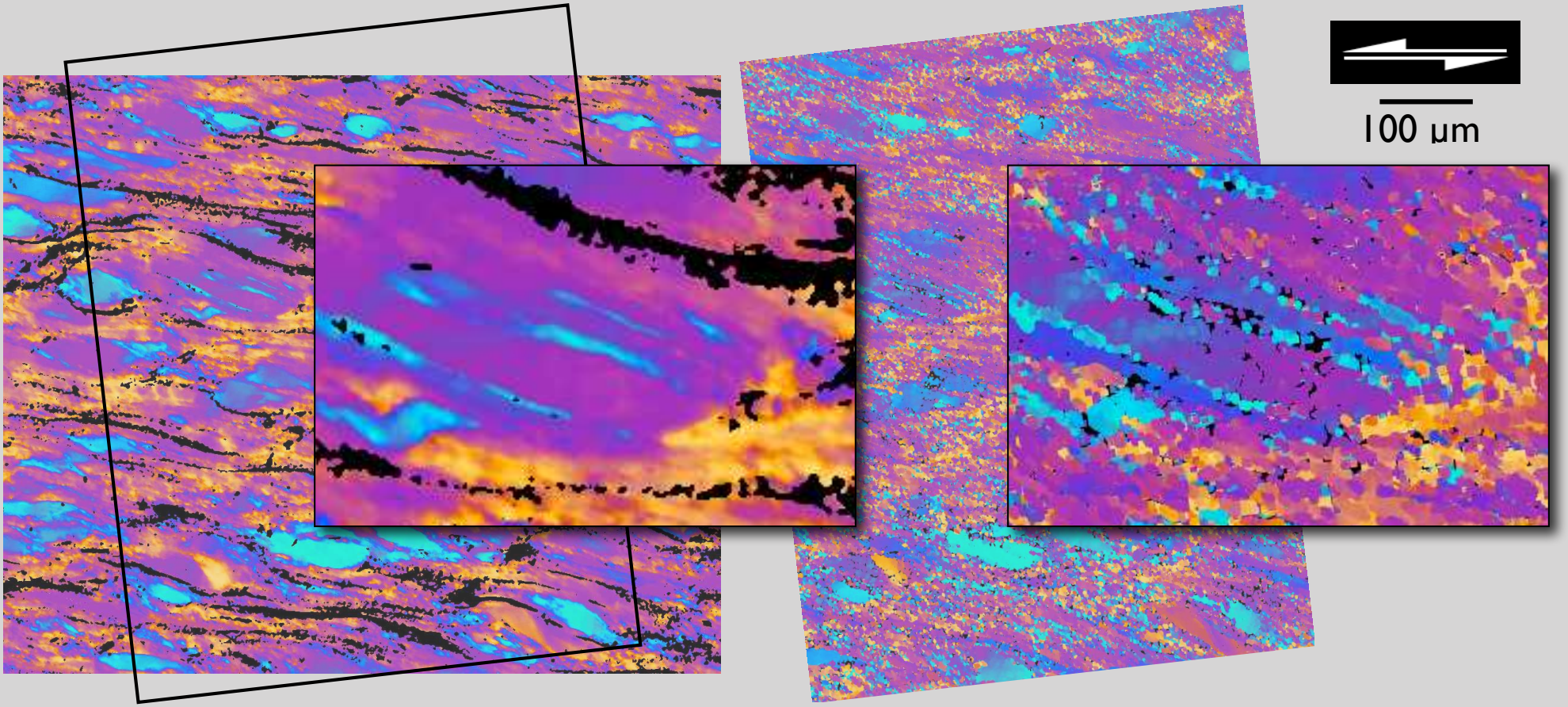
CIP

EBSD

Spectrum CLUT

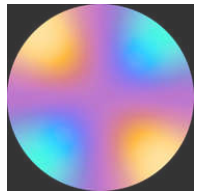
optical microscopy in the SEM

regime 1 (w1092) – shearing



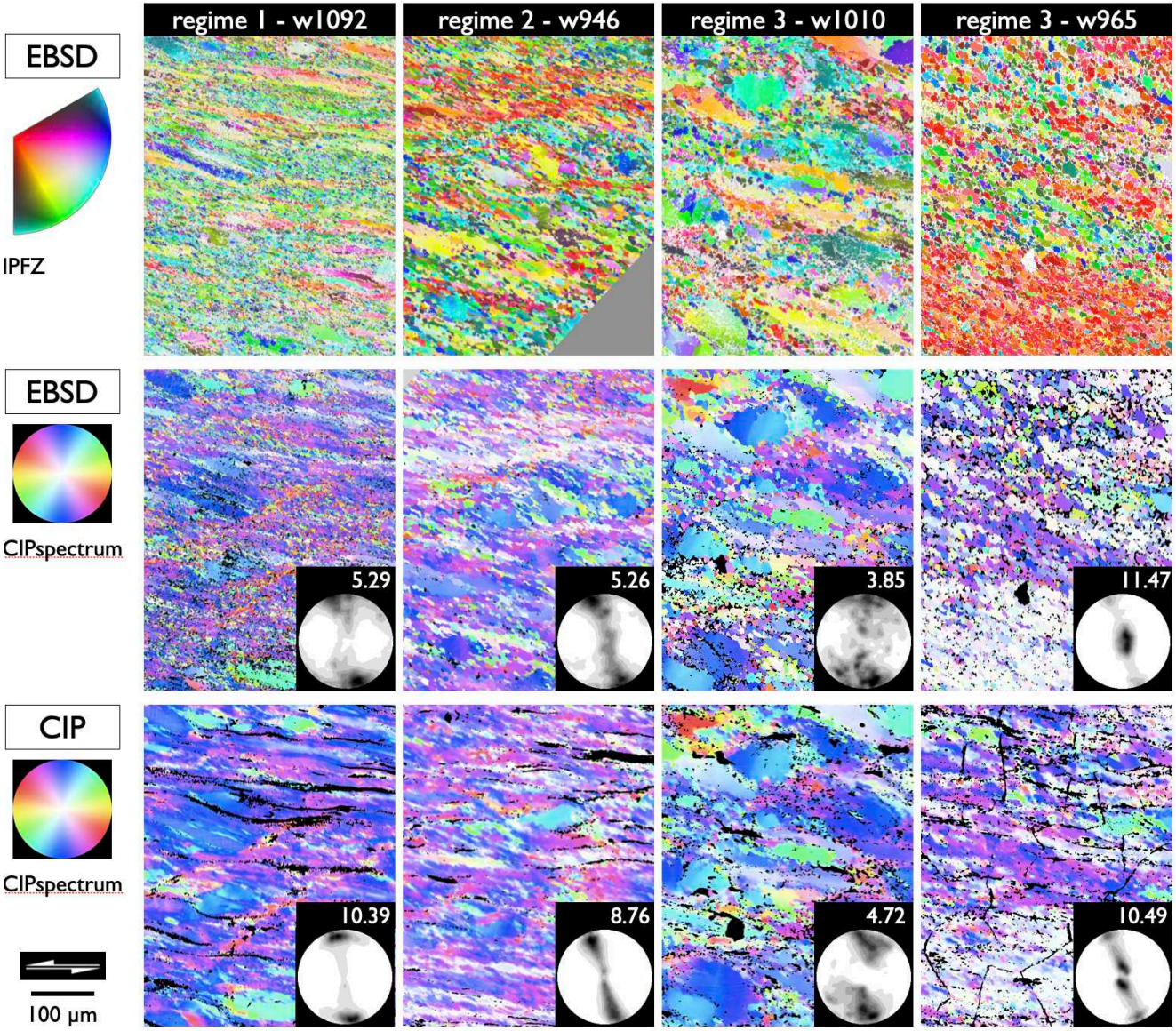
CIP

EBSD



Positive CLUT

BHQ revisited



true or false ?

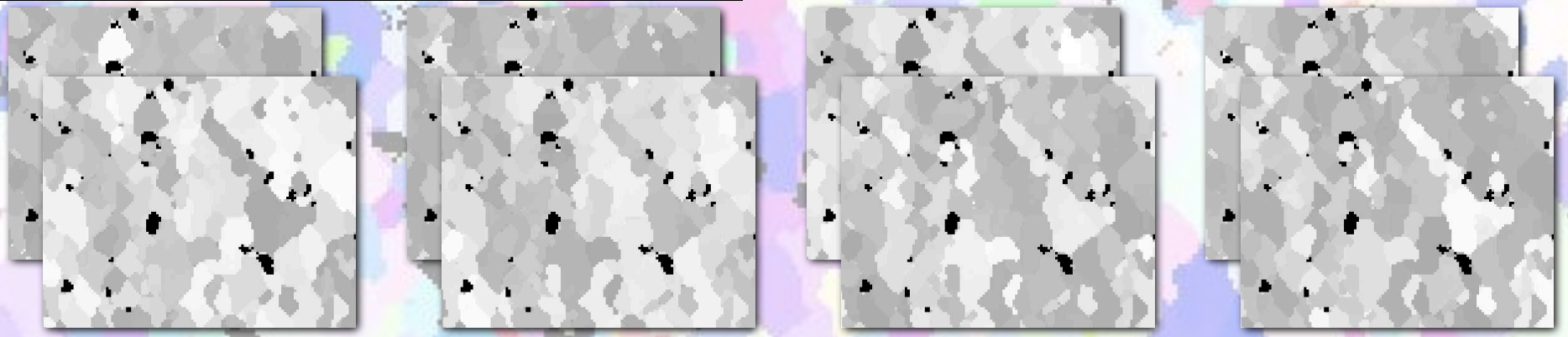
"... the recrystallized grain size of the rhomb domain is approximately 12µm and that of the prism domain is approximately 19µm, corresponding to shear stresses of 93 and 64 MPa, respectively."

Heilbronner, R. and Tullis, J. (2006) JGR

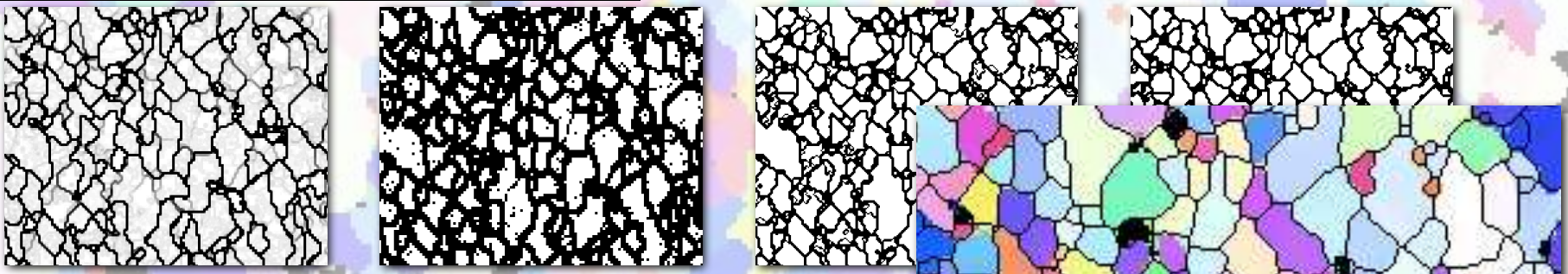
Heilbronner, R. & Kilian, R. (2017), Solid Earth.

CIP segmentation by shape

misor stack → find edges → add →

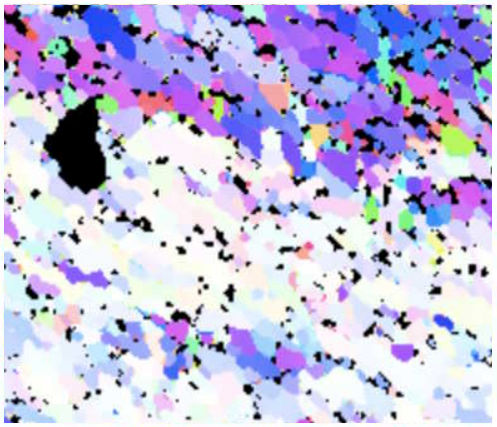


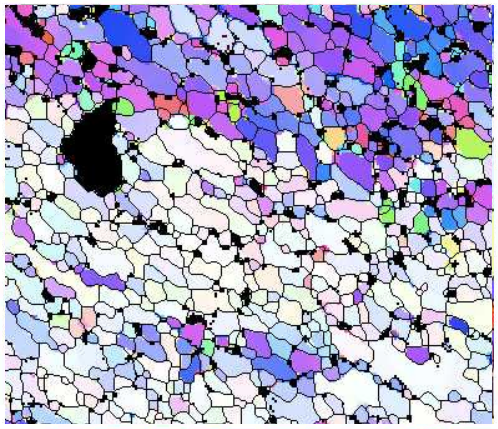
threshold → erode → dilate →



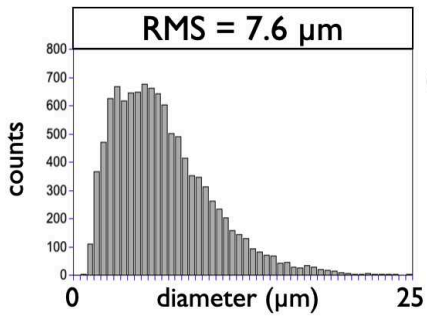
sceletonize → thin → thick →invert

EBSD segmentation by texture

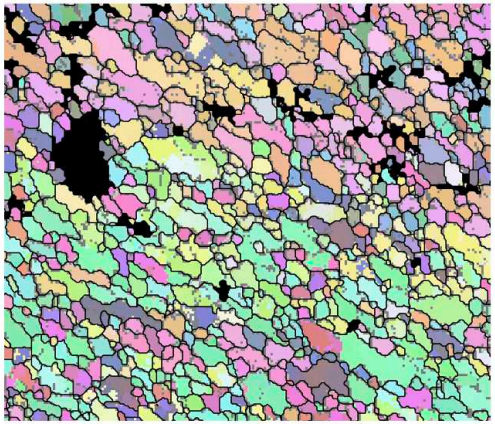


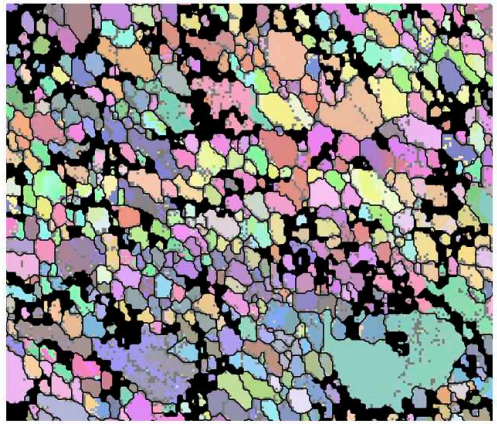


EBSD to CIP outlines >75%

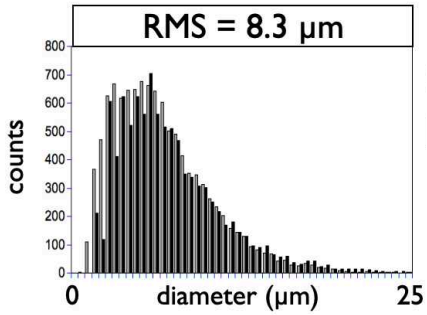


CIP

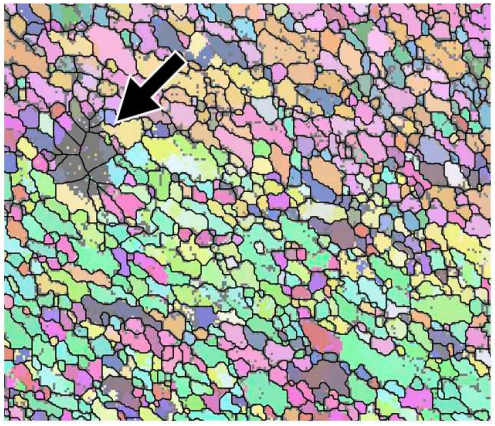


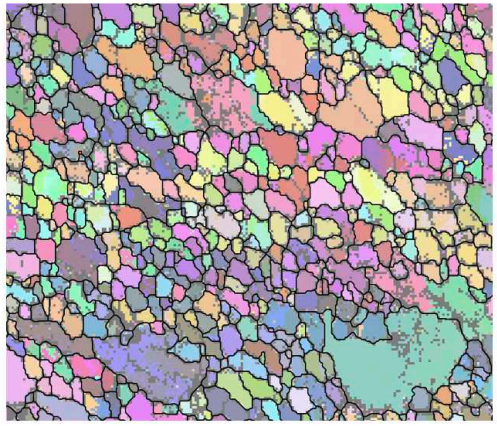


EBSD without grain completion

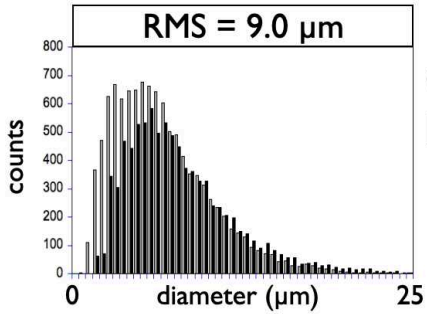


CIP ≈ EBSD





EBSD with grain completion

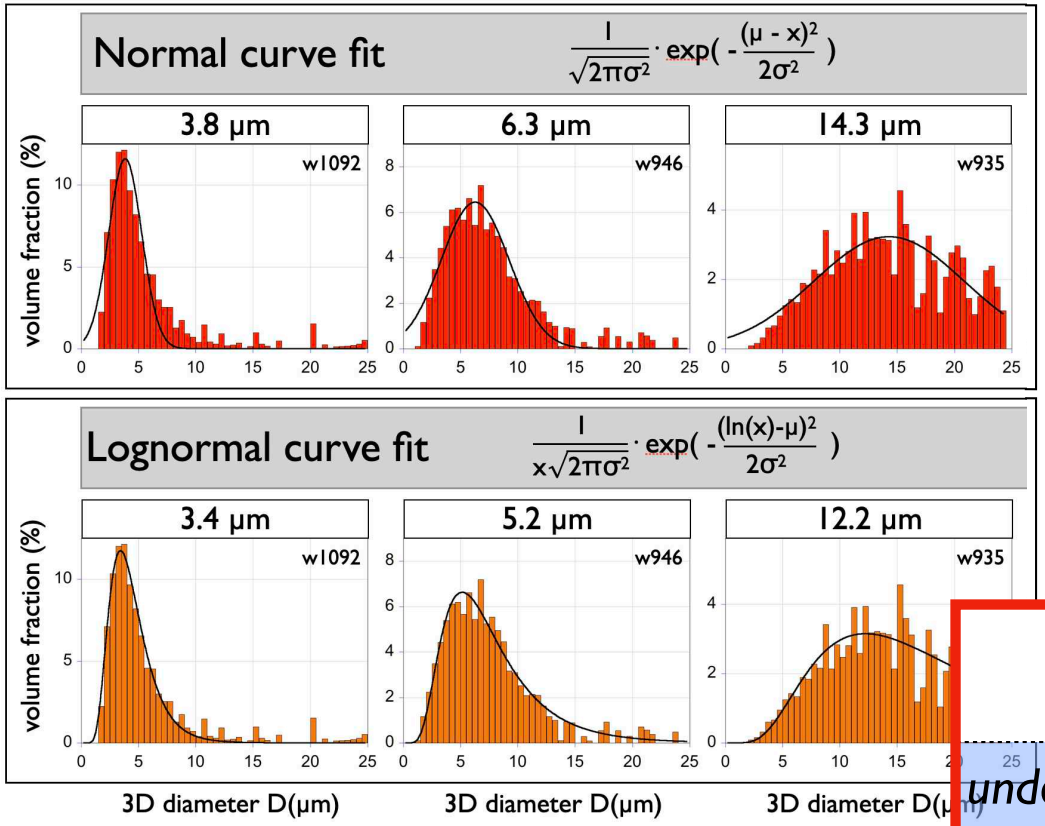


CIP

EBSD

grain size as f(curve fit)

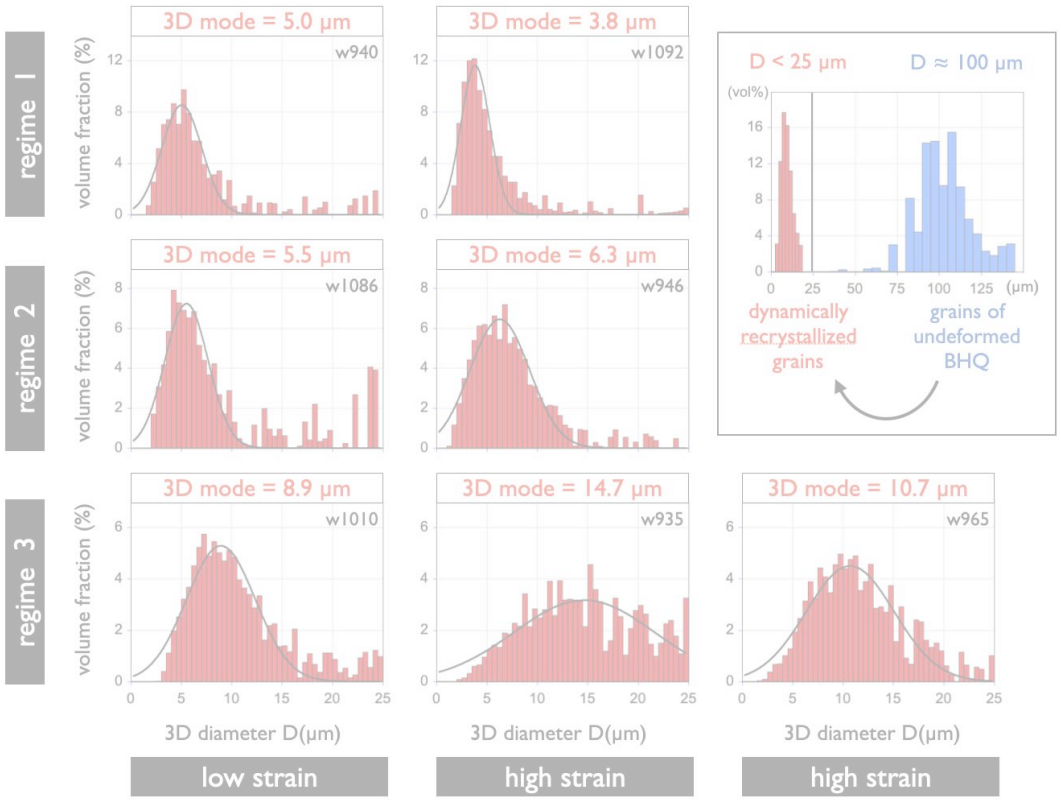
regime 1 *regime 2* *regime 3*

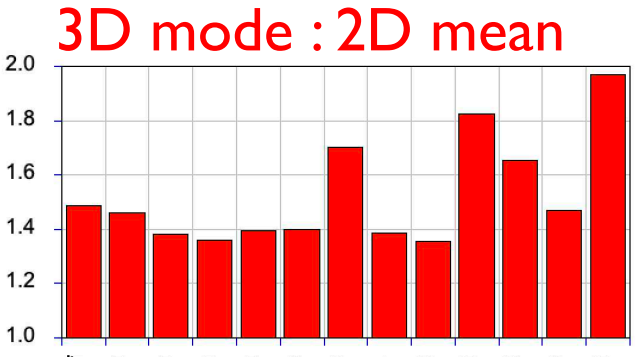


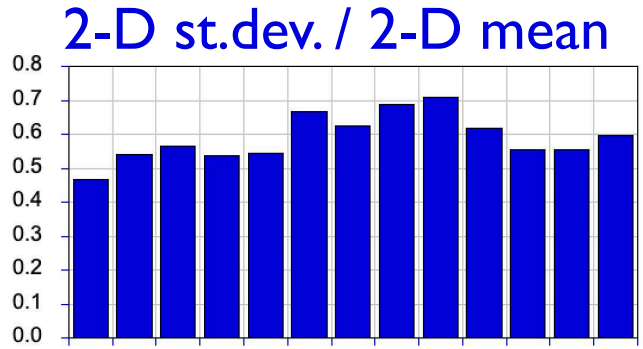
	CIP (2002) 3D mode (µm)	CIP (2006) 3D mode (µm)	EBSD (2017) 3D mode (µm)
undef.	104	99	101.1
regime 1	7	-	3.8
regime 2	8	-	6.3
regime 3	14	15	14.3

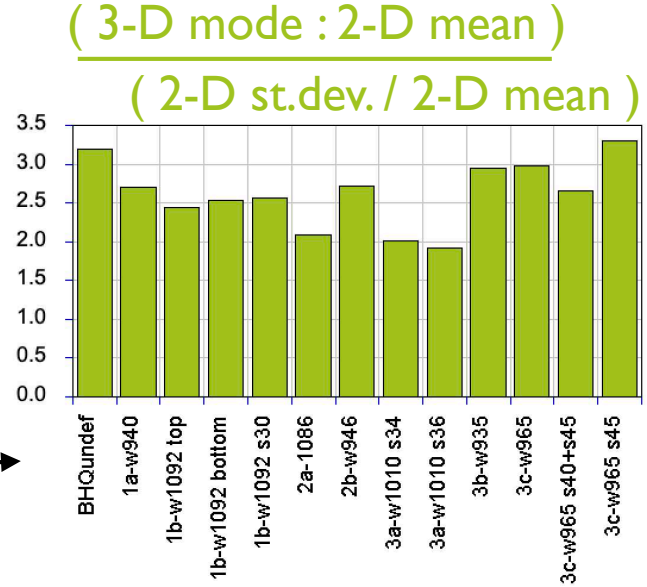
(using normal curve fits)

the infamous 'correction factor'









put the numbers back into the picture

image processing

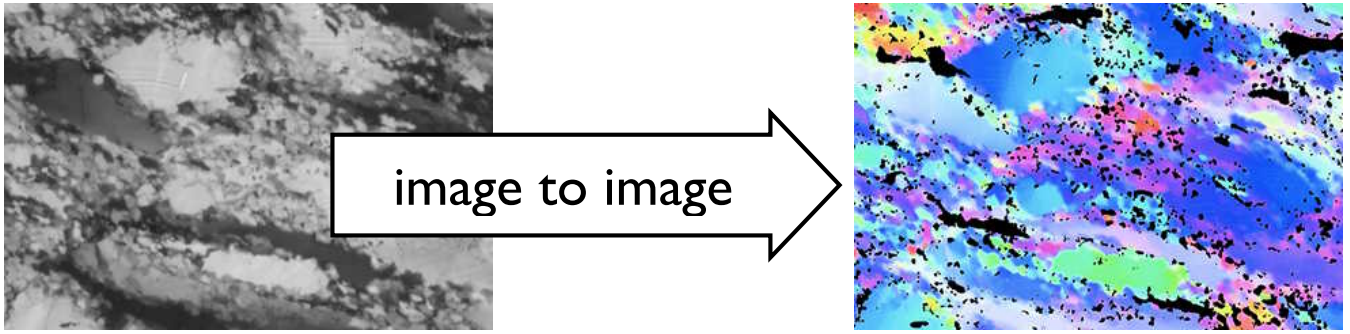
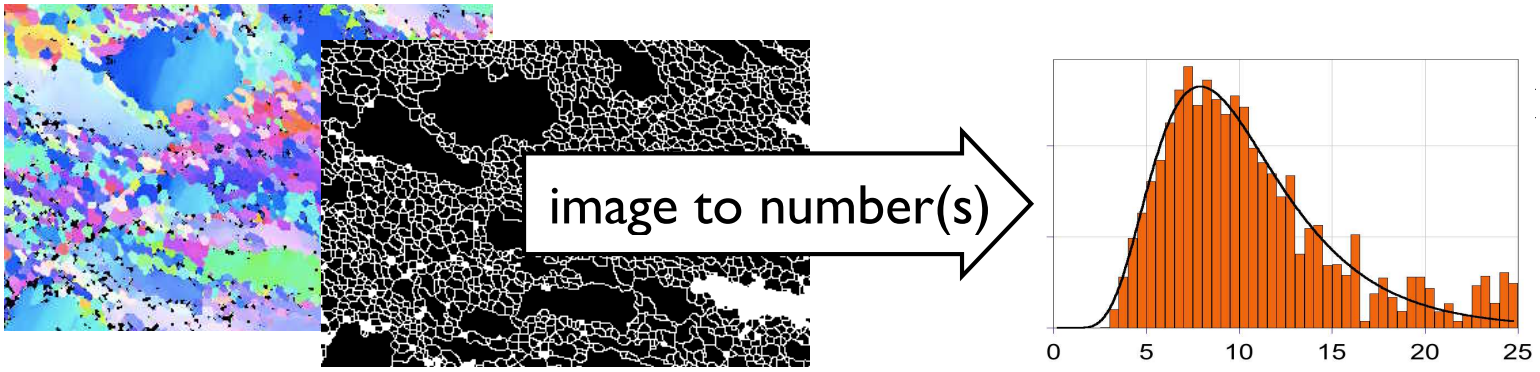
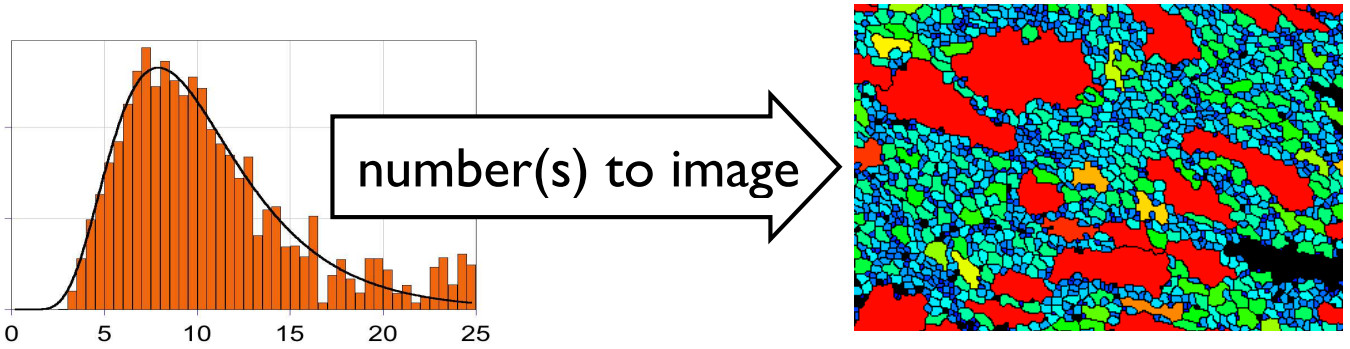


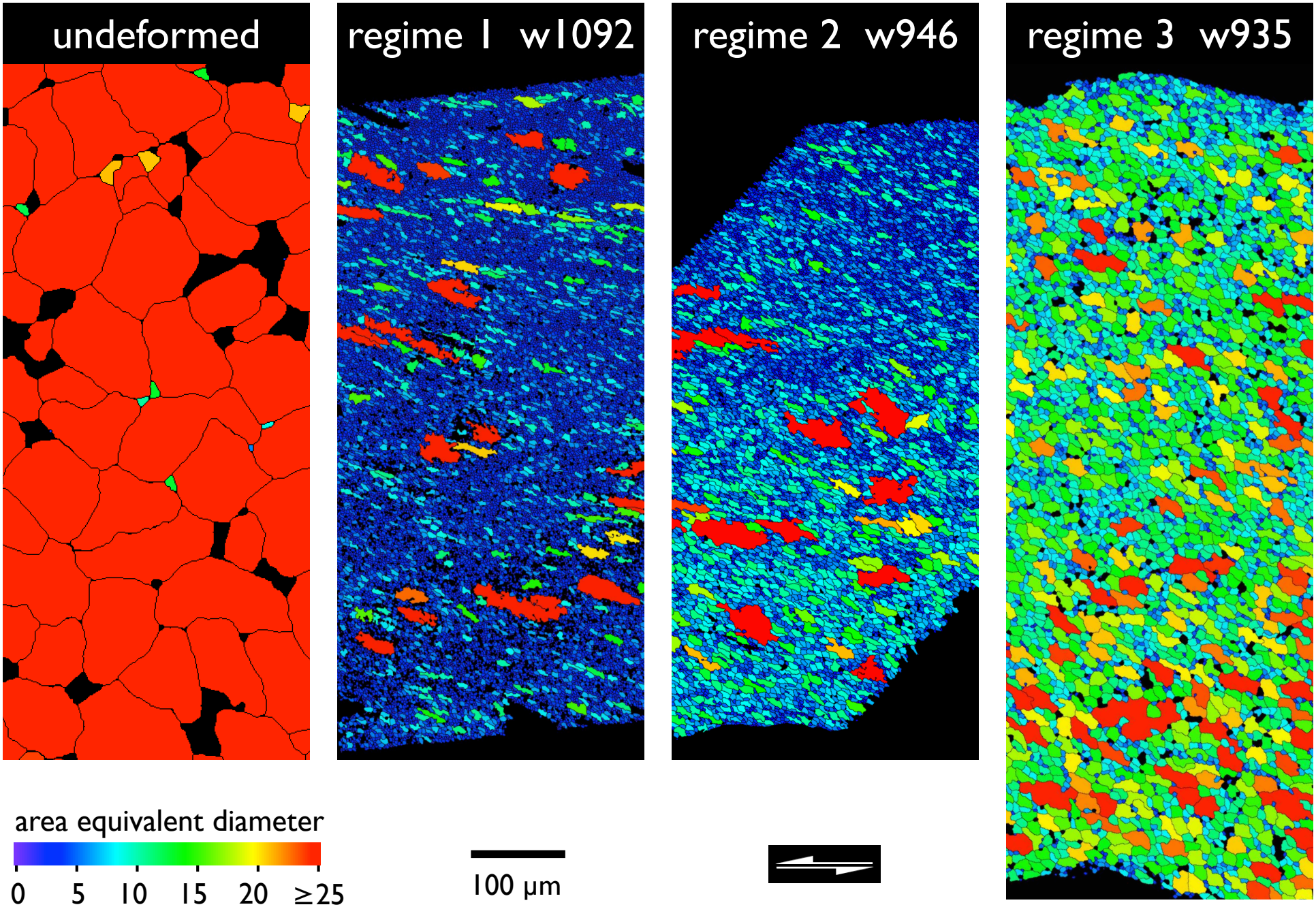
image analysis



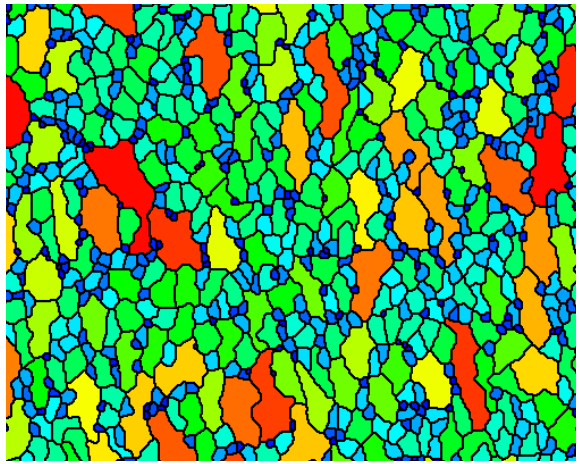
property mapping

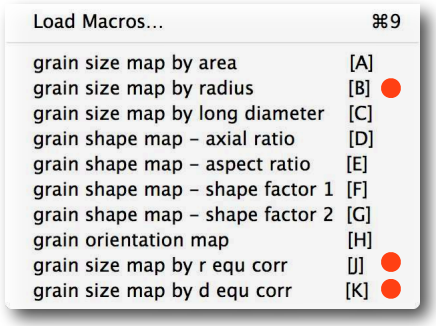


grain size mapping

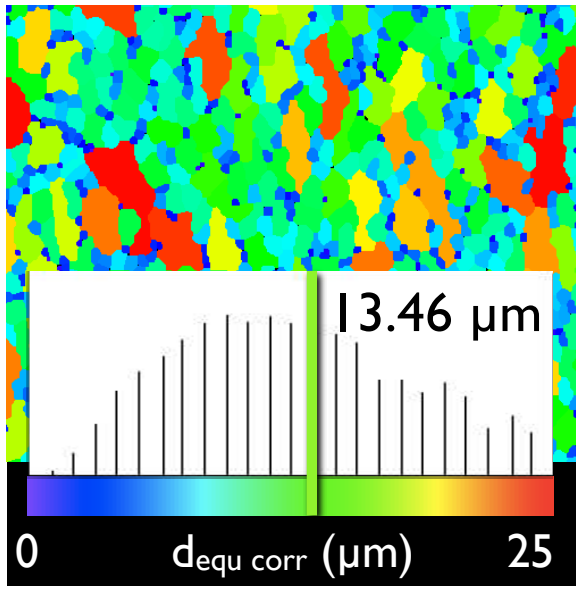


if you are allergic to 3D grain size ...

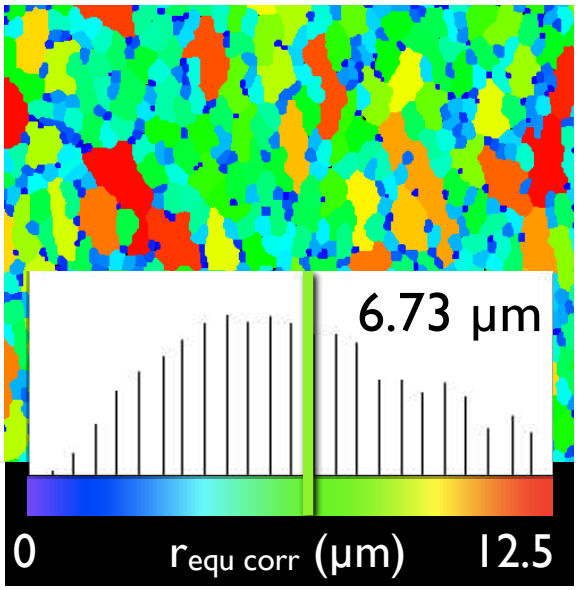




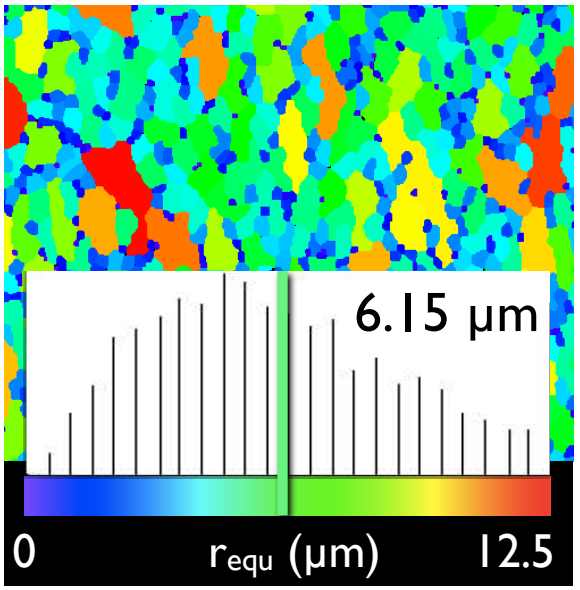
[K] $d_{equ\ corr}$



[J] $r_{equ\ corr}$ = corrected

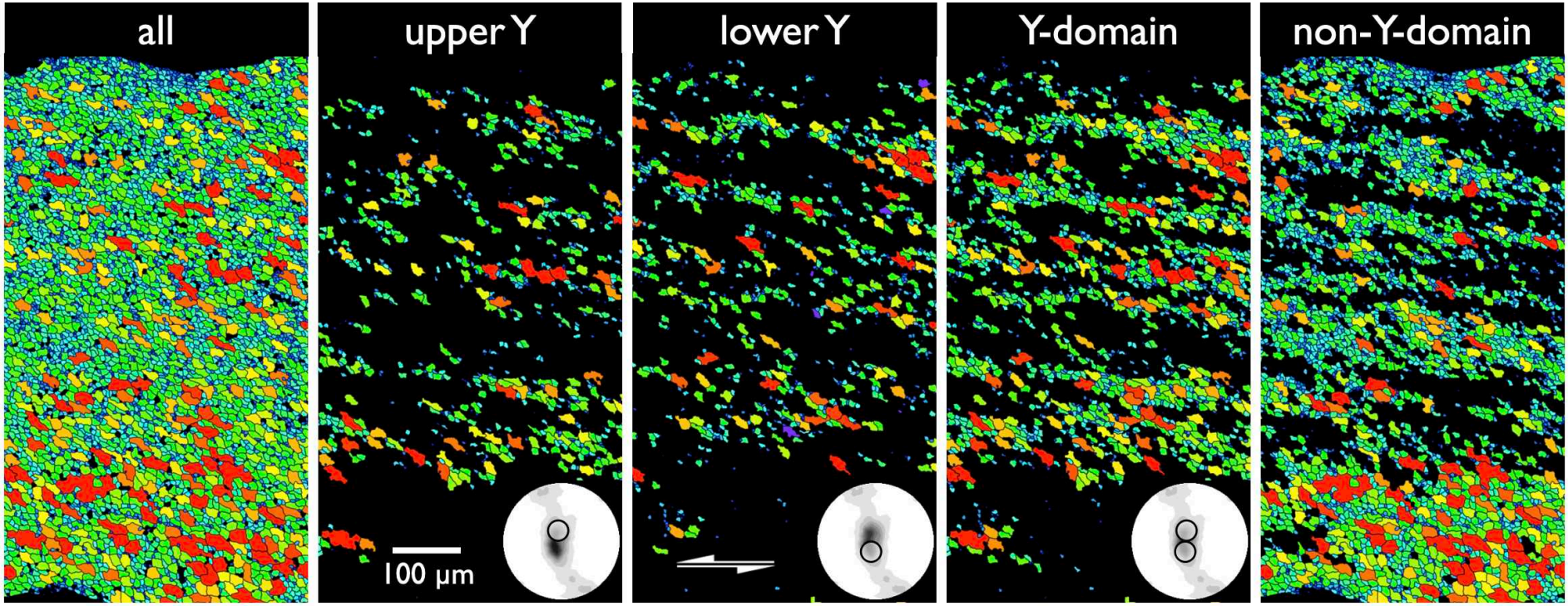


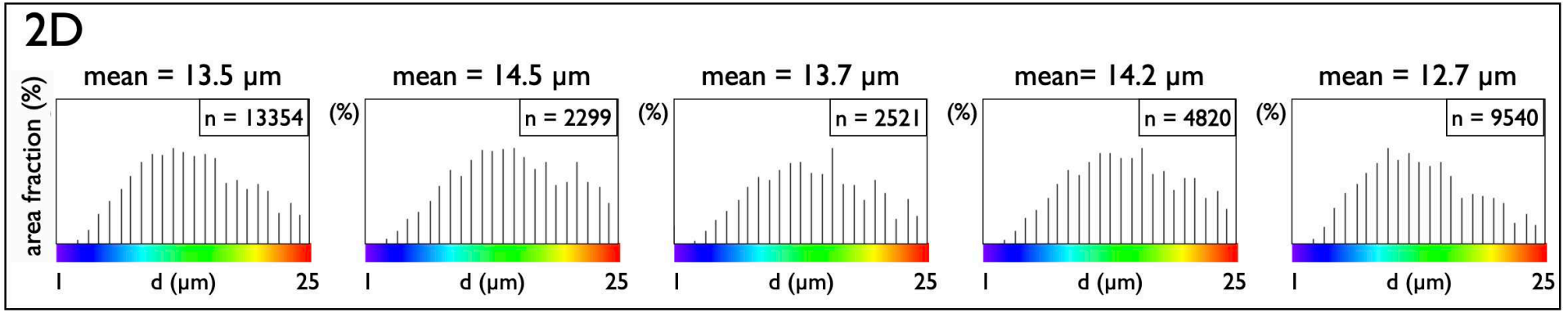
[B] r_{equ} ≠ corrected



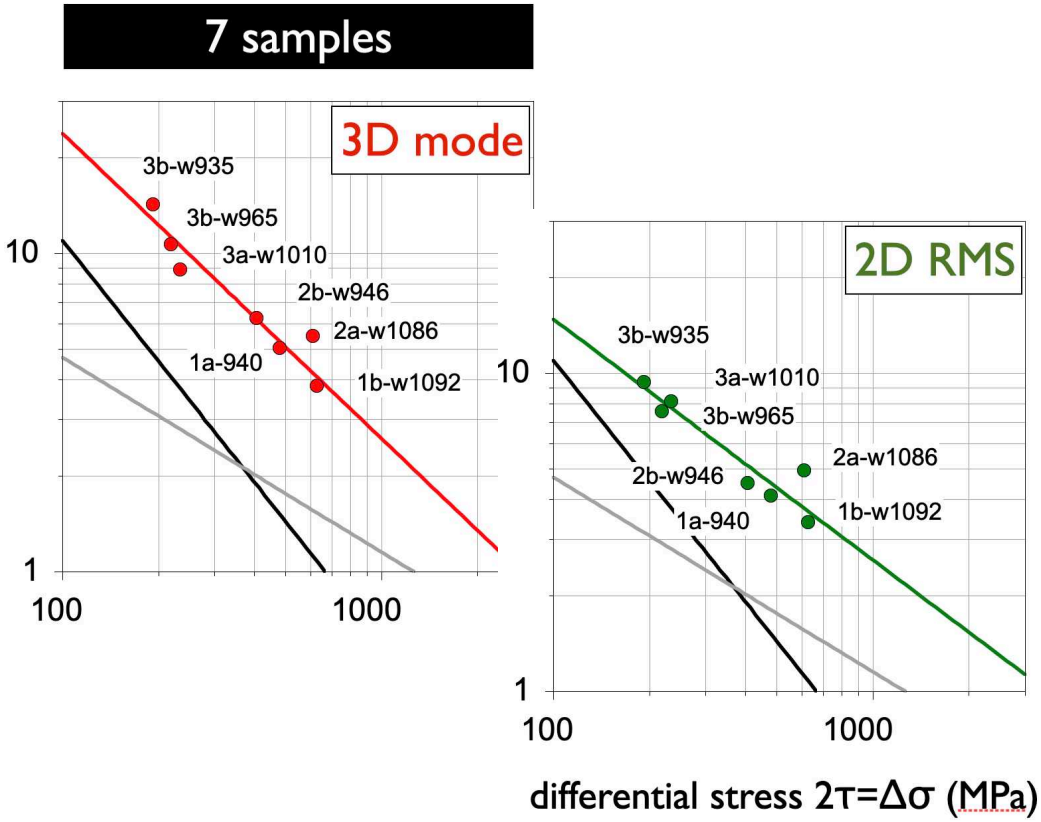
texture dependent grain size

area weighting of 2D

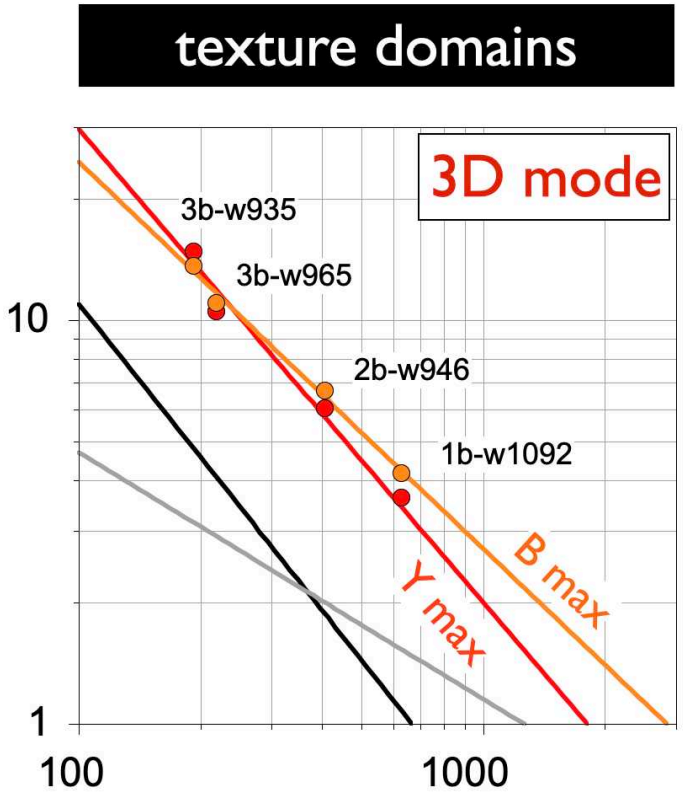




the quartz piezometer(s)



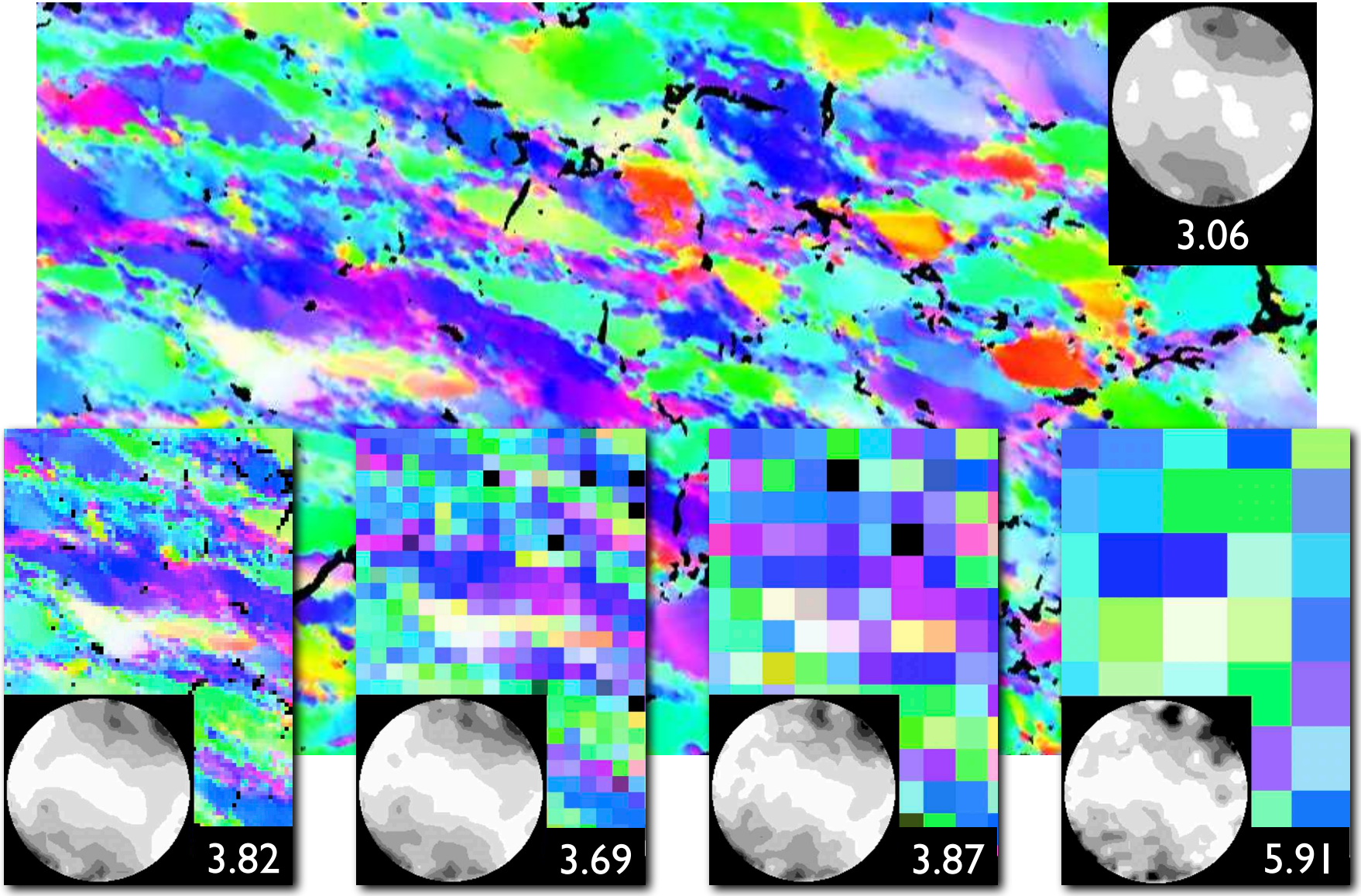
piezometer different for shearing vs. axial ?
– unresolved



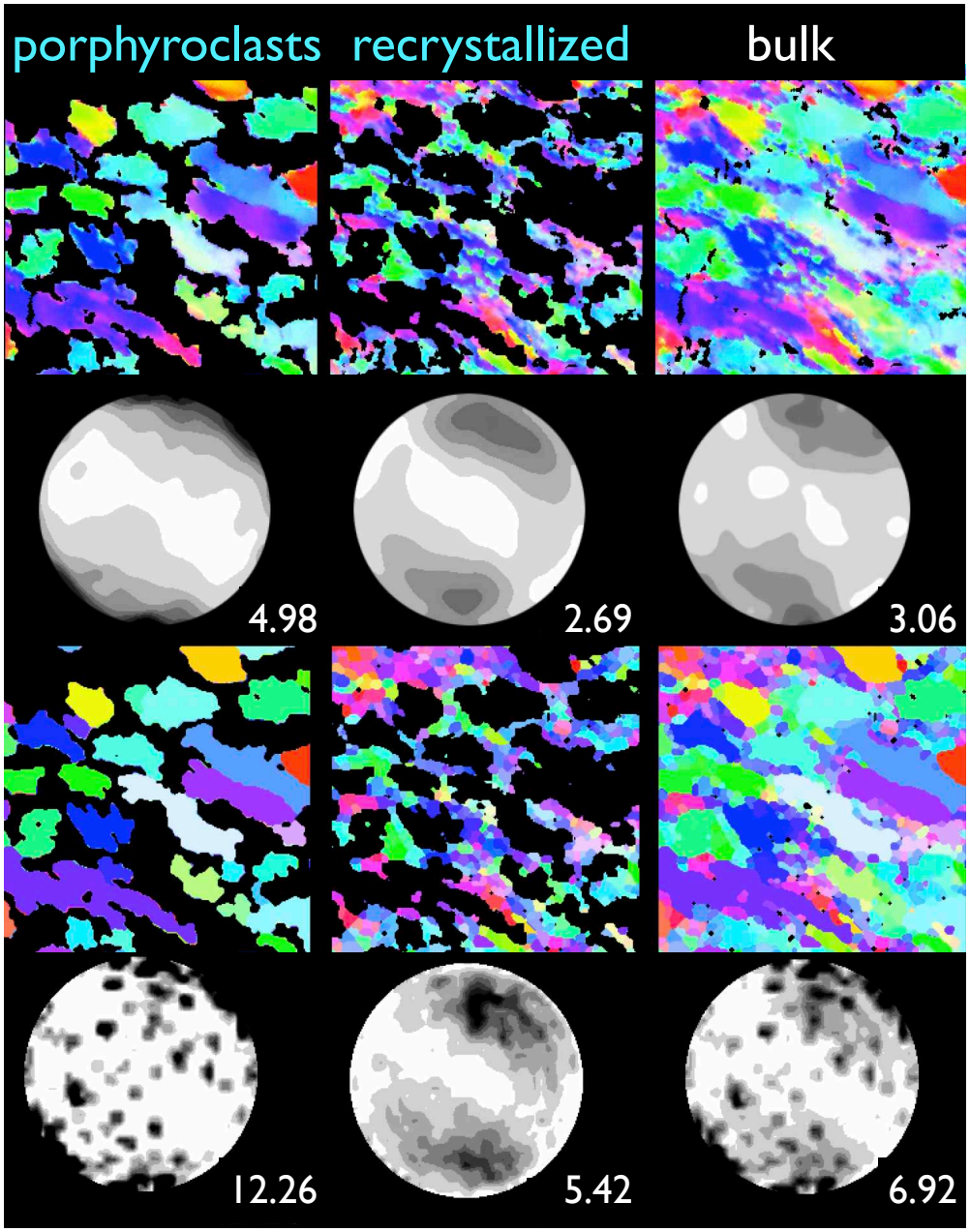
piezometer different
for different domains ?
– unresolved

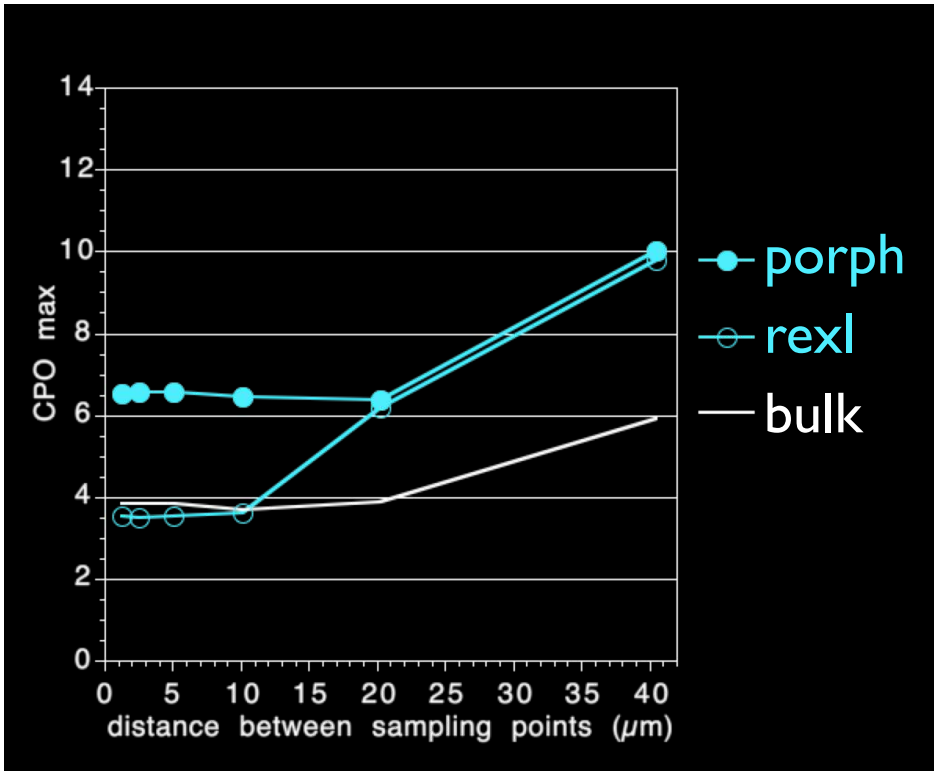
7
about texture

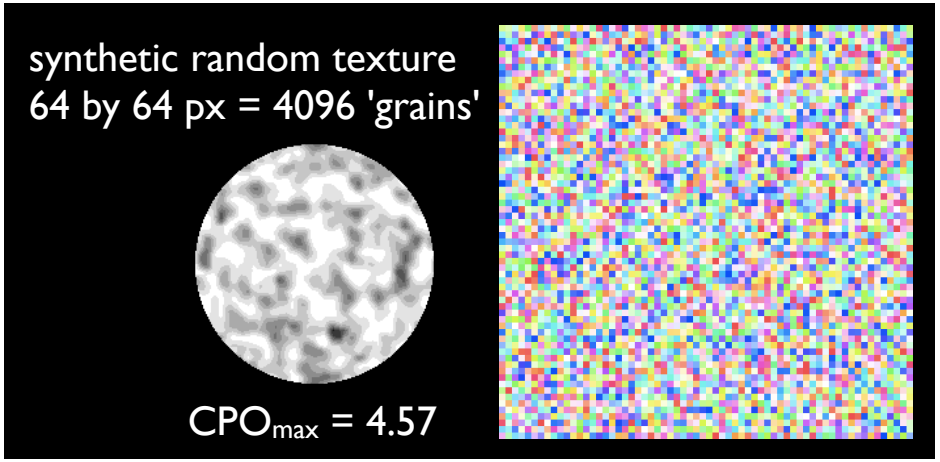
texture strength – spatial resolution



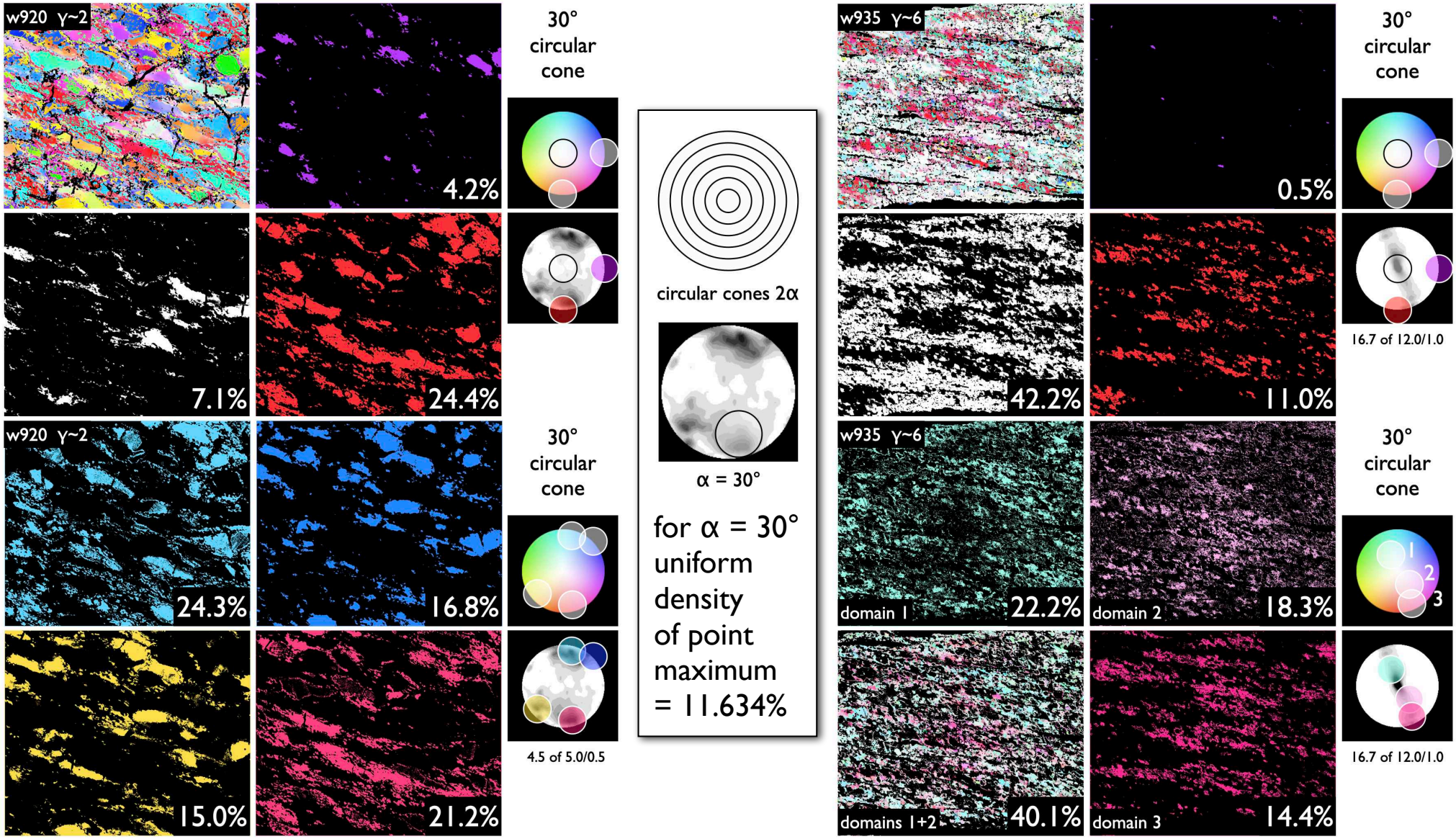
texture strength – grain size







texture mapping



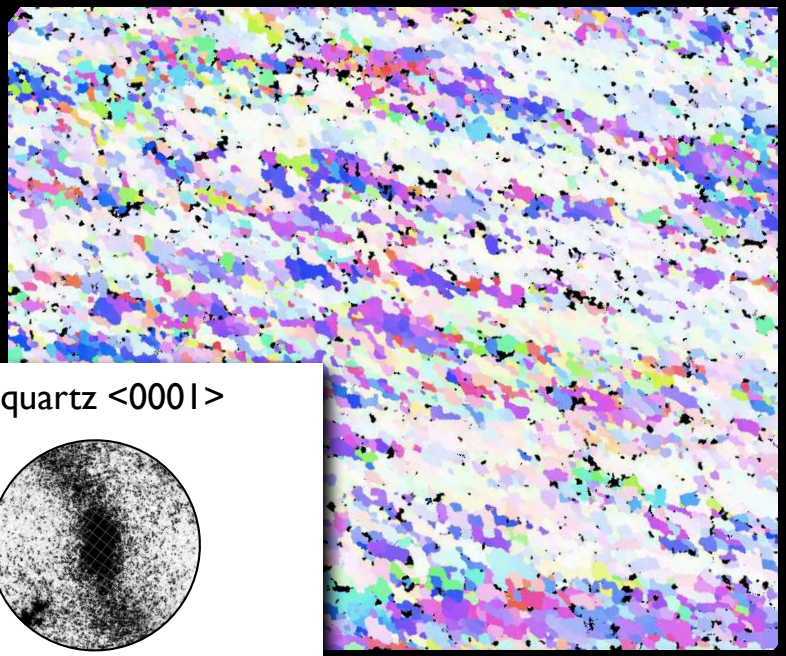
so ...?

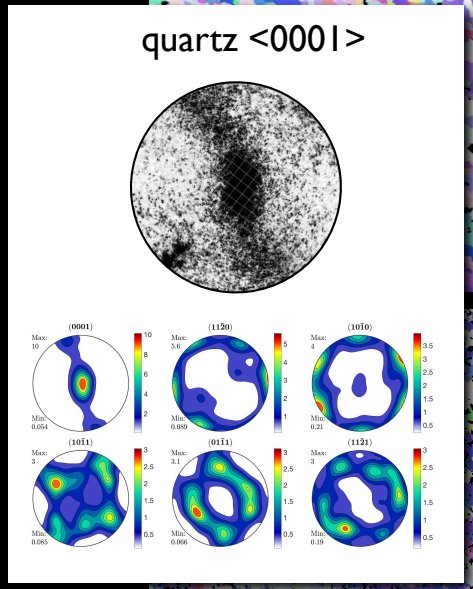
to summarize

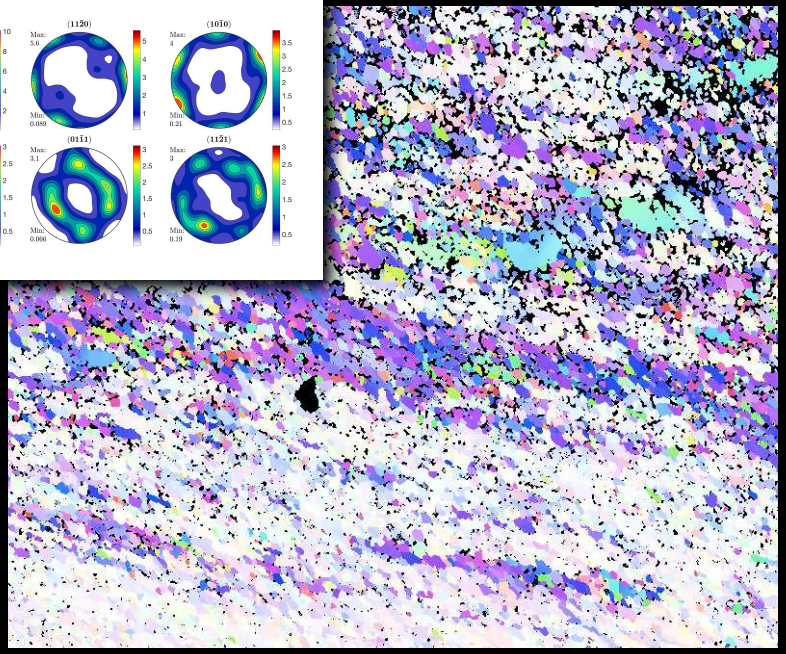
- what has digital added to 'manual' image analysis ?
- what is the relation between Bambi and Godzilla ?
- should we worry about grain size ?
- why should we visualize ?

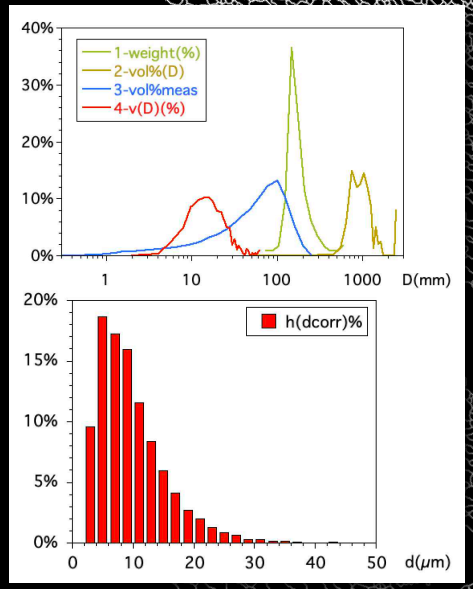
... in any case ....

... "you can observe a lot by watching"

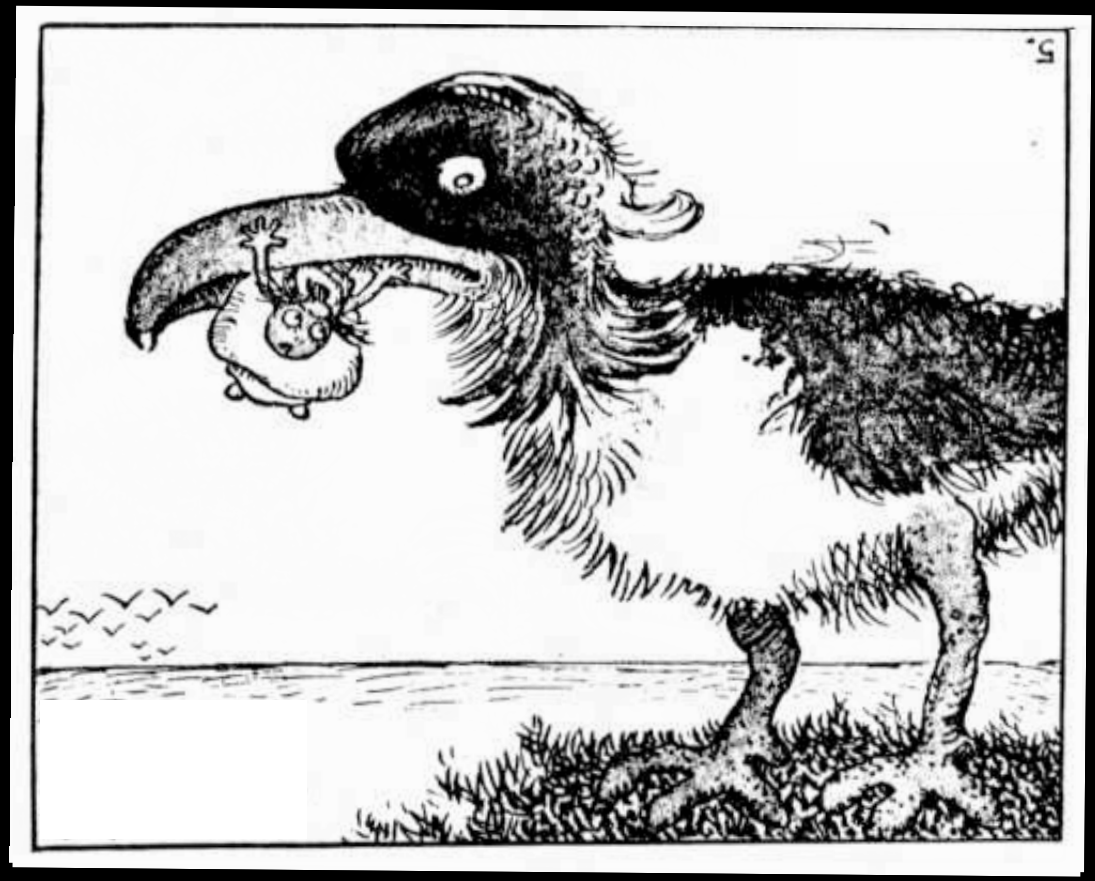






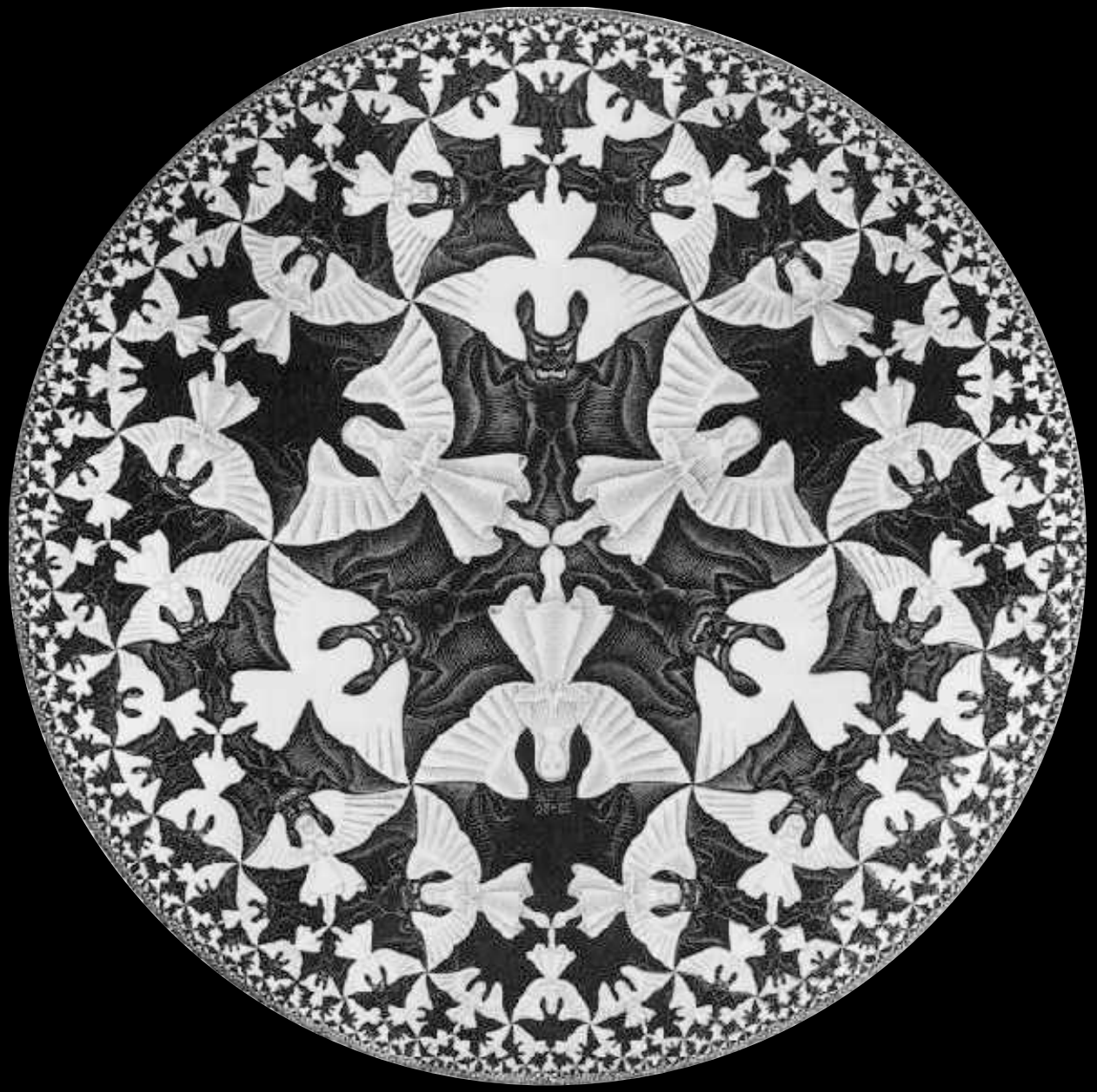


what image analysis teaches you ...



what image analysis teaches you ...

what image analysis teaches you ...



... so why use image analysis ?

because it makes you ...
... look at your data
... play with your data

you may even solve some problems ...

but most importantly ...
... image analysis makes you ask questions

and finally, ...

... image analysis has let me meet a lot of nice people,
who have asked a lot of very intersting questions
therefore ...

... thanks go to all participants of all my workshops –
without whom this award would not have been possible

... thanks go to all participants of all my workshops –
without whom this award would not have been possible