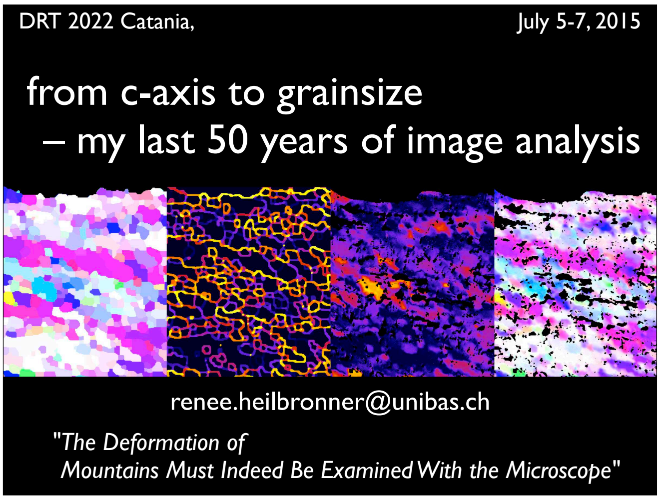
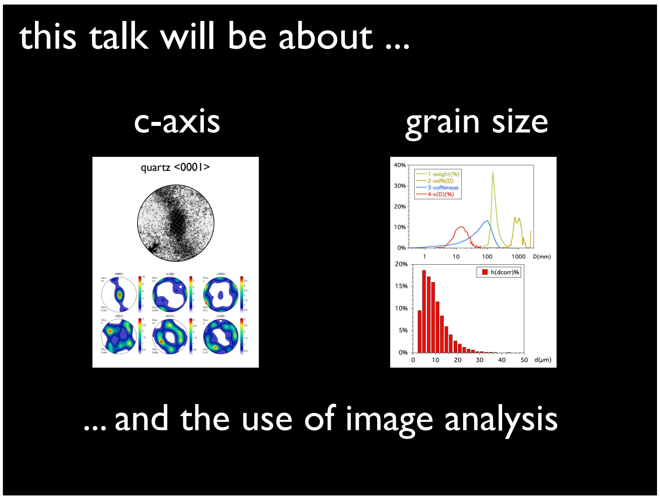


1

NOTE: change of title !
NOTE: quote Henk Zwart

THANKS go to presidents of TecTask now IASTG - Enrique Gomez-Rivas, Manish Mamtani, THANKS go to members of the DRT organizing committee - Eugenio, Rosalda, Gaetano



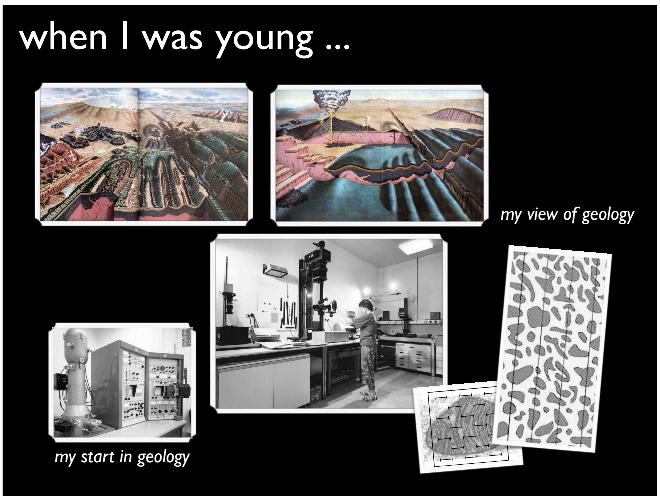
2

how can we best quantify texture and grain size ?
this talk will be about how I got close ...
... or not so close ... to answering these questions
... over the last 50 years

I
decades ago –
before microstructure and texture analysis went digital

3

Talk
1. pre-computer time
2. to early image analysis (vector graphics, tablets)
3. to beginning of true digital image analysis (raster graphics)
4. 3D grainsize
5. CIP meets EBSD
6. about gs
(7. about texture) - this was actually canceled because of time



4

A look into my photo album shows my 'direct' road to geology (...)

stereology and point counting ...

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

find volume density:

Achille Ernest Oscar Joseph Delesse (1817-1881)

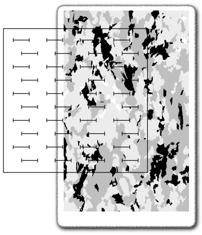
$V_V = A_A$

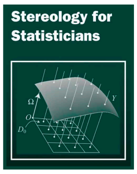
August Karl Rosiwal (1860-1923)

$V_V = A_A = L_L$

Andrei Aleksandrovich Glagolev (1894-1969)

$V_V = A_A = L_L = P_P$



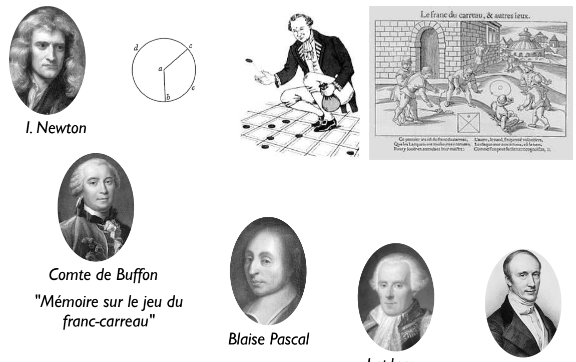


5

All geologists:
F: Delesse: oily paper - tracing - weighing
GB: Sorby: microscope, camera lucida (Amateur naturalist, founder of metallurgy (?) (1826-1908)
AU: Rosiwal: linear approx. - linear intercept

---

which is all about probabilities ...



I. Newton

Comte de Buffon "Mémoire sur le jeu du franc-carreau"

Blaise Pascal

Laplace

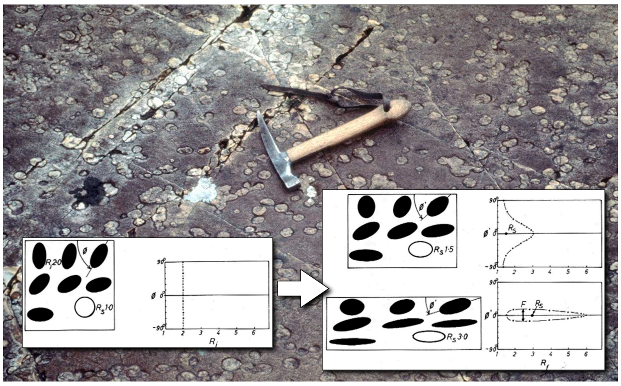
A.-L. Cauchy

6

Newton, 1967 (sic!)
Georges-Louis Leclerc Comte de Buffon (1707–1788)
Blaise Pascal, (1623-1662)
Pierre Simon Marquis de Laplace (1745-1827)
Augustin-Louis Cauchy (1789–1857)
Joseph Emile Barbier (1839-1889)
Sarkis Andreevich Saltykov (1906-)
... stereological theorems

John Ramsay: R_f / φ ...

... or how to measure strain



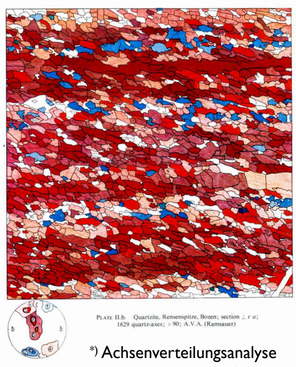
7

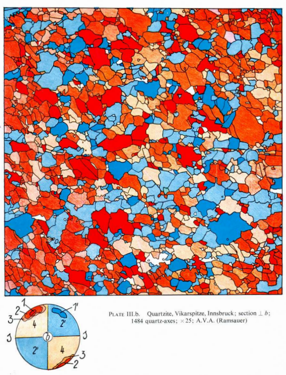
... still no computer involved
John Graham Ramsay CBE FRS (17 June 1931 – 12 January 2021), British structural geologist

Ramsay & Huber, Fig 5.1 R&H showing Cambrian quartzite with cross sectional areas of deformed worm tubes.
NOTE shape ≠ spheres but cylinders !!!

Bruno Sander: AVA*) ...

... or how to map c-axis orientations





*) Achsenverteilungsanalyse

8

... still no computer involved
Bruno Sander (1884 - 1979) Austrian geologist

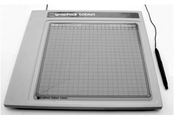
Outlines (segmentation) -> mapping (colouring c-axis orientation)
Pole figure is not localized - thermodynamic concept
Procedure:
1. trace boundaries
2. measure CPO on U-stage
3. color stereoplot
4. color grains
Students and assistants who had to make AVAs called the microscope the "Verblödungsröhre" – they hated it.

9

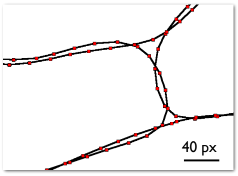
2
early 'digital image analysis' (vector graphics)

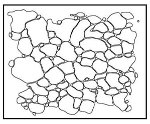
10

manual digitisation



boundaries on tablet





polygonal outline (polyline)
defined by:

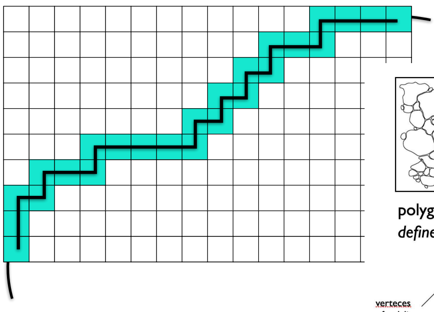
#	x	y
1.	457	11
2.	446	16
3.	432	36
4.	427	49
5.	443	66
6.	484	77
7.	503	68
8.	470	15
9.	457	11
10.	9999	9999
... etc. ...		

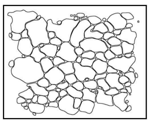
verteces of polyline → (rows 1–9)
delimiter → 10.

seventies and early eighties
1977 Apple II BASIC
1979 Apple tablet
1984 Apple Macintosh Pascal
1987 NIH Image (Pascal)
1993 Image SXM (Pascal)
1997 Image J (Java)
2007 → Fiji ('Fiji is just ImageJ')

11

putting the curve on the grid





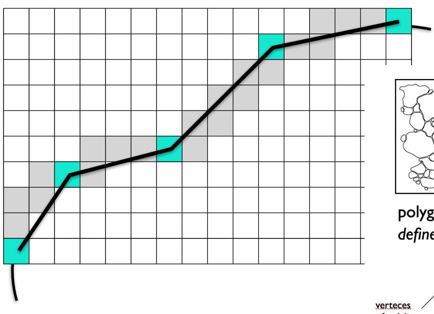
polygonal outline (polyline)
defined by:

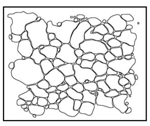
#	x	y
1.	457	11
2.	446	16
3.	432	36
4.	427	49
5.	443	66
6.	484	77
7.	503	68
8.	470	15
9.	457	11
10.	9999	9999
... etc. ...		

verteces of polyline
delimiter

12

try again

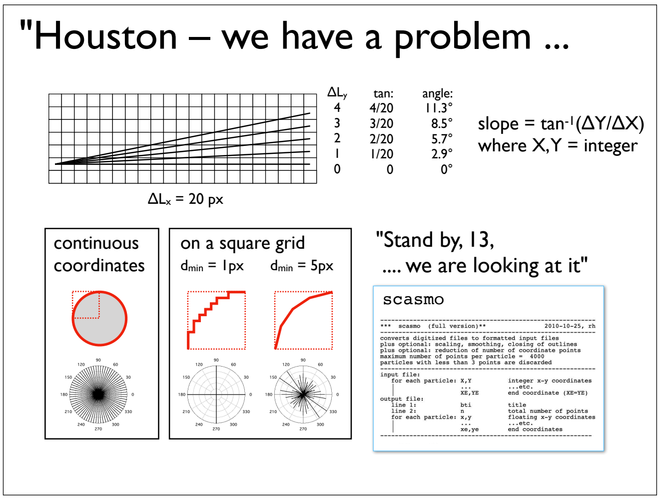




polygonal outline (polyline)
defined by:

#	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. ...		

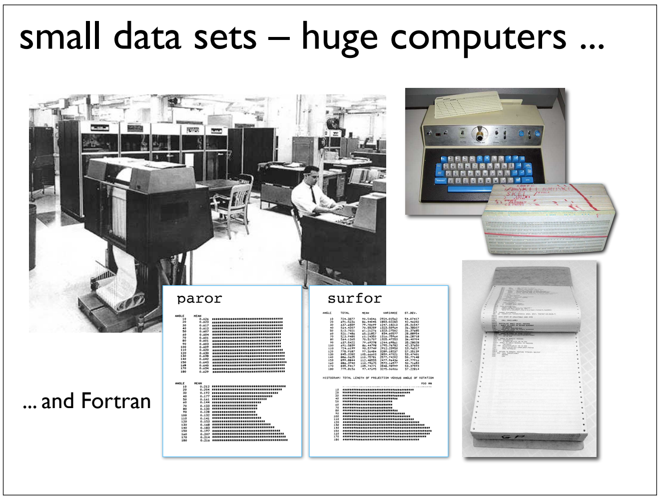
verteces of polyline
delimiter



13

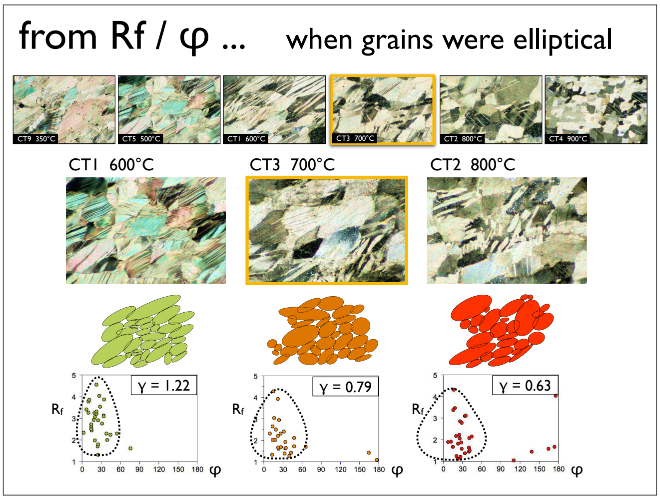
Swigert and Lovell reporting the incident on April 13, 1970 —— about them same time as scasmo was written (the computer power that drove Apollo 13 easily fits on anybody's mobil phone)

An angle of 1.0° (with tan = 0.1745) requires ΔLx = 57.29, i.e. 58 pixels
The density of grid points in a given sector of orientations depends on the length of the line and is not constant for all orientations. It is maximal in the horizontal and vertical orientation and changes irregularly with direction, and minimal distance between points.



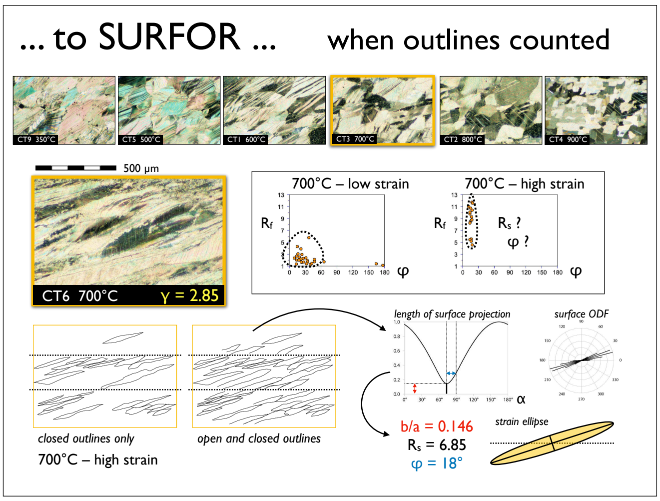
14

Early 70's - around and after Apollo 13 (1970)



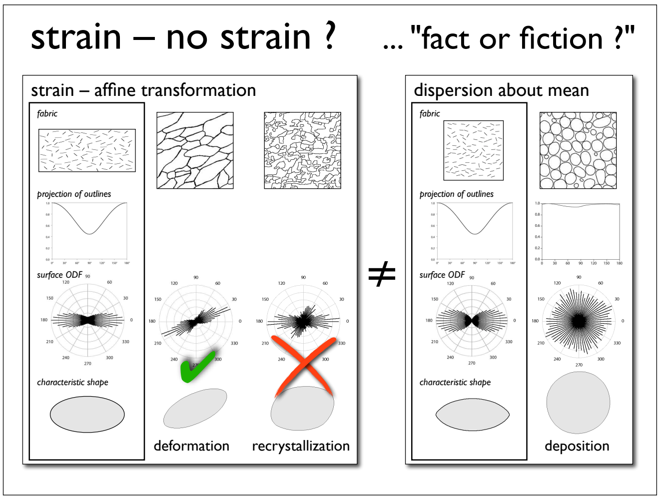
15

Schmid, S.M., Panozzo, R. and Bauer, S. (1987)
The strain (Rs) is ver difficult to estimate – especially with the small number of grains available here. Contours are only eye-balled here.



16

Making use of all grain boundary surface – not only of closed outlines.

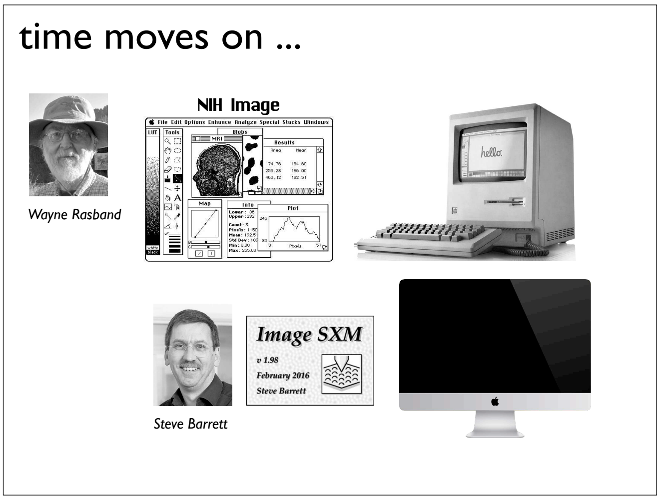


17

modified after Heilbronner, R. and Barrett, S. (2014). Image Analysis in Earth Sciences - Microstructures and Textures of Earth Materials. Springer Verlag, Heidelberg, 520 p. ISBN: 978-3-642-10342-1 (Print) 978-3-642-10343-8 (Online)

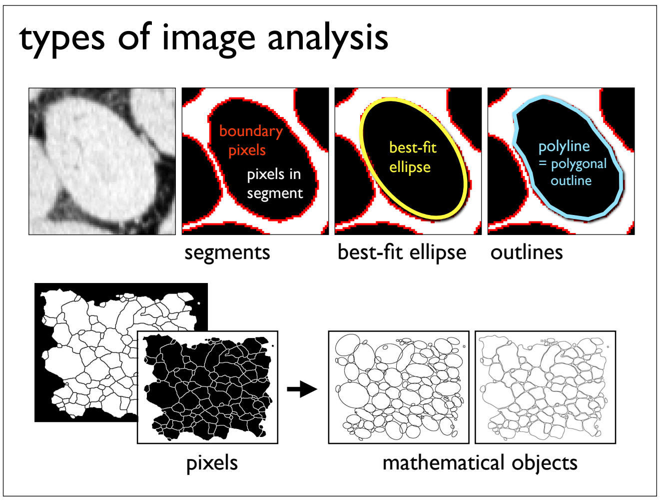
3
the beginning of
digital image analysis
(raster graphics)

18



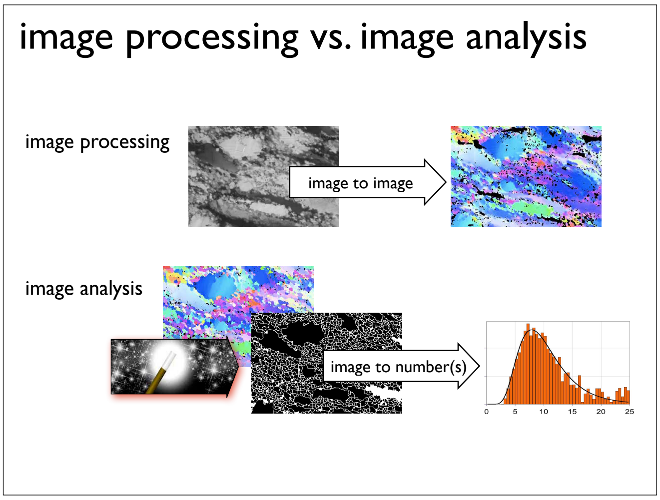
19

1987 NIH Image (Pascal)
1997 Image J (Java)
2007 → Fiji ('Fiji is just ImageJ')
1993 Image SXM (Pascal)

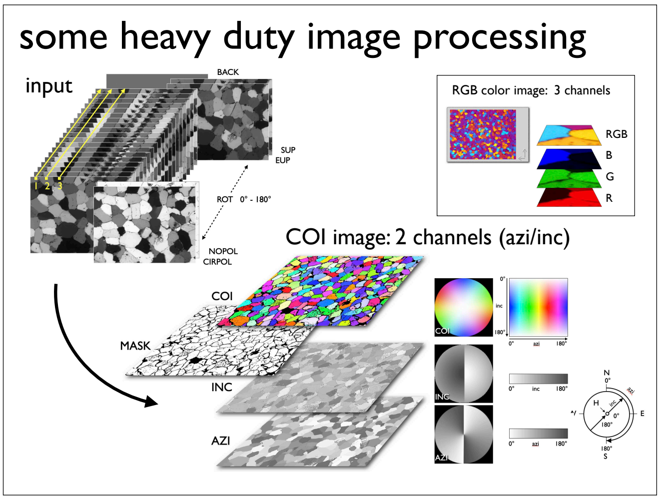


20

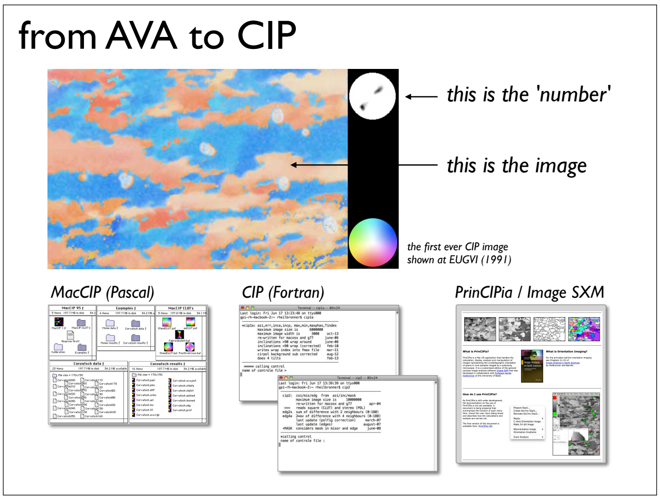
With the advent of 'full-scale' digital image analysis, the expectation was that manual outlining could be replaced by automatic segmentation. And that this would open up a number of types of image analysis. 1) looking at connected pixels and boundary pixels, 2) reducing the data to best fit ellipses, 3) deriving polygonal outlines that can be used in the same way as manually digitized outlines.



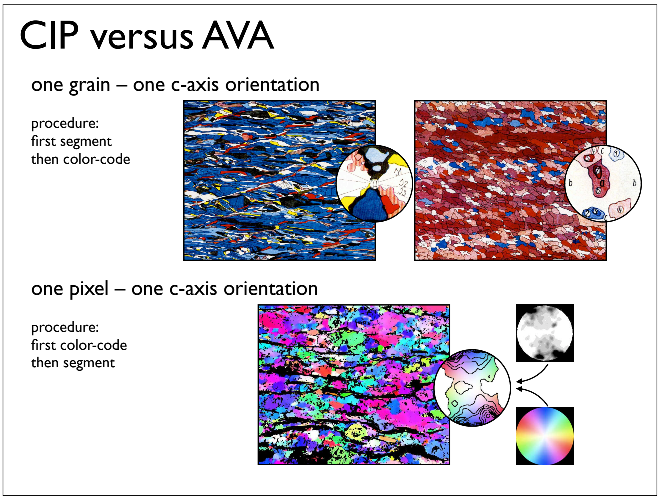
21 As all participants of my workshops know very well, segmentation is always a big effort. In the context of research where the image material is never the same (as might be in undustrial screening, for example) segmentation remains a challenge. There is no such thing as unbiased, automatic segmentaion.



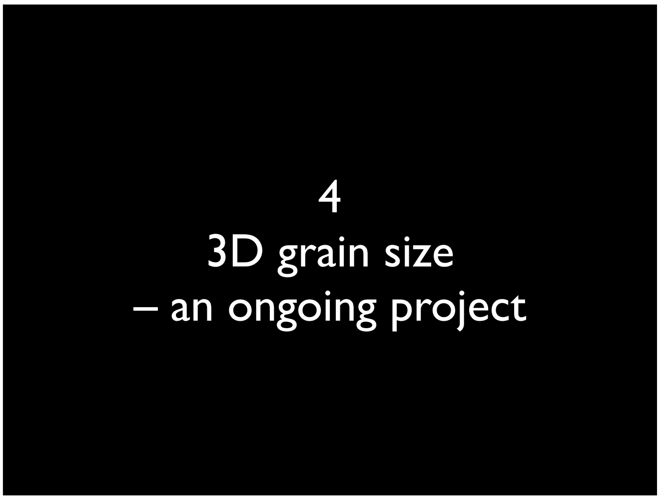
22 CIP is basically an image processing method which transforms a stack of special input images to an orientation image (image to image). The azimuth and inclination plane provide input for a c-axis pole figure, the first 'analysis' step – in the sense of image to number(s).
Orientation images are an excellent basis for segmentation because the threshold can be given in terms of degrees of (mis)orientation.
Still, preprocessing is necessary and at almost every step of the process, decisions have to be taken. In addition to visual inspection (for closing outlines, for example) there is a physical basis for the decision (degree of misorientation at the boundary, for example)



23 EUG-VI 1991 – CIP is launched:
CIP = easy AVA procedure = pole figures without U-stage
the first pole figures ... still looked a bit funny

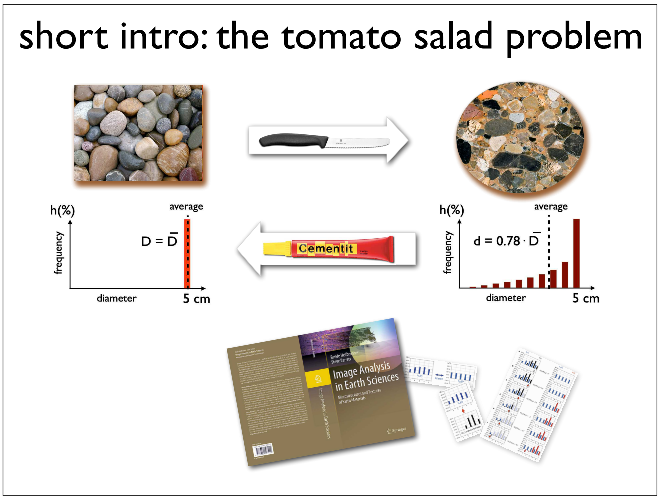


24 we settled for upper hemisphere projection for colouring



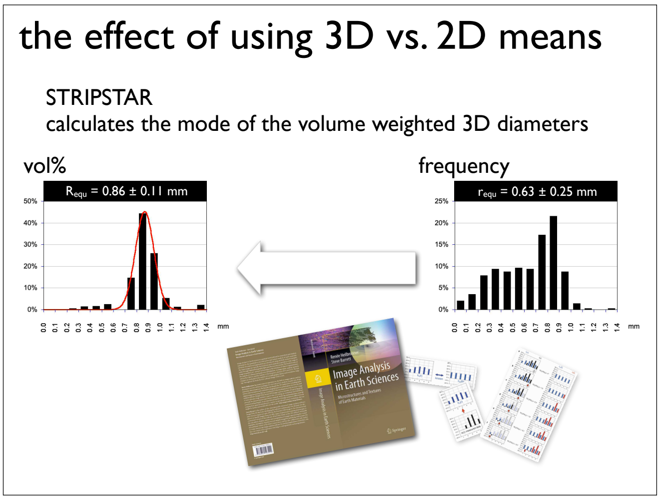
25

... my mission on earth

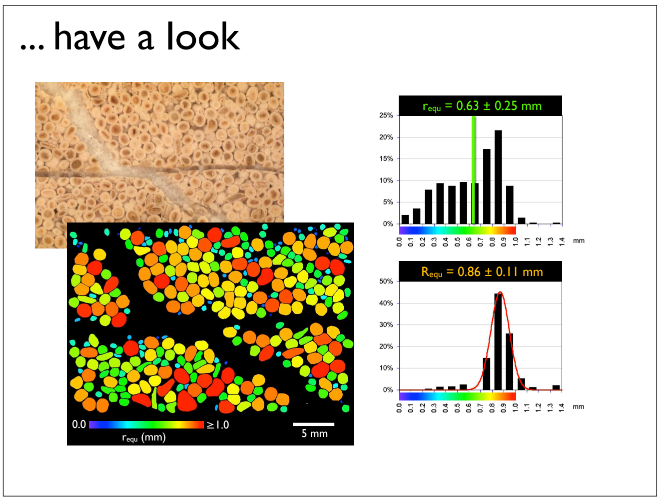


26

NOTE:
3D grain size distribution has a range of grain size from dmin>0 to dmax
2D grain size distribution always has dmin approaching 0
NOTE:
The 2D distribution can always be calculated, no matter if it is mondosiperse, normal, lognormal, bimodal etc.... – the reverse is always impossible.



27



28

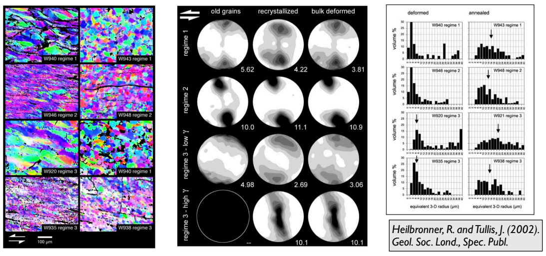
The prevalence – by area – of orange colours indicates that
⇒ 3D mode is closer to the representative grain size
The mean 2D grain size – green colour – is not as prevalent
Blue and green section do not represent small 3D grains, but are sections of larger grains (see absence of small grain in 3D histogram.

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

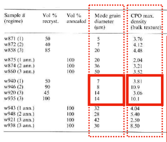
29

---

looking at deformation experiments ...



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



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

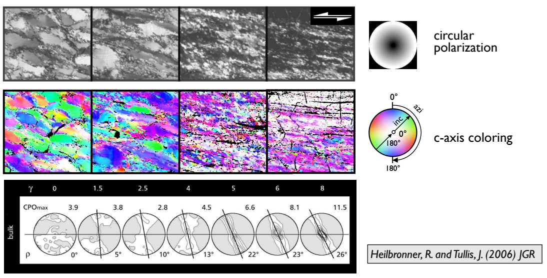
bulk CPO_{max}	
reg.1	3.8
reg.2	10.9
reg.3	10.1

30

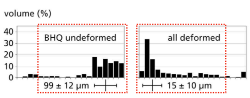
2002 shearing & annealing in regimes 1, 2, 3 – high strain

regime 1 – BLG – bulging rexl
– low T - high strain rate
regime 2 – SGR – subgrain rotation rexl
– med T - med strain rate
regime 3 – GBM – grain boundary migration rexl
– high T - low strain rate

... of Black Hills Quartzite (BHQ)



shearing in regime 3 only to high strains



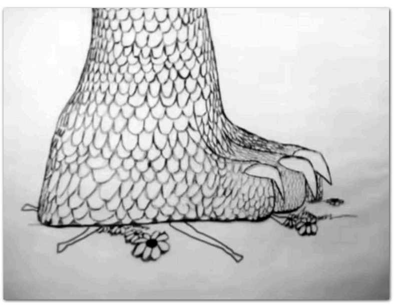
mode D(μm)	
undef.	99±12
reg.3	15±10

31

2006 shearing in regime 3 – low to high strain
QUESTIONS changing polfig ? changing grain size with gamma ?

---

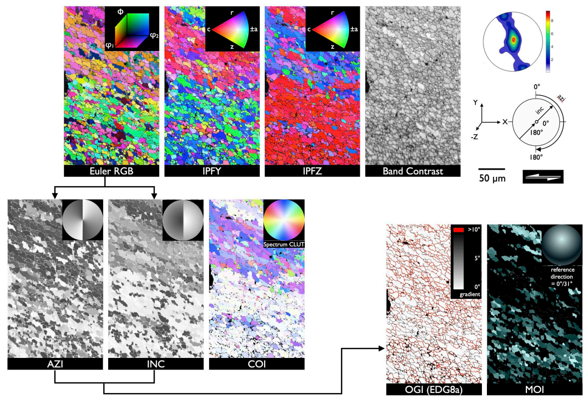
in the meantime, CIP meets EBSD ...



32

Bambi Meets Godzilla is a 1969 black-and-white animated short student film created entirely by Marv Newland. Less than two minutes long, the film is a classic of animation; it was listed #38 in the book The 50 Greatest Cartoons (1994). See Wikipedia, YouTube.

CIP images from EBSD data



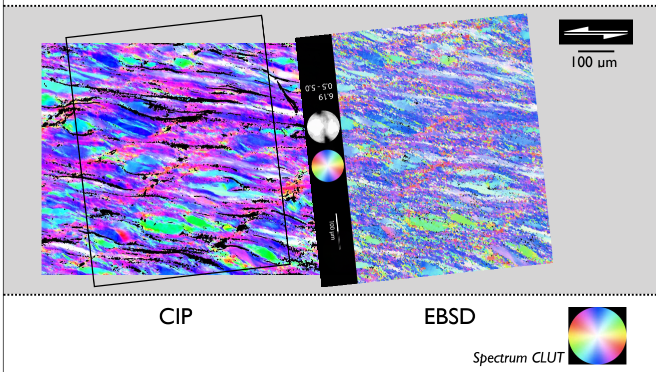
33

COI (showing axis orientation) is more easily interpreted than Euler or IPF coloured maps (showing full crystal orientation)

---

comparing CIP and EBSD

regime 1 (w1092) – shearing



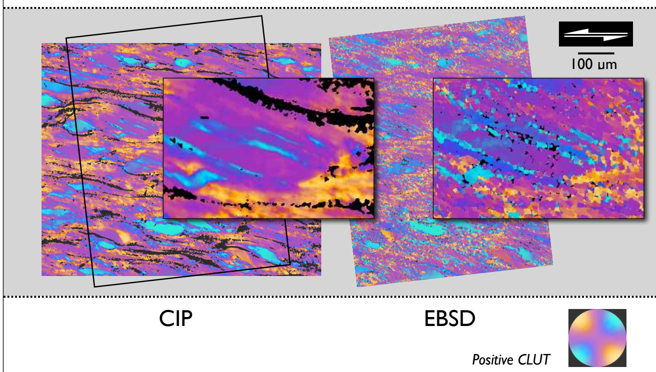
34

EBSD: Obvious improvement of spatial (and orientational) resolution !!
Left: original CIP image, right: EBSD image recalculated for CIP colouring

---

optical microscopy in the SEM

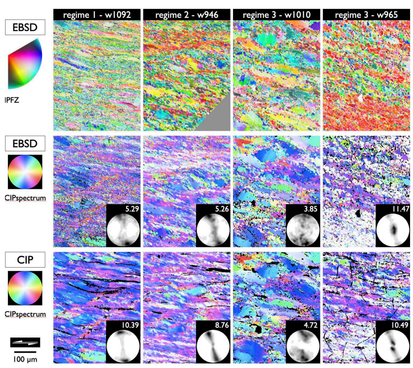
regime 1 (w1092) – shearing



35

Left: original CIP image using the Positive CLUT, right: EBSD image recalculated for Positive colouring.
=> 'optical polarization microscopy' at EBSD resolution

BHQ revisited



true or false ?

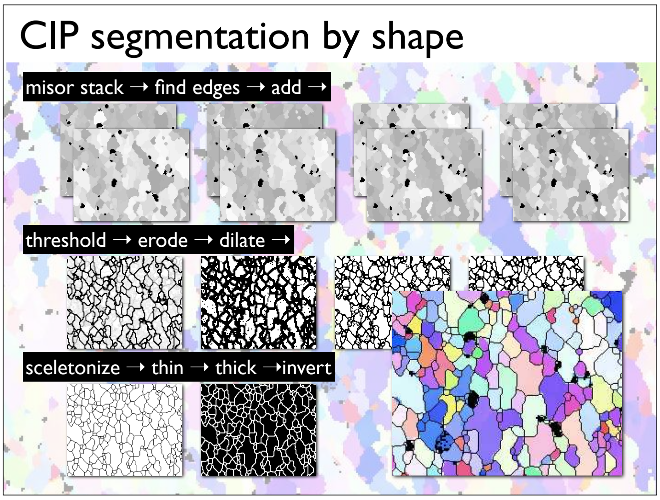
"... the recrystallized grain size of the rhomb domain is approximately 12µm and that of the prism domain is approximately 19µm, corresponding to shear stresses of 93 and 64 MPa, respectively."

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

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

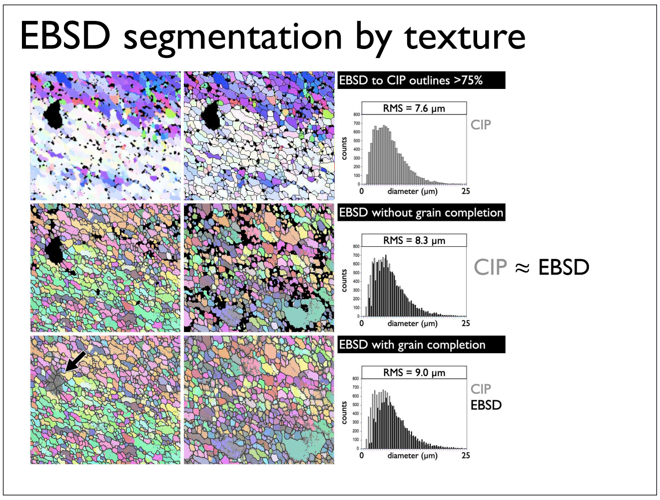
36

NOTE:
For resolution up to 10 µm CIP and EBSD coincide
CIP pole figure = EBSD pole figure ====> note double Y max (≠ an artefact of CIP)
NOTE:
Increasing strain influences polfig:
compare columns at right: both regime 3, left low strain, right high strain (= motivation for 2006 paper)



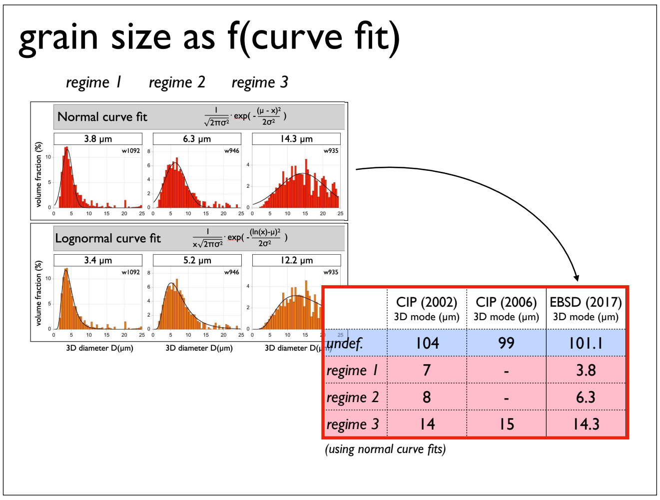
37

Procedure to obtain CIP boundaries
Segmentation is carried out using Image SXM and the Lazy Grain Boundaries (LGB) macro (Heilbronner and Barrett, 2014). The input consists of eight c-axis misorientation im- ages (MOI) calculated with respect to four external reference directions and four internal reference directions corresponding to the four most prominent maxima in the pole figure.
It looks like magic – but it isn't !



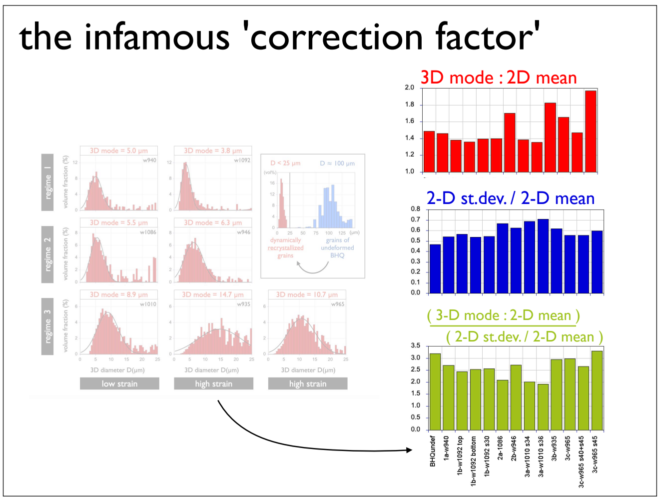
38

RMS instead of mean, following Stipp&Tullis who selected 2D RMS over 2D mean
NOTE:
Segmentation is always difficult and never unbiased !!
grain size distributions as f(procedure)



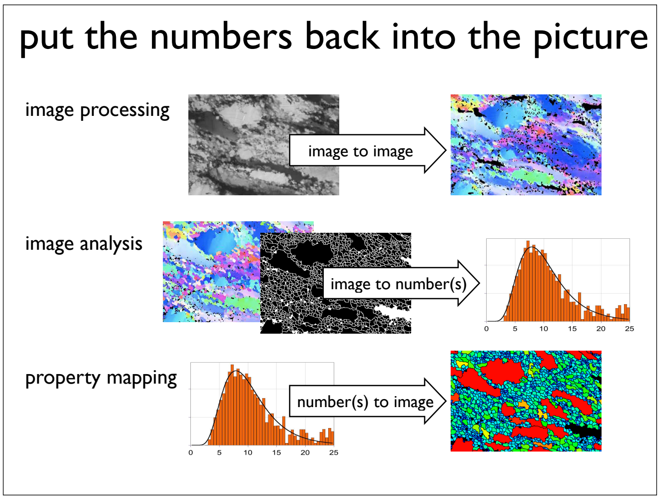
39

Other options: polynomial fit, requires 'eye-balling' to determine mode.

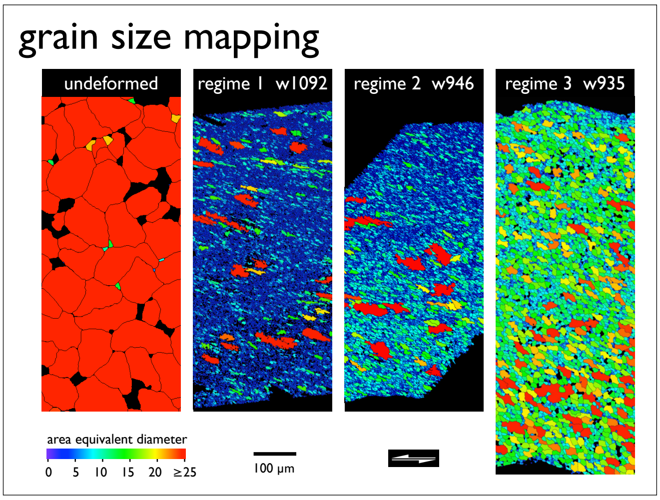


40

IMPORTANT:
do not ever use 'correction factors'

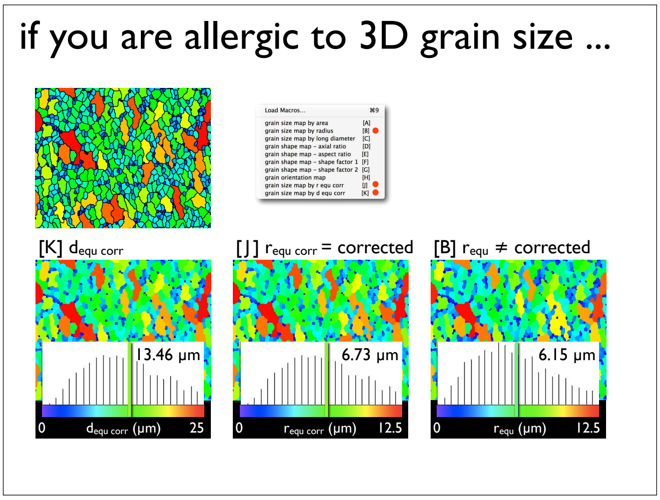


41



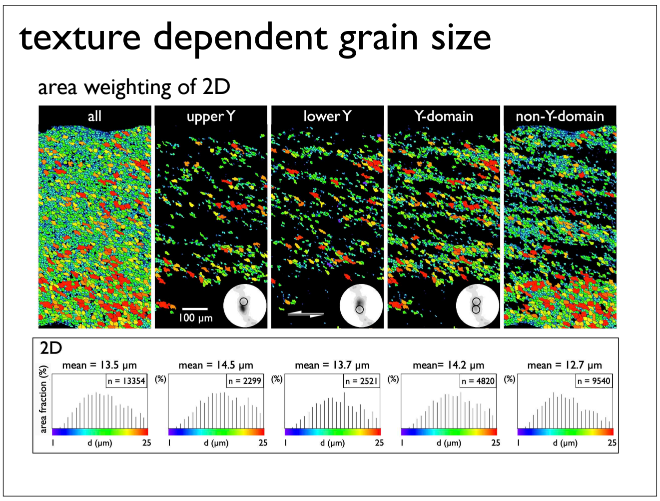
42

NOTE: grain size gradient in regime 2 experiment



43

see Heilbronner and Barrett, (2014)



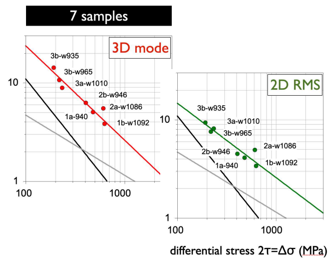
44

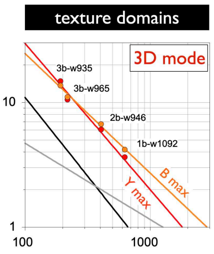
See Heilbronner, R. & Kilian, R. (2017). The grain size(s) of Black Hills Quartzite deformed in the dislocation creep regime. Solid Earth, 8, 1071–1093, 2017, doi.org/10.5194/se-8-1071-2017.

NOTE:

area weighting of 2D ≠ volume weighting of 3D

the quartz piezometer(s)





piezometer different for shearing vs. axial ?
– unresolved

piezometer different
for different domains ?
– unresolved

45

7
about texture

46

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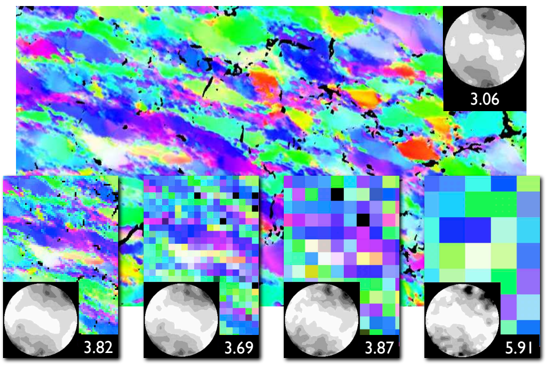
texture strength – spatial resolution



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The meaning of pole figure maxima ... if any.

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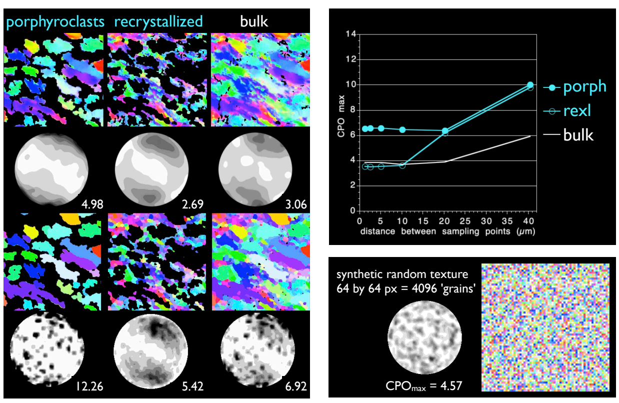
texture strength – grain size



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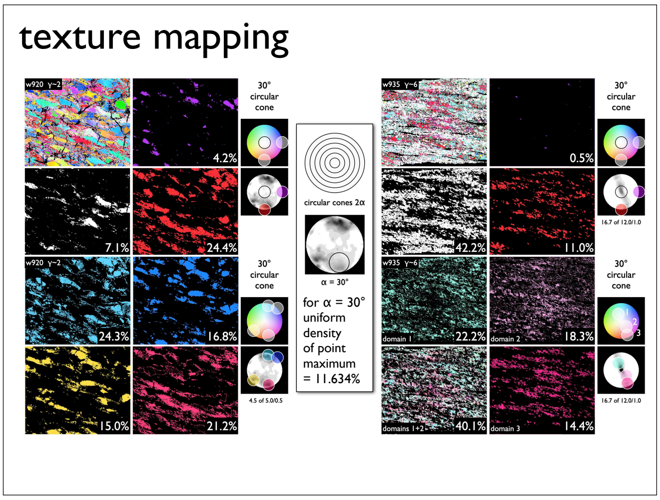
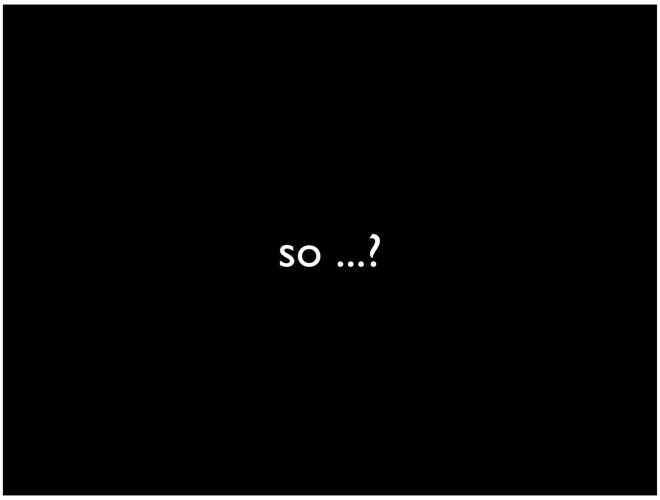
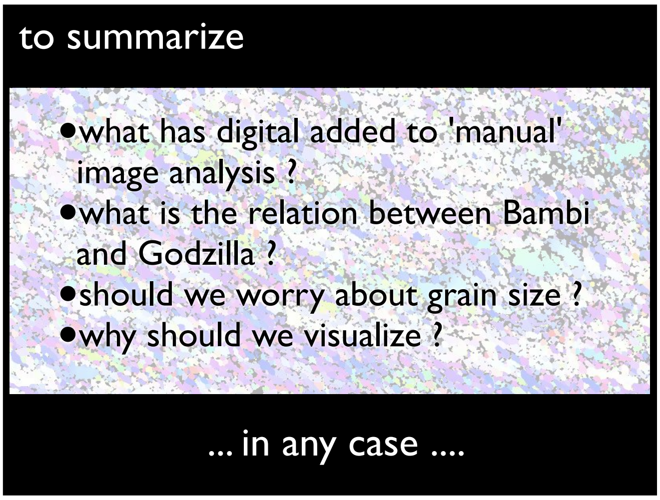
Presented at IAMG 2002
Renée Heilbronner (1), K.Gerald van den Boogaart (2), Helmut Schaeben (2)
Comparison of Coarse- and Fine-Grained Quartz Textures Using the Pole Density Index (PDI)



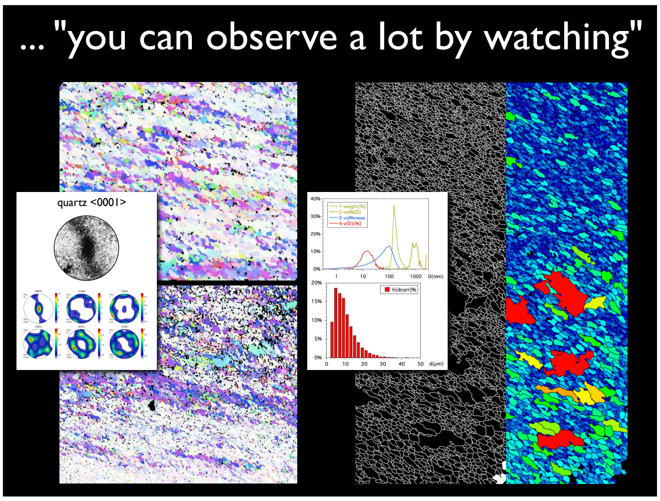
49 see Heilbronner and Barrett, (2014)



50

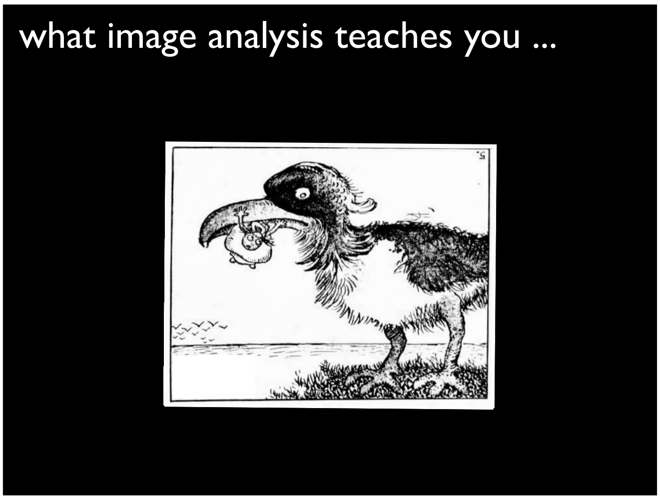


51 from ellipsoids to surfaces
spatial distribution as important as size distribution
CIP for mapping - visualization - play =====
EBSD for detail analysis
yes, dont worry just do it right



52 Localisation is important! – One (average) number is never sufficient to explain rock behaviour.

The spatial distribution of grains with a given a size distribution is crucial.
Question, for example: Is the size randomly distributed or layered ? i.e., random, clustered or ordered?isotropic or anisotropic?



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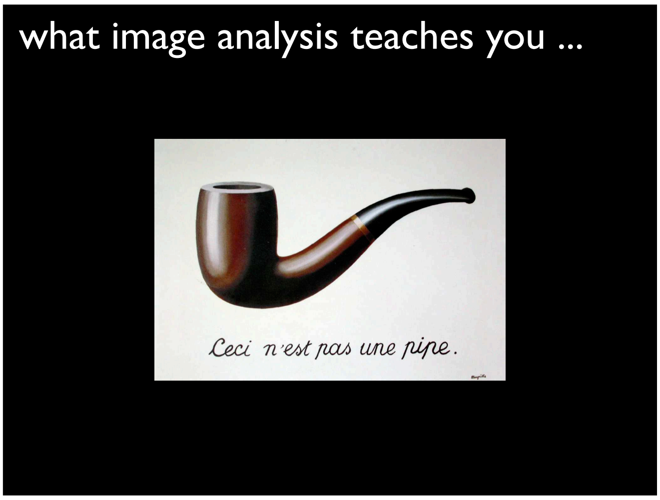
Little Lady Lovekins and Old Man Muffaroo
if you think you know what it is - ... it may be different

Verbeek was of Dutch descent, but born in Nagasaki, Japan in 1867. His father, Guido Verbeck was a missionary for the Reformed Church in America, and later a head of the Tokyo Imperial University. Gustave spent his childhood in Japan, moved to Paris for art school, and eventually to the United States in 1900 for work as an illustrator and cartoonist for Harper's Magazine, The Saturday Evening Post, and The New York Herald. The latter was where The Upside-Downs of Little Lady Lovekins and Old Man Muffaroo premiered on May 25th of 1902.



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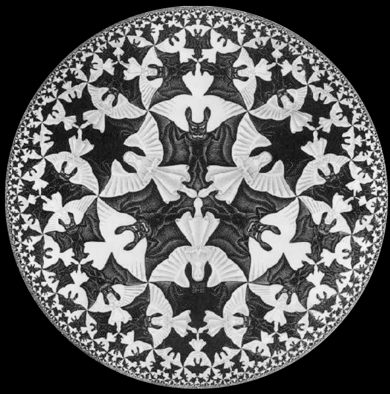
René Magritte: La trahison des images
Image ≠ object shown on it

René François Ghislain Magritte (21 November 1898 – 15 August 1967) was a Belgian surrealist artist.
La Trahison des Images is a 1929 painting by Magritte who painted it when he was 30 years old. It is on display at the Los Angeles County Museum of Art.

"The famous pipe. How people reproached me for it! And yet, could you stuff my pipe? No, it's just a representation, is it not? So if I had written on my picture "This is a pipe", I'd have been lying!"
(René Magritte)

what image analysis teaches you …



55

After looking at the black objects, look at what separates them.

… 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

56

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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

57

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

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