grain size – the good, the bad ... and the ugly

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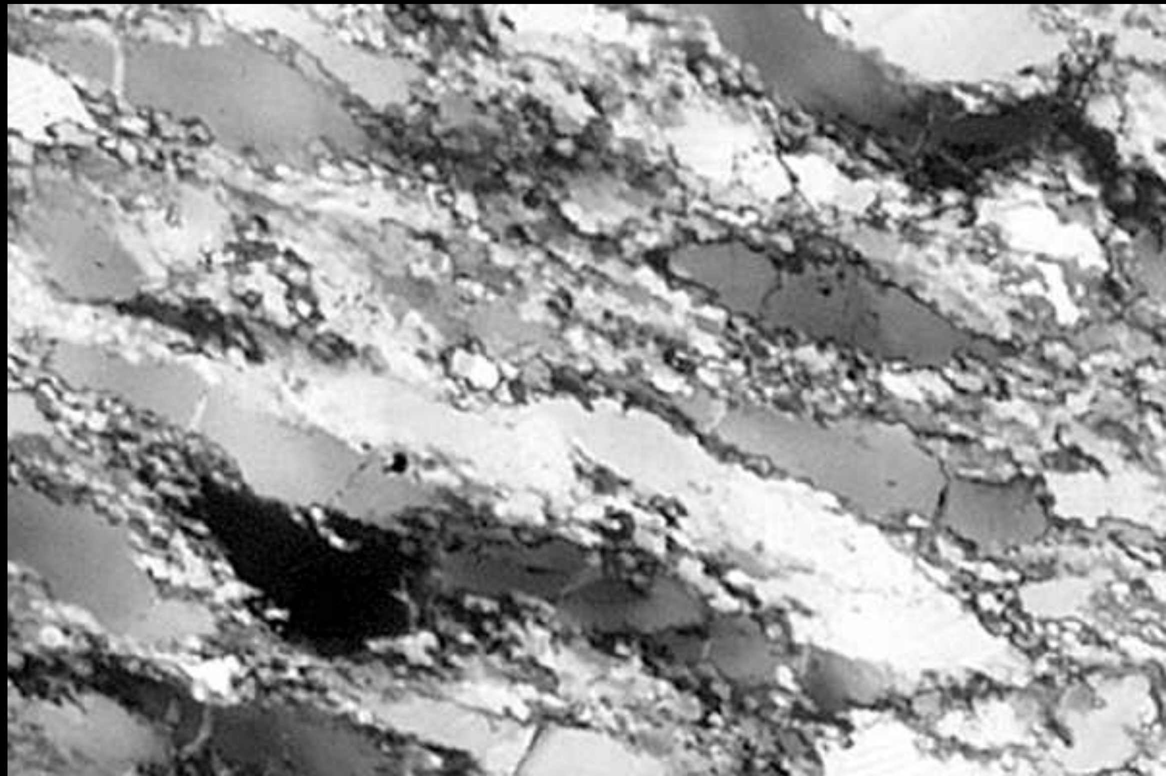
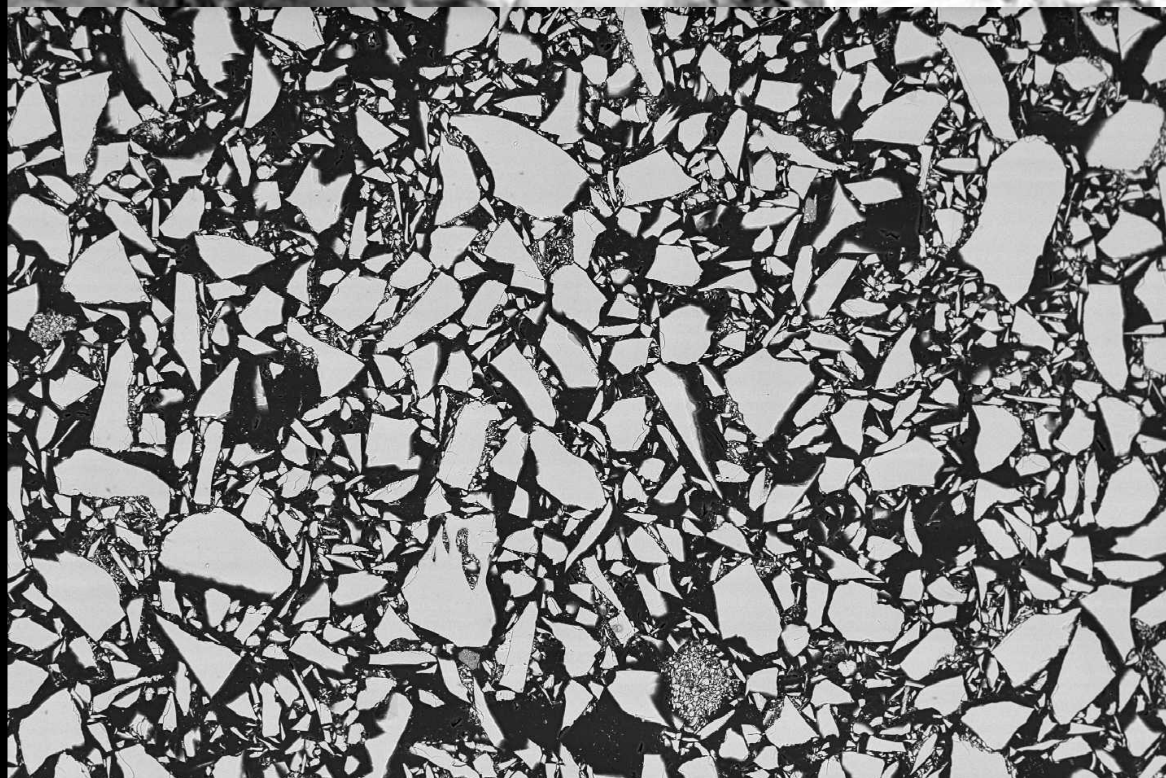
Martin-Luther-Universität
Halle, 23. Januar 2023



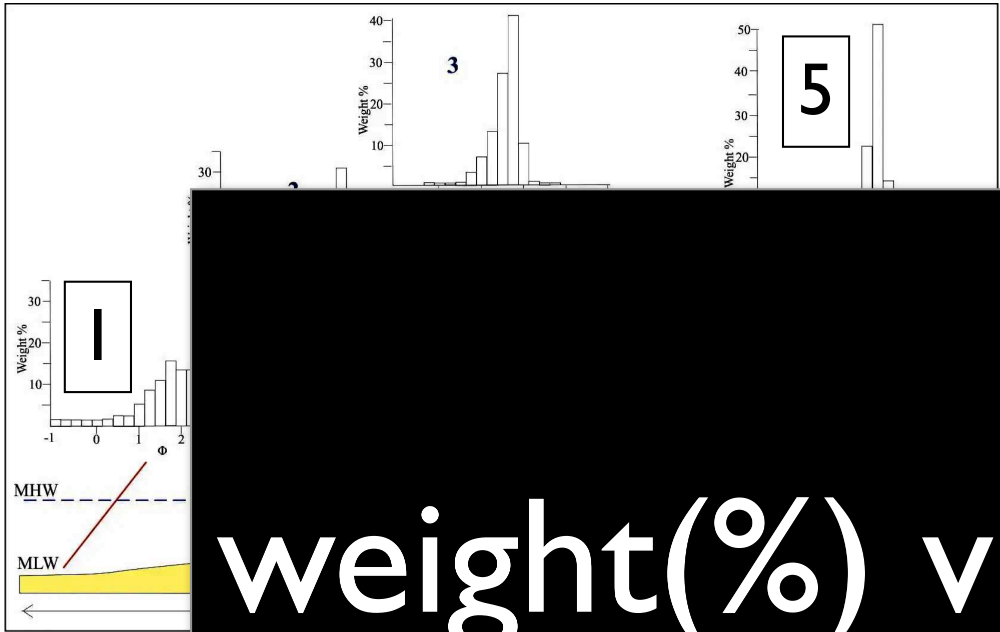


In this talk, we will follow a fictitious rock through an imagined geological cycle:

- sedimentation
- cementation
- grain growth
- dynamic recrystallization
- fragmentation
- healing

... and observe the associated "grain size"

"grain size" I – sieving



"Grain size":

Mean $M\varphi = (\varphi_{16}+\varphi_{50}+\varphi_{84})/3$

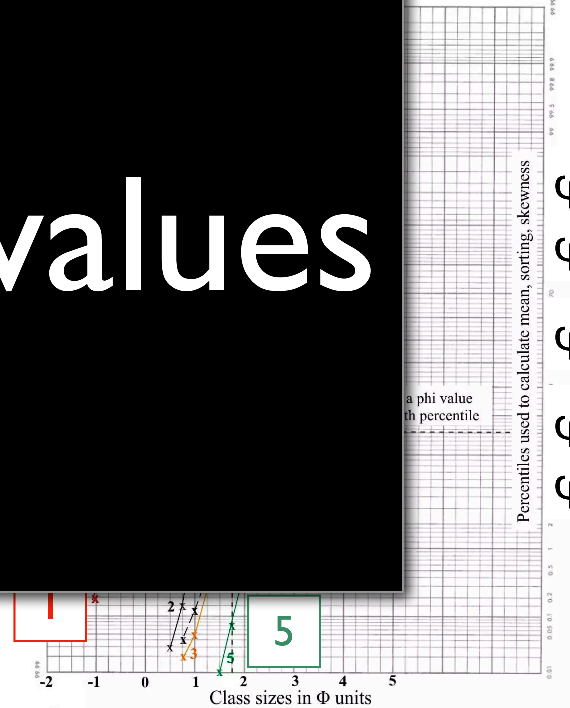
Sorting $\sigma\varphi$ = … $+ (\varphi_{95}-\varphi_{5})/6.6$

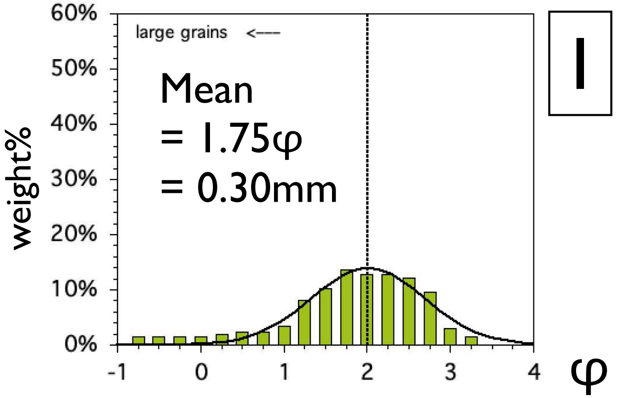
…er)

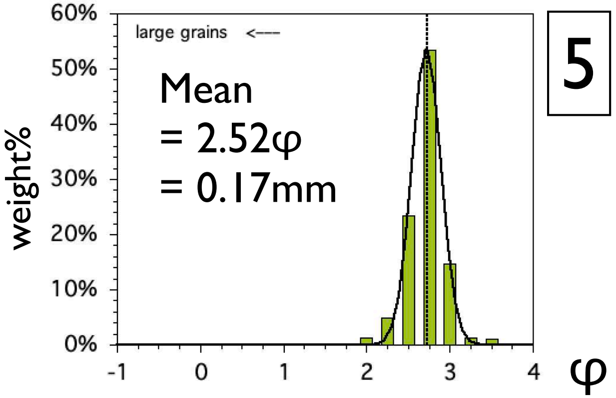
weight(%) vs. φ-values

Great Exhibitio…
https://www.ge…

low …





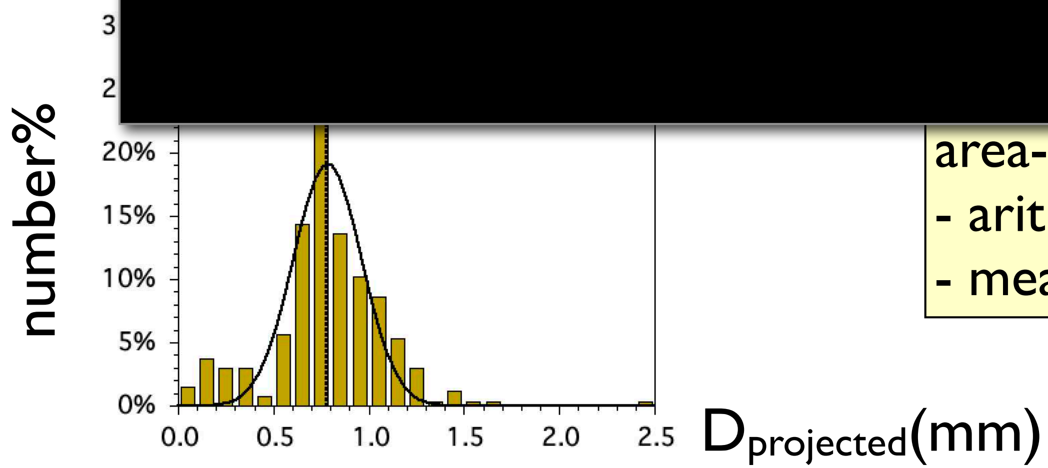


"grain size" 2 – strewn samples

n = 258

Solheim, A.:
marine chronology
– 0 cal years BP.

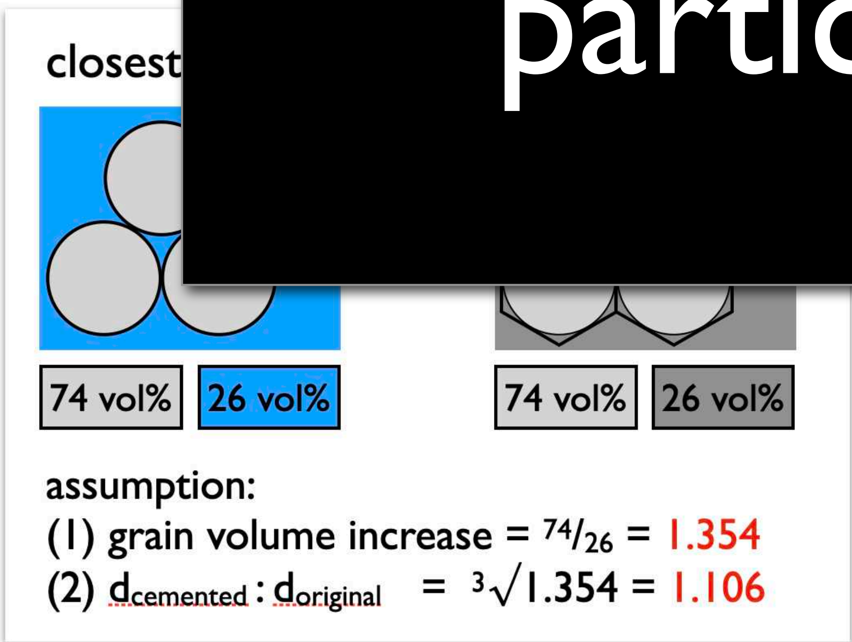
number(%) vs. projected diameter

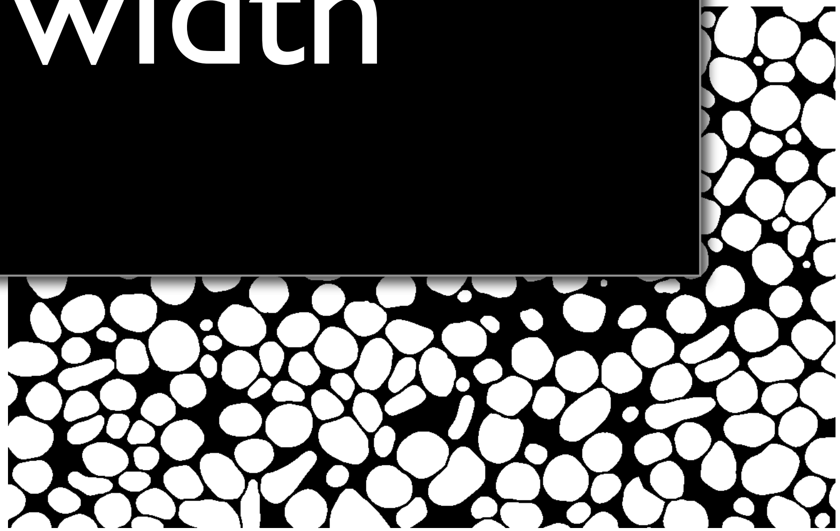


of
area-equivalent circles of projected areas
- arithmetic mean
- mean/mode of Gaussian curve fit

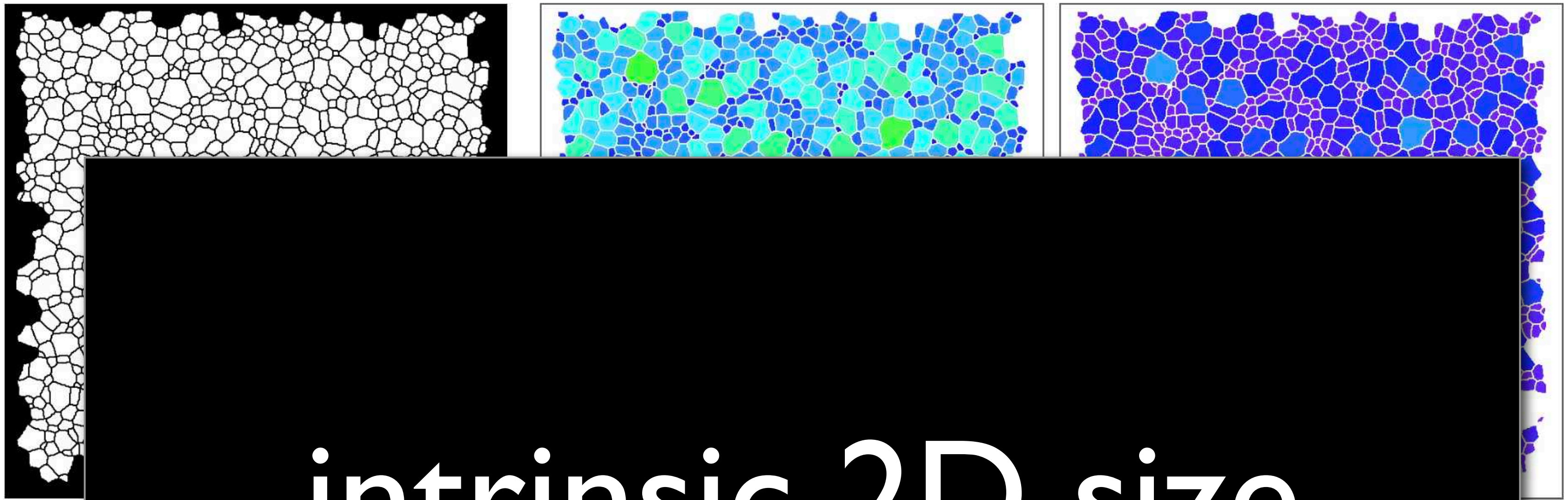
"grain size" 3 – intercept length

average transsected particle width





"grain size" 4 – numerical simulation



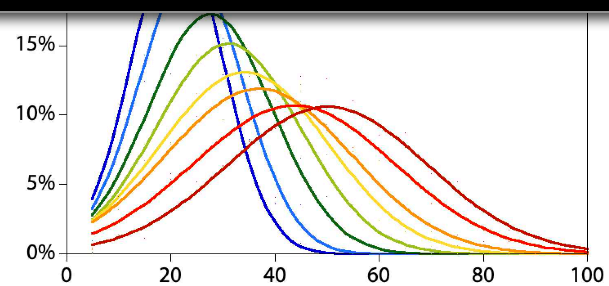
intrinsic 2D size

0 sqpx

grain gr

Chen LQ, Yang W
Computer-simula
quenched system
order parameter
Phys Rev B 50: 15752--15756
https://www.youtube.com/watch?v=p0rY2r0E_2k

erage size
increasing spread

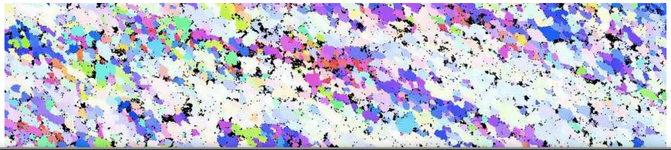


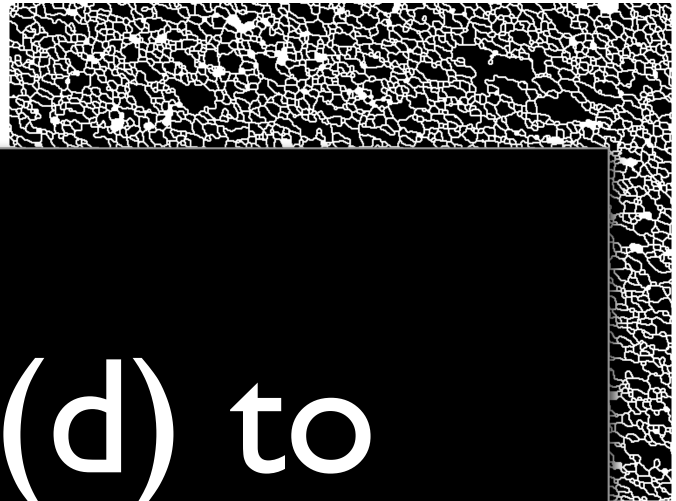
in terms of normal distribution:
→ increasing mean (μ)
→ increasing standard deviation (σ)

⇒ distribution matters

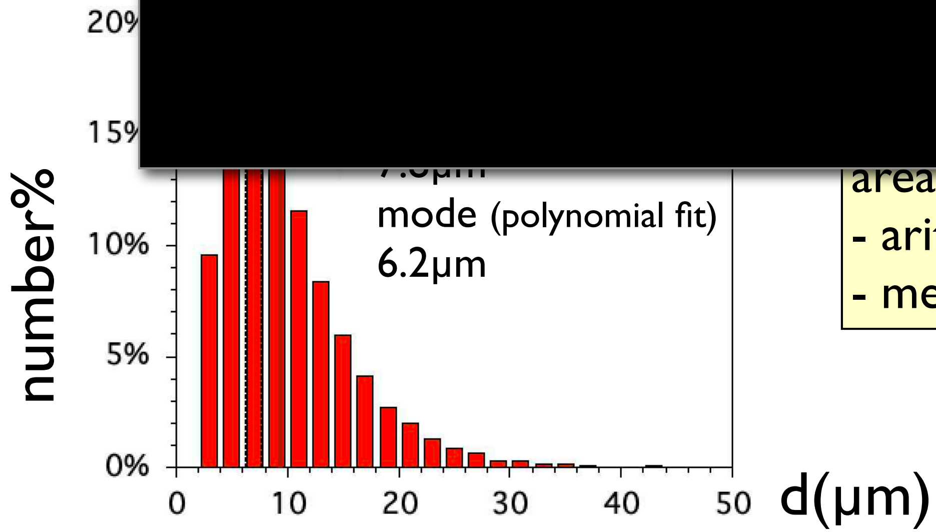
"Grain size":
- arithmetic mean of 2D diameter
- mean/mode of curve fit

"grain size" 5 – thin sections





from 2D h(d) to
3D vol%(D)

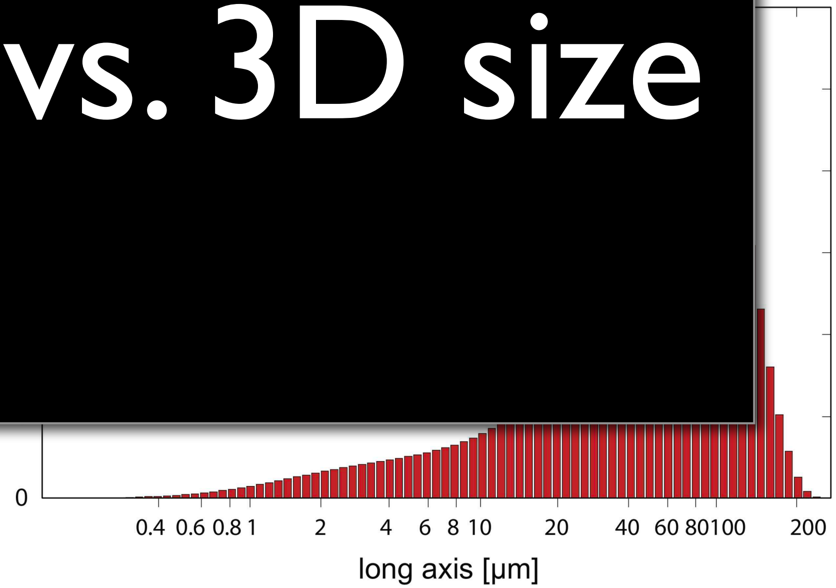


area-equivalent circles of sectional shapes
- arithmetic mean μ
- mean/mode of curve fits

"grain size" 6 – particle analyzer

volume(%) vs. 3D size

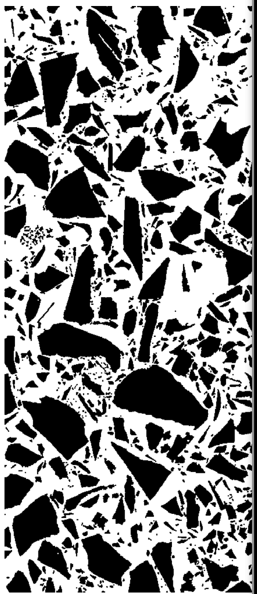
Range [redacted]
Mean [redacted]
Mode [redacted]



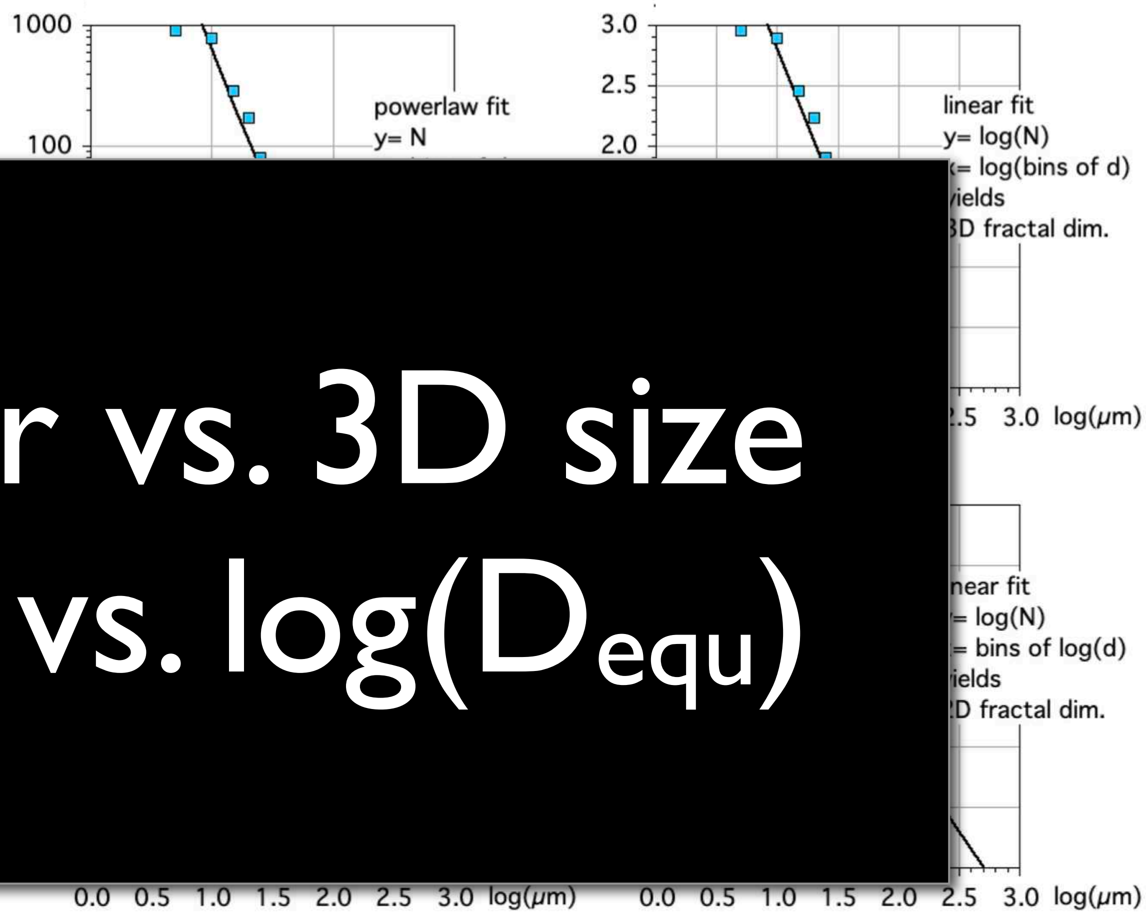
"Grain size":
mean or mode of <u>log (3D size</u>)
(e.g., long axes of particles)
- arithmetic mean
- mean/mode of curve fits

Richter, B., 2017, The brittle-to-viscous transition in experimentally deformed quartz gouge. Dissertation, Basel University. https://edoc.unibas.ch/57805/

"grain size" 7 – multi-scale analysis



00143336



number vs. 3D size
log(N) vs. log(D_{equ})

fractal dimension for 2 or 3 dimensions

$D_{2d} = D_{3d} - 1$

Fractal size distributions should span at least 3 orders of magnitude when we talk about grain size ...

why look at grain size ?

grain size data carries information

sediments, sands, silts

→ environment of deposition

statically recrystallized rocks

→ time and conditions of grain growth

dynamically recrystallized rocks

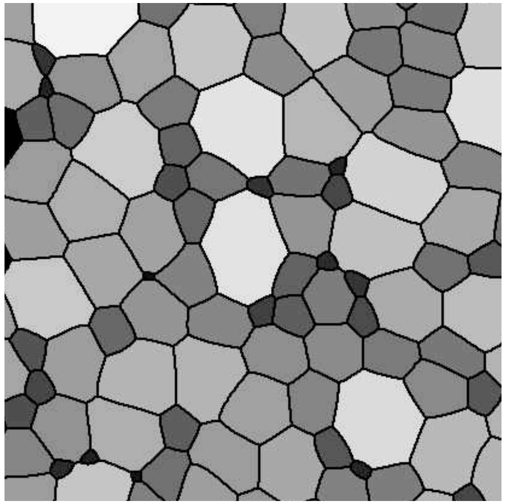
→ level of flow stress

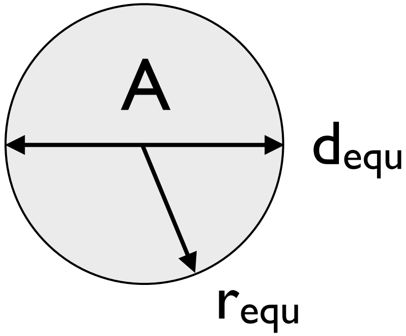
crushed rocks, powders

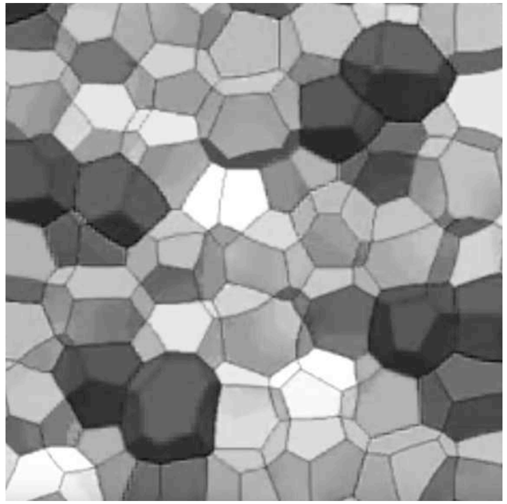
→ types of fragmentation processes

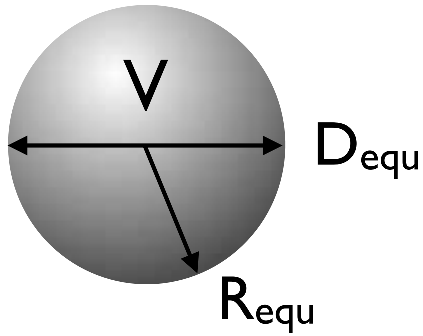
... etc.

the size of a grain – a scalar









thin sections:
size = diameter, d, of area

area of circle: $A = \pi \cdot r^2$

$\Rightarrow \; d = 2 \cdot \sqrt[2]{(A/\pi)}$

$d = 2r$ (lower case)

loose grains, particles:
size = diameter, D, of volume

volume of sphere: $V = 4\pi/3 \cdot R^3$

$\Rightarrow \; D = 2 \cdot \sqrt[3]{(3V/(4\pi))}$

$D = 2R$ (upper case)

the (in)famous 'mean grain size'

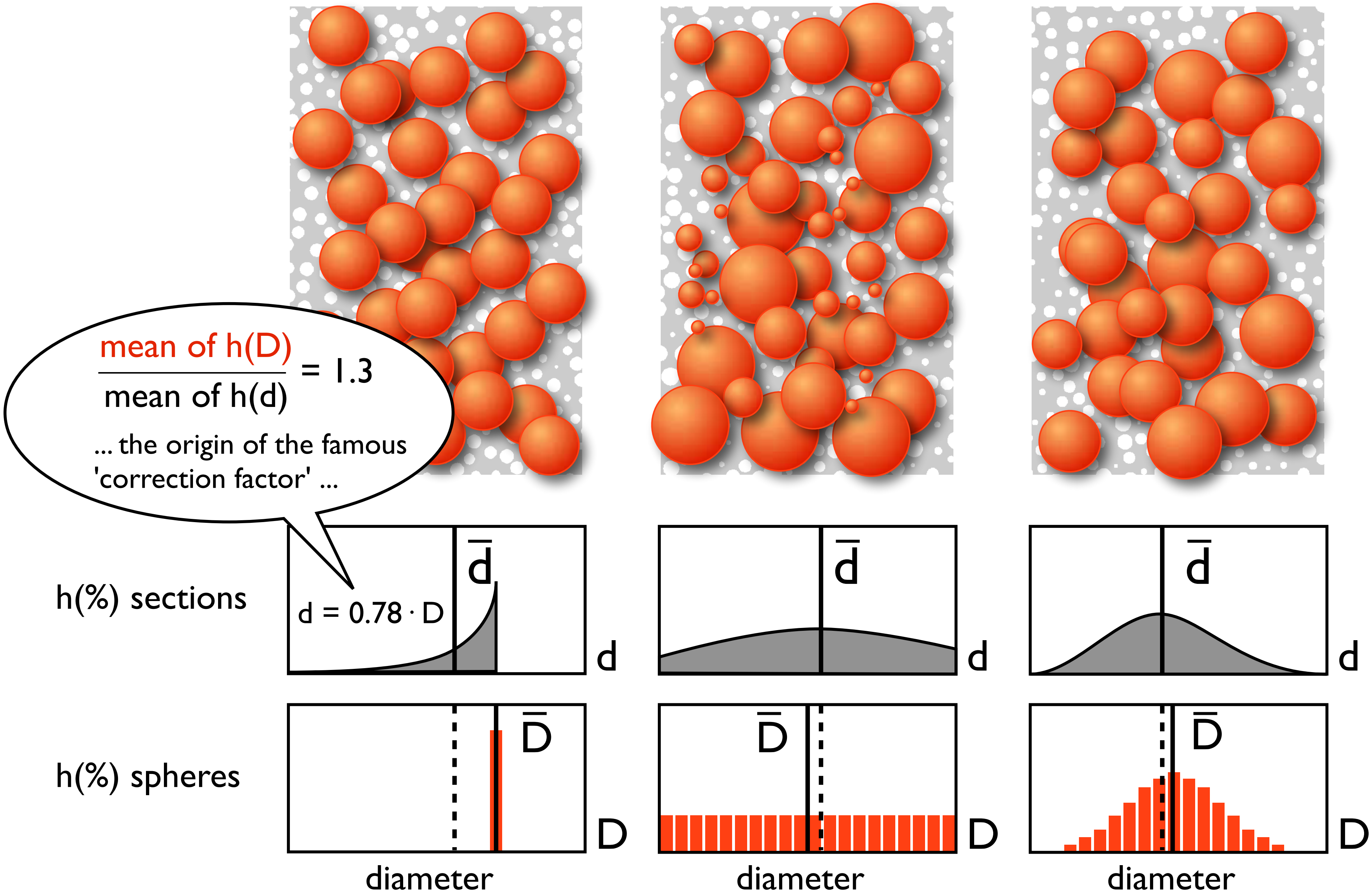
arithmetic mean	$\bar{X}$	=	$1/n \cdot \sum x_i$	
geometric mean	G	=	$\sqrt[n]{\prod x_i}$	
harmonic mean	H	=	$1 / (1/n \cdot \sum 1/x_i)$	
		=	$n / \sum 1/x_i$	
root-mean-square	RMS	=	$\sqrt{(1/n \cdot \sum x_i^2)}$	

$\sum$ = sum
$\prod$ = product
i = 1, … n

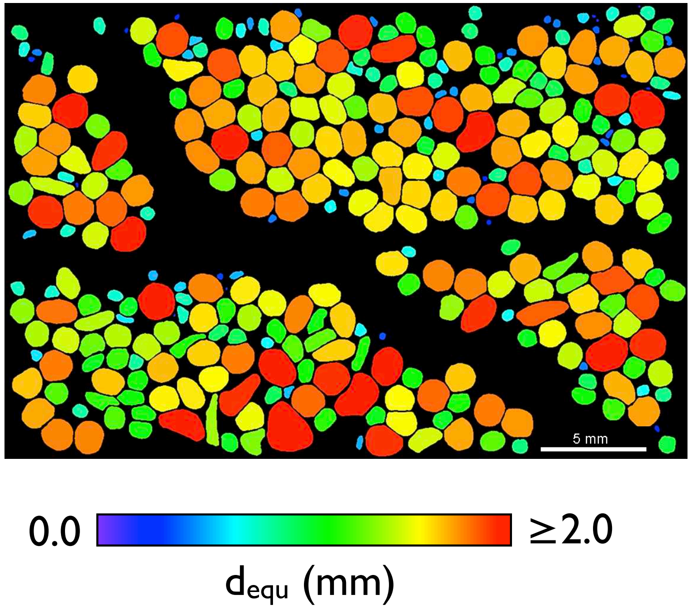
$$RMS > \bar{X} \geq G \geq H$$

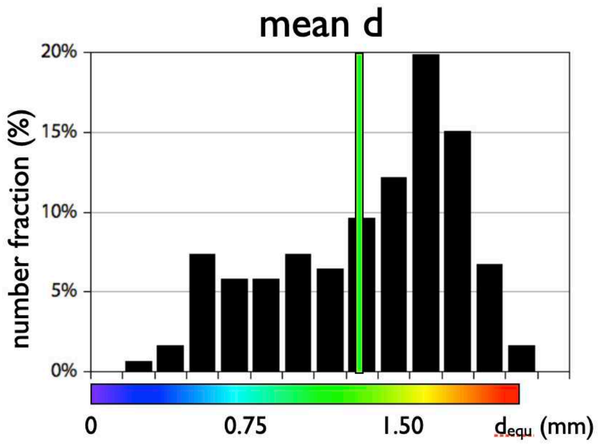
median	=	$x_{(n+1)/2}$	if n = odd
	=	$(x_{n/2} + x_{n/2+1}) /$	if n = even
mode	=	most frequent value	

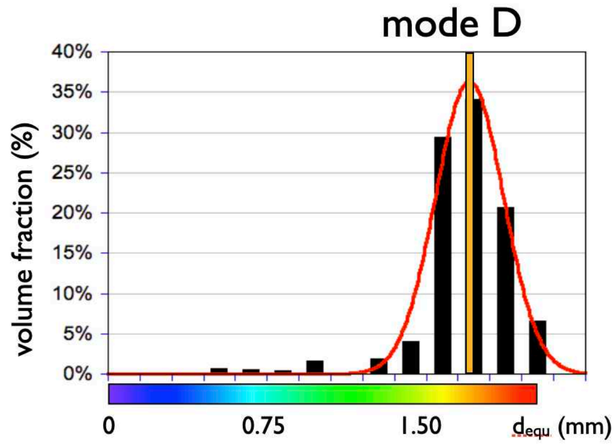
why 3D ?! ... that's why !



we 'see' 3D, not 2D, modal grain size

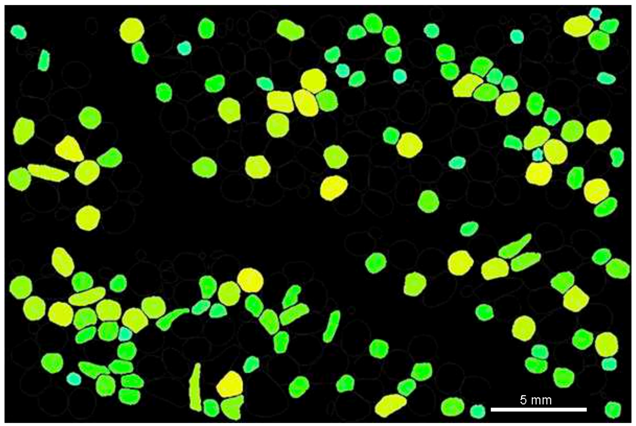




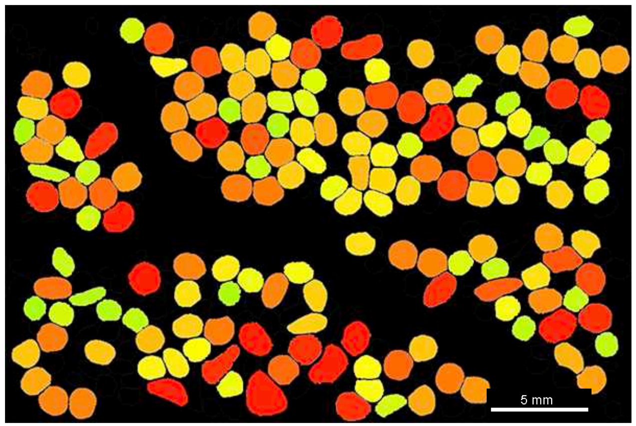


number-weighted	
2D mean	1.31
2D st.dev.	0.43

volume-weighted	
3D mode	1.70
3D st.dev.	0.11

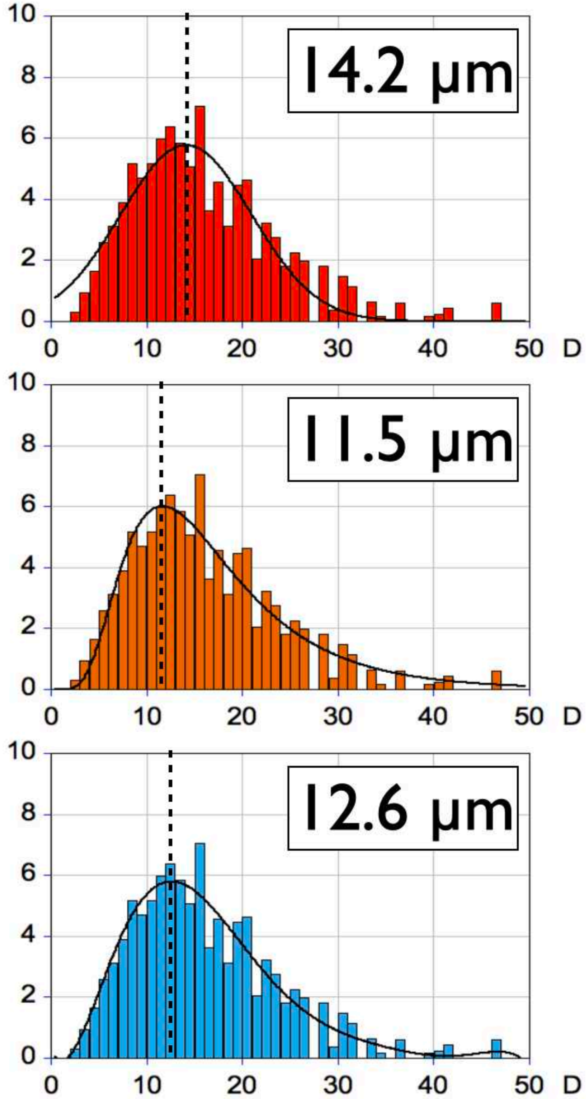


≠ *visual impression*



= *visual impression*

finding the mode by curve fitting



Normal curve fit

$$\frac{1}{\sqrt{2\pi\sigma^2}} \cdot \exp\left(-\frac{(\mu - x)^2}{2\sigma^2}\right)$$

Lognormal curve fit

$$\frac{1}{x\sqrt{2\pi\sigma^2}} \cdot \exp\left(-\frac{(\ln(x)-\mu)^2}{2\sigma^2}\right)$$

Polynomial curve fit

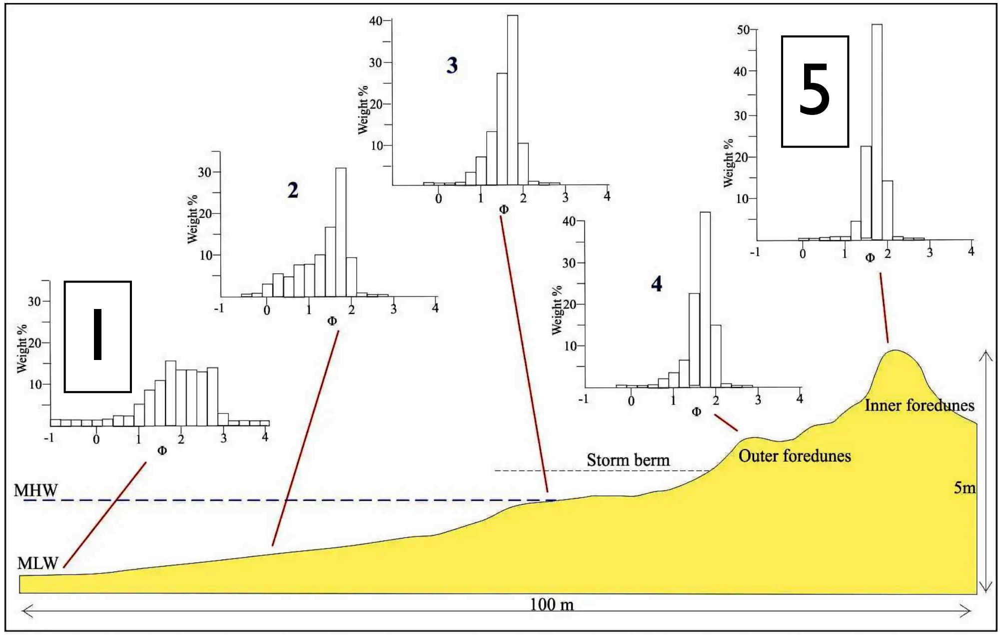
$$m_0 + m_1 x + m_2 x^2 + m_3 x^3 + \ldots.$$

in all cases: fit through center of bin !

"grain size" I sedimentation

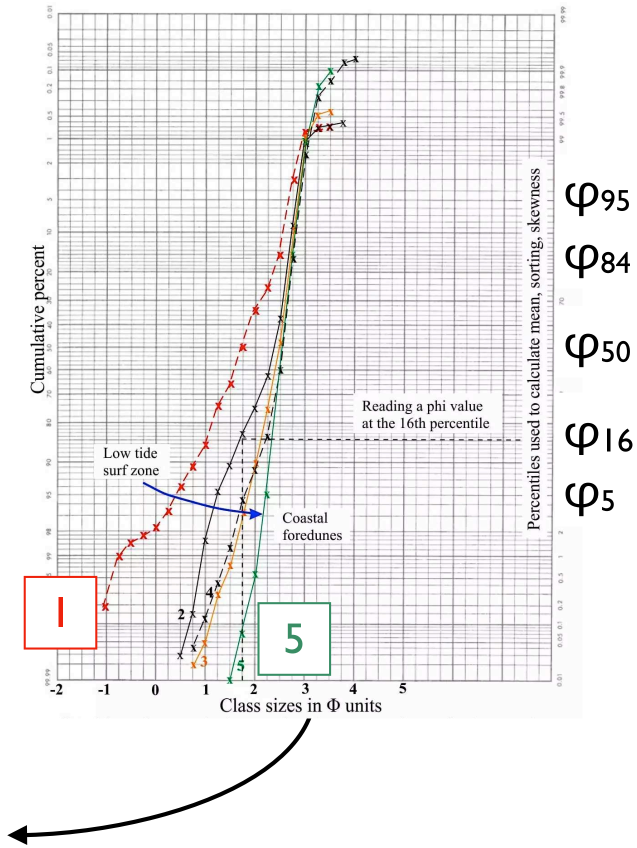
sieving

"grain size" 1: beach sand

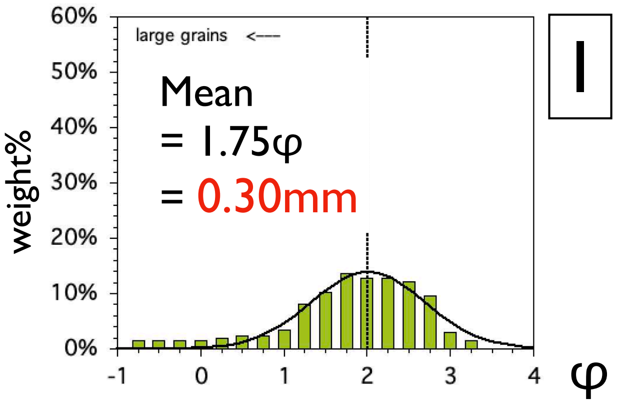


"Grain size":
Mean $M\varphi = (\varphi_{16}+\varphi_{50}+\varphi_{84})/3$
Sorting $\sigma\varphi = (\varphi_{84}-\varphi_{16})/4 + (\varphi_{95}-\varphi_{5})/6.6$
φ equivalent to log(3D diameter)

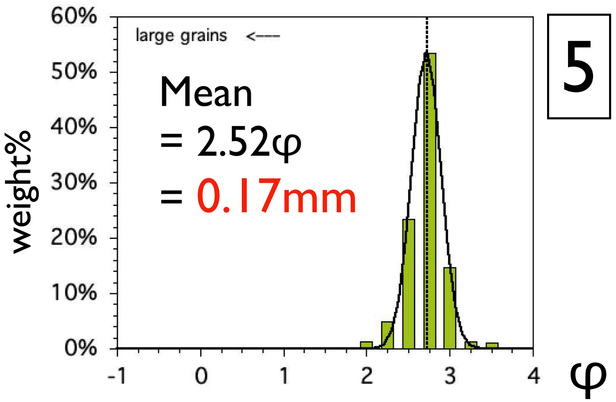
Great Exhibition Bay, NZ
https://www.geological-digressions.com/analysis-of-sediment-grain-size-distributions/



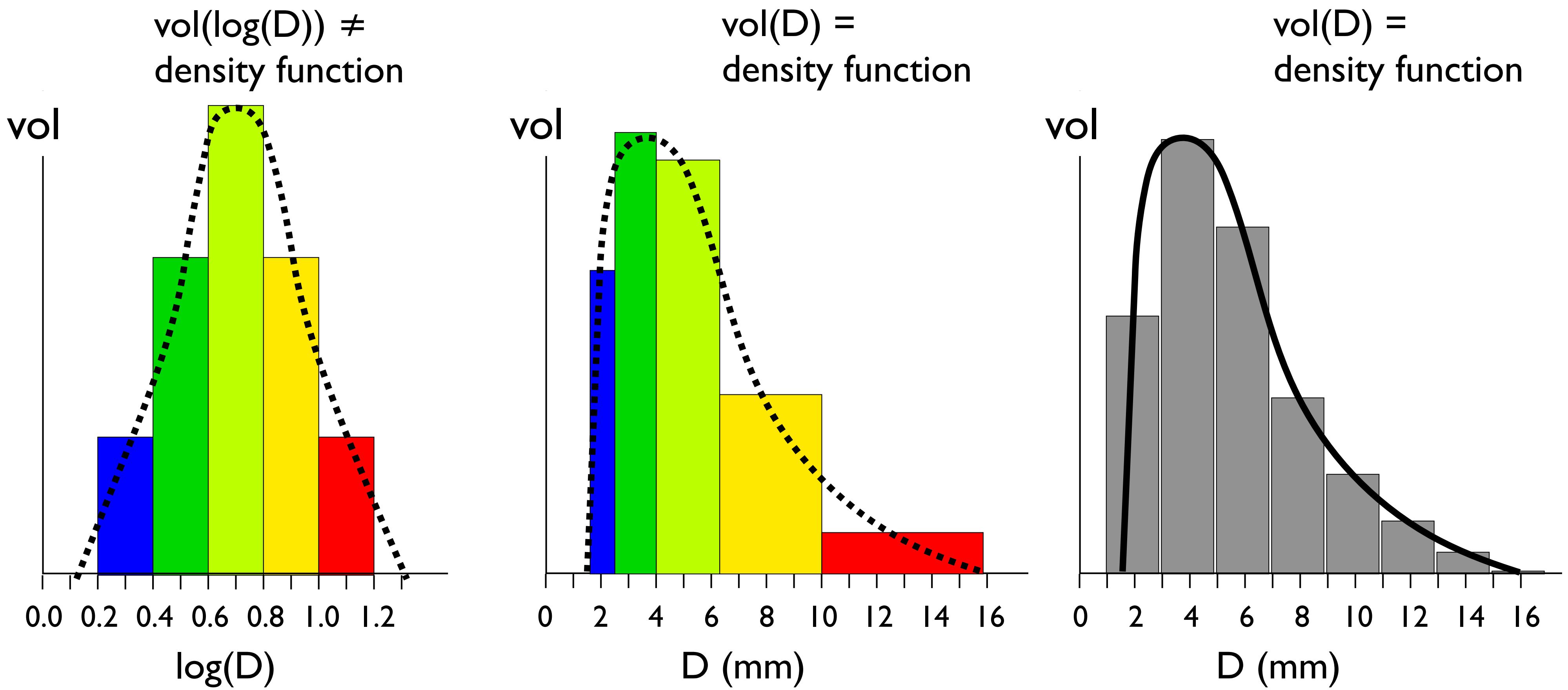
low tide surf zone



coastal foredunes



from logarithmic to linear



$\Delta\log(D)$ = constant
$\Delta D \neq$ constant

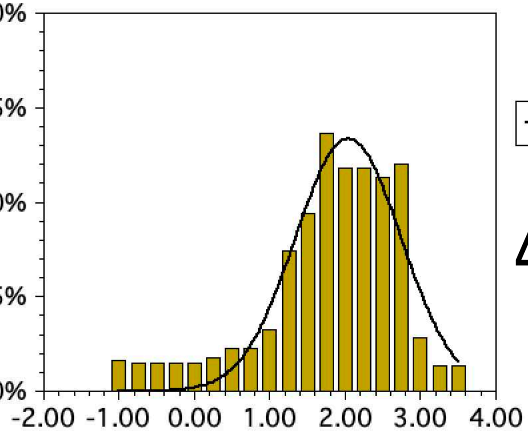
vol / ΔD = density
blue, green, ... etc. area on log(D)-plot = blue, green, ... etc. area on D-plot

ΔD = constant

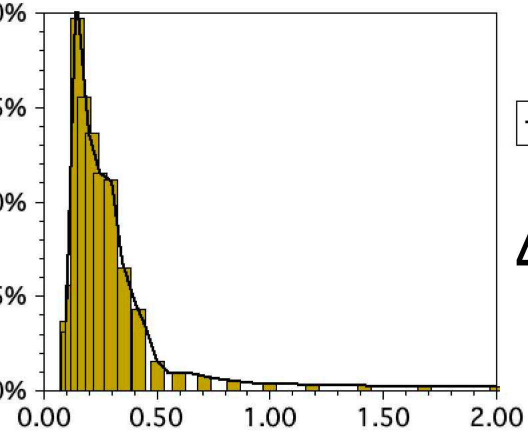
Σ area of histogram bars = area under curve = constant

φ-values... – double trouble

surf zone



$\Delta\log(D)$ = const

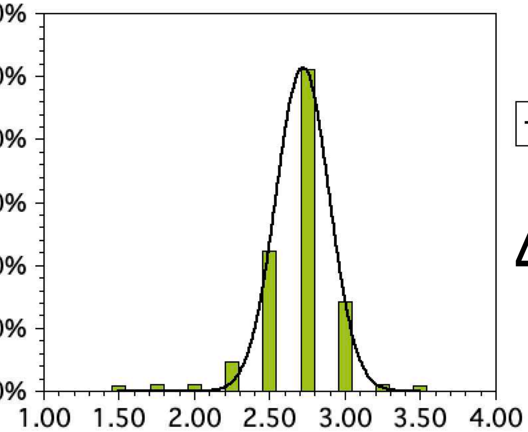


$\Delta D \neq$ const

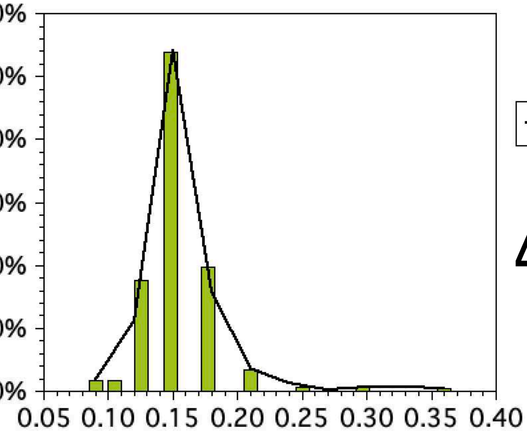
weight% vs. φ Gaussian normal fit
Mφ = 2.05 ⇒ D_{mean} = 0.241mm

weight% vs. D(mm) w% binwidth corrected
overlay = cubic spline fit (39pts)

foredune



$\Delta\log(D)$ = const



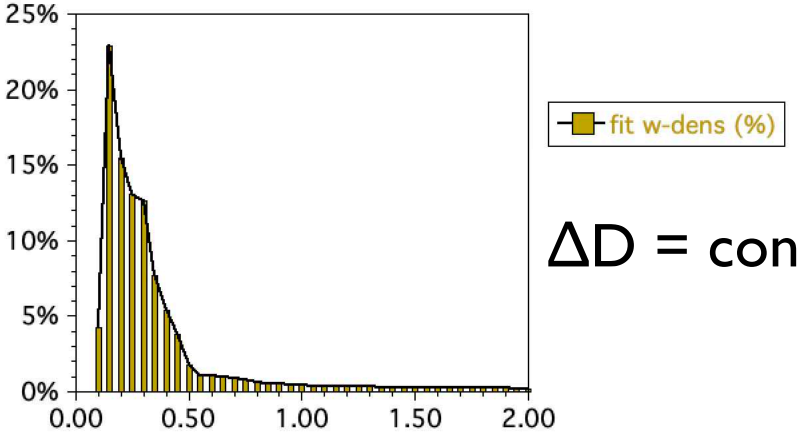
$\Delta D \neq$ const

weight% vs. φ Gaussian normal fit
Mφ = 2.72 ⇒ D_{mean} = 0.152mm

weight% vs. D(mm) w% binwidth corrected
overlay = cubic spline fit (10pts)

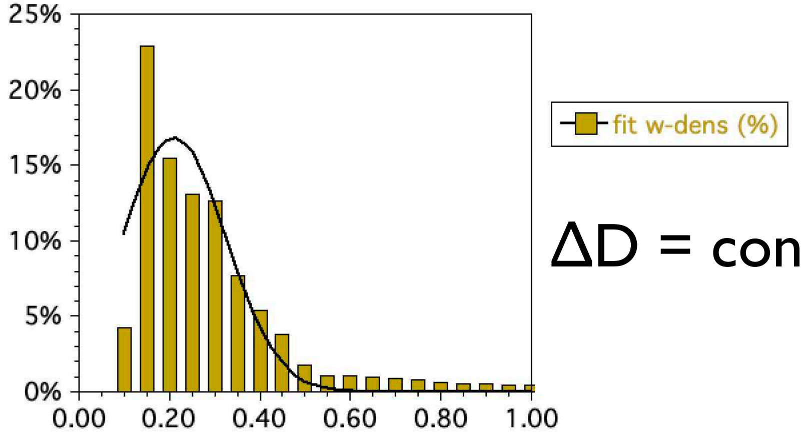
converting the data

surf zone



ΔD = const

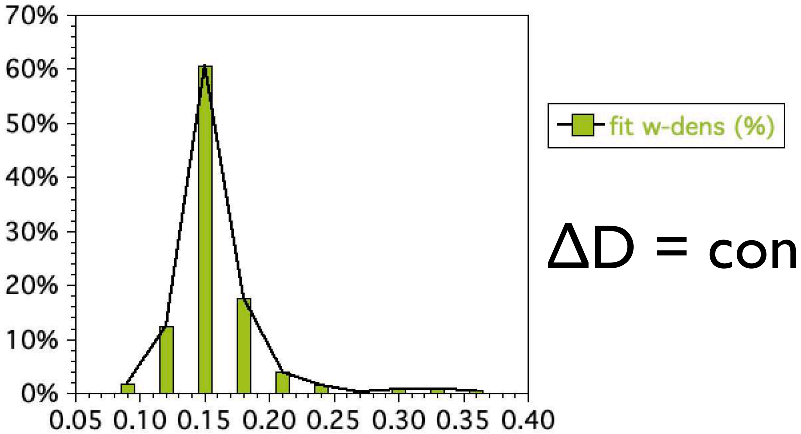
weight% vs. D(mm) d from cubic spline fit
overlay = cubic spline fit (39pts)



ΔD = const

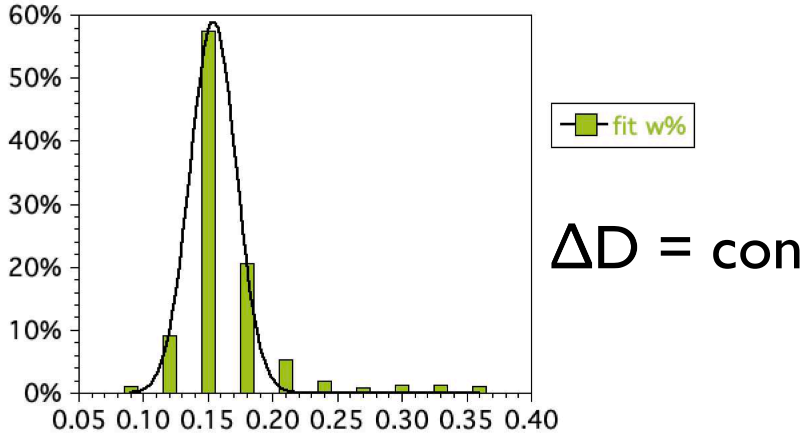
weight% vs. D(mm) Gaussian normal fit
D_{mean} = 0.212mm (σ = 0.130mm)

foredune



ΔD = const

weight% vs. D(mm) d from cubic spline fit
overlay = cubic spline fit (10pts)



ΔD = const

weight% vs. D(mm) Gaussian normal fit
D_{mean} = 0.154mm (σ = 0.020mm)

φ-derived versus converted

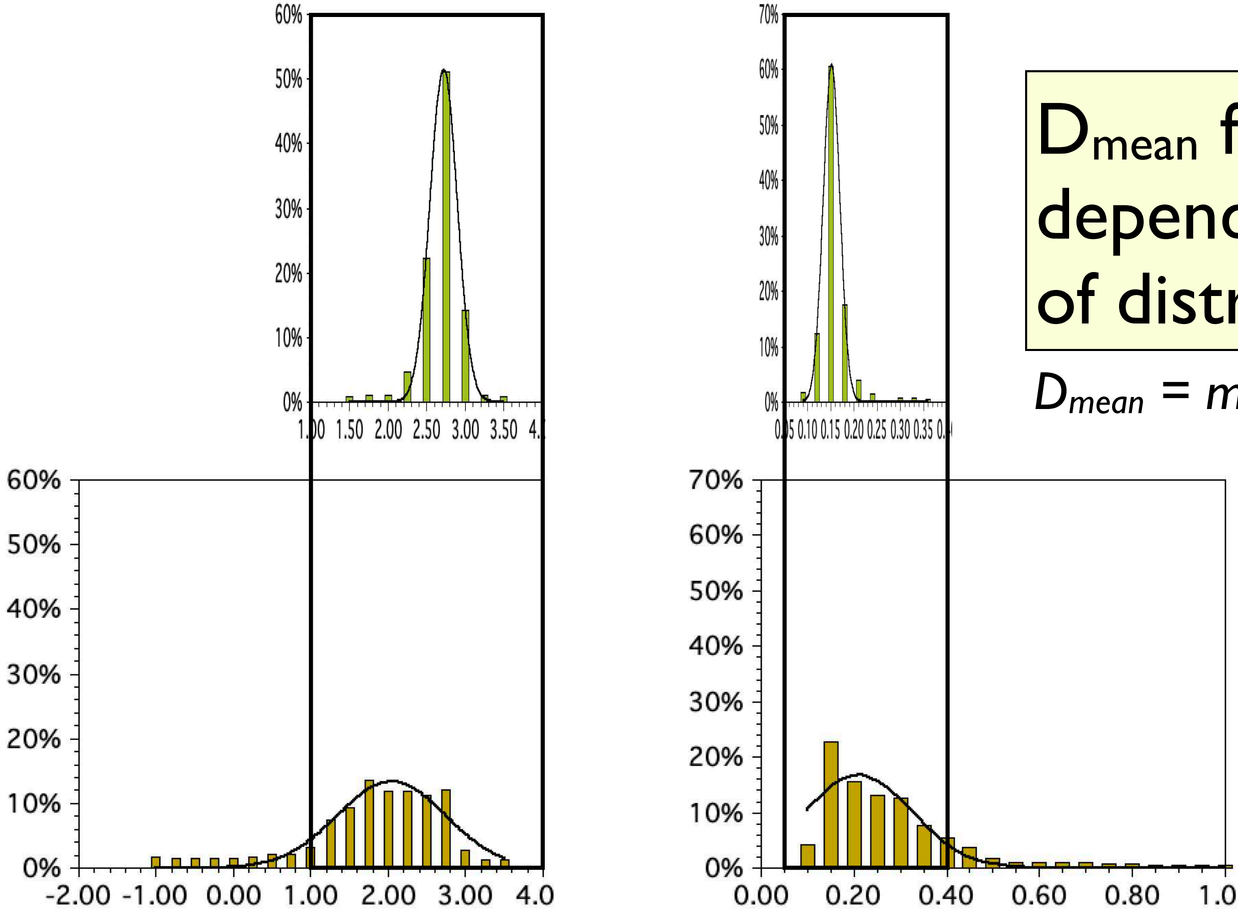
$M\varphi = 2.05$
$D_{mean} = 0.24$mm

weight%.vs.φ
⟹ $D_{mean} = 0.15$mm

weight%.vs.D(mm)
$D_{mean} = 0.15$mm

foredune

surf zone



D_{mean} from φ depends on width of distribution

D_{mean} = mode of vol%(D)

$M\varphi = 2.72$
$D_{mean} = 0.30$mm

weight%.vs.φ
⟹ $D_{mean} = 0.24$mm

weight%.vs.D(mm)
$D_{mean} = 0.21$mm

what have we learned ?

Results from sieving are difficult to interpret
(... unless you are a sedimentologist ...)

To derive a meaningful mean grain size, φ-values are best converted to vol% vs. linear size.

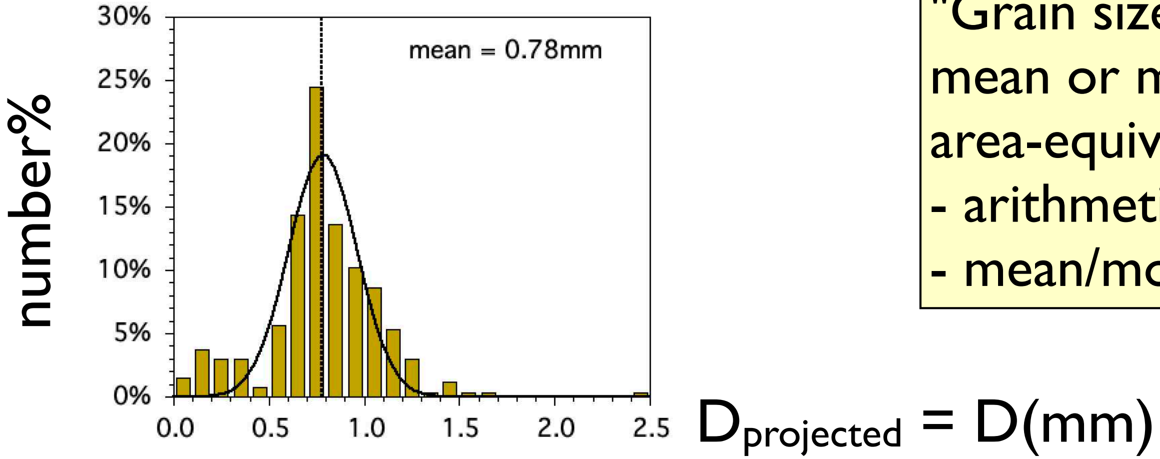
Derived D_{mean} - values depend on standard deviation.

"grain size" 2
glacial transport
strewn samples

"grain size" 2: glacigenic sediments

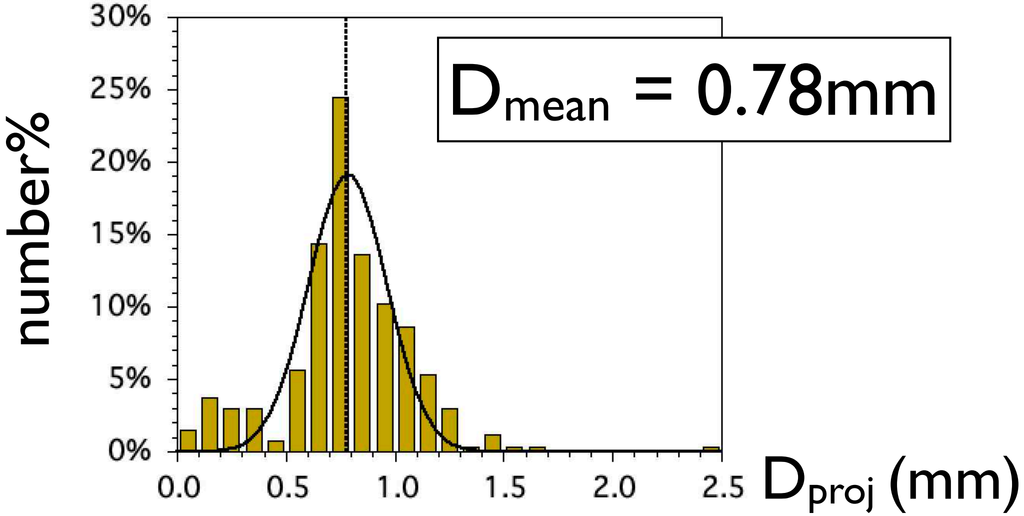
incident light *transmission* *bitmap*

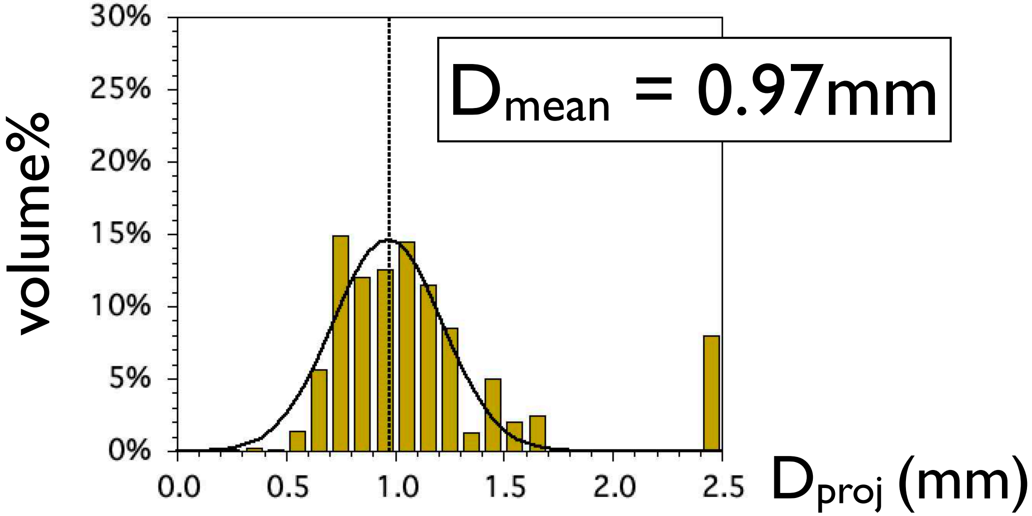
Jessen, S.P., Rasmussen, T.L. , Nielsen, T., Solheim, A.:
A new Late Weichselian and Holocene marine chronology for the western Svalbard slope 30,000 – 0 cal years BP.
Quaternary Science Reviews ,
doi:10.1016/j.quascirev.2010.02.020

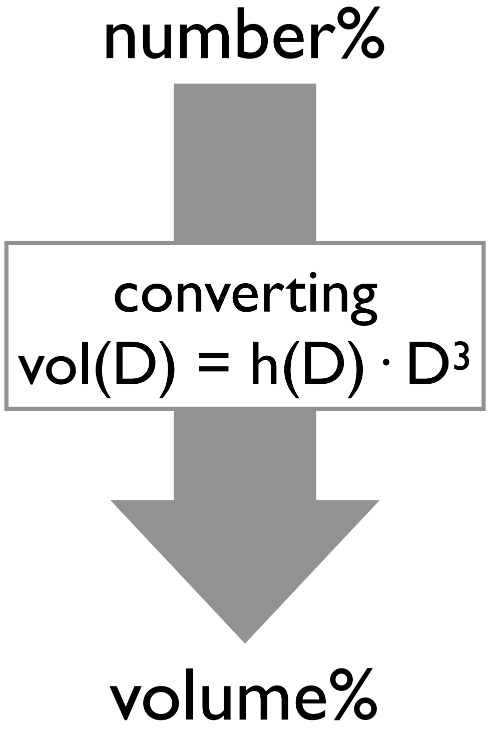


"Grain size":
mean or mode of <u>3D diameters</u> of
area-equivalent circles of projected areas
- arithmetic mean
- mean/mode of Gaussian curve fit

volume weighting







D_{mean} from vol%(D) $\neq$ D_{mean} from h(D)

Note: $D_{projected}$ = diameter of area-equivalent circle of projected area

what have we learned ?

Sands and powders are easily analyzed using a scanner.

In this case, the area-equivalent diameters $d_{equ} = D_{equ}$ represent the diameters of the volume-equivalent spheres D_{equ}.

No conversion from 2D to 3D is necessary

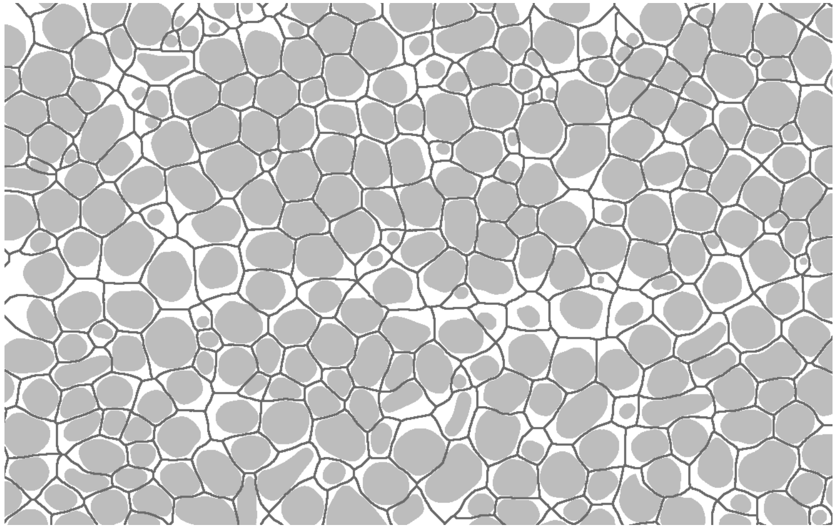
The conversion from h(D) to vol(D) is trivial:
$vol(D) = h(D) \cdot D^3$

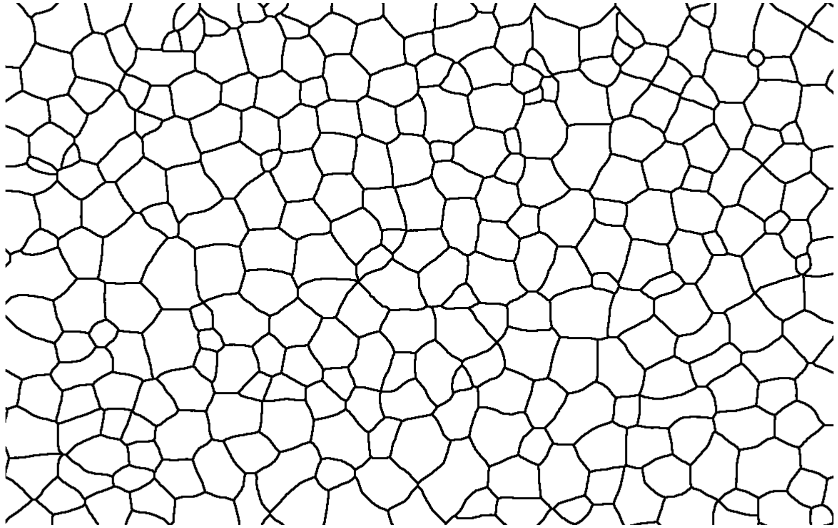
"grain size" 3

cementation

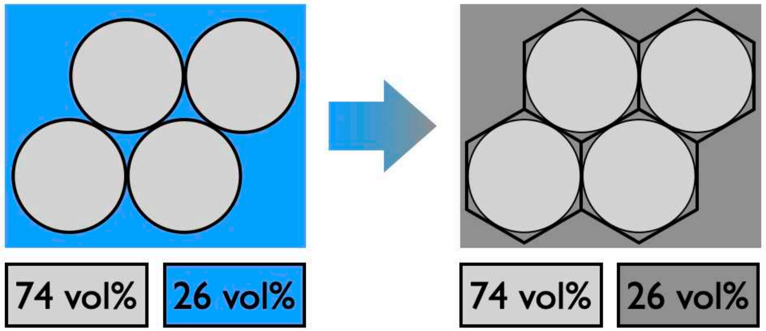
intercept method

"grain size" 3: cemented sandstone





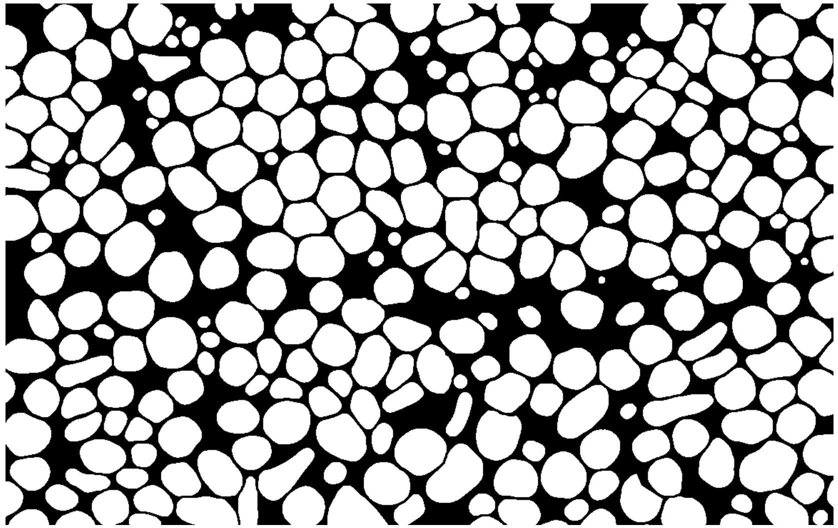
closest packing = 74 vol%



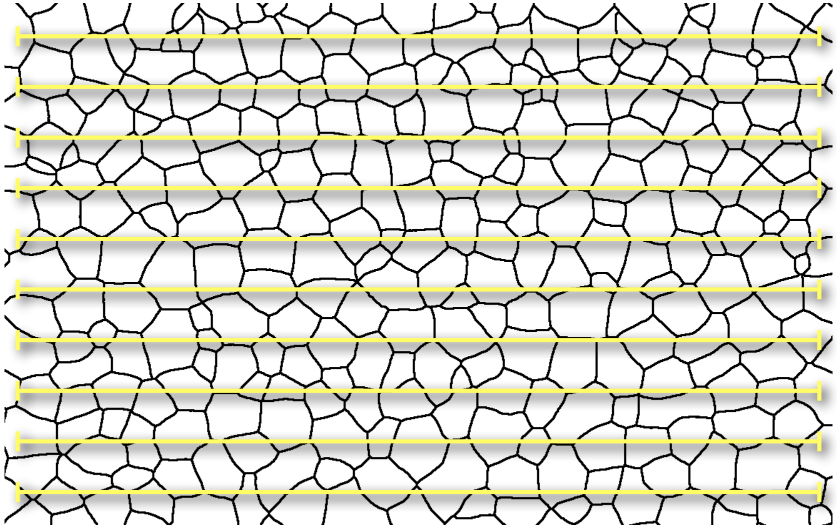
assumption:

(1) grain volume increase = $^{74}/_{26}$ = 1.354

(2) $d_{cemented} : d_{original}$ = $\sqrt[3]{1.354}$ = 1.106



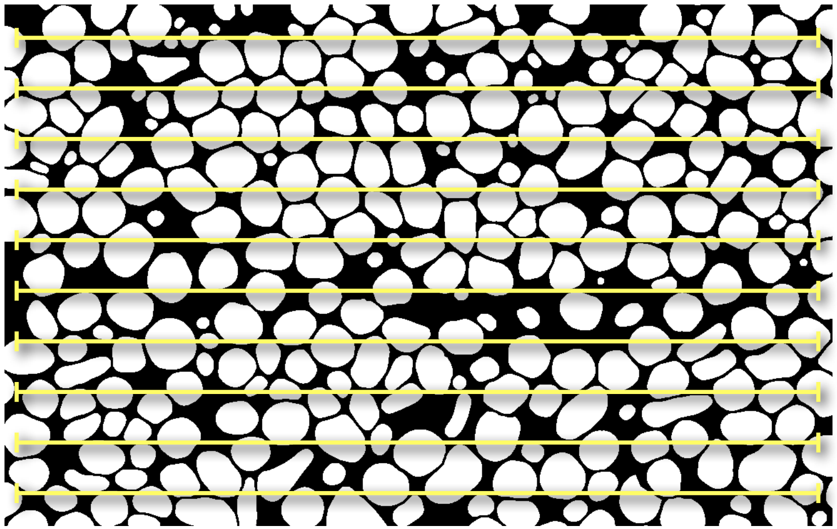
intercept method – limitations



grainsize = $\frac{\text{length of test line (L)}}{\text{number of transected grains (N)}}$

from grain boundaries:
L = 23100 µm, N = 221

size of (grains+cement) = L / N = 105 µm

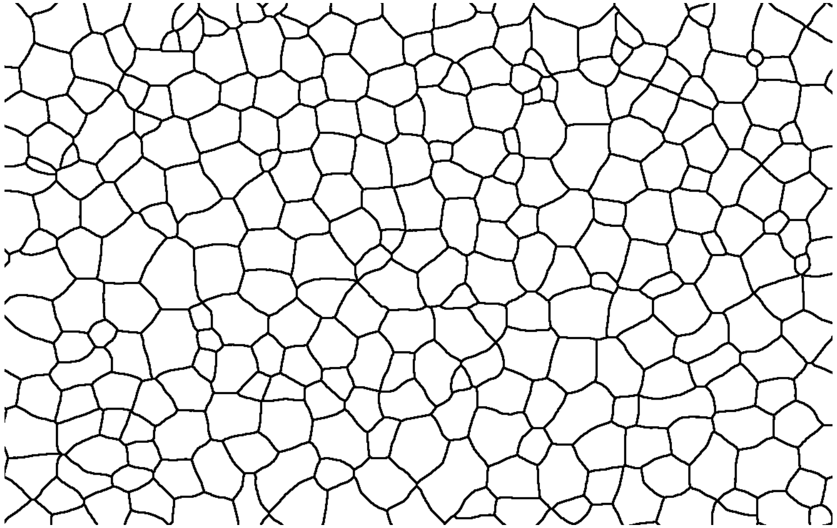


for uncemented grains:
??

"Grain size":
mean of intercept lengths
(= <u>2D size</u>, no distribution)

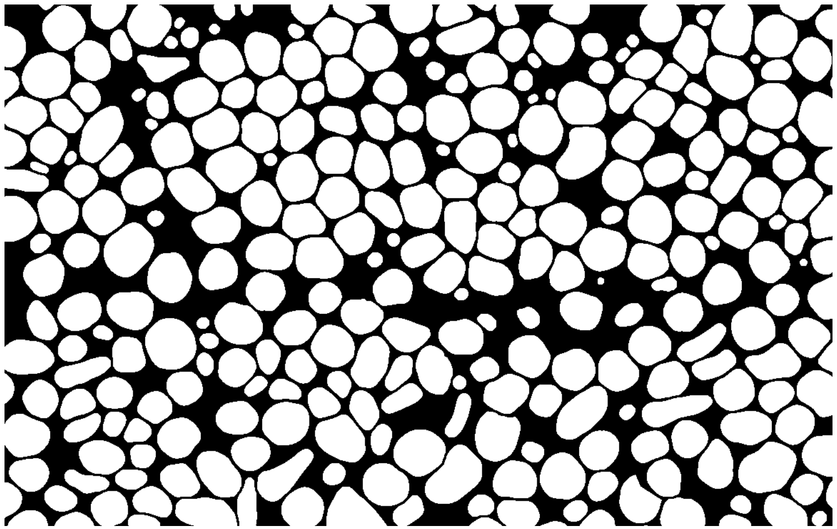
does not work for grains in matrix

check against digital image analysis



check (1) diameters (long axis fit ellipse)

grains from intercept	105 μm
grains from ellipse fit	110 μm



check (2) ratios

long axes of fit ellipse:

grains	110 μm
(grains+cement)	130 μm

(grains+cement) : grains = 1.22 ≠ 1.11

area%

grains	72.9 vol%
(grains+cement)	100.0 vol%

(grains+cement) : grains = 1.37 ≈ 1.35

what have we learned ?

The intercept method is practical and fast – can be done at the microscope – or on un-segmented micrographs, ... but ...

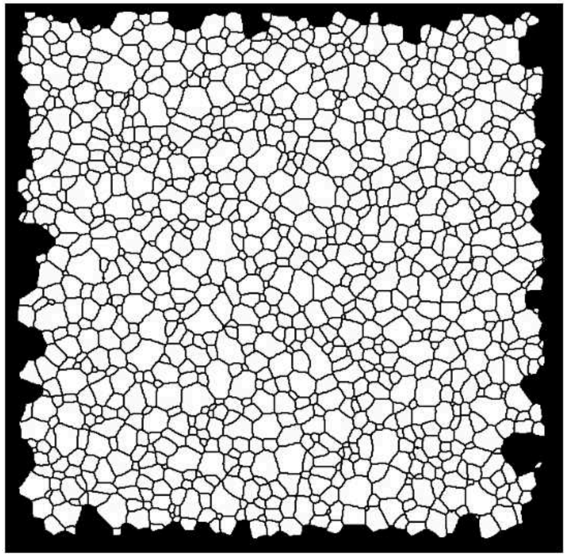
Only mean the arithmetic 2D mean can be calculated.

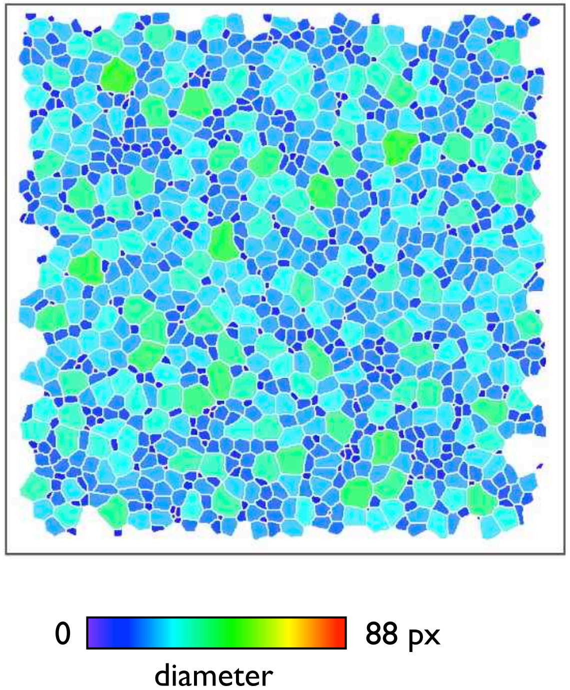
Cannot be used for grains in matrix.

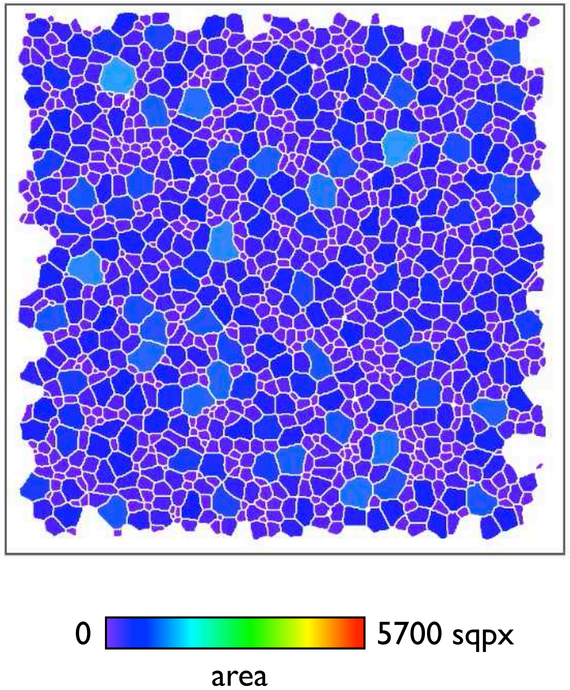
"grain size" 4 grain growth

2D experiment

"grain size" 4: Ostwald ripening

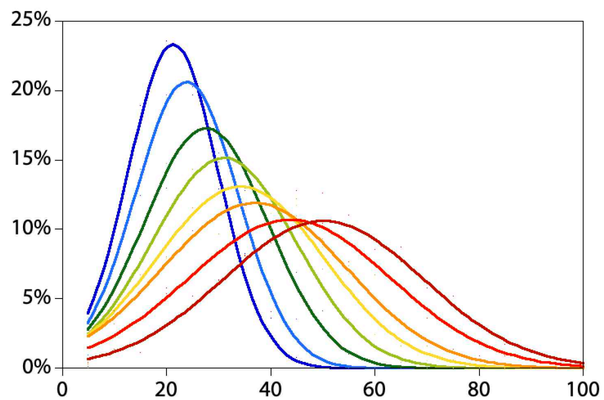






grain growth kinetics

Chen LQ, Yang W (1994)
Computer-simulation of the domain dynamics of a quenched system with a large number of nonconserved order parameters—the grain-growth kinetics.
Phys Rev B 50: 15752--15756
https://www.youtube.com/watch?v=p0rY2r0E_2k



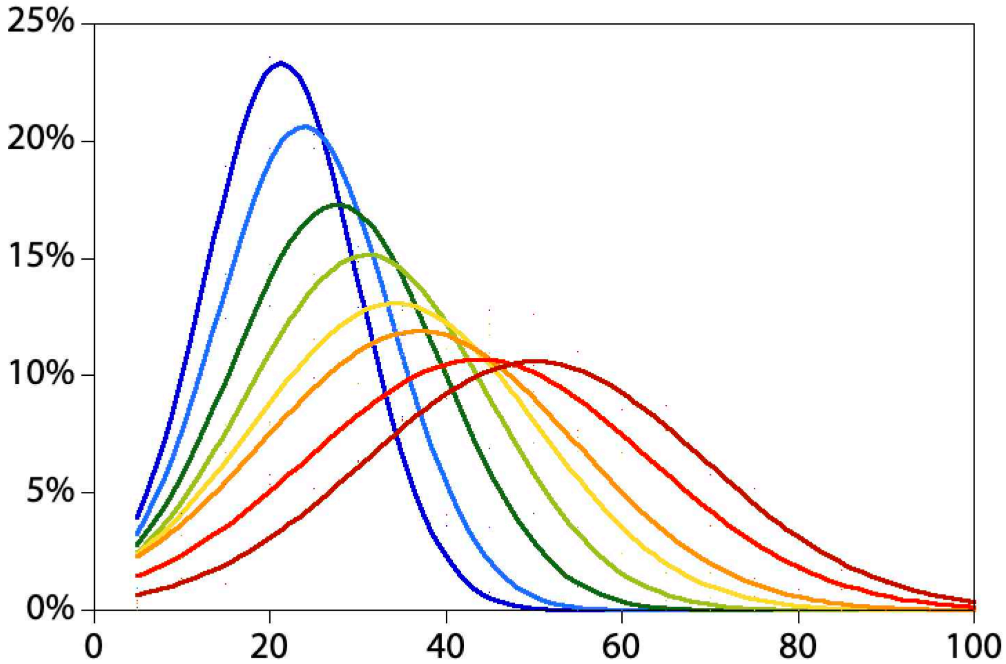
grain growth
→ increasing average size
→ increasing spread

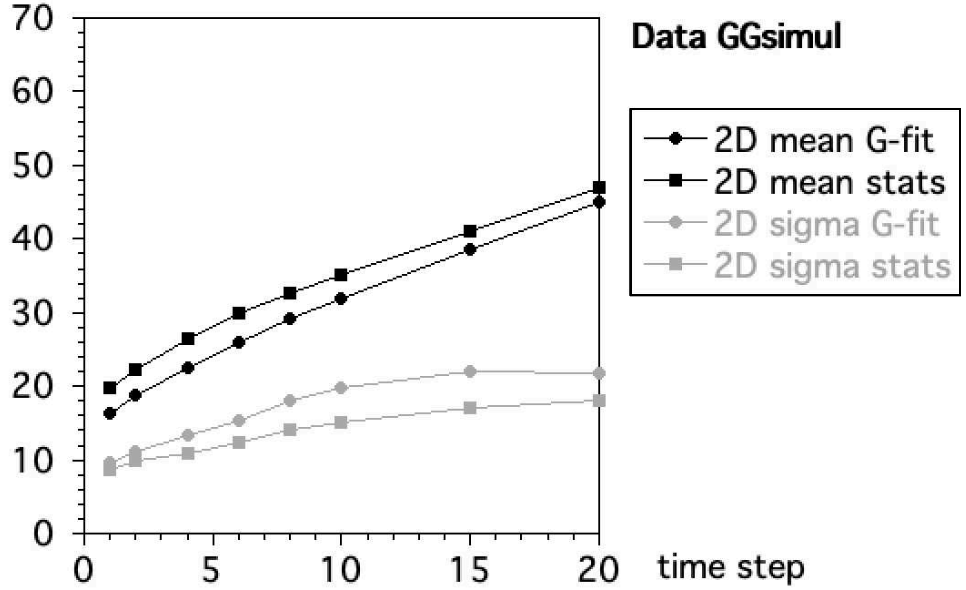
in terms of normal distribution:
→ increasing <u>mean</u> (μ)
→ increasing <u>standard</u> <u>deviation</u> (σ)

⇒ distribution matters

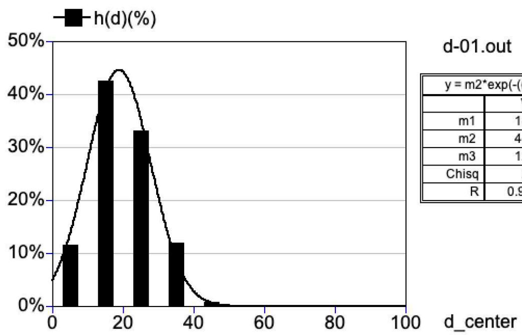
"Grain size":
- arithmetic mean of <u>2D diameter</u>
- mean/mode of curve fit

2D simulation





G-fit = curve fitting



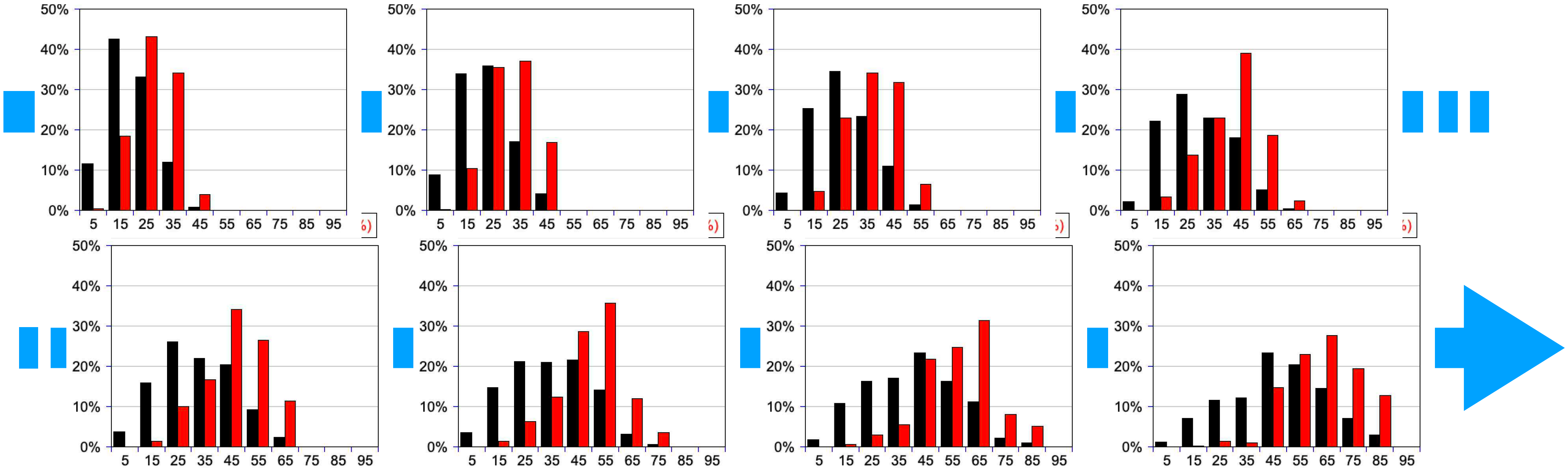
y = m2*exp(-((M0-m1)/m3)^ 2)		
	Value	Error
m1	18.896	0.38953
m2	44.579	1.7004
m3	12.732	0.57973
Chisq	20.75	NA
R	0.99525	NA

stats = arithmetic mean

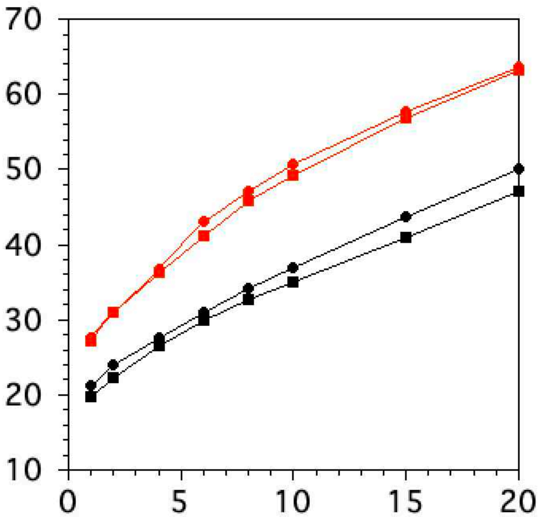
```
------------------------------------------
statistics for output file d-01.out.txt
(data not saved - need to copy from screen):

                            mean      st.dev.
statistics of d          19.76689    8.74732
statistics of D          19.70738    8.28300
statistics of V          27.25517    8.04039
statistics of D*         19.70738    8.28300
statistics of V*         27.25517    8.04039
------------------------------------------
```

should we convert to 3D...?

h(d) frequency of 2D size | v(D) volume% of 3D size

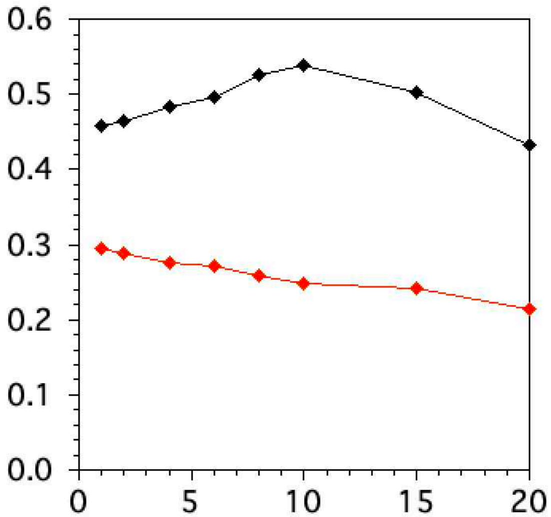


diameter(t)



timestep

(stdev/mean)(t)



timestep

what have we learned ?

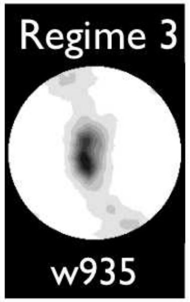
In a fully cemented / fully crystallized rock grain growth has to be volume conserving.

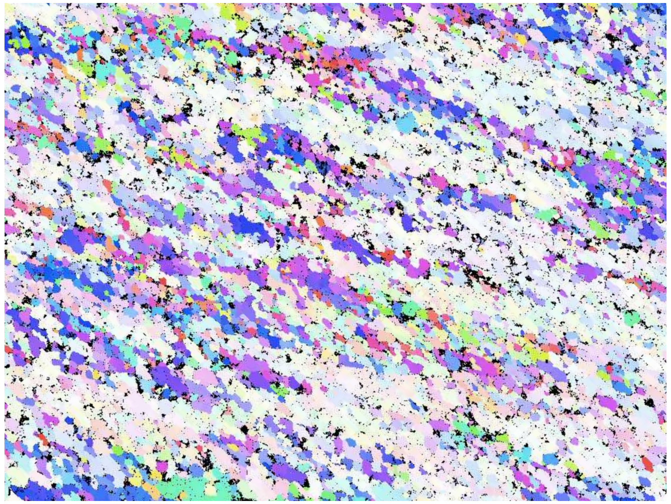
Ostwald ripening is a valid model for such a process: starting with a normally distributed grain size, both the mean and the standard deviation increase with time.

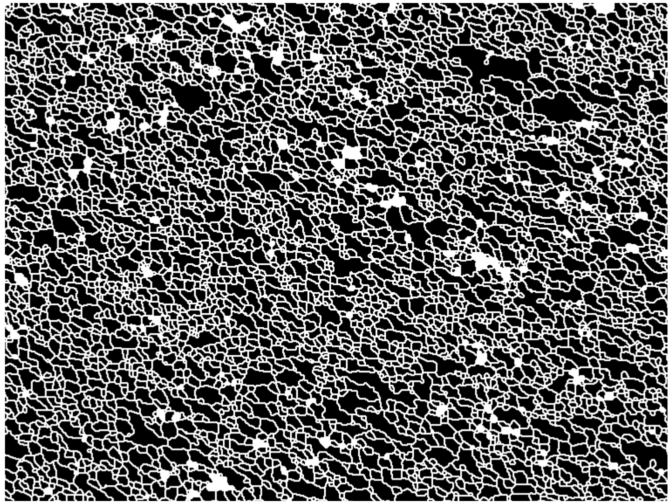
"grain size" 5 dynamic recrystallization

from 2D to 3D

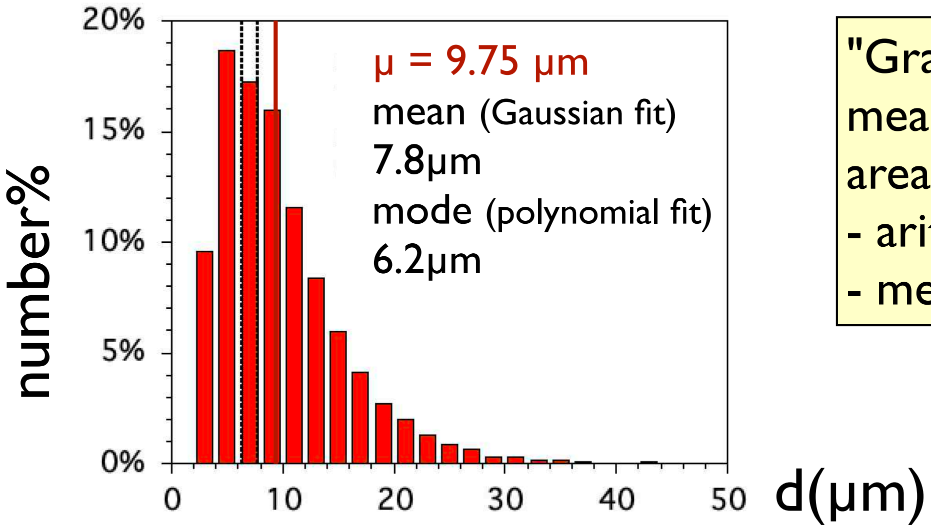
"grain size" 5: sheared quartzite





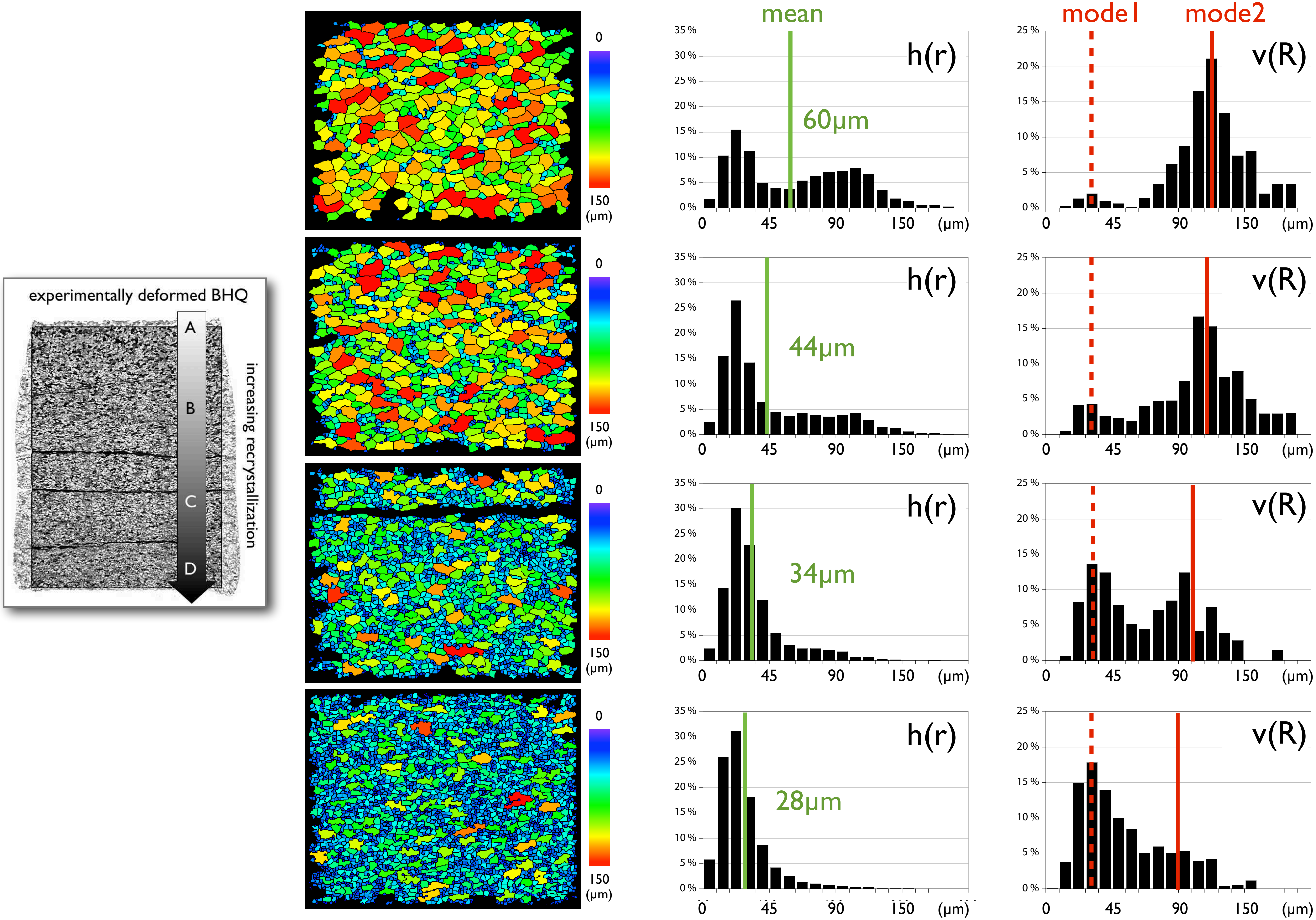


Heilbronner, R. & Kilian, R. (2017). The grain size(s) of Black Hills Quartzite deformed in the dislocation creep regime. Solid Earth, 8, 1071–1093, 2017, doi.org/10.5194/se-8-1071-2017.

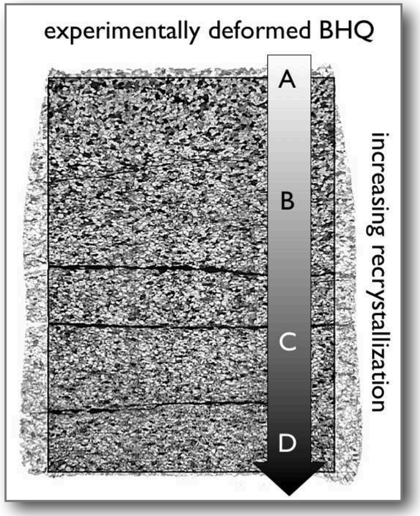


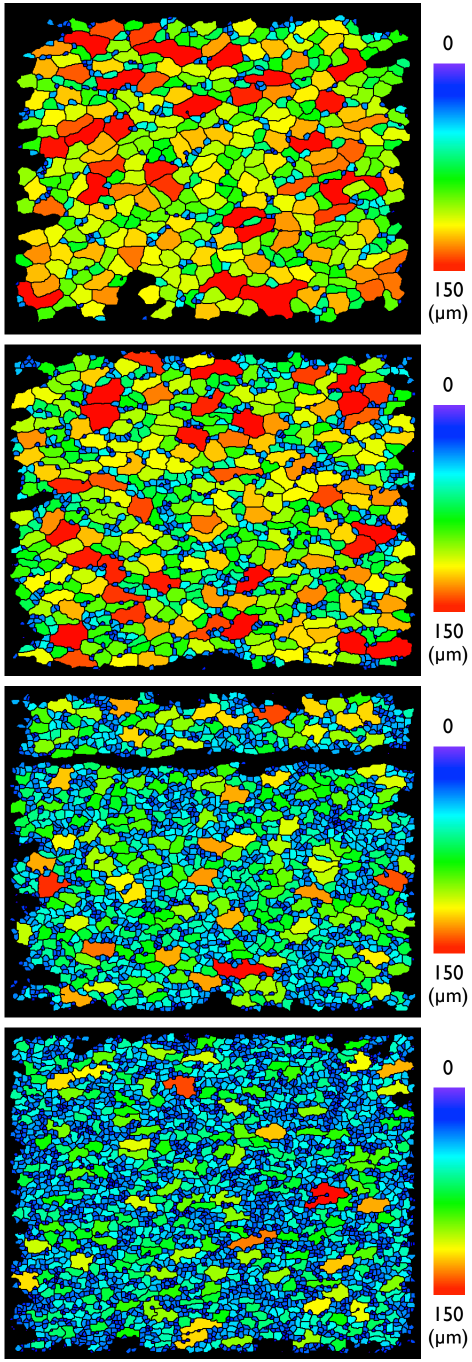
"Grain size":
mean or mode of <u>2D diameters</u> of
area-equivalent circles of sectional shapes
- arithmetic mean µ
- mean/mode of curve fits

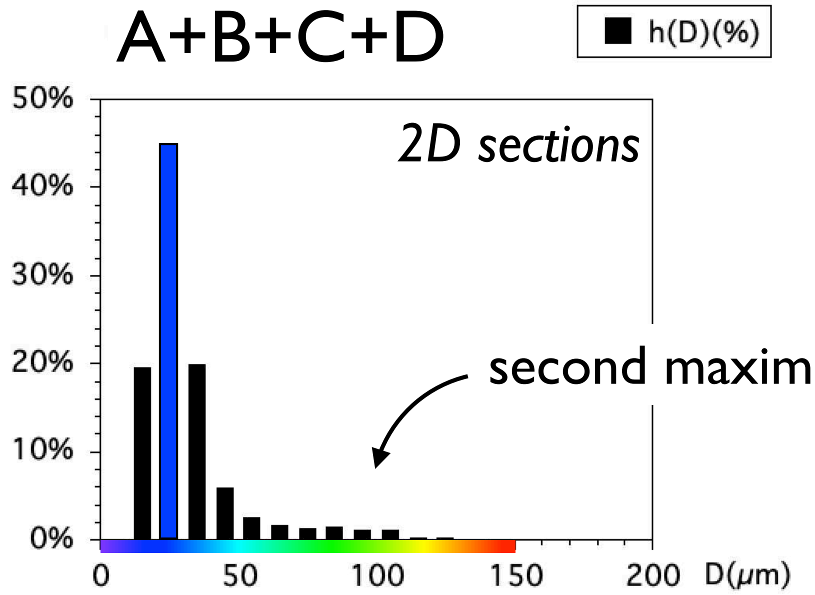
2D versus 3D – mean versus mode

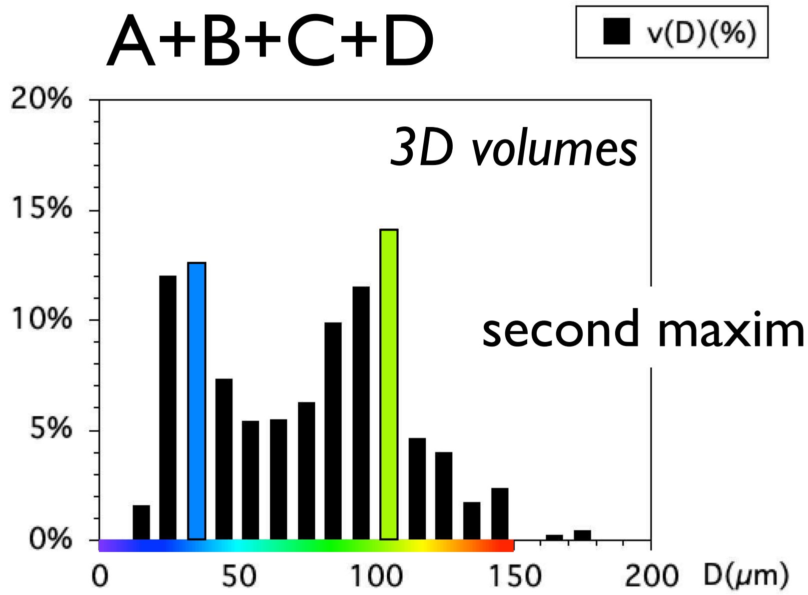


detect second maximum









what have we learned ?

Converting 2D grain size data to 3D is highly recommended!

Volume weighted 3D histograms should be used – they are free from sectioning artefacts!

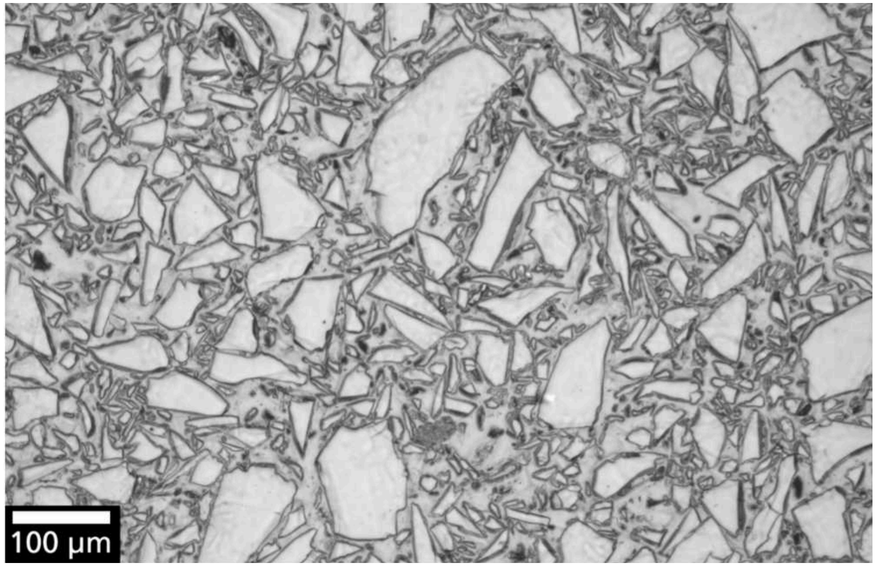
Modal 3D grain size identifies the physically most relevant grain size(s).

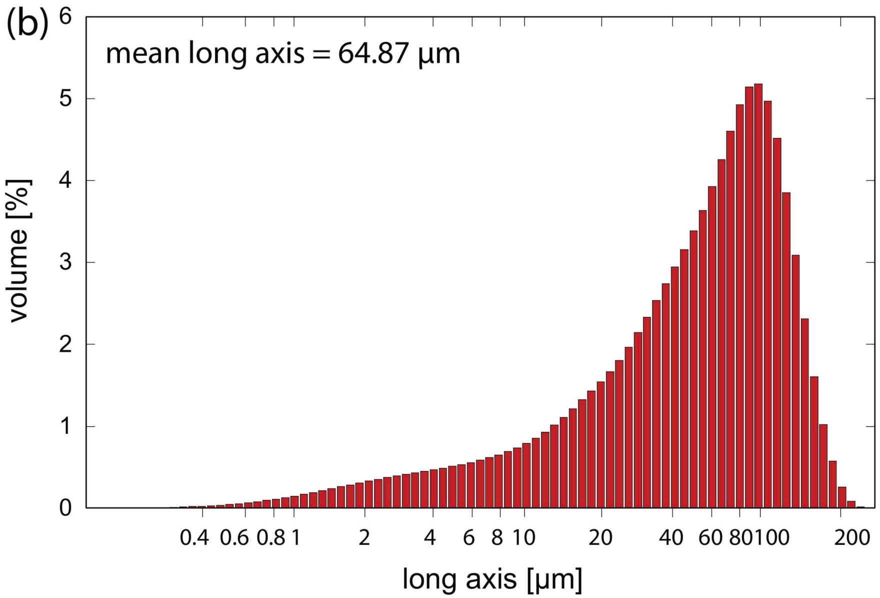
"grain size" 6

powder

particle analyzer

"grain size" 6: crushed quartz





Range from 0.2 µm up to 300 µm
Mean length is about 65 µm and
Mode between 90 and 95 µm.

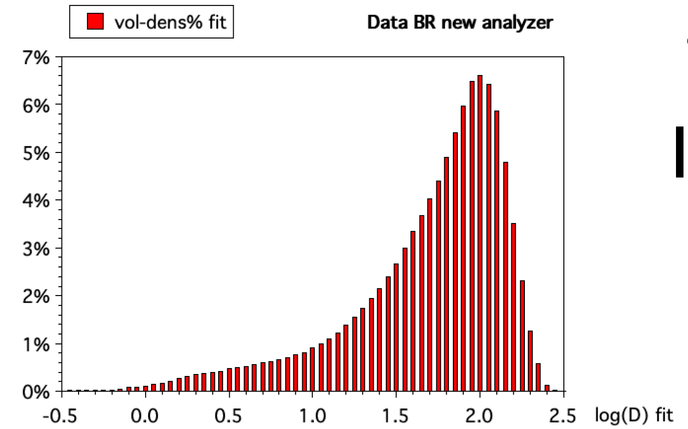
"Grain size":
mean or mode of log (3D size)
(e.g., long axes of particles)
- arithmetic mean
- mean/mode of curve fits

Richter, B., 2017, The brittle-to-viscous transition in experimentally deformed quartz gouge. Dissertation, Basel University. https://edoc.unibas.ch/57805/

to get the mean grain size ...

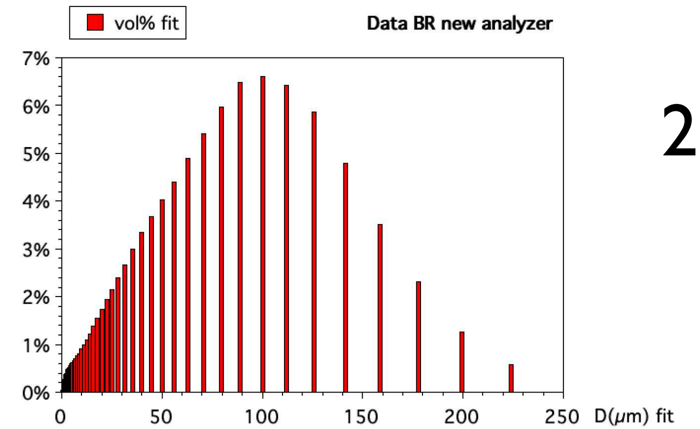
... proceed like this:

1



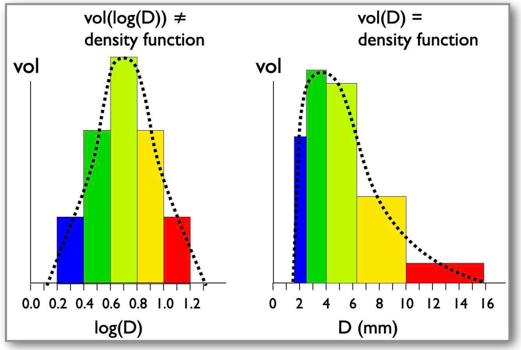
1. Clean original data:
   Plot = vol% vs. log(D)

2

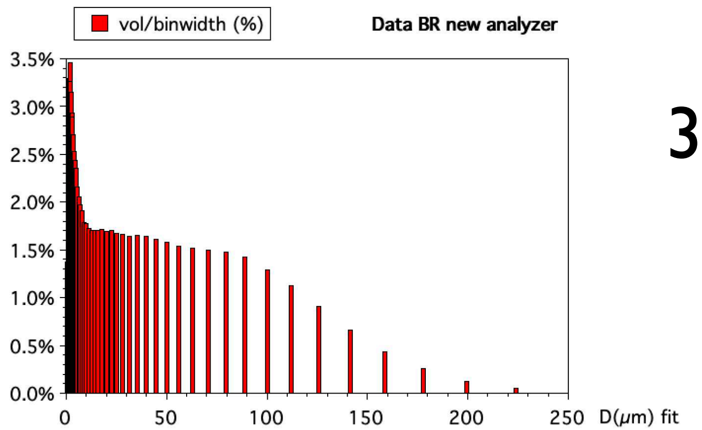


2. Convert to linear D:
   $d = 10^{\log(d)}$
   Plot = vol% vs. D(μm)

pro memoria:



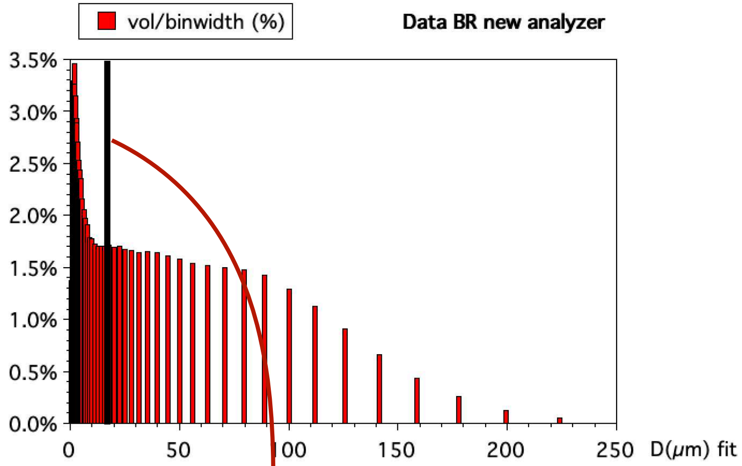
3



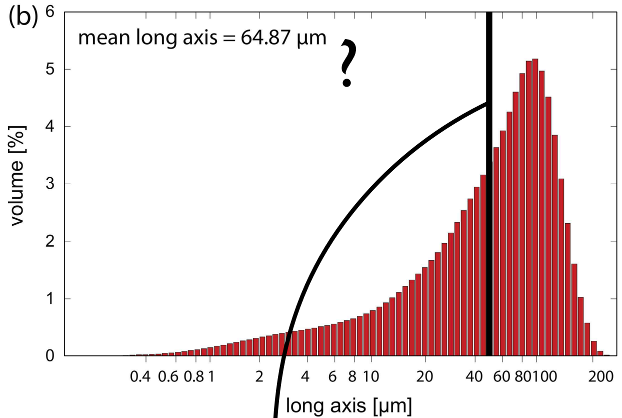
3. Correct for bin width:
   vol_{corr} = vol / bin width*)

*) *if* $\Delta \log(d) =$ *constant*
$\Rightarrow \Delta d \neq$ *constant*

... ≠ the mean of log histograms !



mean long axis =
D_{mean} = 17.5μm !!



"mean" long axis = 49μm

evaluated from linear data

⇒ D_{mean} = 17.5μm

depends on upper and lower bound,
only true for (-0.5 ≤ log(D) ≤ 2.3)
i.e., for (3μm ≤ D ≤ 200μm) !!!

evaluated from log data

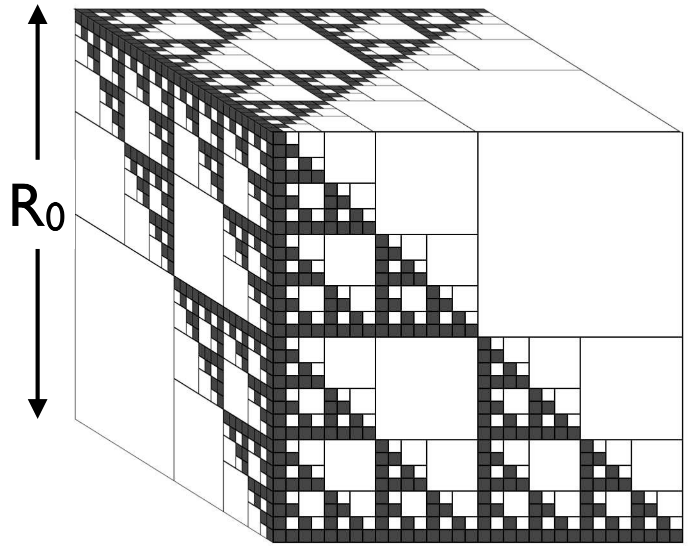
mean value of log(D) = 1.69
⇒ $D_{mean} = 10^{1.69}$ = 49μm

modal value of log(D) = 1.95
⇒ $D_{mean} = 10^{1.95}$ = 90μm

Range from 0.2 μm up to 300 μm
Mean length is about 65 μm and
Mode between 90 and 95 μm.

Richter, B., 2017, The brittle-to-viscous transition in experimentally deformed quartz gouge. Dissertation, Basel University. https://edoc.unibas.ch/57805/

intermezzo: fractal size distributions



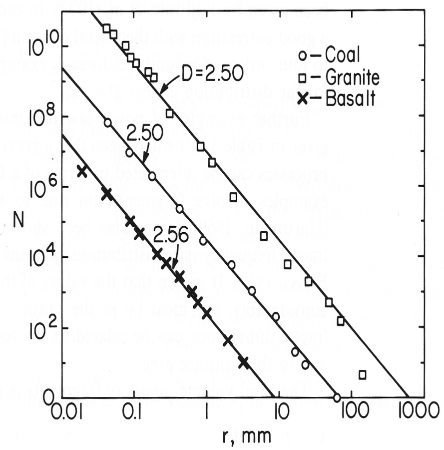
F	number of fragments created
C	number of fragments being fragmented
f = C/F	fragmentation fraction
R_i	size (diameter) of fragment
N_i	number of cracked fragments

Fractal dimension

$$D = \frac{\log (N_{i+1} / N_i)}{\log (R_i / R_{i+1})}$$

published example:

The number N of fragments with cube root of volume greater than r is given as a function of r for broken coal (Bennett, 1936), broken granite from a 61 kt underground nuclear detonation (Schoutens, 1979), and impact ejecta due to a 2.6 km s^{-1} polycarbonate projectile impacting on basalt (Fujiwara *et al.*, 1977). The best-fit fractal distribution from (2.6) is shown for each data set.



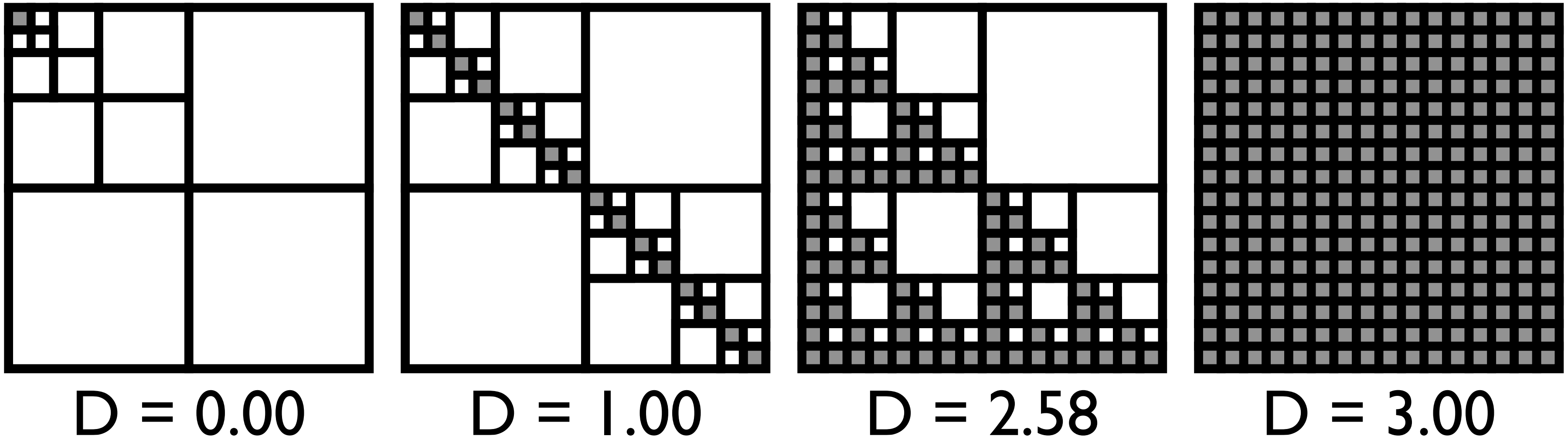
Example:

F = 8	$R_1 = R_0/2$	$N_1 = 6$
C = 6	$R_2 = R_0/4$	$N_2 = 36$
f = 6 / 8		

$$D = \frac{\log (N_2/N_1)}{\log (R_1/R_2)} = \frac{\log (6)}{\log (2)} = 2.585$$

maximum value for D = 3.00 – why ?

map views of cube:



The fractal distribution $N_i(R_i)$ is characterised by a constant ratio $D = \dfrac{\log (N_{i+1} / N_i)}{\log (R_i / R_{i+1})}$ $(0 \leq D \leq 3.00)$

N_{i+1} / N_1 = frequency ratio of smaller to larger grain size
R_i / R_{i+1} = size ratio of larger to smaller grain size

At the maximum vale of D = 3.0, the 2-dimensional fracture surface (grain boundary surface) is completely room-filling, and thus itself a 3-d volume. A higher value than D = 3 cannot be attained by this process of fragmentation

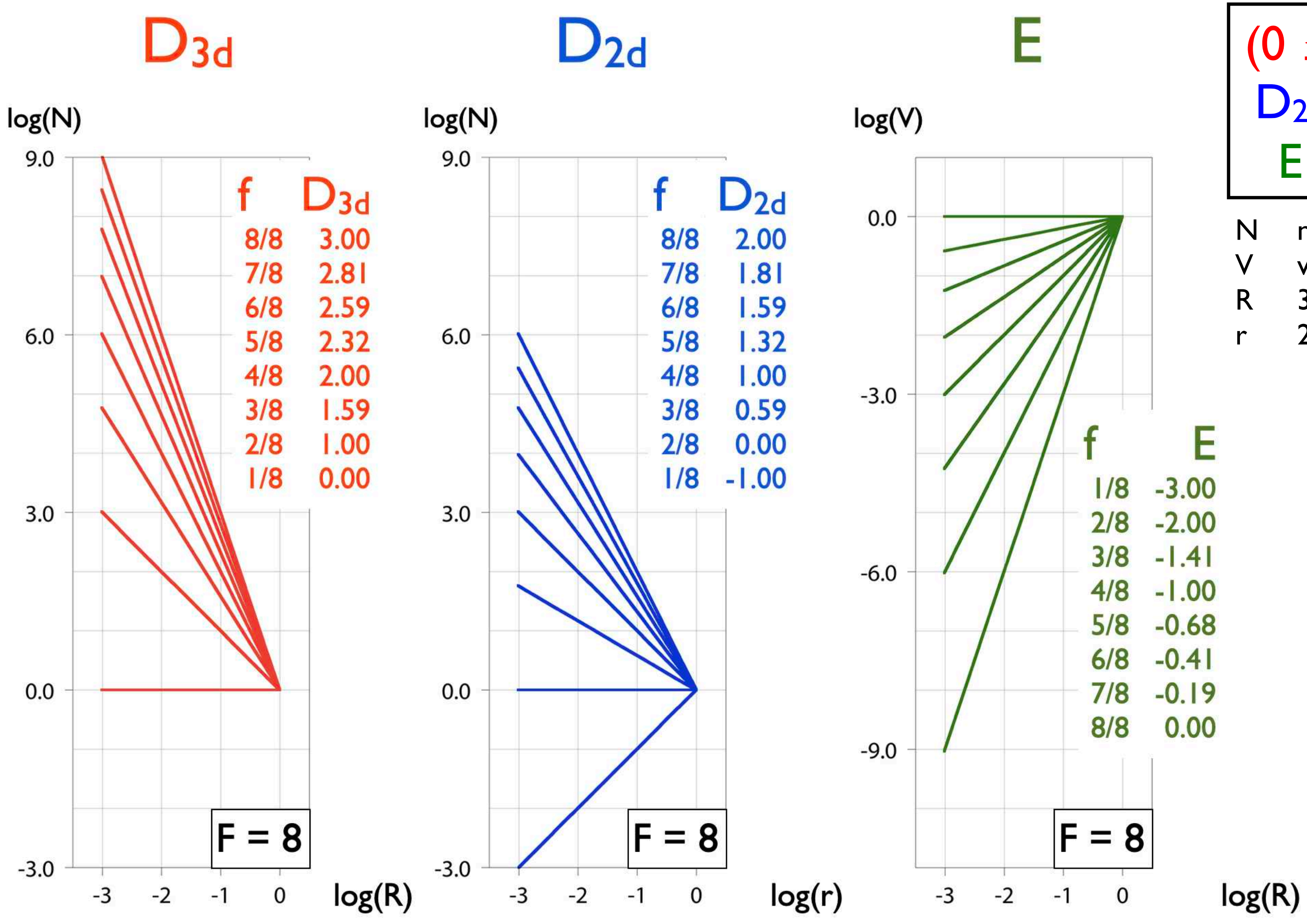
more from the fractal world

$(0 \leq D_{3d} \leq 3)$

$D_{2d} = D_{3d} - 1$

$E = 3 - D_{3d}$

N number of fragments
V volume of fragments
R 3D diameter of fragments
r 2D section diamater



fractal dimension (number of 3D grains)

fractal dimension (number of 2D sections)

volume fraction (volume % of 3D grains)

D_{2d}, D_{3d}, E from N/R or log(N)/log(R)

powerlaw fit to linear data

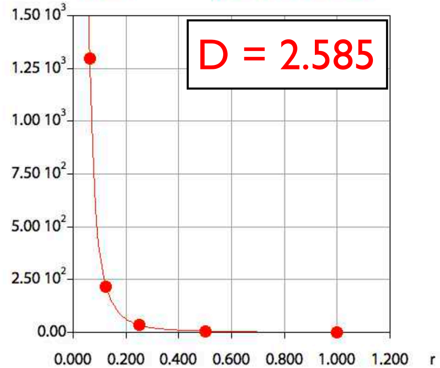
exponent = D

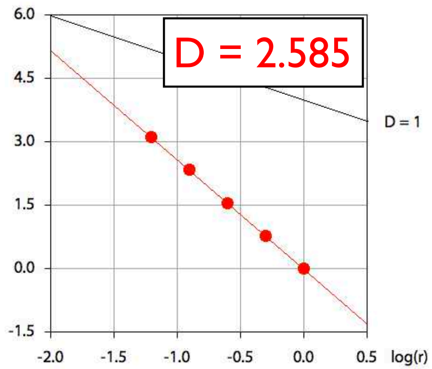
linear fit to log data

slope = D

D_{3d}

$N = R^{(-D_{3d})}$



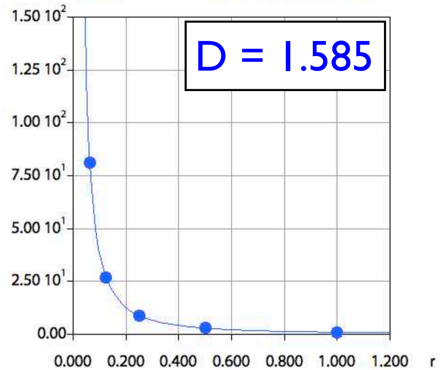


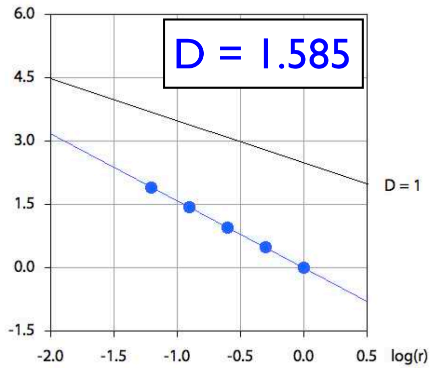
D_{3d}

$\log N = -D_{3d} \cdot \log R$

$D_{2d} = D_{3d} - 1$

$N = R^{(-D_{2d})}$



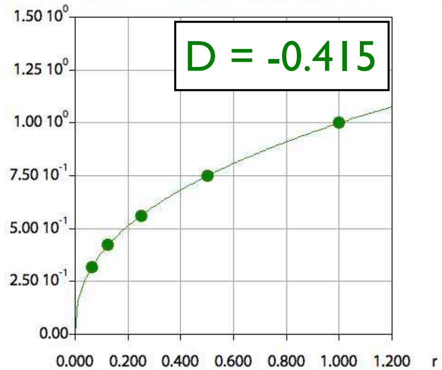


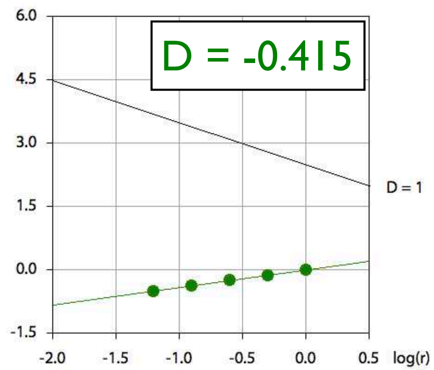
$D_{2d} = D_{3d} - 1$

$\log N = -D_{2d} \cdot \log R$

$E = 3 - D_{3d}$

$N = R^{(E)}$

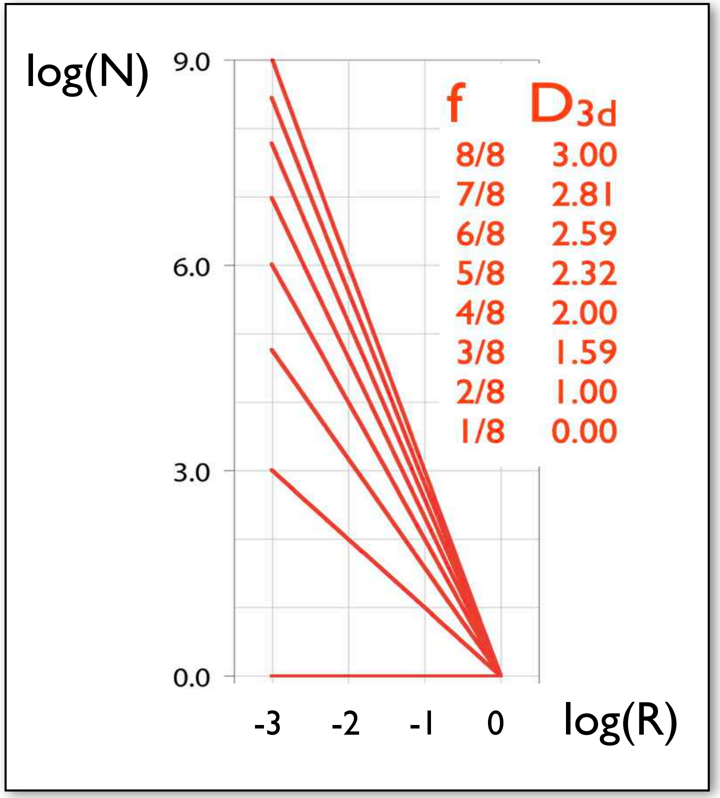


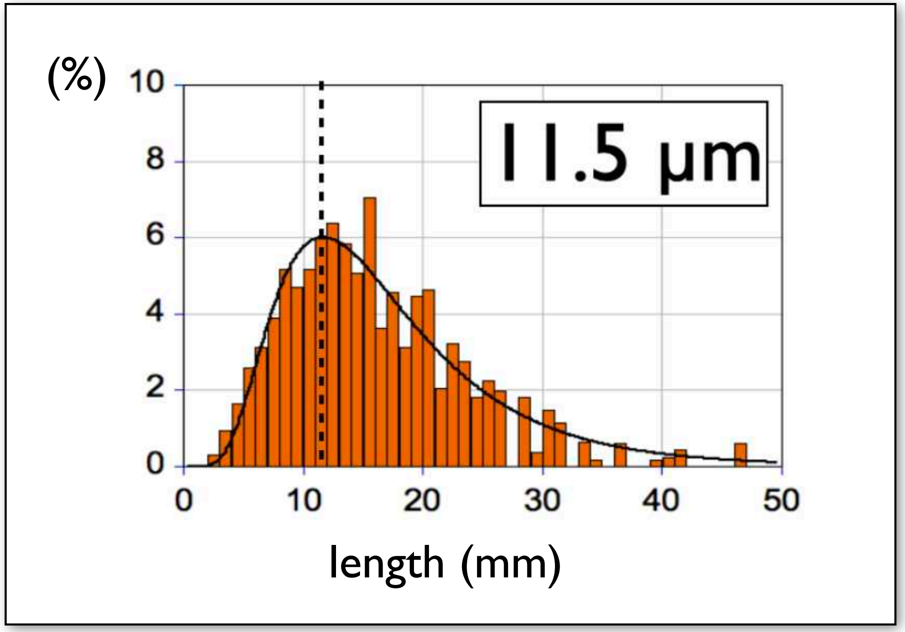


$E = 3 - D_{3d}$

$\log N = E \cdot \log R$

beware: fractal ≠ modal distribution

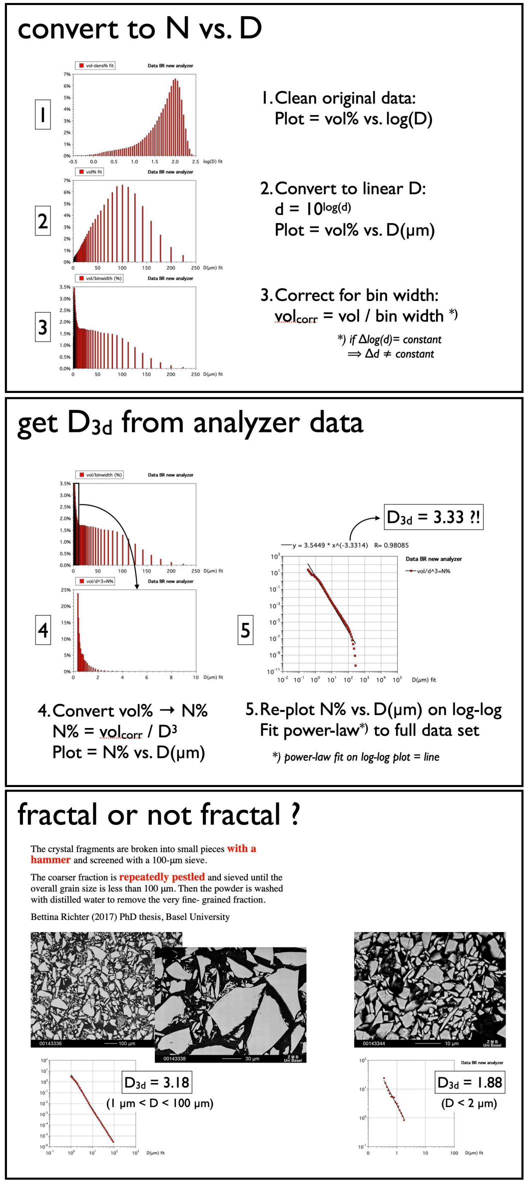




characteristics:
- fractal dimension D
  = grain size ratio
- unbounded:
- no minimum, no maximum
- no mean or mode

characteristics:
- moment of central tendency
  = most significant grain size
- mean or mode of distribution
- bounded:
- total (area under curve) = 100%

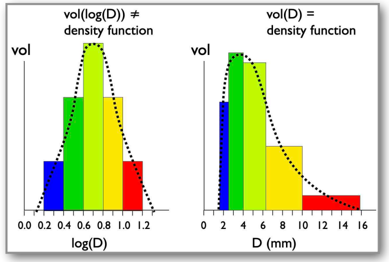
… returning to the talk



what was said in the talk:

- you should correct analyzer vol% to account for increasing bin width with size: vol_{corr} = vol% / bin width
- after calculating N% from vol_{corr}, N% was plotted versus D(µm) and the powerlaw fit yielded $D_{3d} > 3.0$

keeping this in mind:

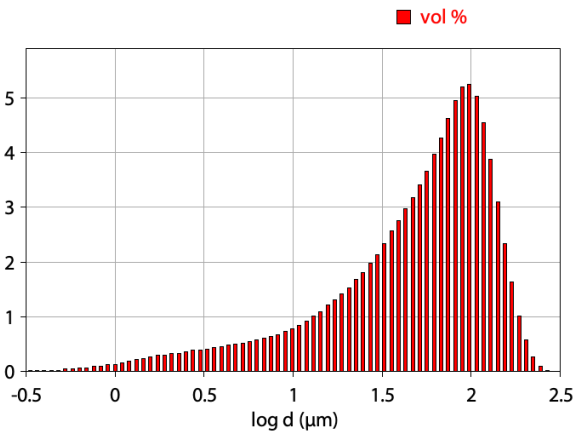


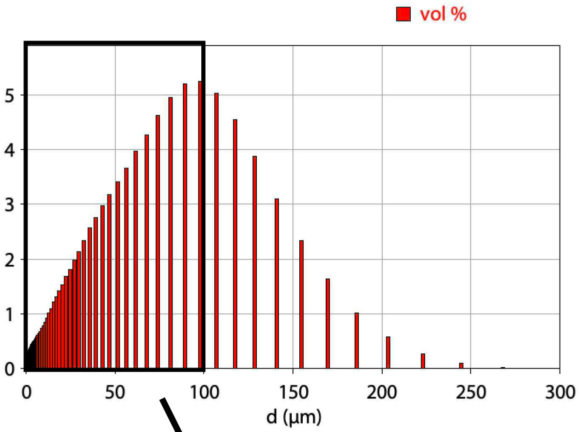
how this was explained in the talk:

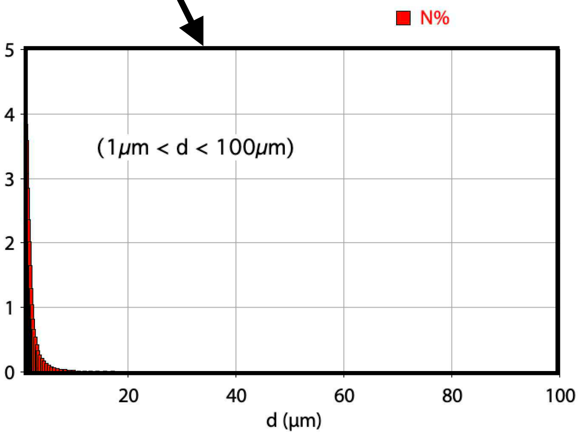
- the processes of hammering and pestling do not correspond to fractal fragmentation

unfortunately, that was rubbish !!

...doing it right

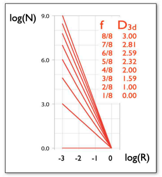
1


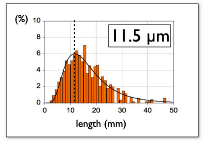
2


3


now we know:

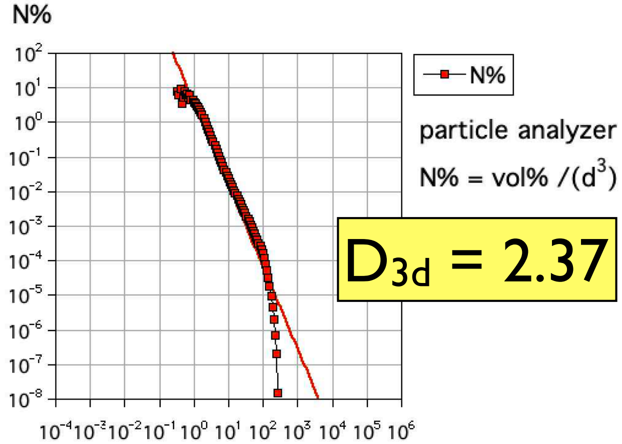
beware: fractal ≠ modal distribution

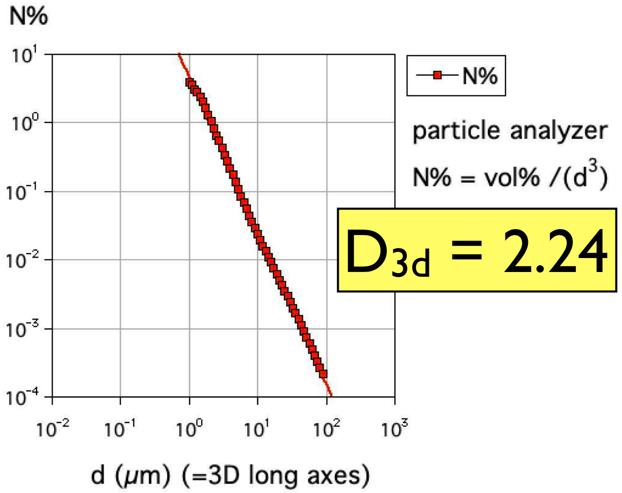




characteristics:
- fractal dimension D
  = grain size ratio
- unbounded:
- no minimum, no maximum
- no mean or mode

characteristics:
- moment of central tendency
  = most significant grain size
- mean or mode of distribution
- bounded:
- total (area under curve) = 100%

4


5


Therefore

1. Clean original data:
   Plot = vol% vs. log(d)

2. Convert to linear bin size:
   $d = 10^{\log(d)}$
   Plot = vol% vs. d(µm)

~~3. Correct for bin width:~~
~~volcorr = vol / bin width *)~~

3. Directly
   convert vol% → N%
   no% = vol% / d^3
   Plot = N% vs. d(µm)

4. Plot N% vs. d(µm) on log-log
   Fit power-law to full data

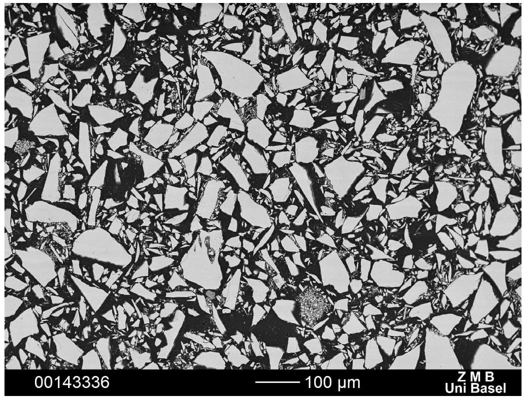
5. Fit power-law to cropped
   (1µm ≤ d ≤ 100µm)

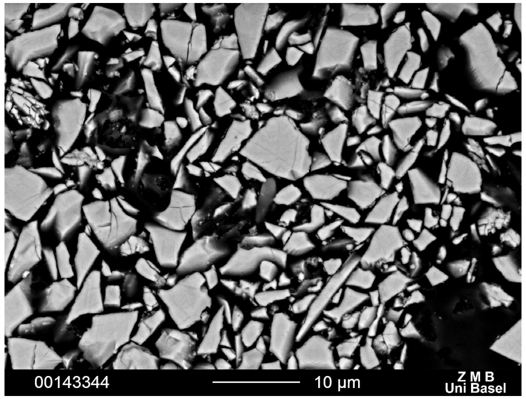
what does D_{3d} mean ?

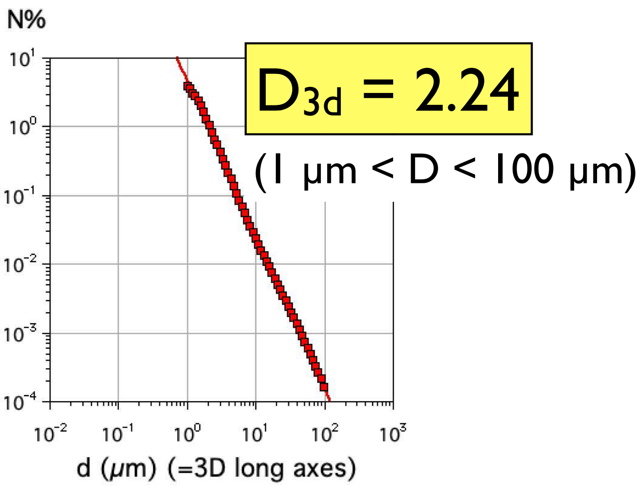
The crystal fragments are broken into small pieces **with a hammer** and screened with a 100-µm sieve.

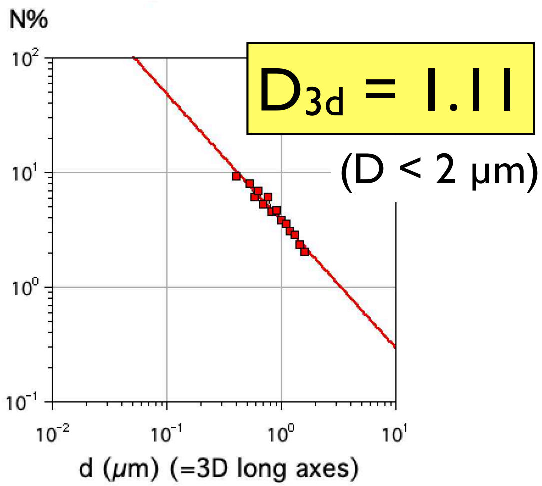
The coarser fraction is **repeatedly pestled** and sieved until the overall grain size is less than 100 µm.

Bettina Richter (2017) PhD thesis, Basel University









how this is explained:

- the processes of hammering and pestling generate grain size distributions with $D_{3d} < 3.00$ i.e., compatible with fractal fragmentation processes
- $D_{3d} = 2.24$ (fragmentation fraction ≈ 5/8) for grains > 1 µm
- $D_{3d} = 1.11$ (fragmentation fraction ≈ 2/8) for grains < 2µm (below grinding limit)

what have we learned ?

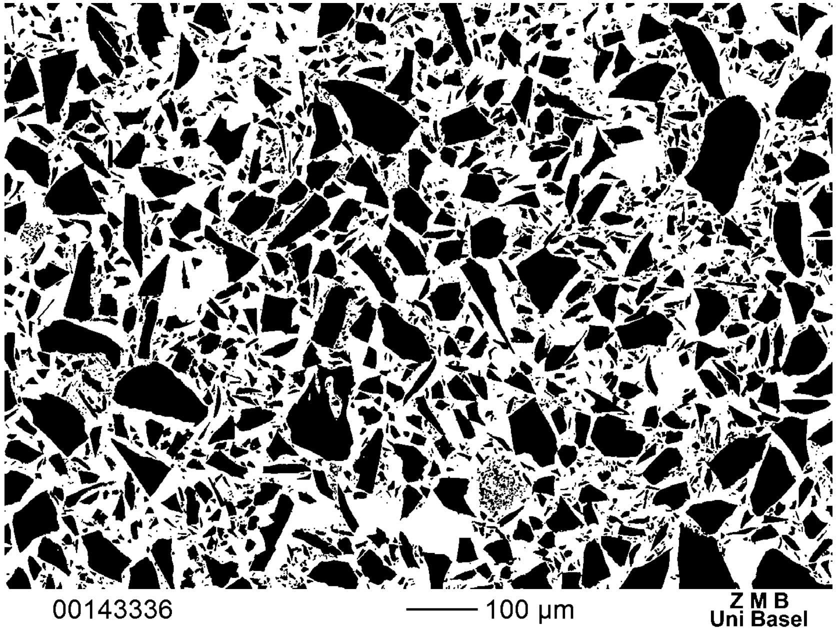
Data from particle analyzers are particularly prone to misinterpretation.

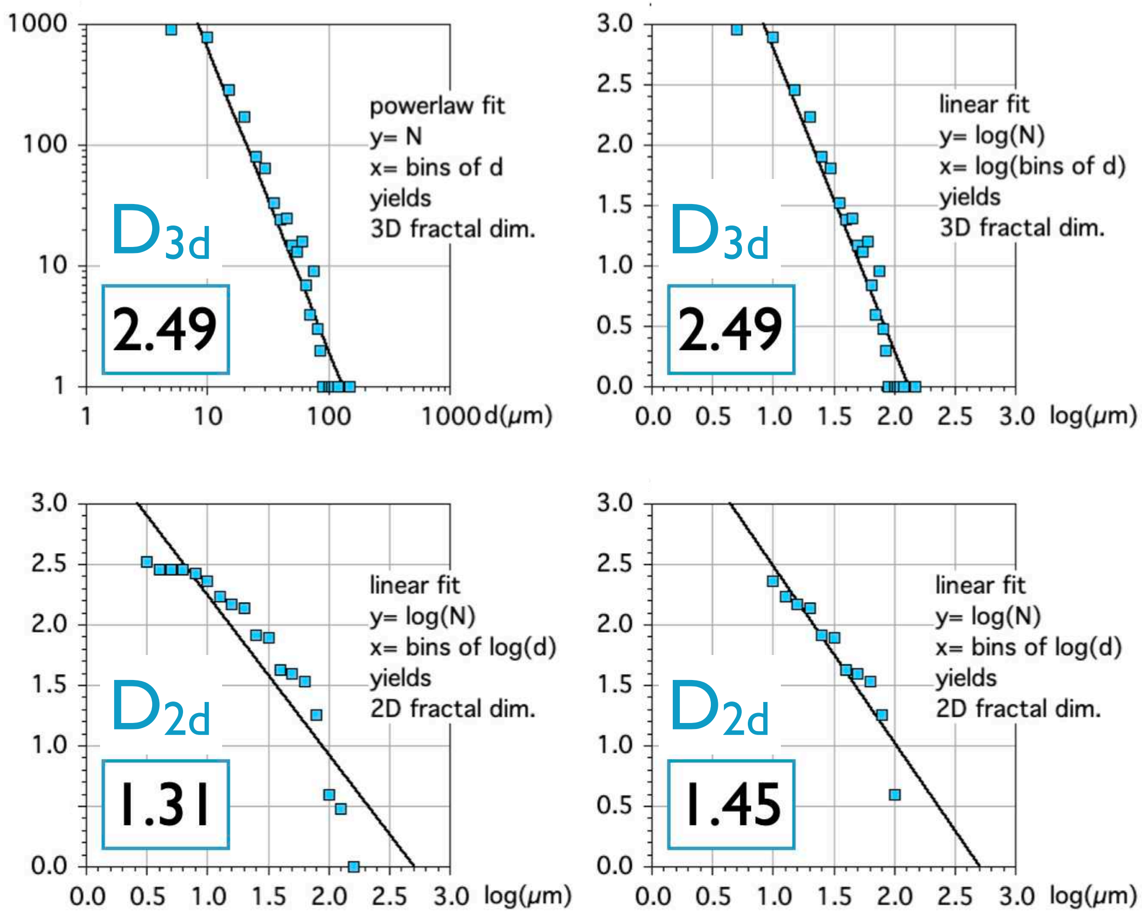
The mean of a fractal distribution is quite meaningless.

Rather, convert analyzer data to linear histograms of volume density versus linear size...
... and check on a log-log plot of N.vs.size:
if the slope, D, of the powerlaw fit is a straight line, and if ($0 \leq -D \leq 3$), the distribution may be due to fractal fragmentation.

"grain size" 7
friction & healing
fractal dimension

"grain size" 7: brittle fault rocks





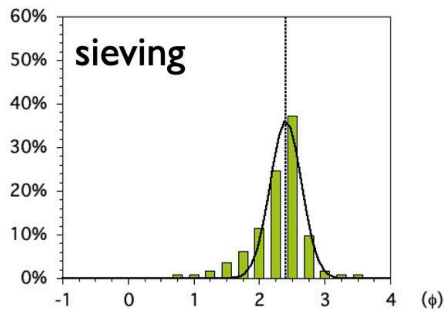
fractal dimension for 2 or 3 dimensions

$D_{2d} = D_{3d} - 1$

... but fractal size distributions should span at least 3 orders of magnitude

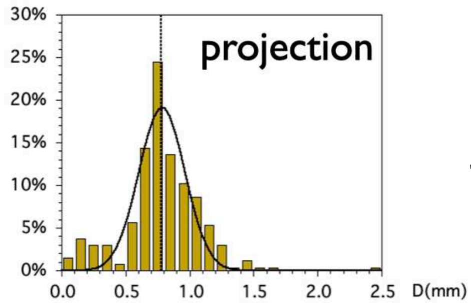
comparing grain size distributions

1



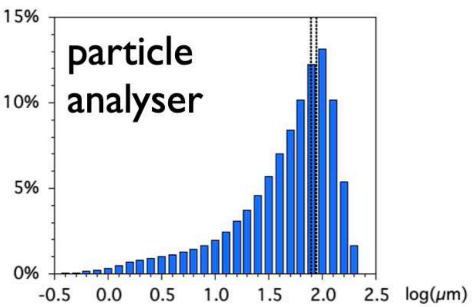
y= weight (%)
x= bins of 3D d(φ)

2



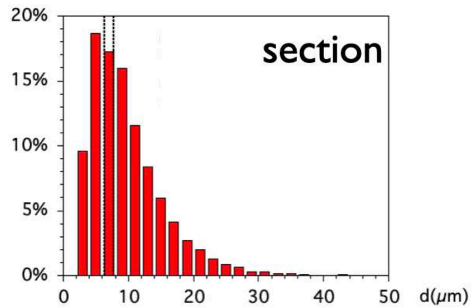
y= number (%)
x= bins of 3D d(mm)

3



y= volume (%)
x= bins of log 3D d(μm)

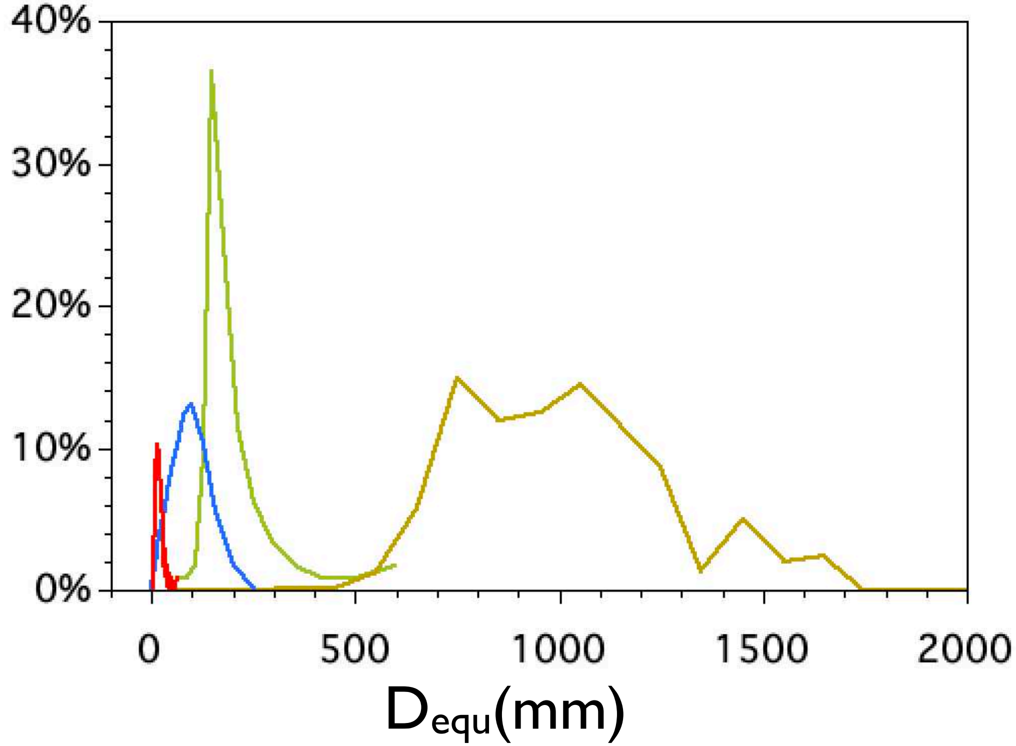
4



y= number (%)
x= bins of 2D d(μm)

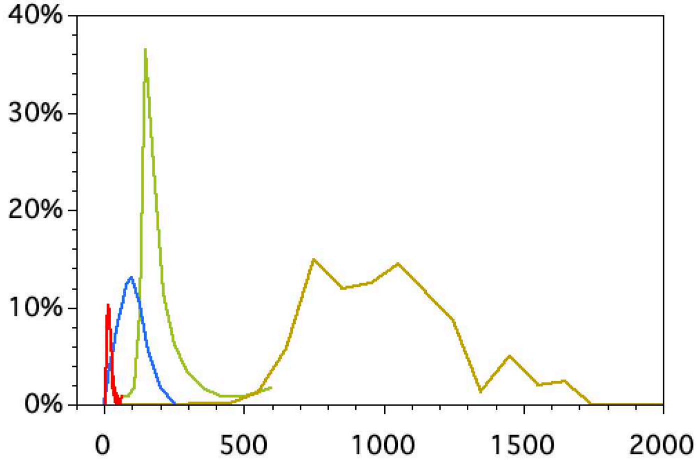
all plotted as
vol% vs. linear D

vol%

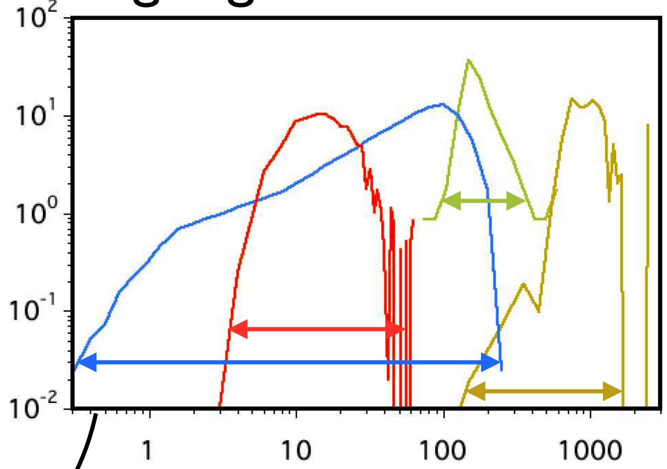


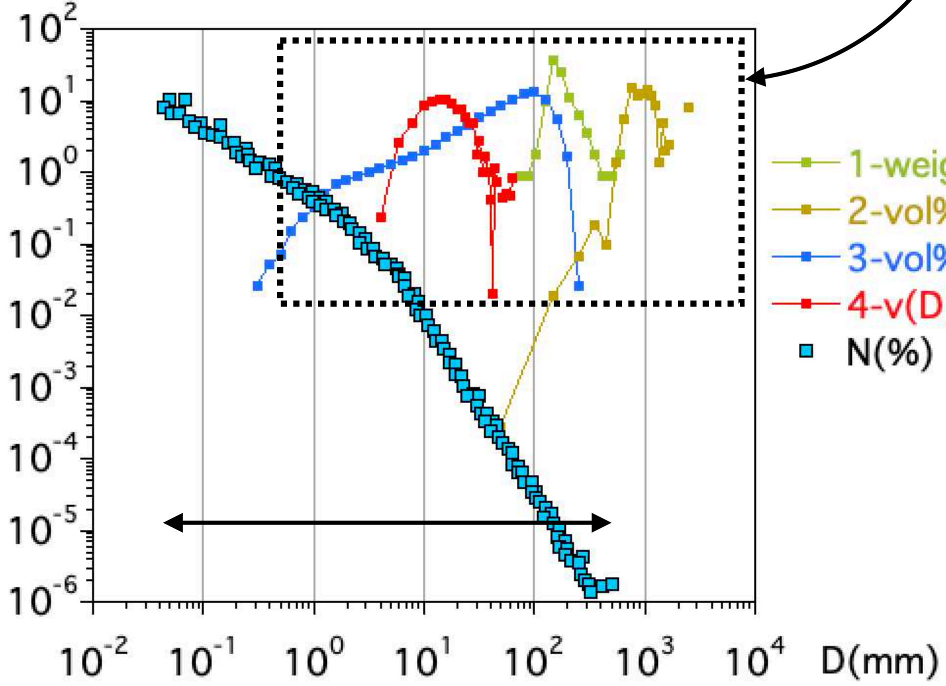
typical data ranges

lin-lin



log-log

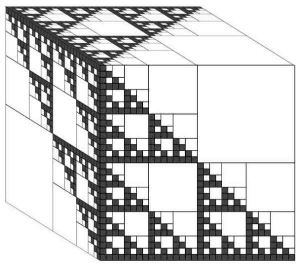




		data range (orders of magnitude)
1-weight(%)	sieved beach sand	0.6
2-vol%(D)	scanned glacig.	0.8
3-vol%meas	part.analyzer crushed	~3
4-v(D)(%)	thin section rexl.qtz	0.9
N(%)	polyscale NK	~4

Keulen, N., Heilbronner, R., Stünitz, H., Boullier, A.-M. and Ito, H. (2007). Grain size distributions of fault rocks: a comparison between experimentally and naturally deformed granitoids, J. Struct. Geol., 29, 1282-1300, doi: 10.1016/j.jsg.2007.04.003.

the 'universal' fractal dimension

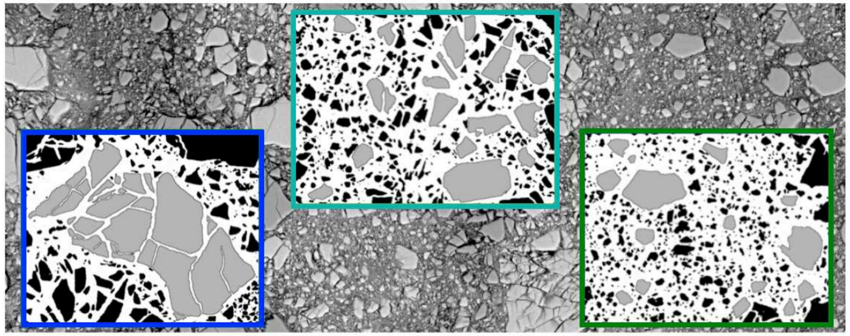


$D_{3d} = 2.585$

$\Longrightarrow$ fragmentation fraction = 6/8

intermediate

cracked

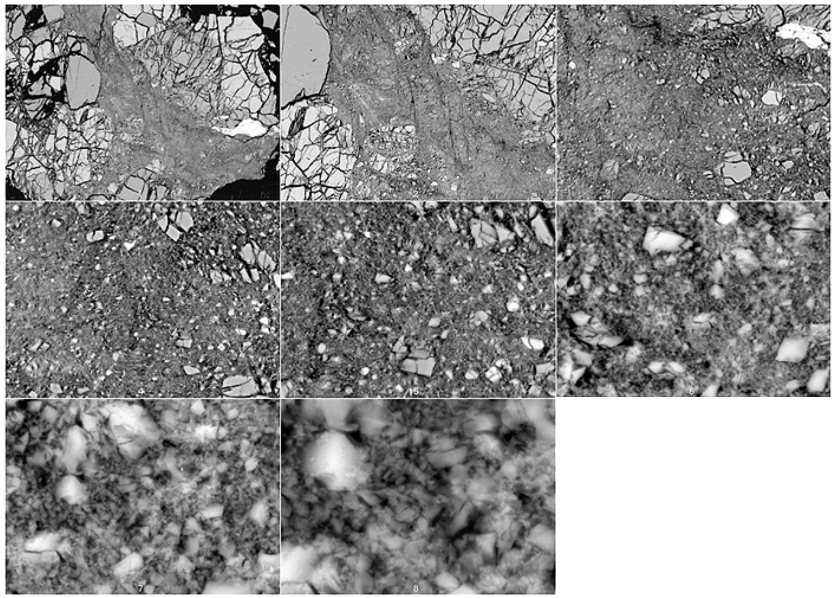


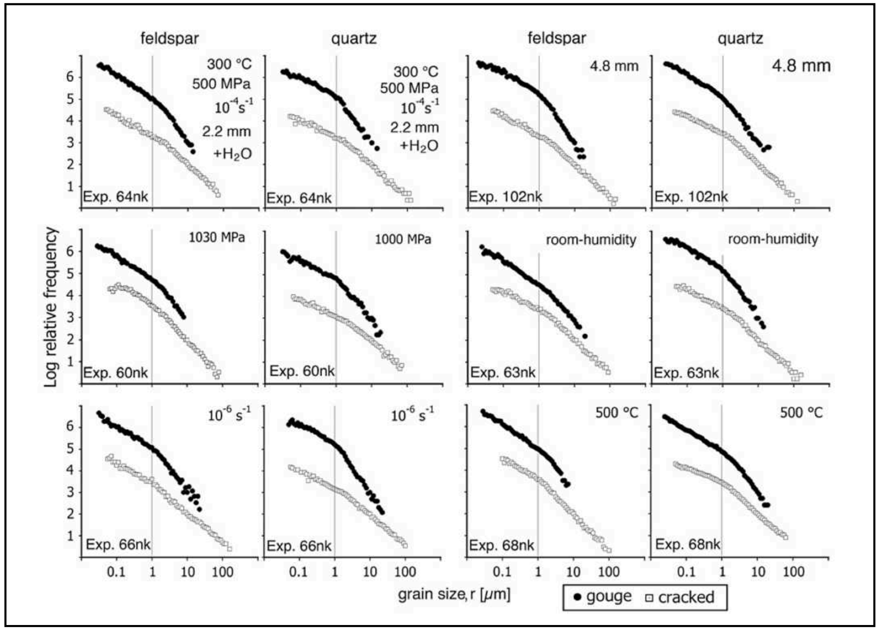
gouge

D_{3d} cracked = ~2.5

D_{3d} gouge = 3.0 - 3.2 !!

$D_{<\text{grinding limit}}$ = 1.8 - 2.0





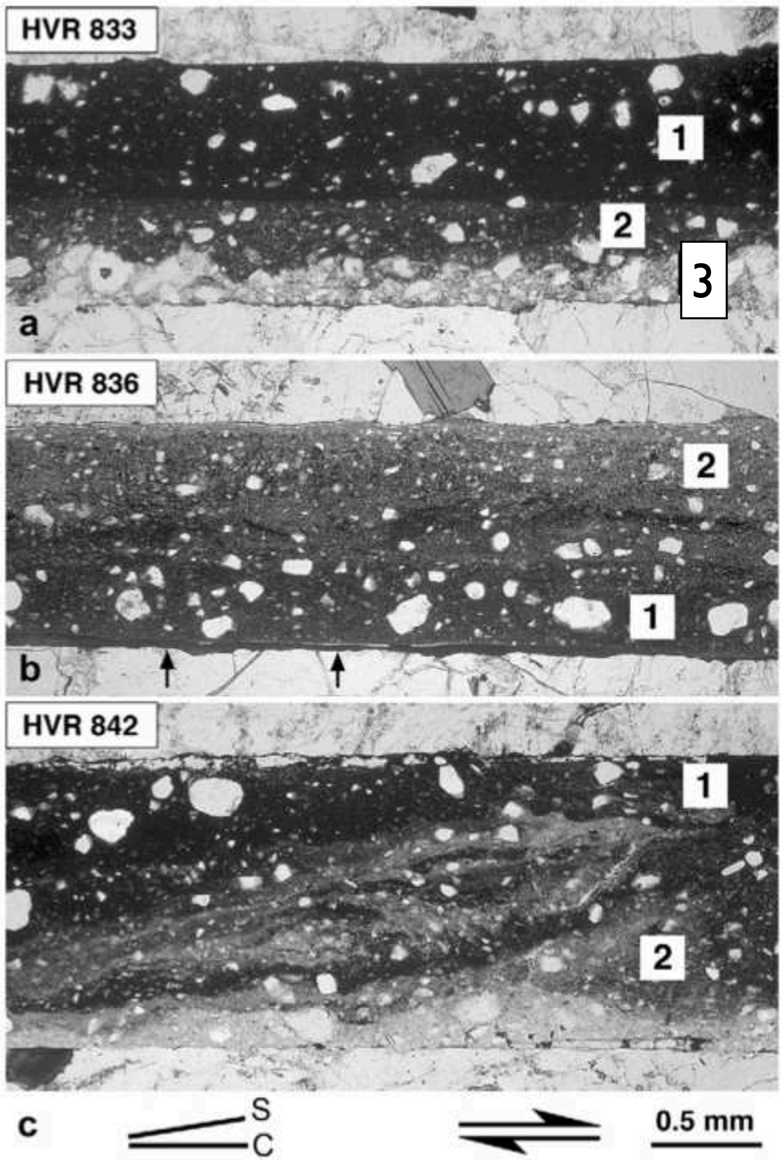
Keulen, N., Heilbronner, R., Stünitz, H., Boullier, A.-M., Ito, H. (2007). Grain size distributions of fault rocks: a comparison between experimentally and naturally deformed granitoids, Journal of Structural Geology, 29, 1282-1300, doi:10.1016/j.jsg.2007.04.003.

D_{3d} gouge ≠ f(displacement)

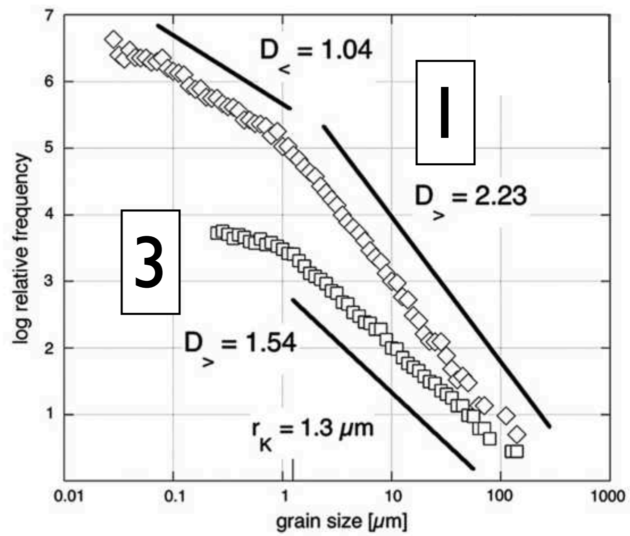
d = 24m

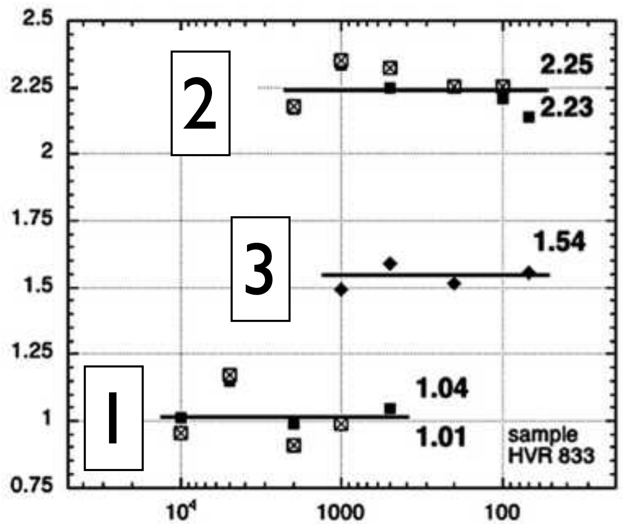
20m

40m



high velocity friction experiments (rotary shear apparatus)

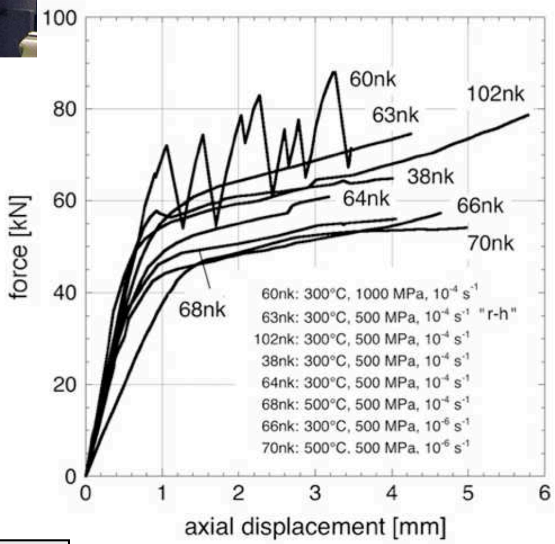


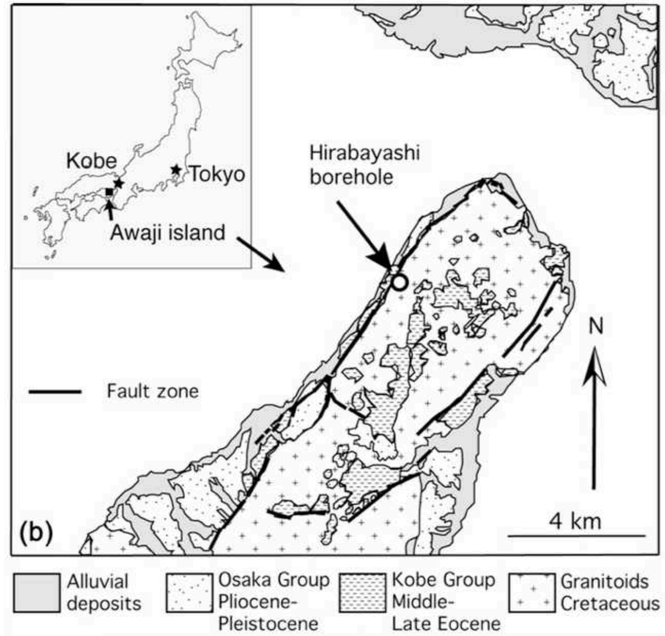


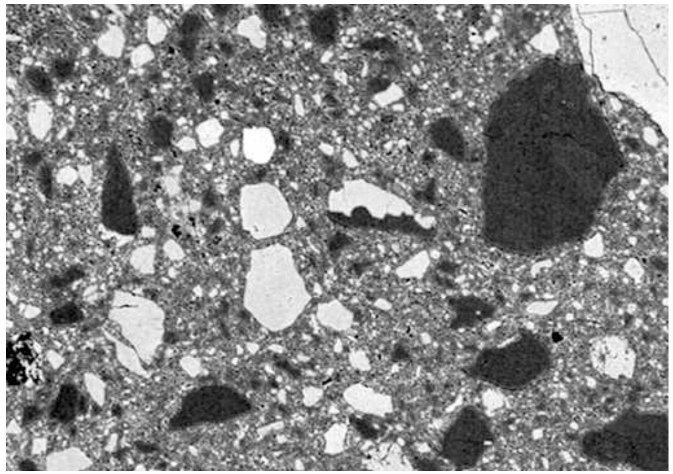
Stünitz, H., Keulen, N., Hirose, T., Heilbronner, R. (2010). Grain size distribution and microstructures of experimentally sheared granitoid gouge at coseismic slip rates – criteria to distinguish seismic and aseismic faults? J. Structural Geology, 32, 59-69, doi:10.1016/j.jsg.2009.08.002

experimental and natural fault rocks

experimentally produced fault rock ⟷ naturally produced fault rock







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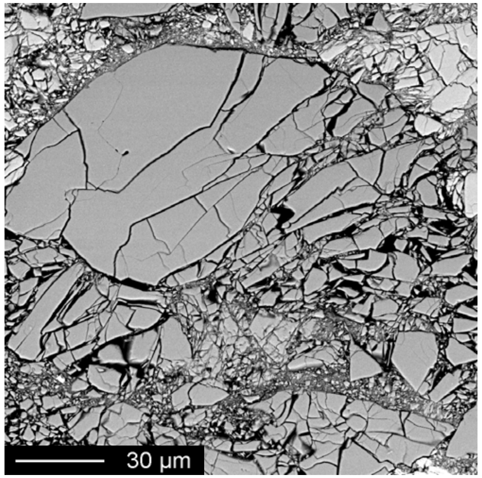
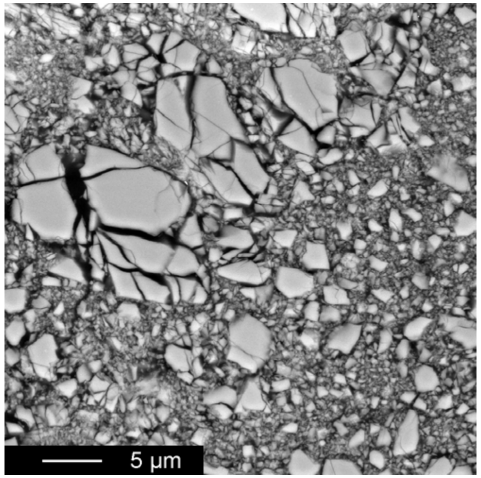
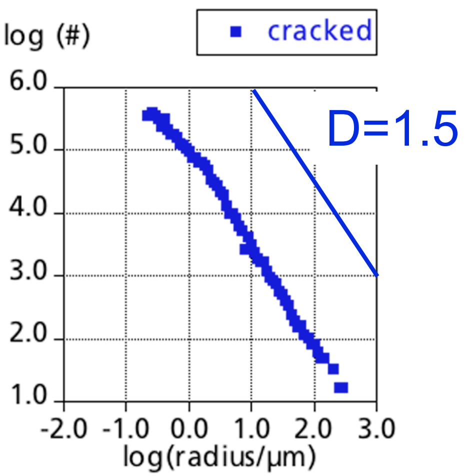
rupture – faulting – healing

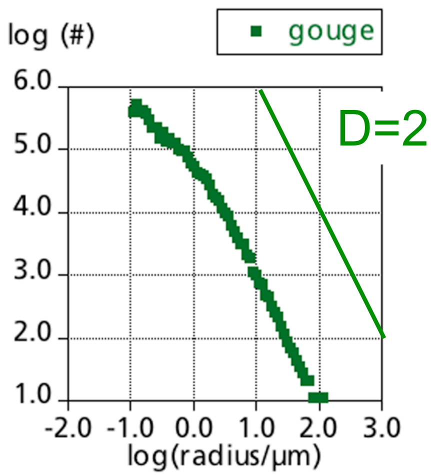
deformation and healing experiments



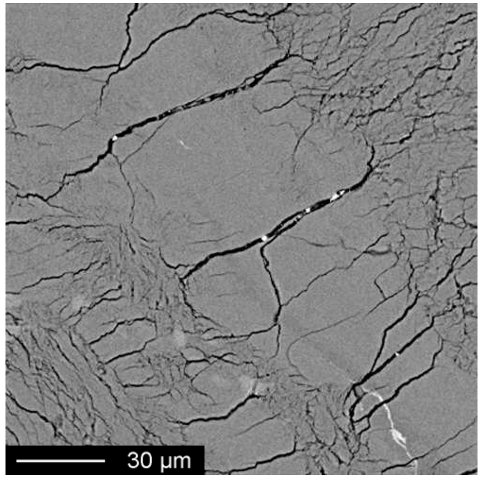


fresh

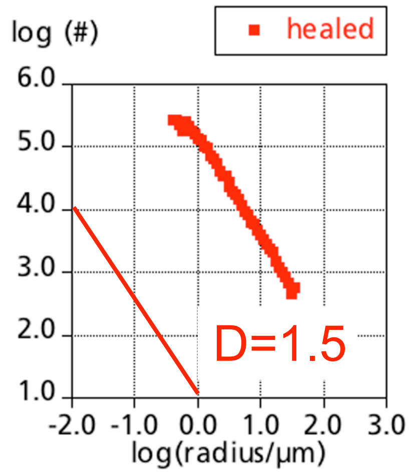




Keulen, N., Stünitz, H., and Heilbronner, R. (2008). Healing microstructures of experimental and natural fault gouge. Journal of Geophysical Research-Solid Earth 113.



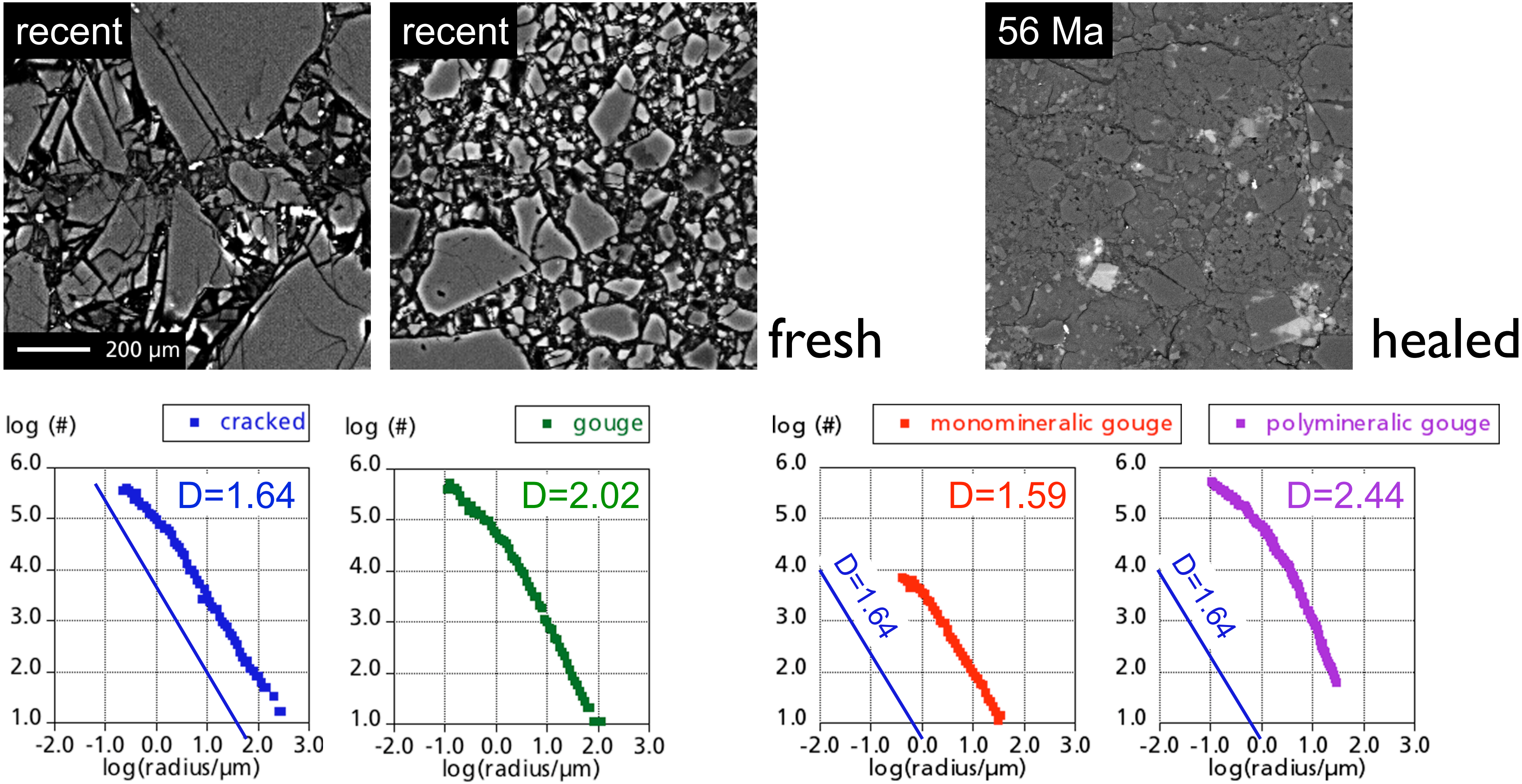
healed



"A hydrostatic healing law for qtz and fs:
$\Delta D(t) = D(t) - D_f = A \cdot e^{(-\lambda t)}$,
⇒ Healing of monomineralic gouge:
in ~1 year at T = 100° - 200°C."

Nojima Fault

natural fault rocks



Keulen, N., Stünitz, H., and Heilbronner, R. (2008). Healing microstructures of experimental and natural fault gouge. Journal of Geophysical Research-Solid Earth 113.

what have we learned ?

The fractal dimension of freshly fragmented rocks seems to be a 'universal': $D_{3d} = 2.58$.

Mature gouge is 'supra-fractal' with a saturation values of $D_{3d} > 3.00$, indicating the contribution of non-fractal processes (spalling, abrasion), and is independent of the amount of displacement.

Healing of monomineralic fault rocks (gouge) yields $D_{3d} = 2.58$; healing is very fast (on the order of years); for polymineralic rocks D_{3d} remains >3.

in summary ...

we have considered ...

1. what φ-values mean in the physical (linear) world
2. the usefulness of a flatbed scanner
3. the fast and easy intercept method
4. if d_{mean} from 2D simulations can be extrapolated to 3D
5. how to convert d_{mean} from 2D sections to D_{mean} in 3D
6. how to derive fractal dimensions from particle analyzers
7. that fractal grain size distributions have no mean

… and we found that …

for any given distribution of grains …

the arithmetic mean of $h(d_{equ})$
$\neq$ mean of $h(D_{equ})$
$\neq$ mode of vol%(D_{equ})
$\neq$ $M\varphi$
$\neq$ mean of vol%($\log(D_{equ})$)
$\neq$ … etc.

see *data from:*
image analysis
scanner
stripstar
sieving
particle analyzer

$\Longrightarrow$ ask yourself:
which "grain size" you need to know

grain size – 3D, 2D ... and fractal

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Martin-Luther-Universität
Halle,   23. Januar 2023