Anisotropic spatial clustering and ordering of olivine and orthopyroxene during rheological weakening conditions

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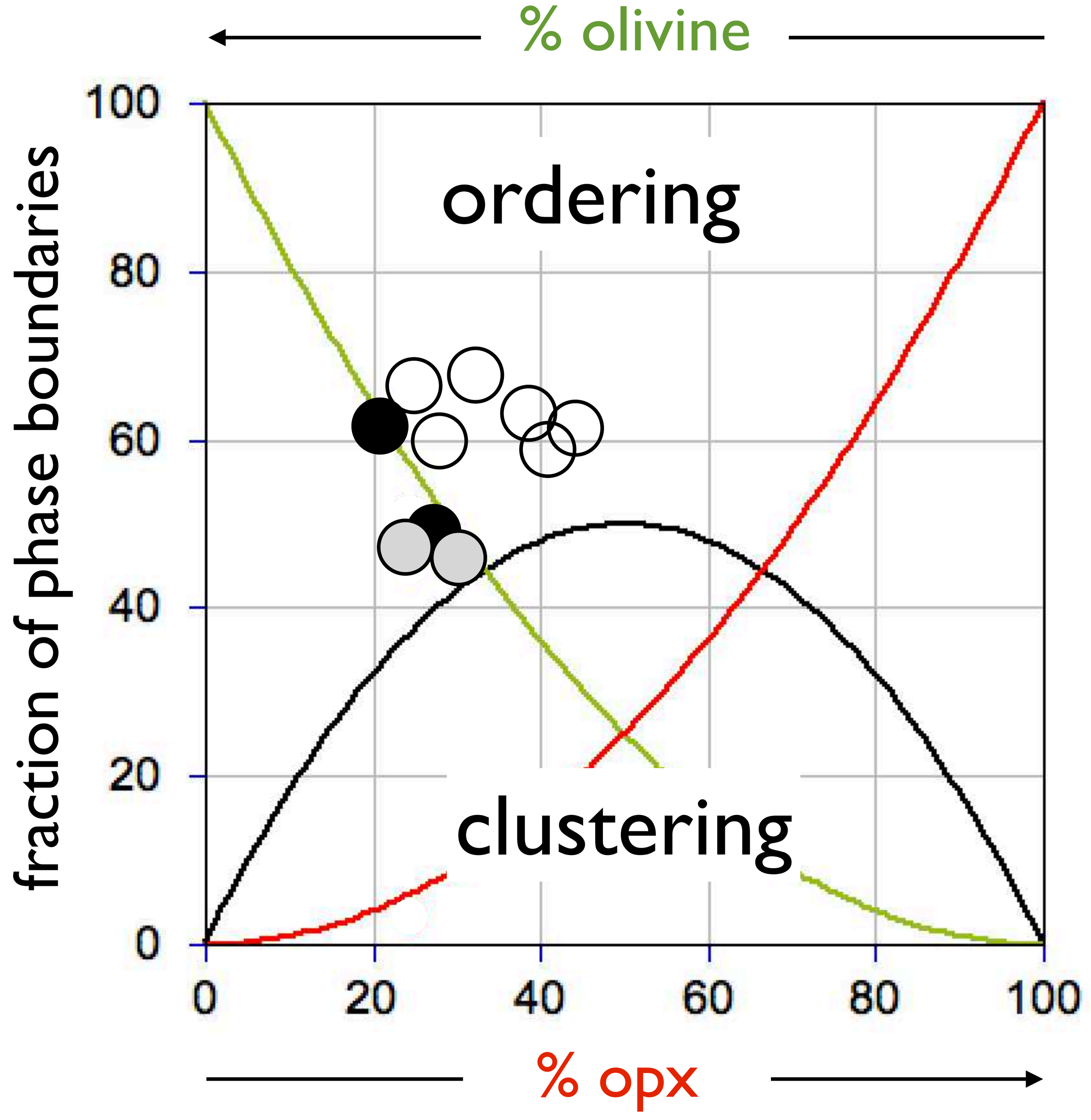


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Rheological weakening of olivine + orthopyroxene aggregates due to phase mixing, Part2: Microstructural development
Miki Tasaka, Mark E. Zimmerman, David L. Kohlstedt, Holger Stünitz, Renée Heilbronner
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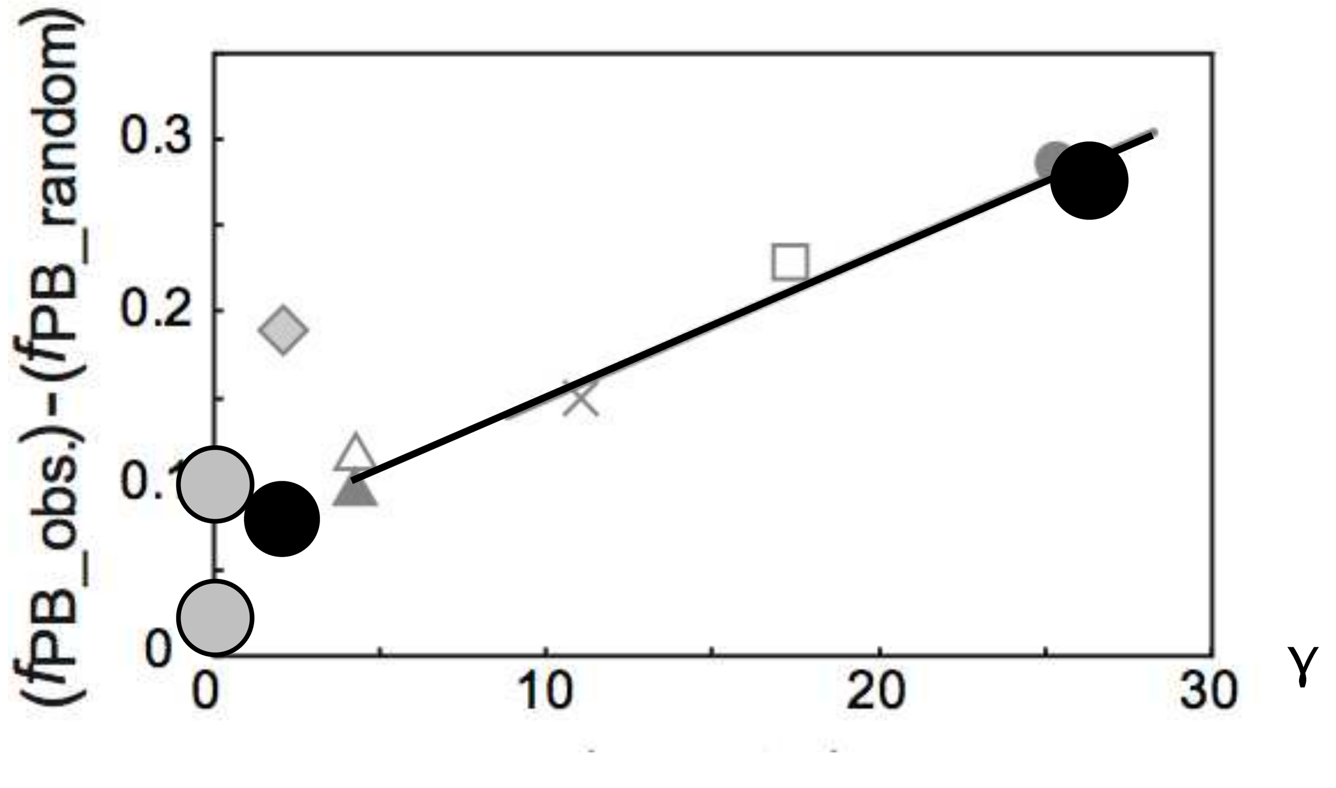


So, what else is there to do ?

1. use surface % instead of volume %
2. observe oxp-oxp and ol-ol contacts in addition to phase
3. consider influence of grain size
4. observe directional variations of clustering & ordering

to overview >>

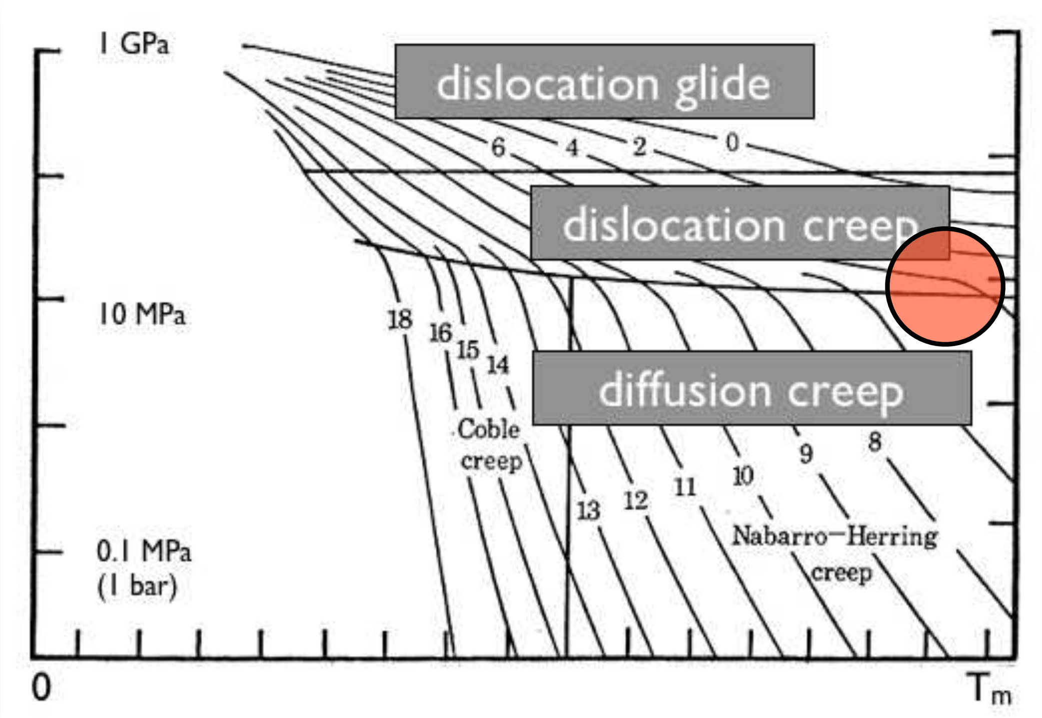
the experiments

the lab

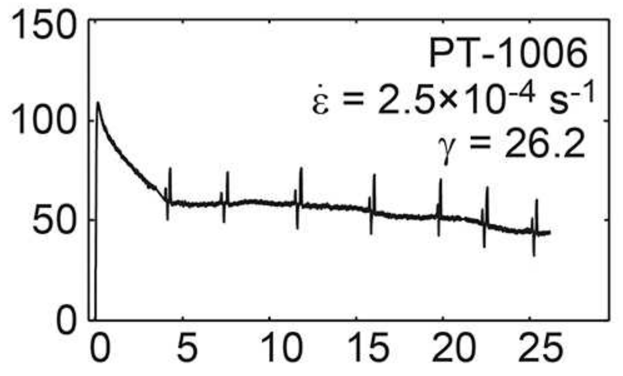
Gas medium High pressure Torsion apparatus (UMN)



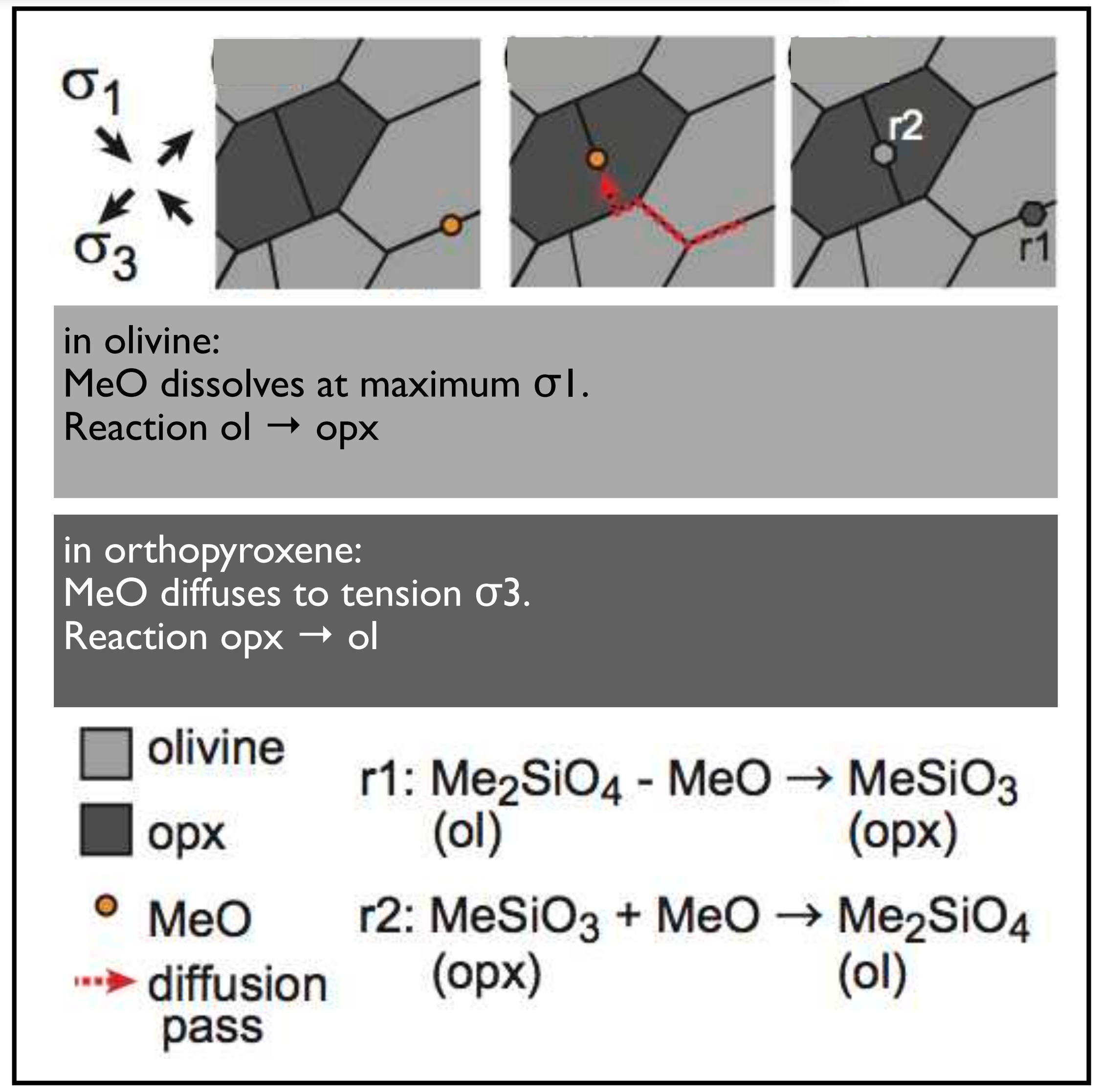
Miki Tasaka *Mark Zimmerman* *David Kohlstedt*



70% iron-rich olivine
30% orthopyroxene
hotpressed @1200°C
d ~15 µm

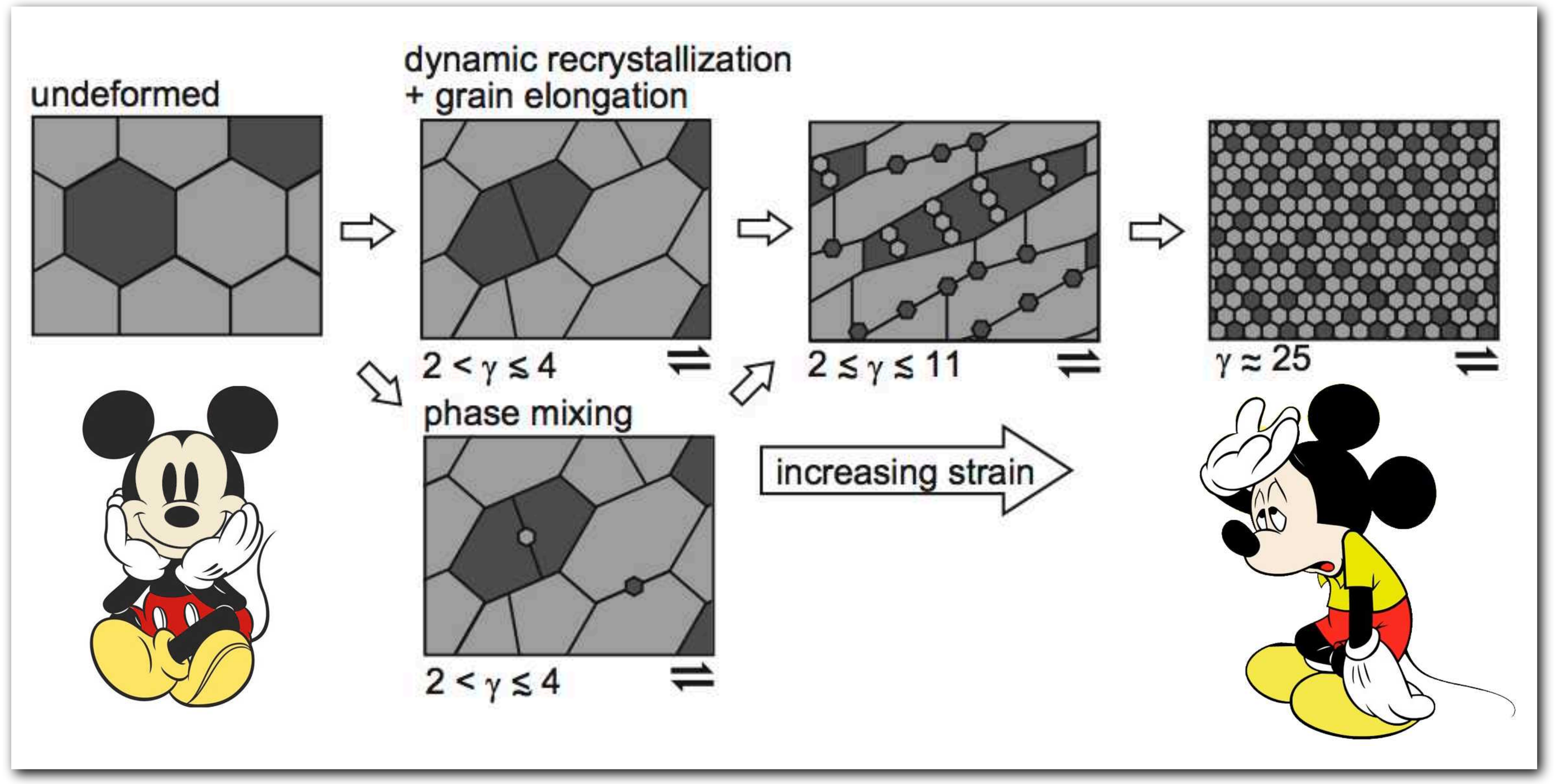


p_c = 300 MPa
T = 1200°C

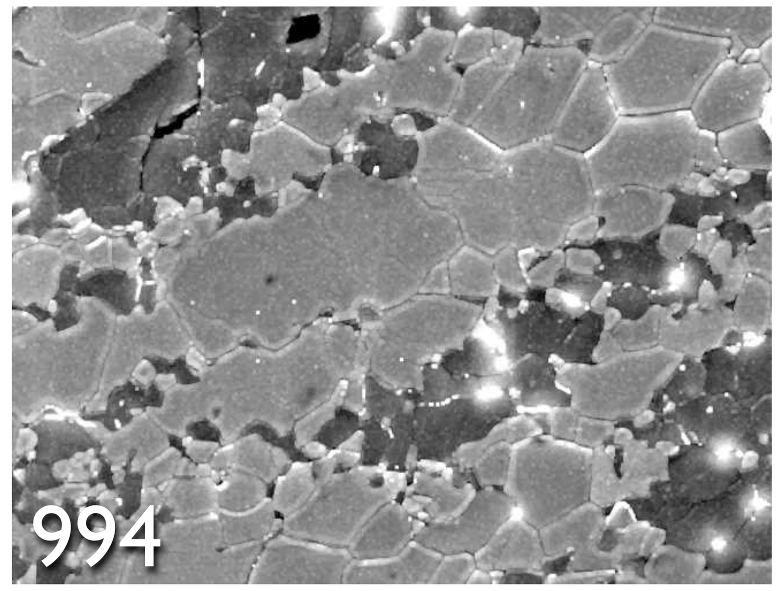


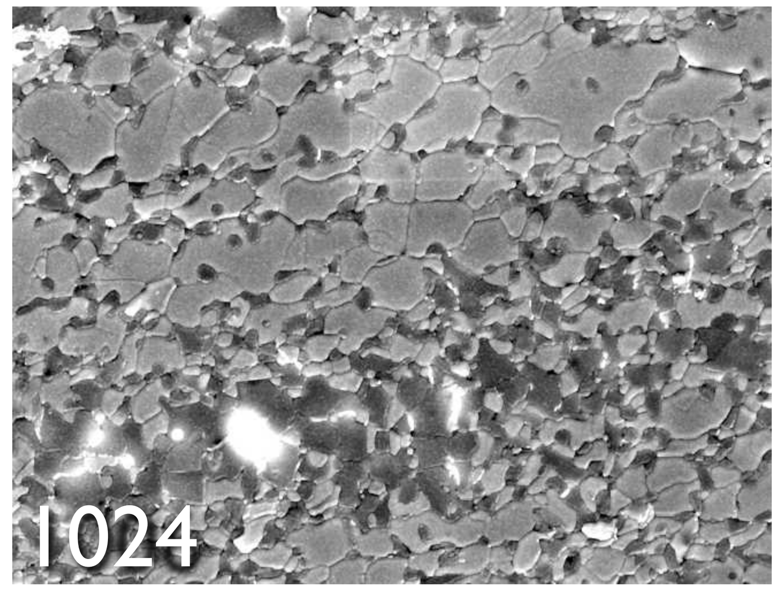
the motivation

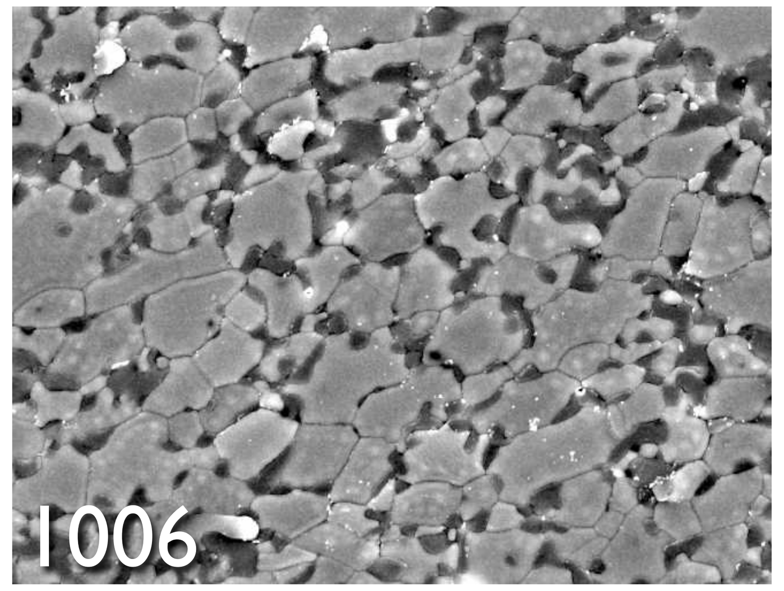
$\dot{\varepsilon} = A \cdot \Delta\sigma^n \cdot exp(-Q/RT)$ → increasing strain → $\dot{\varepsilon} = A \cdot \Delta\sigma^n \cdot d^m \cdot exp(-Q/RT)$



dislocation creep ? phase mixing ? diffusion creep ?







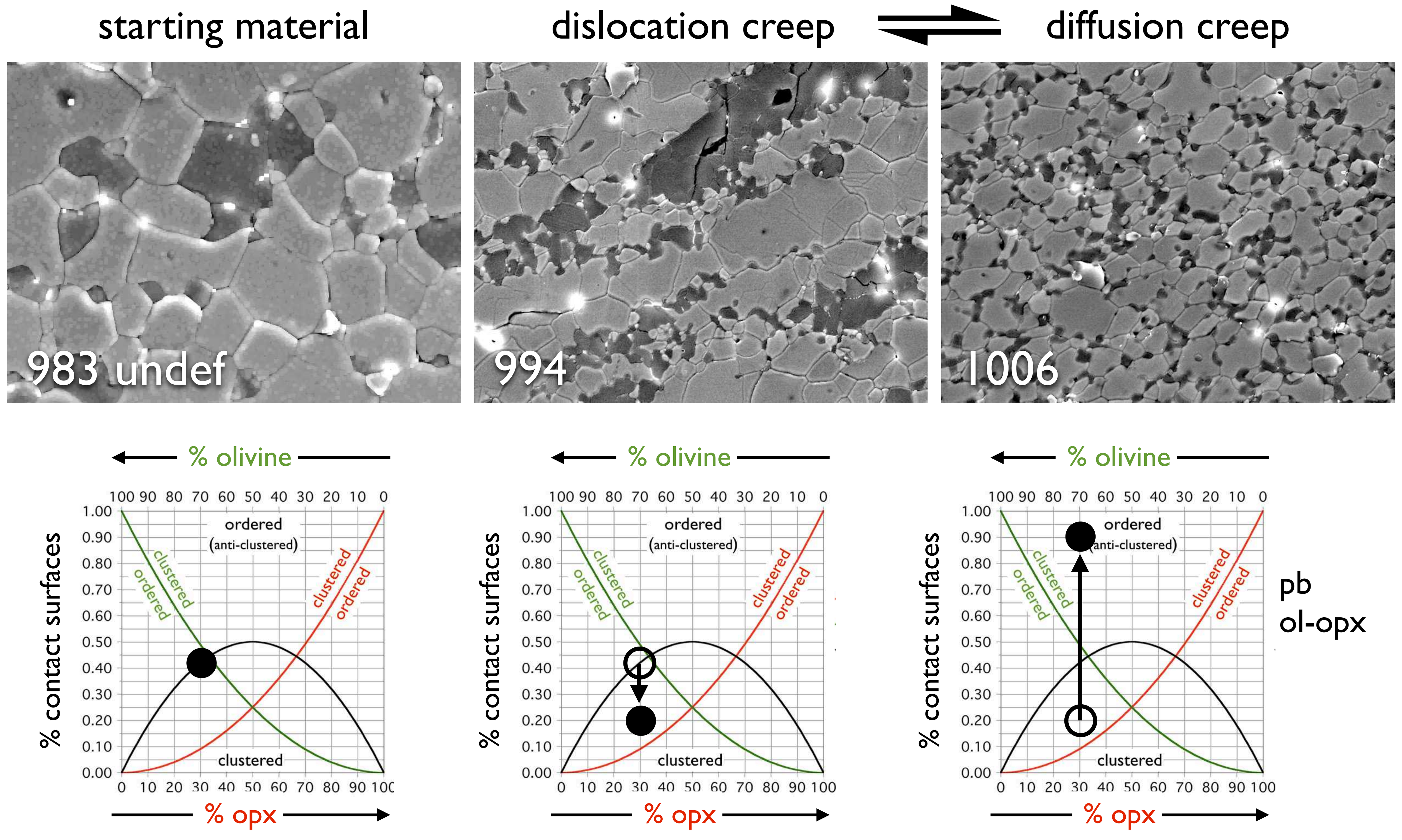
10 µm

the paper

Check: Tasaka, M., Zimmerman, M. E., Kohlstedt, D. L., Stünitz, H., & Heilbronner, R. (2017). Rheological weakening of olivine + orthopyroxene aggregates due to phase mixing: Part 2. Microstructural development. Journal Geophysical Research: Solid Earth, 122, 7597–7612. https://doi.org/10.1002/ 2017JB014311

<< to overview >>

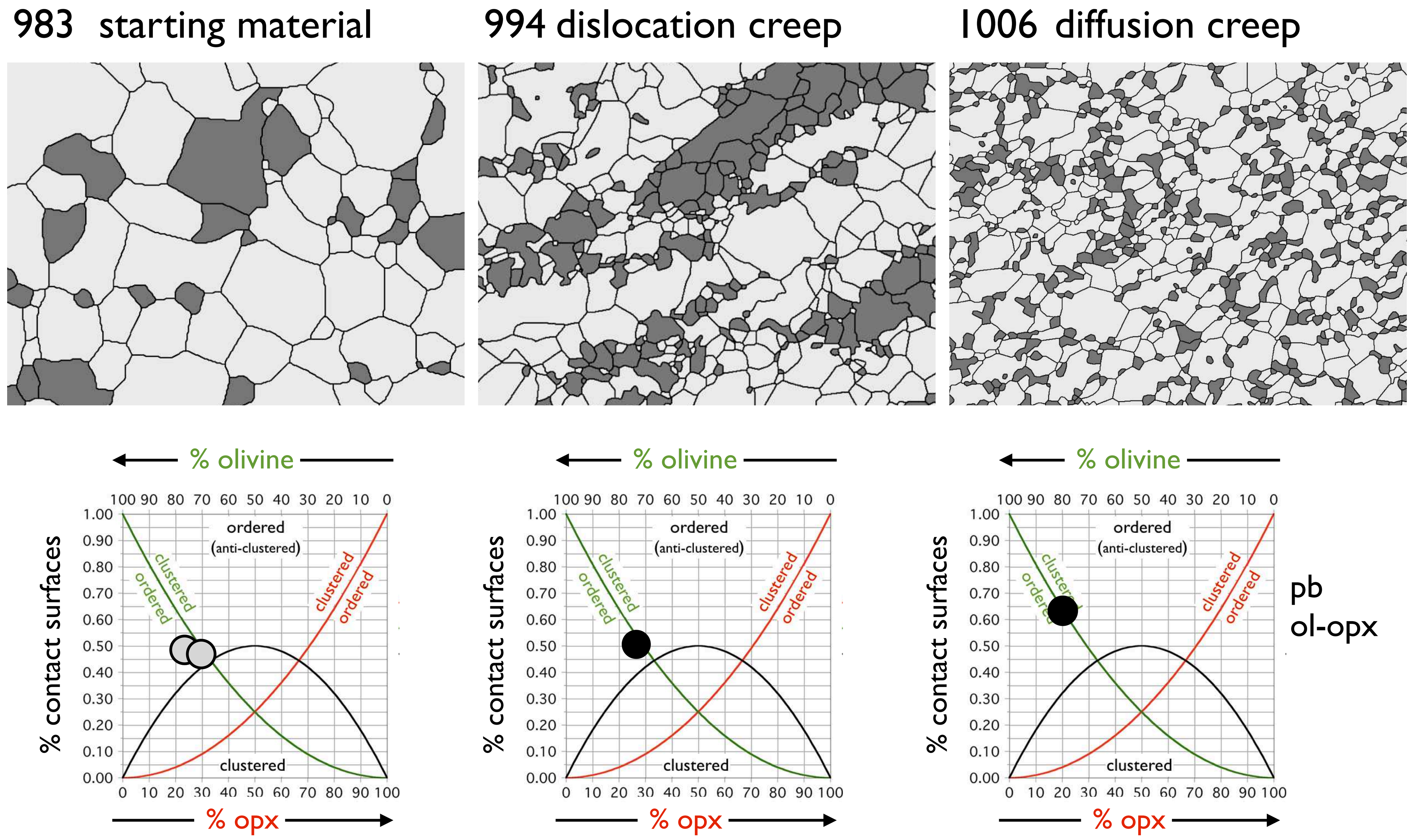
what we expected ... and what we got



'great expectations'

with respect to spatial distribution

1. mixing creates random starting material
2. recrystallization creates clusterring during dislocation creep
3. heterogeneous nucleation creates ordering during diffusion creep



... but, instead ...

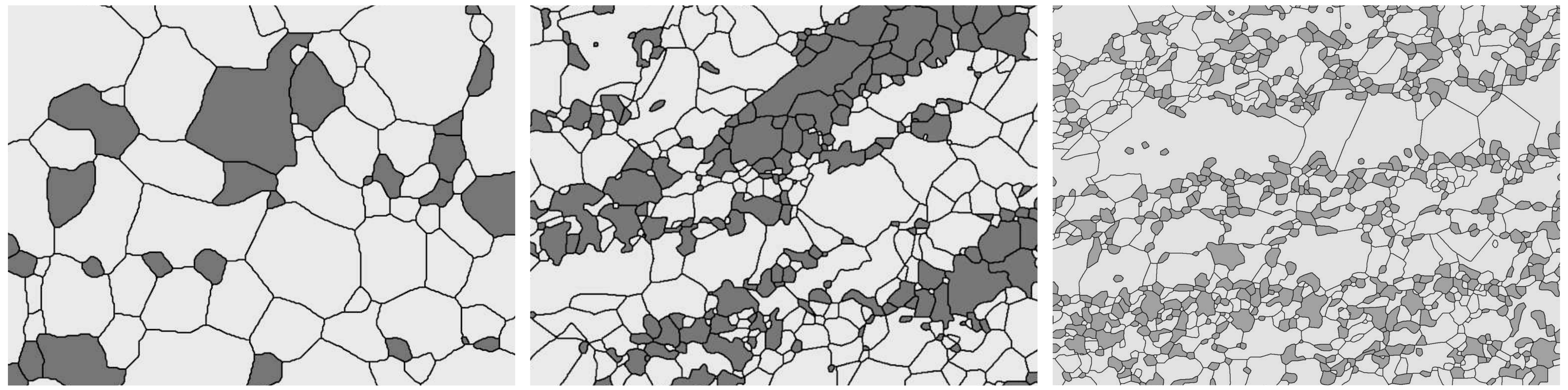
with respect to spatial distribution

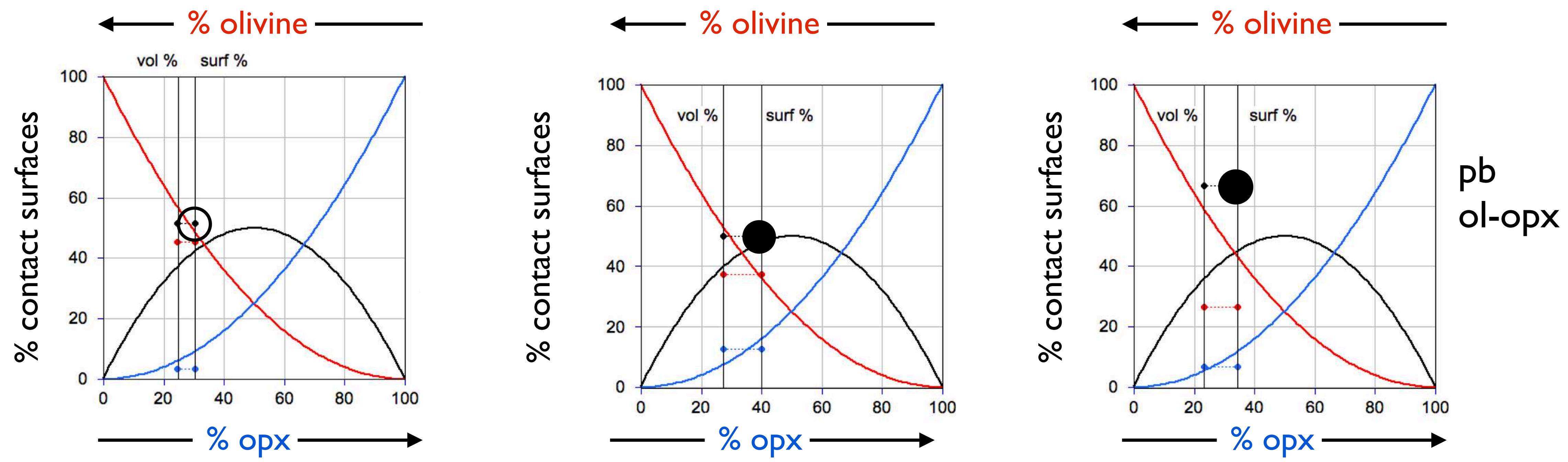
1. starting material is ordered
2. ordering increases already during dislocation creep
3. continuously increasing ordering during diffusion creep

<< to overview >>

1. using surface fractions

983 starting material | 994 dislocation creep | 1024 diffusion creep





plotted against surface fraction !

what is the effect ?

with respect to spatial distribution

1. starting material is still ordered
2. during dislocation creep ordering is reduced, more clustered
3. during diffusion creep strong ordering is achieved

reasoning behind it

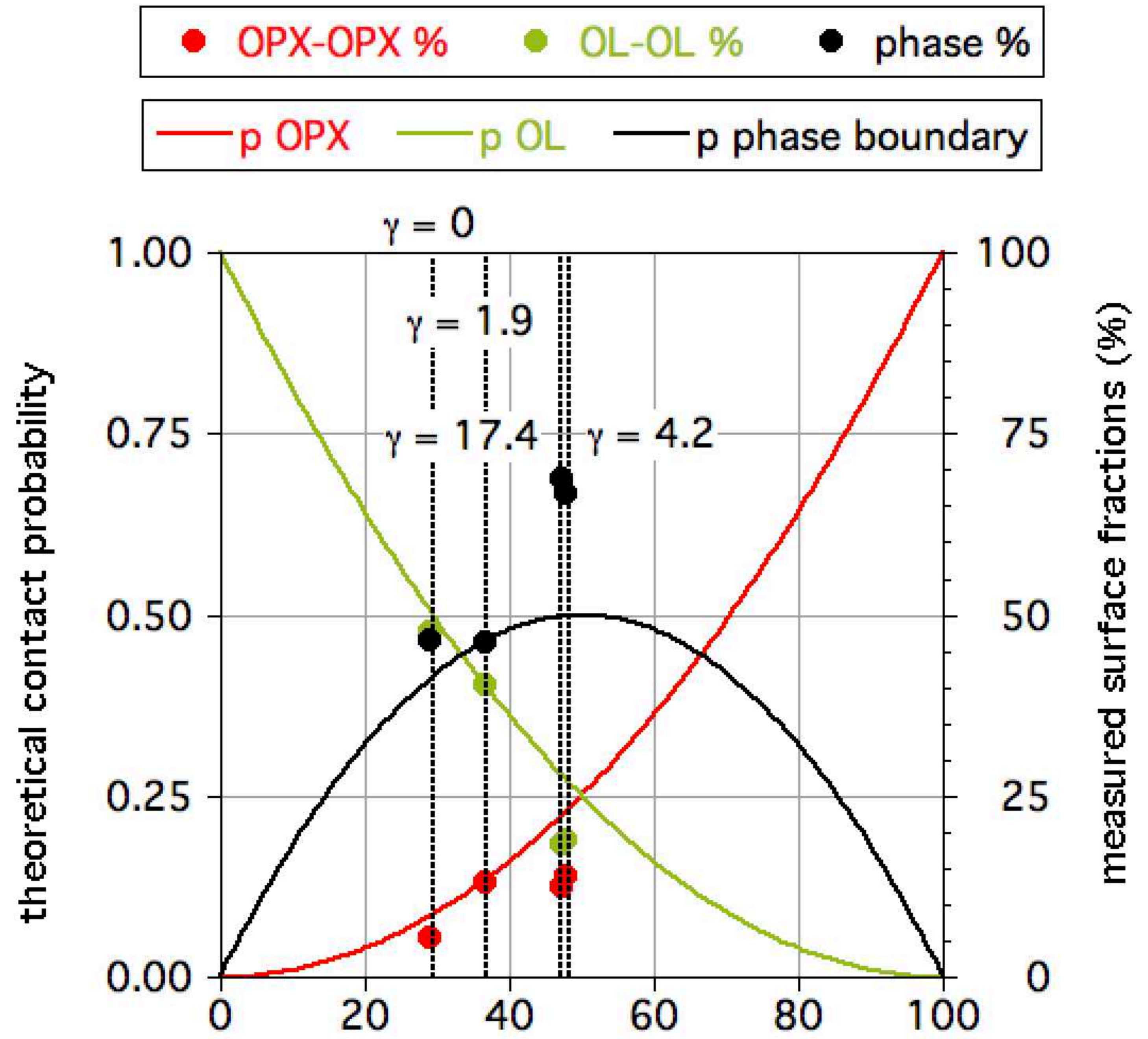
if grain size of both phases is the same, i.e.,
if gs A = gs B (and same shape):
⇒ volume proportions and surface proportions are the same
⇒ vol% A = surf% A and vol% B = surf% B
BUT
if the grain size is different, for example
if gs A < gs B (but both the same shape*)):
then, for a given volume proportion of A,
⇒ surface proportions of A is larger than the surface proportion of B
⇒ if vol% A = vol% B, surf%A > surf% B

*) same / similar elongation
same / similar PARIS factor, etc.

grain size and shape are important

<< to overview >>

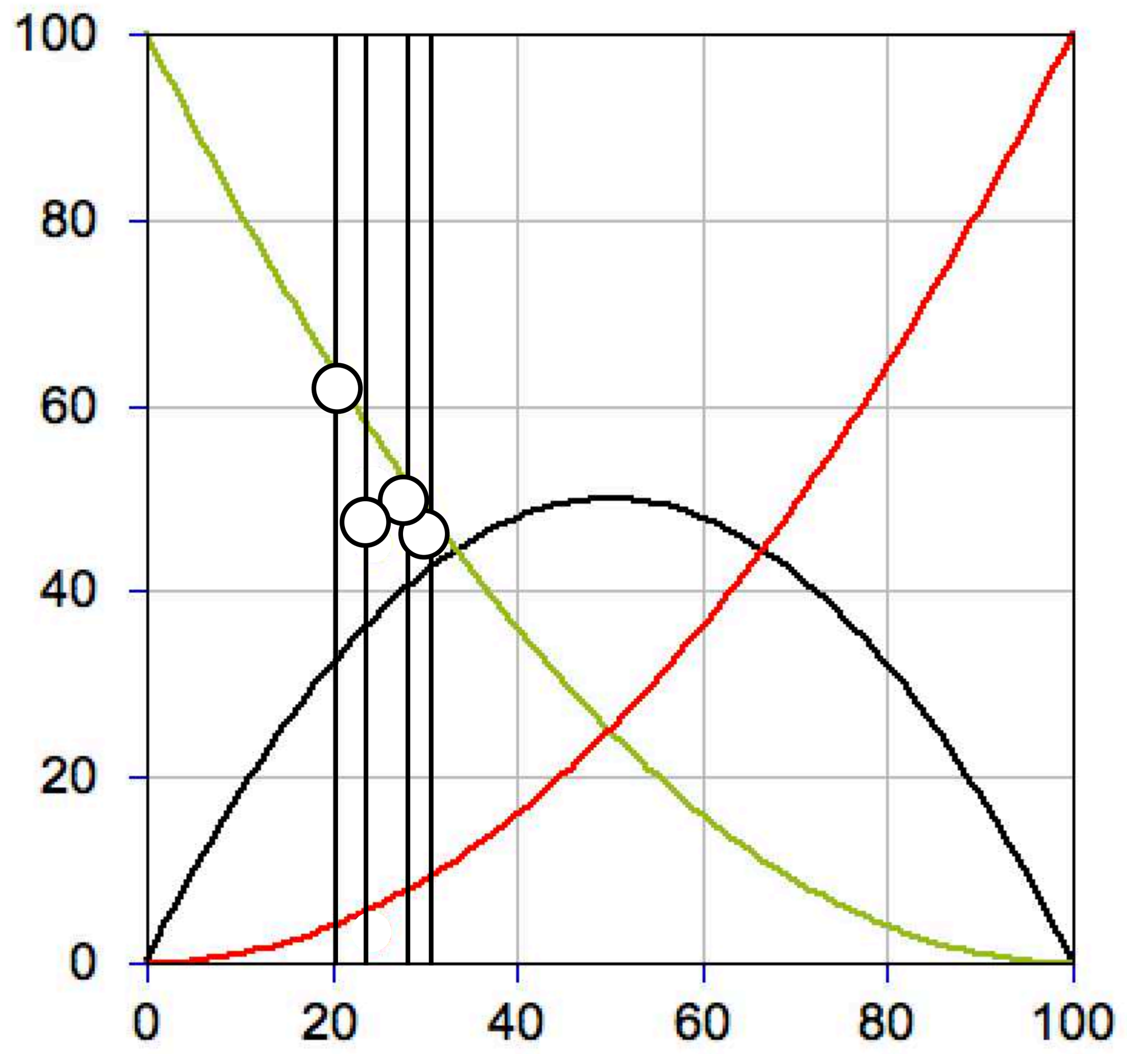
2. additional observations of opx-opx and ol-ol contacts



surface fraction opx

comparison

phase data from JGR
same samples as above



volume fraction opx

Tasaka, et al.Journal JGR
doi.org/10.1002/ 2017JB014311

information we had from phase contacts

1. $phase_{observed}$ > $phase_{expected}$ ⇒ excess phase boundaries
   ⇒ starting material is still ordered
2. $phase_{observed}$ ≈ $phase_{expected}$ ⇒ random spatial distribution
   ⇒ during dislocation creep ordering is reduced, more clustering
3. $phase_{observed}$ >> $phase_{expected}$ ⇒ excess phase boundaries
   ⇒ during diffusion creep strong ordering is achieved

additional information from opx-opx
additional information from opx-opx

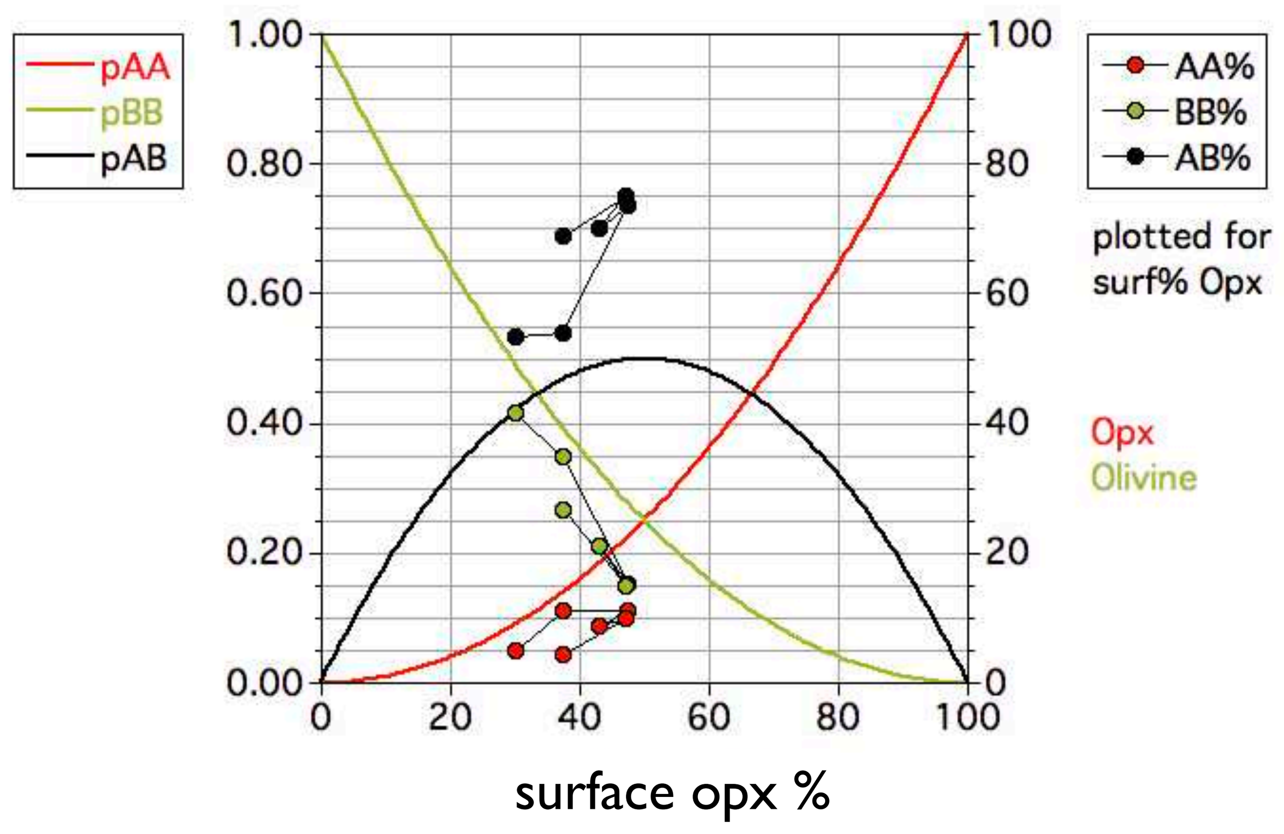
1. OPX_{obs} < OPX_{exp} and OL_{obs} < OL_{exp} ⇒ too few grain boundaries
   ⇒ starting material is still ordered
2. OPX_{obs} ≈ OPX_{exp} and OL_{obs} ≈ OL_{exp} ⇒ random
   ⇒ during dislocation creep ordering is reduced, more clustering
3. OPX_{obs} << OPX_{exp} and OL_{obs} << OL_{exp} ⇒ too few grain boundaries
   ⇒ during diffusion creep strong ordering is achieved

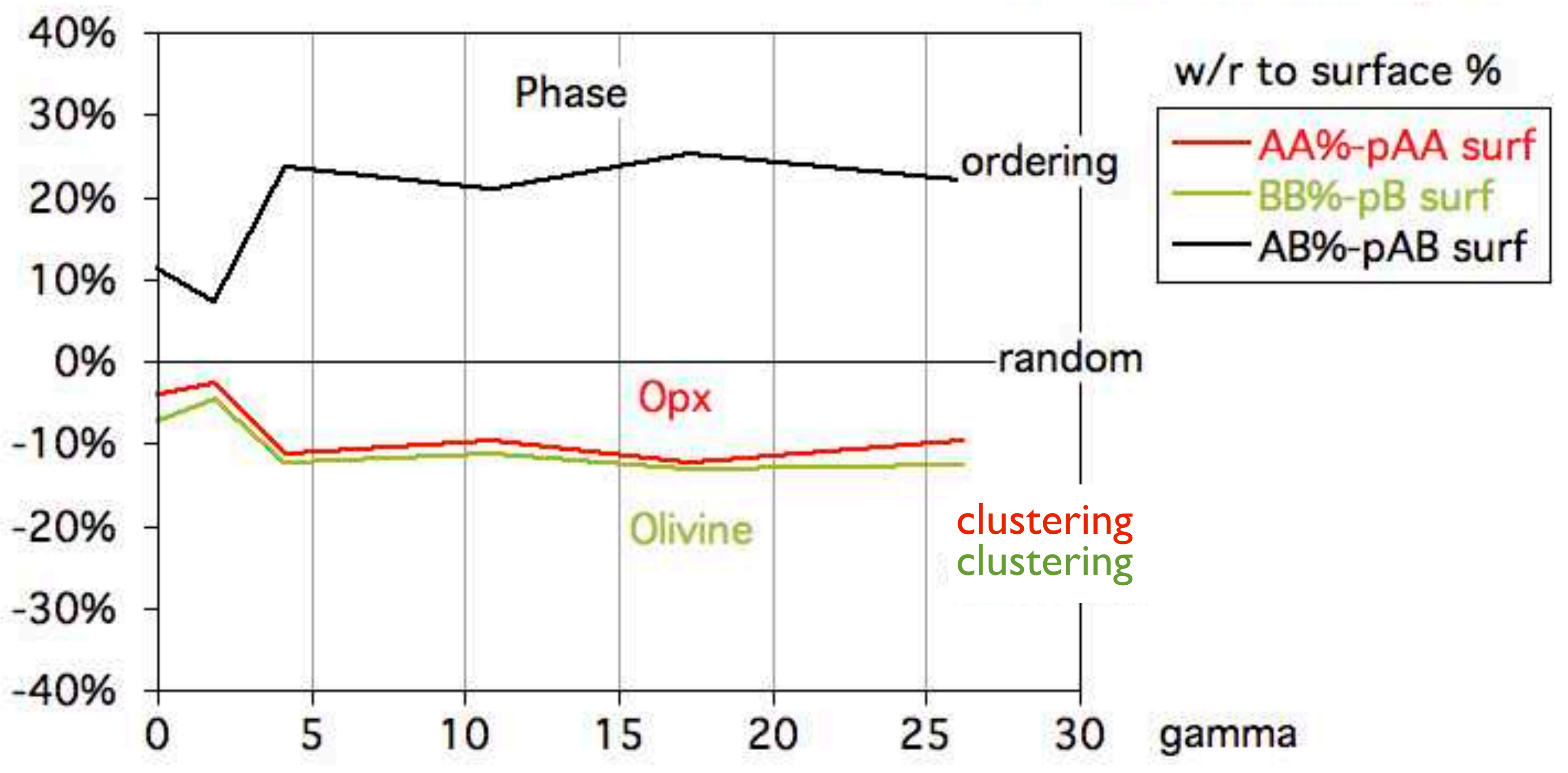
results of opx-opx and ol-ol are consistent

:-)

complete range of shear strains

undef 983-2 | γ = 1.9 994-16 | γ = 4.2 984-2 | γ = 10.9 1024-2 | γ = 17.3 990-14 | γ = 26.2 1006-6





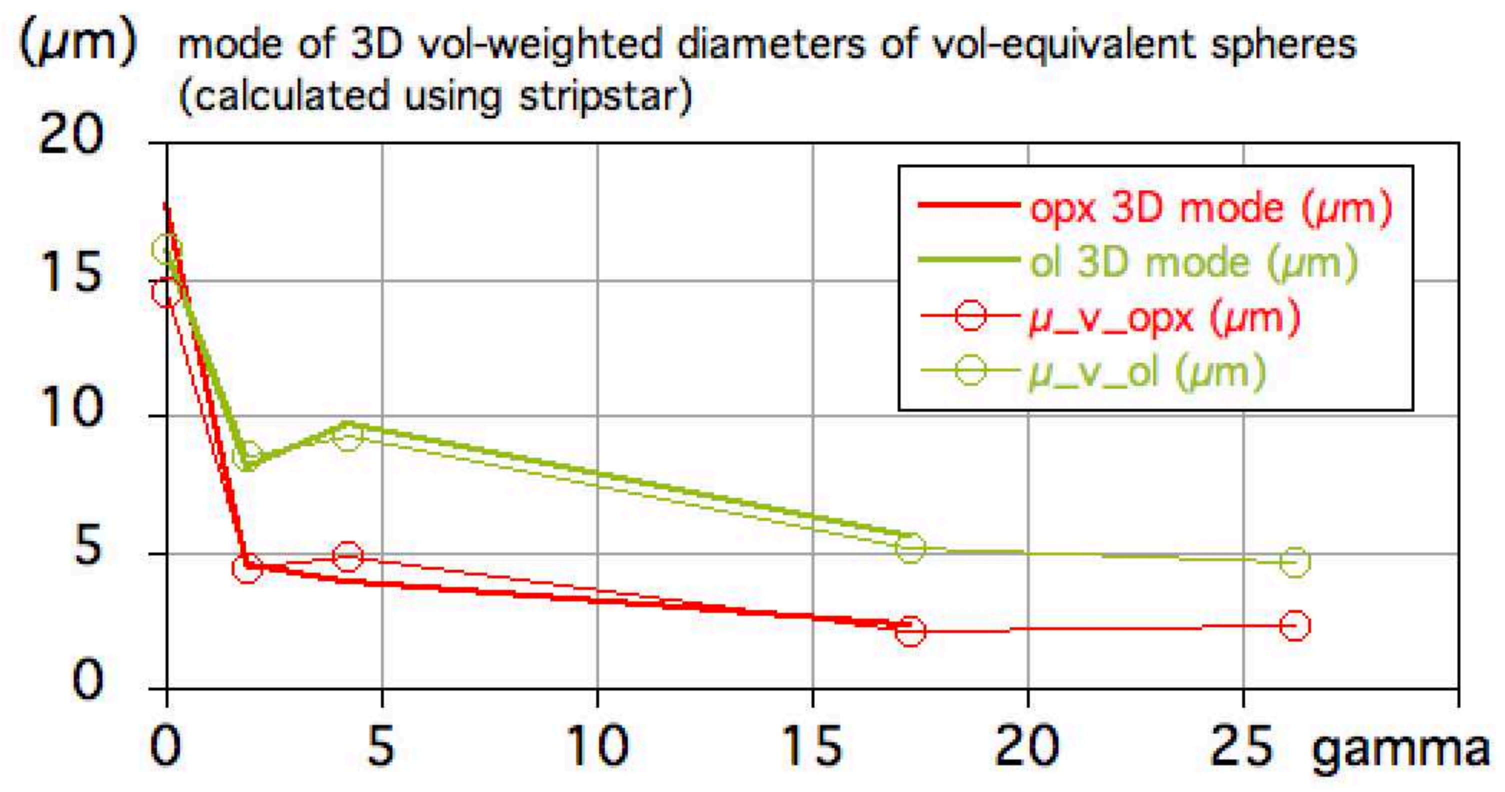
filename	γ	sample	scale
0.0 983-2 84px=10µm	0.0	983-2	84px=10µm
1.9 994-16 200px=10µm	1.9	994-16	200px=10µm
4.2 984-2 177px=10µm	4.2	984-2	177px=10µm
10.9 1024-2	10.9	1024-2	299px=10µm
17.3 990-14	17.3	990-14	300px=10µm
26.2 1006-6	26.2	1006-6	299px=10µm

results for 6 experiments
lines connect
for increasing shear strain
AA = orthopyroxene
BB = olivine

deviation from random
for increasing shear strain
+(%) for phase boundary = ordering
-(%) for grain boundary contacts = ordering
AA = orthopyroxene BB = olivine

<< to overview >>

3. consider grain size



grain size evolution with shear strain

orthopyroxene

at start grain size $D_{equ} \approx$ 14 µm
at $\gamma \leq 4$ decreases to 4-5 µm
at $\gamma \geq 17$ levels off to ~ 2 µm

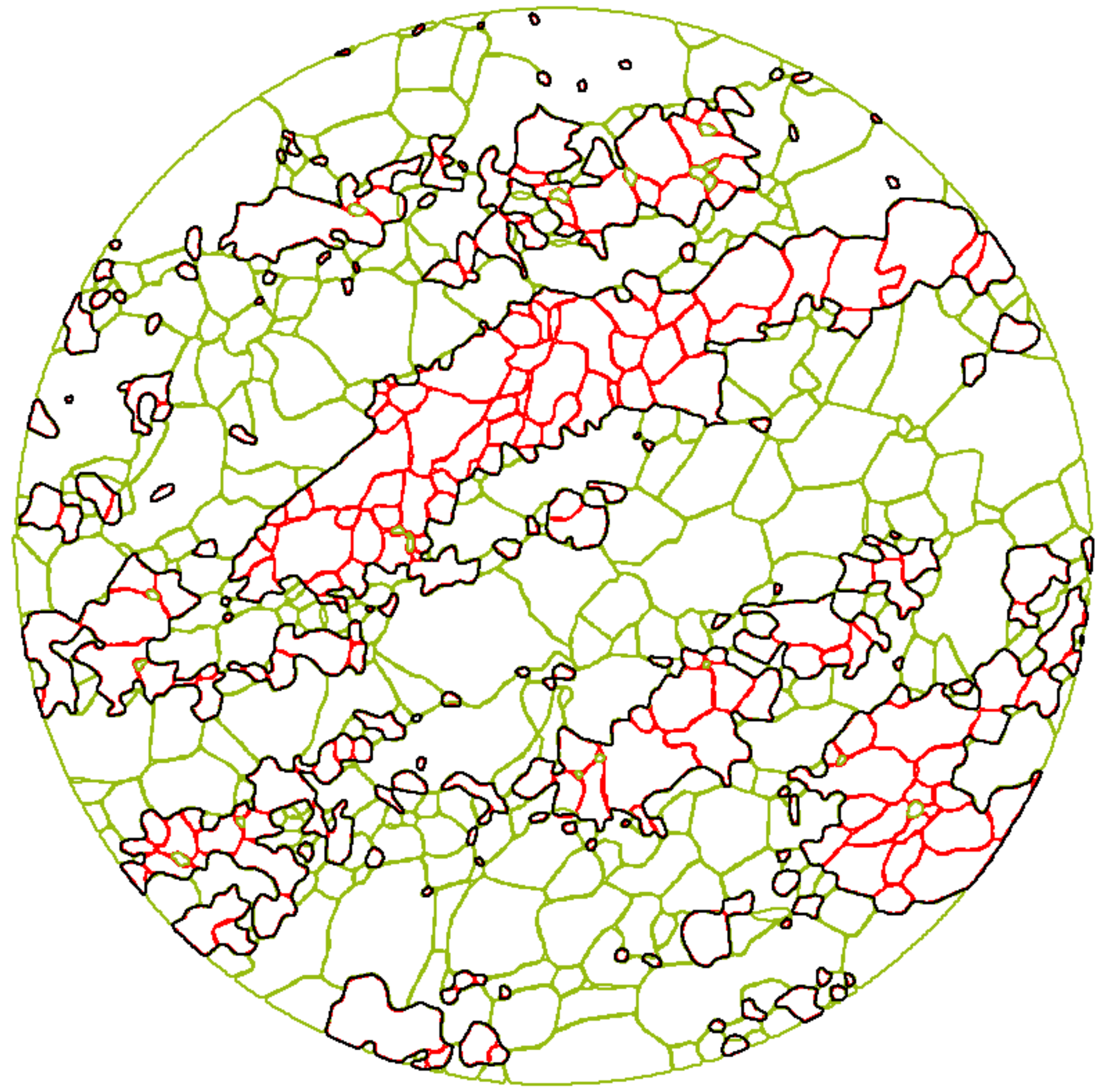
olivine

at start grain size $D_{equ} \approx$ 16 µm
at $\gamma \leq 4$ decreases to 8-9 µm
at $\gamma \geq 17$ levels of to ~ 5 µm

<< to overview >>

4. directional variations of clustering & ordering

what to measure ?

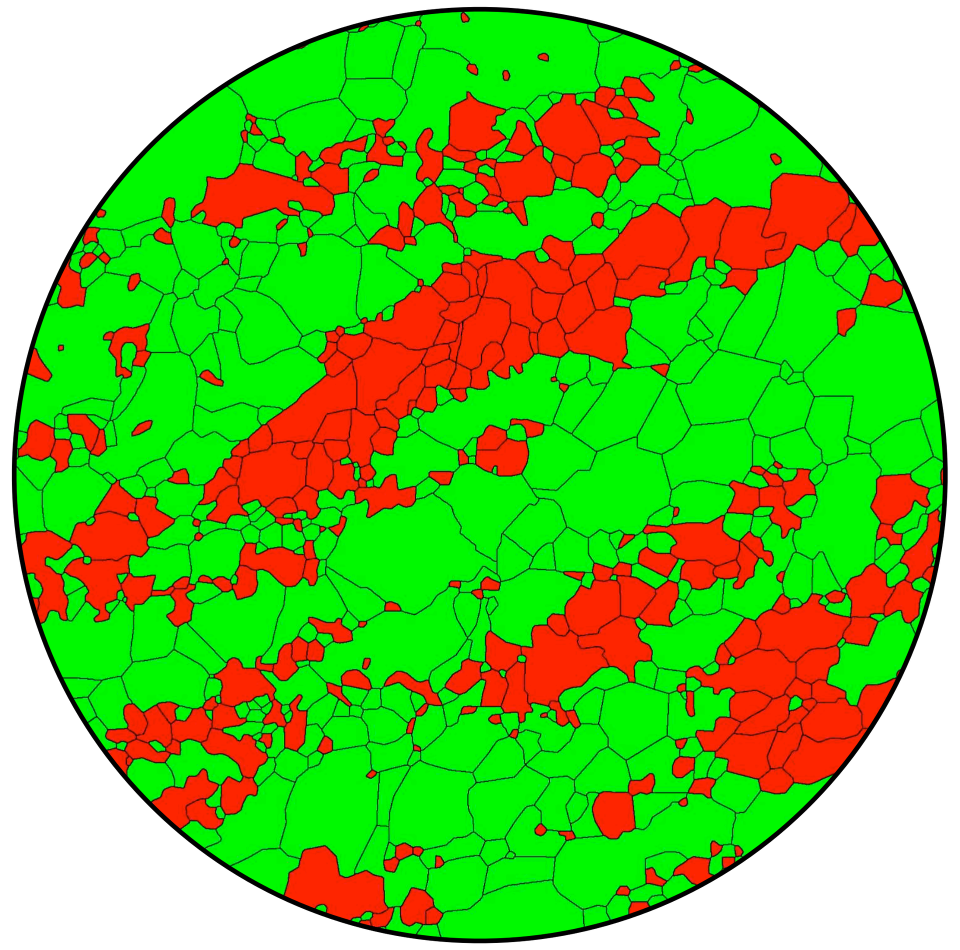


opx-opx contact surfaces (gb s.s.)
ol-ol contact surfaces (gb s.s.)
opx-ol contacts (phase boundaries)

idea behind it:

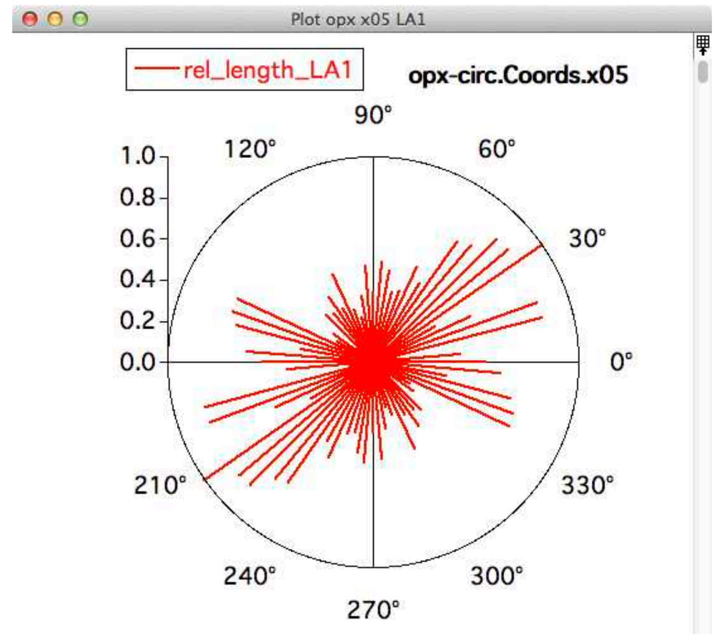
total length of projection of phase is proportional to contact frequency (contact frequency = probability of being transsected by test line in given direction)

pro memoria:

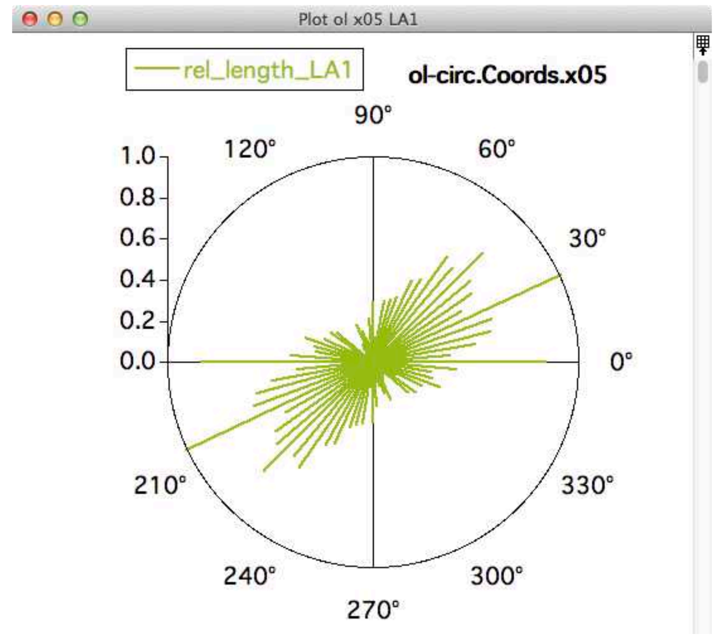


paror:

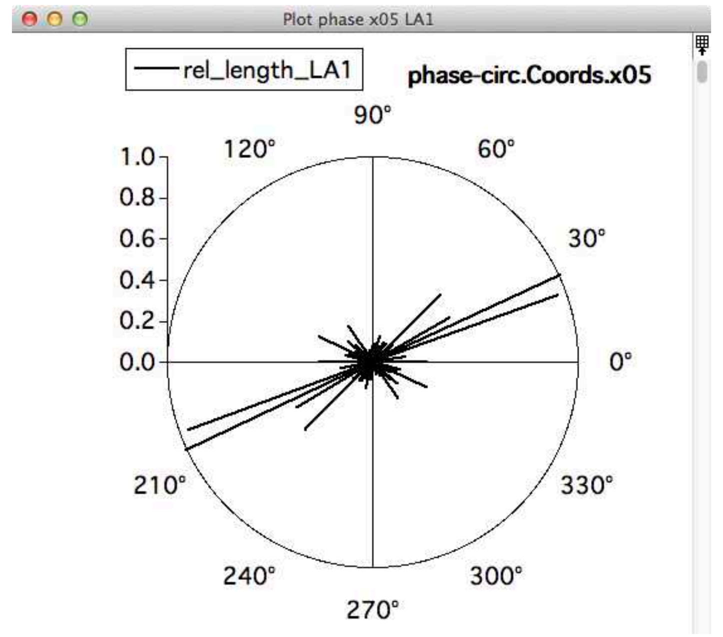
orietation of particle long axes of grains and aggregates



opx



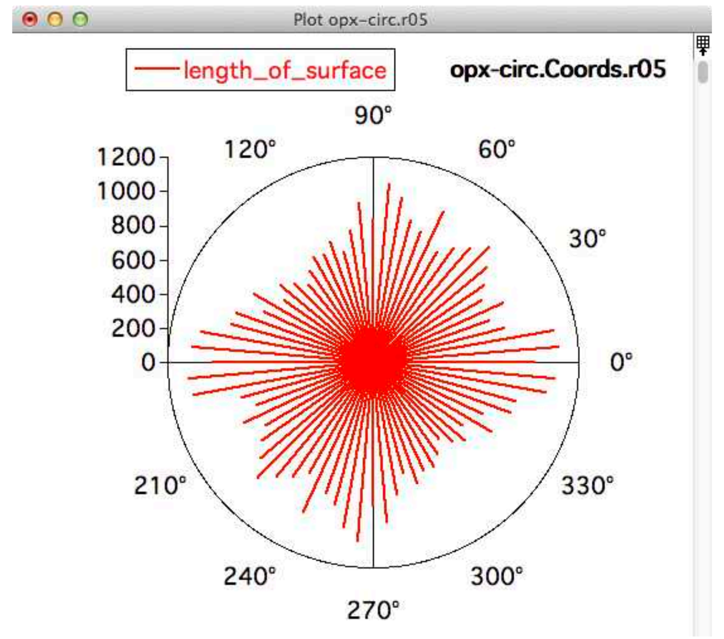
ol



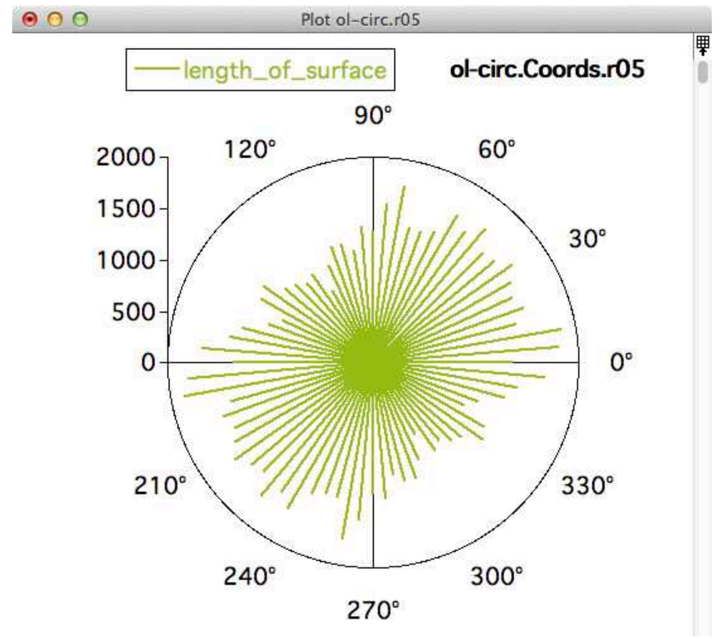
aggregates

surfor:

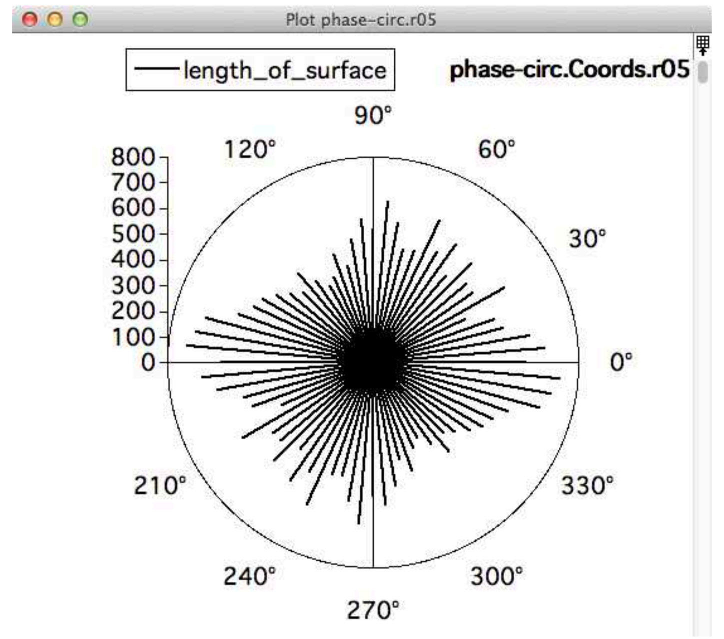
orietation of surface of grains and aggregates



opx



ol



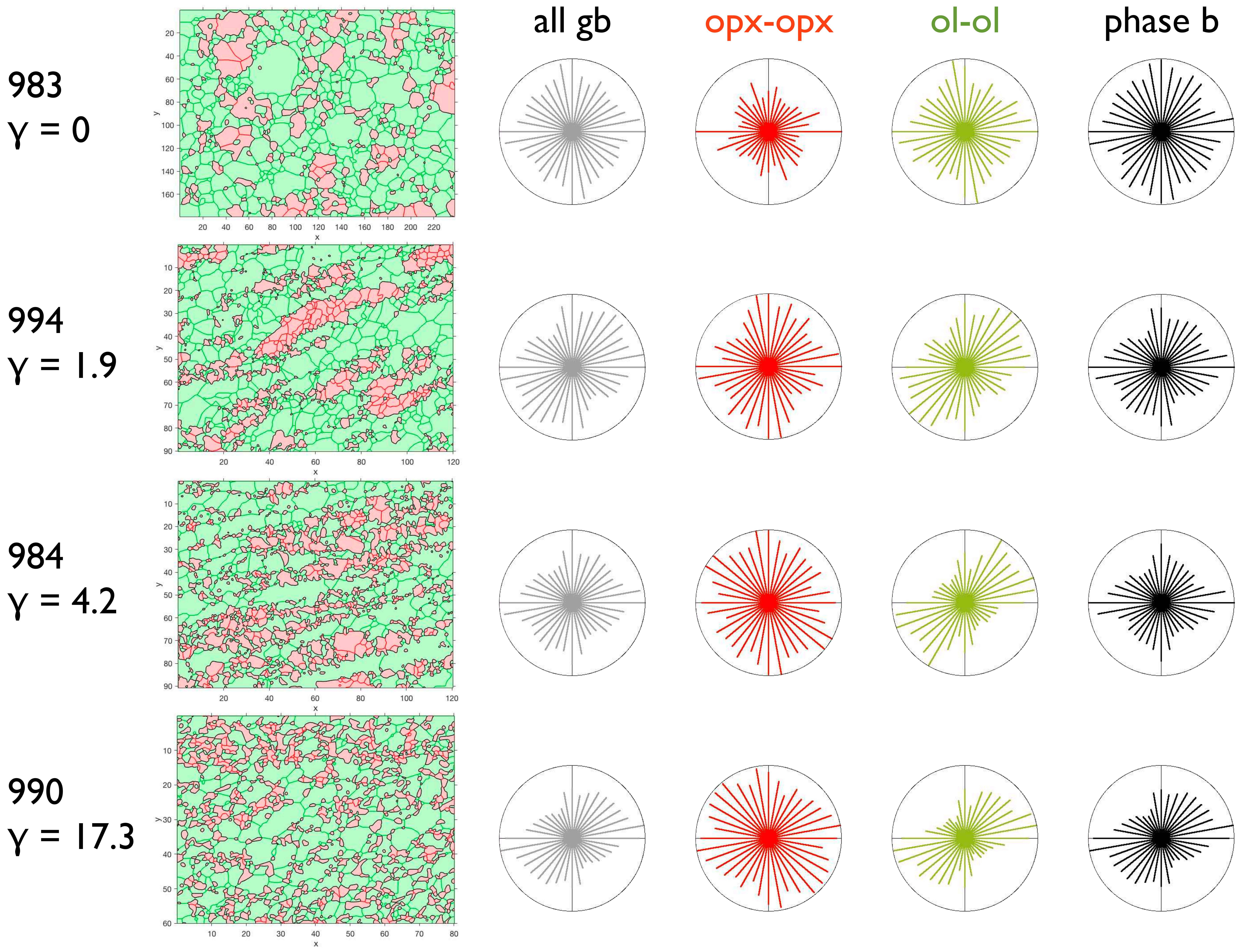
surface of aggregates
= phase boundary

now need surfor

... of contact surfaces ... (next slide)

<< to overview >>

surface orientation of grain contacts = input for surfor



ODFs of relative boundary length of

all grain boundaries (gb s.l.)
opx-opx contact surfaces (gb s.s.)
ol-ol contact surfaces (gb s.s.)
opx-ol contacts (phase boundaries)

gb s.l. = phase b + opx-opx + ol-ol

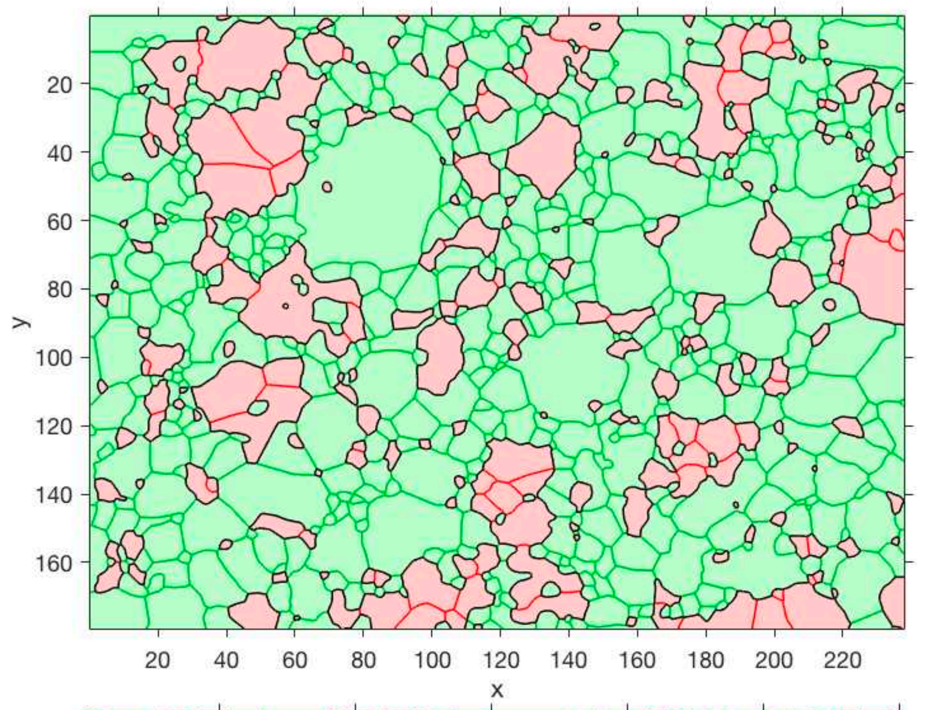
Digitization of contact segment is achieved using mtex / matlab and a code developed by Rüdiger Kilian.

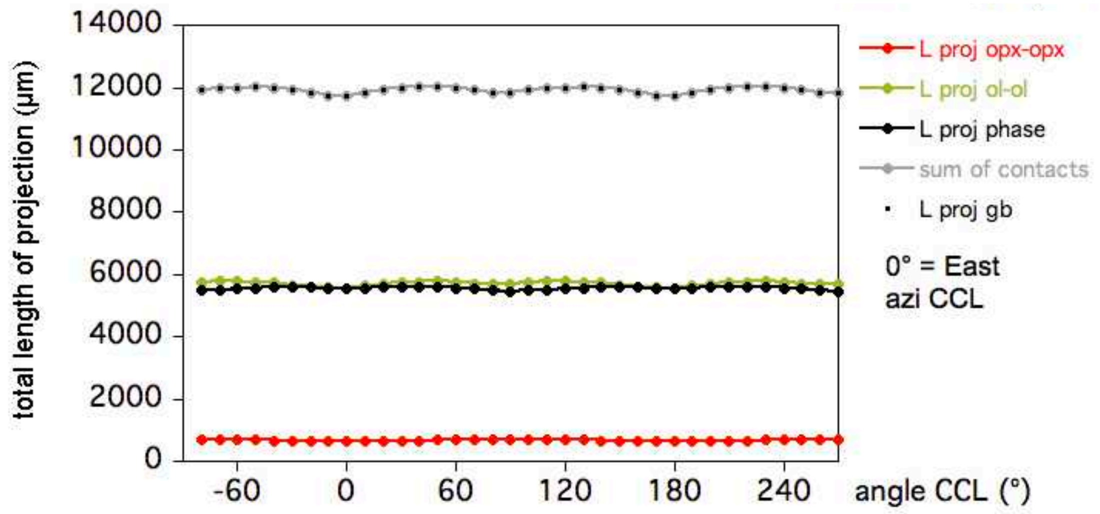
length of projection of contacts (surfor) = contact frequency

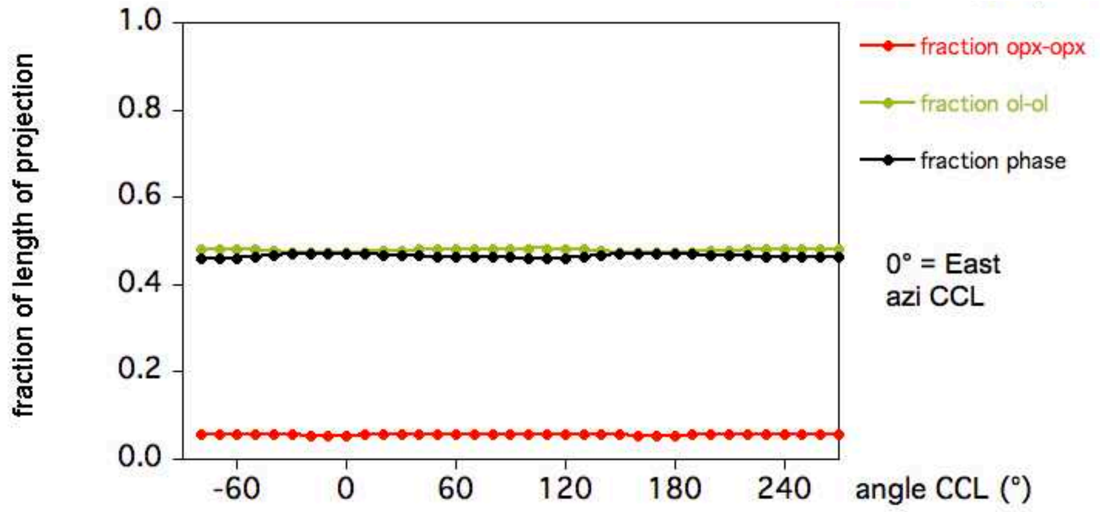
total L_{proj} (α)

rel. L_{proj} (α)

983
γ = 0

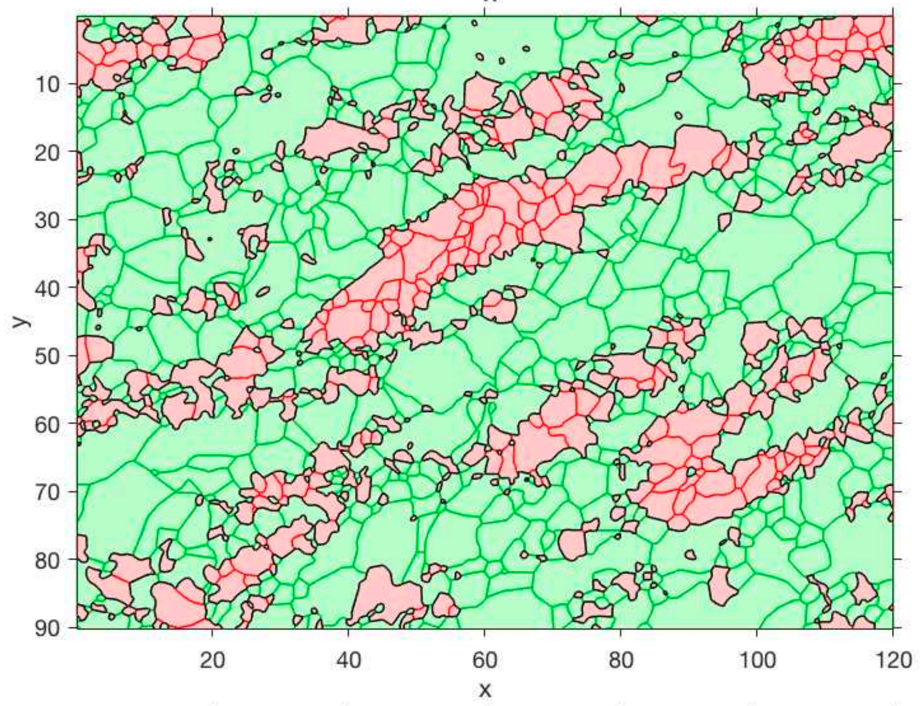


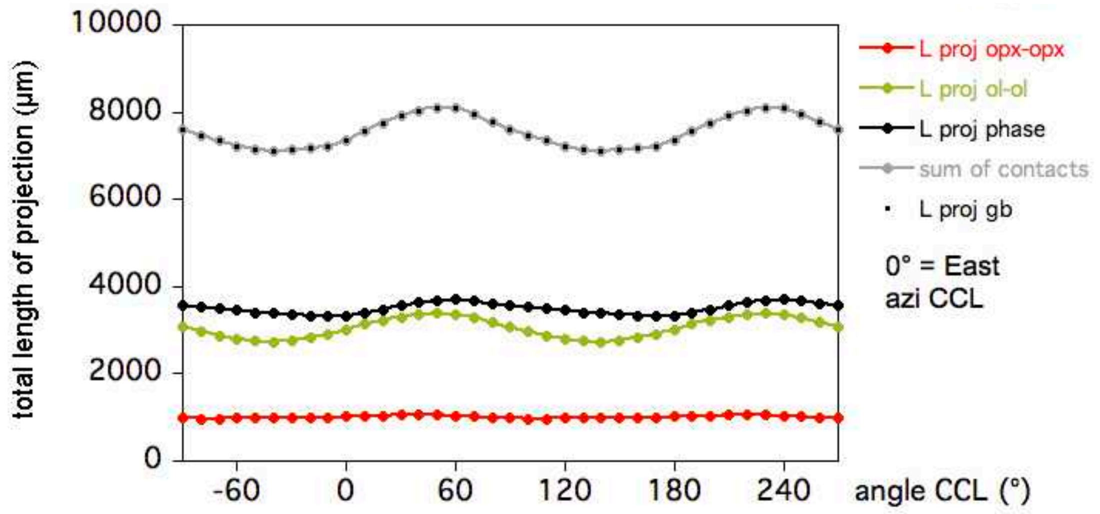


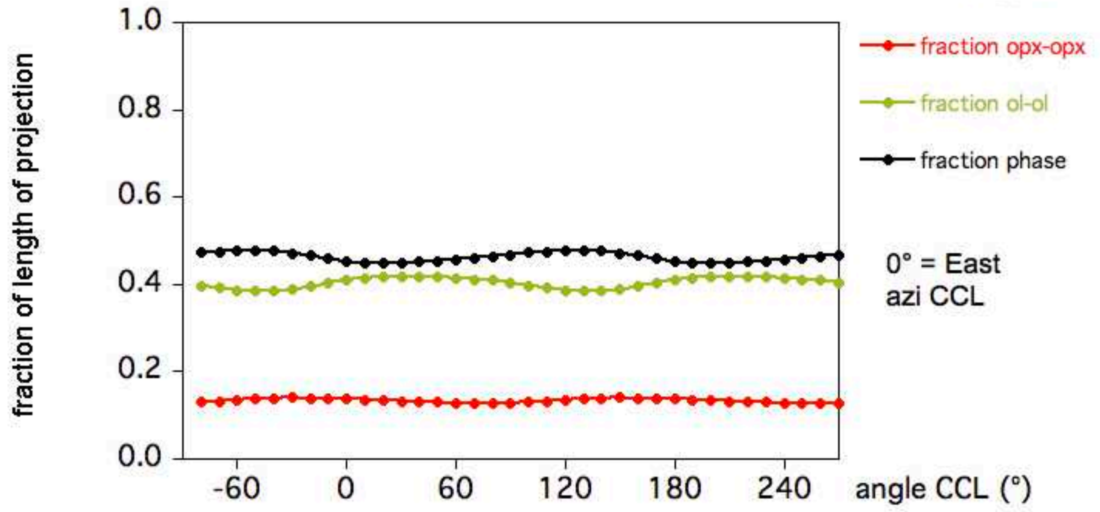


(= rectangular version of surfor rose diagram)

994
γ = 1.9

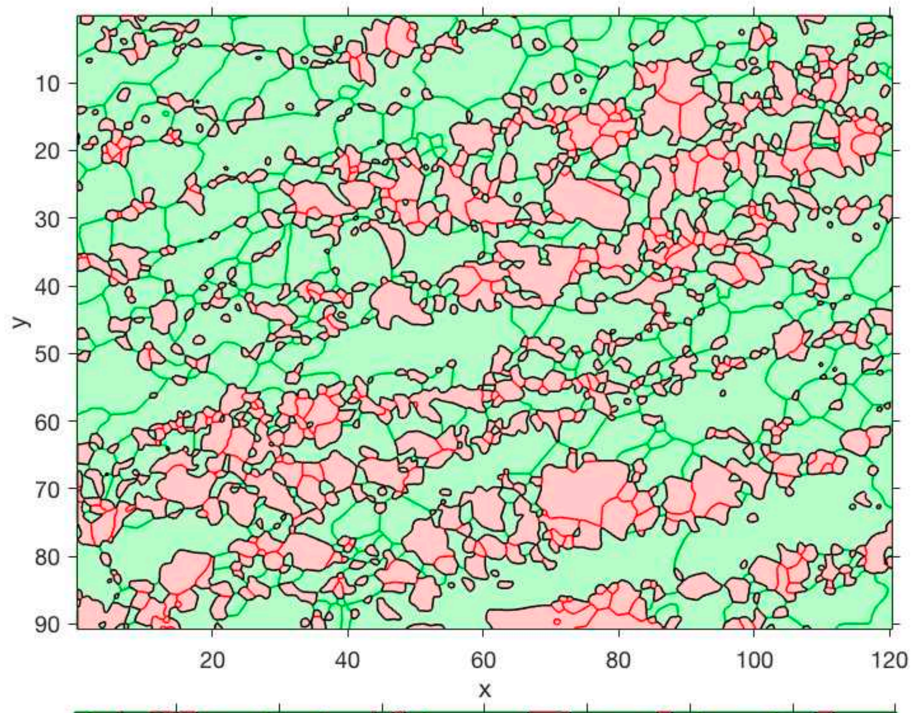


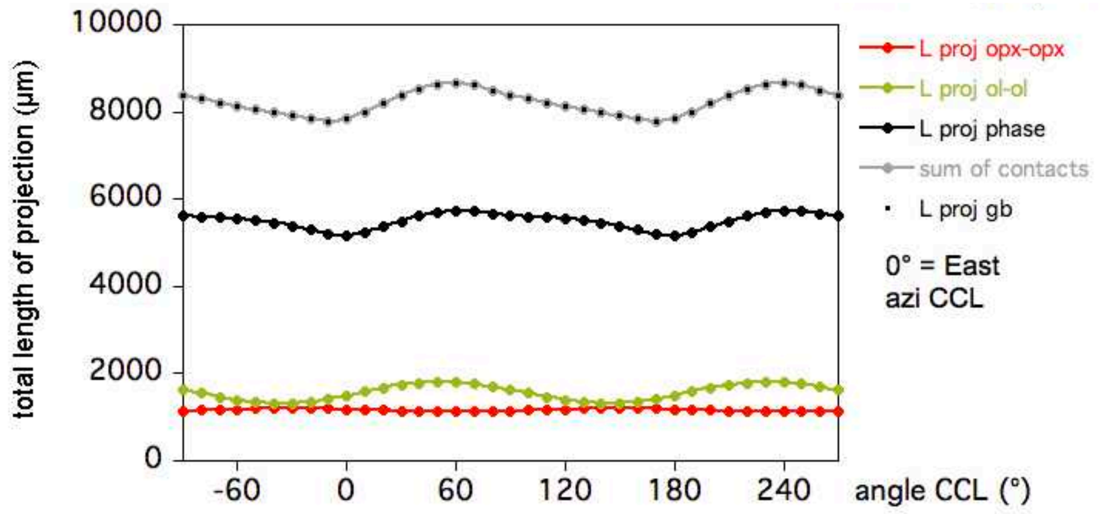


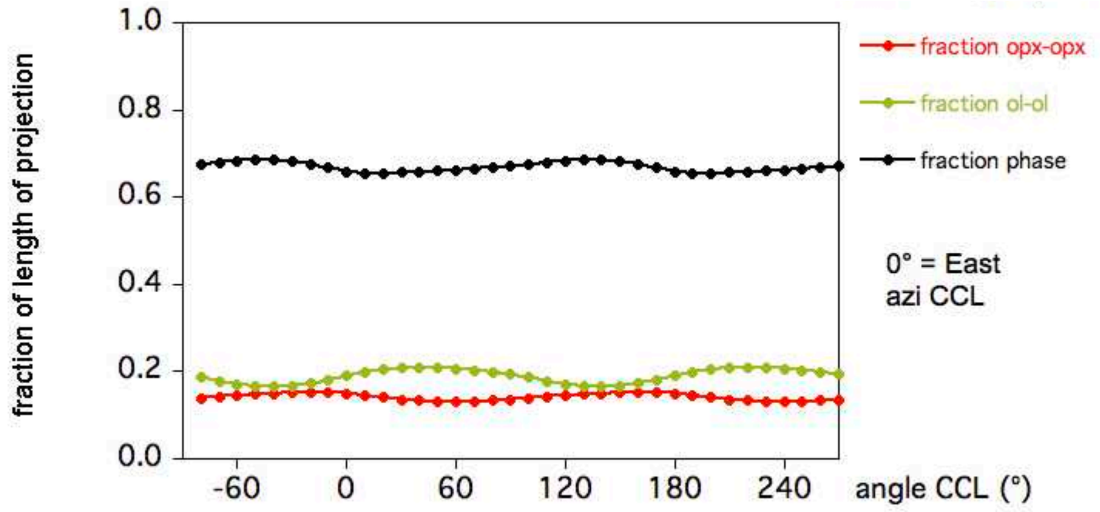


(= rectangular version of surfor rose diagram)

984
γ = 4.2

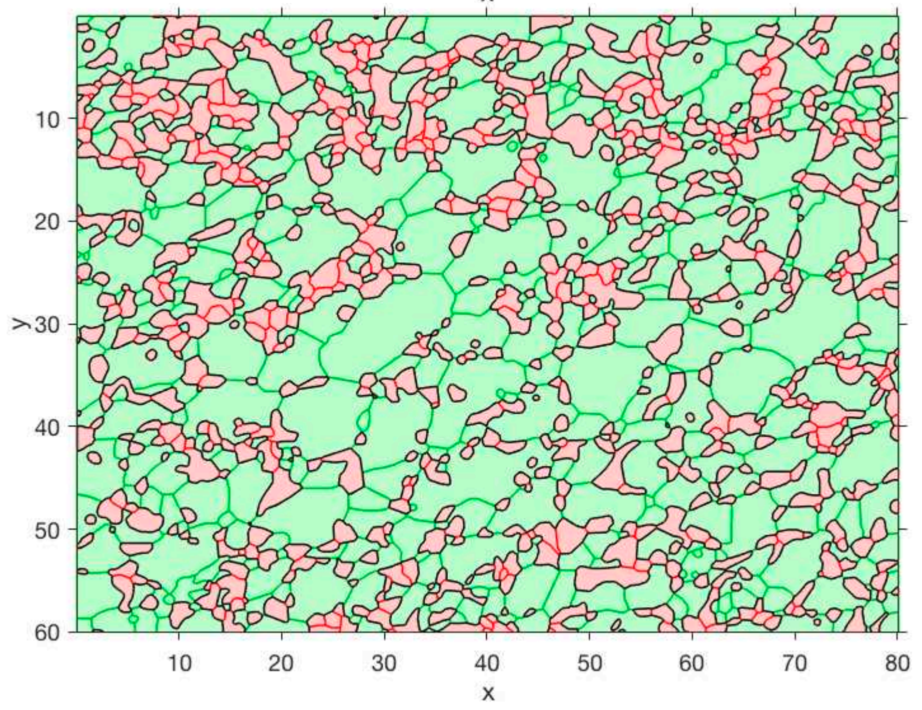


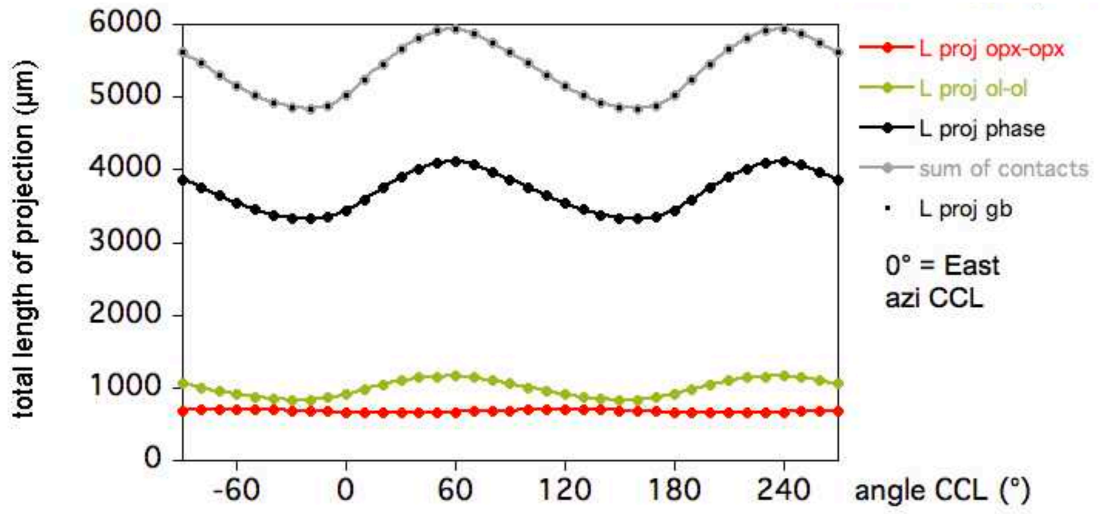


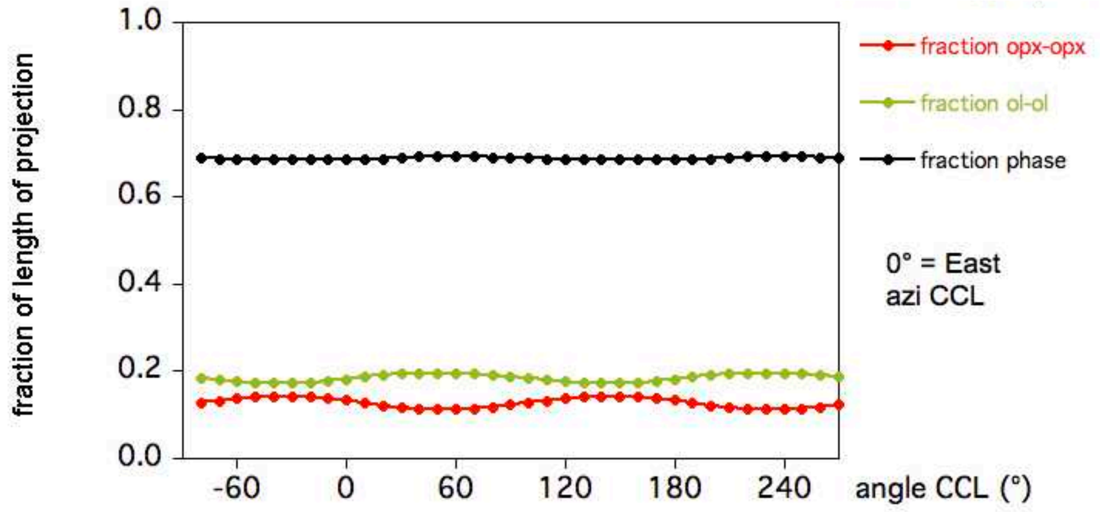


(= rectangular version of surfor rose diagram)

990
γ = 17.3

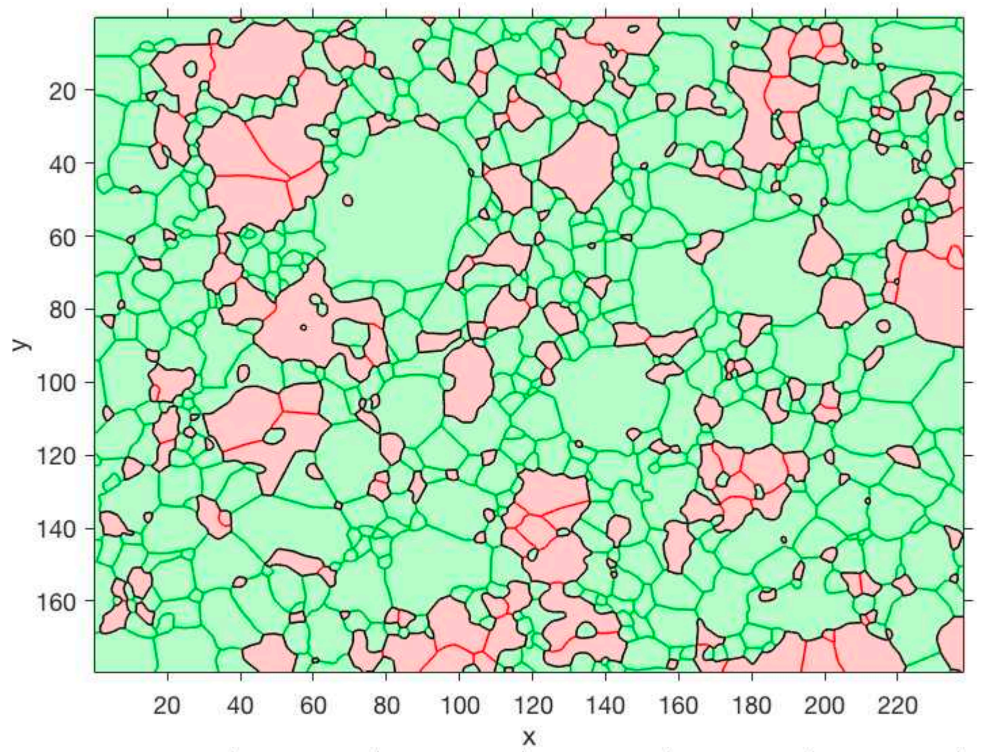




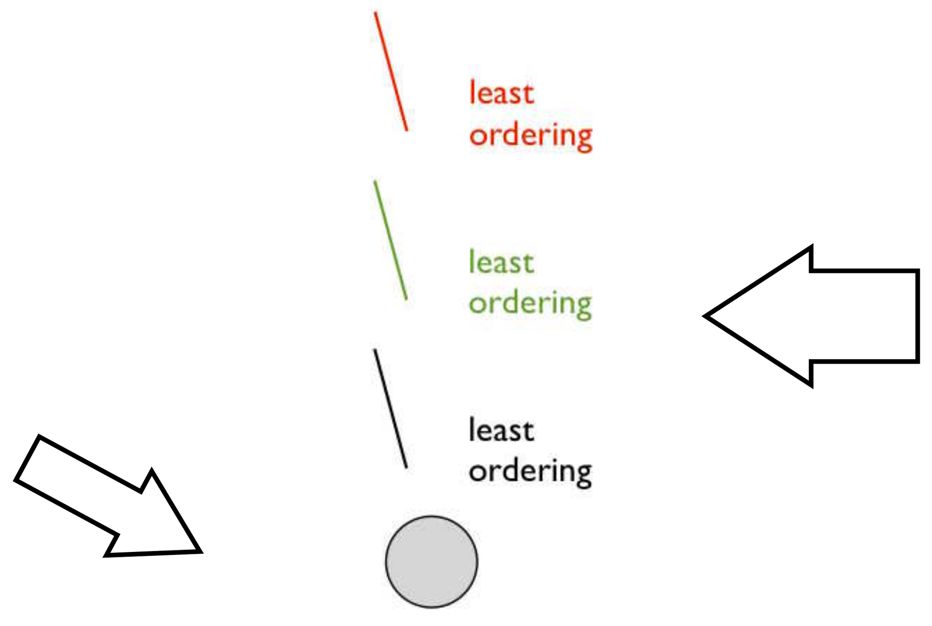


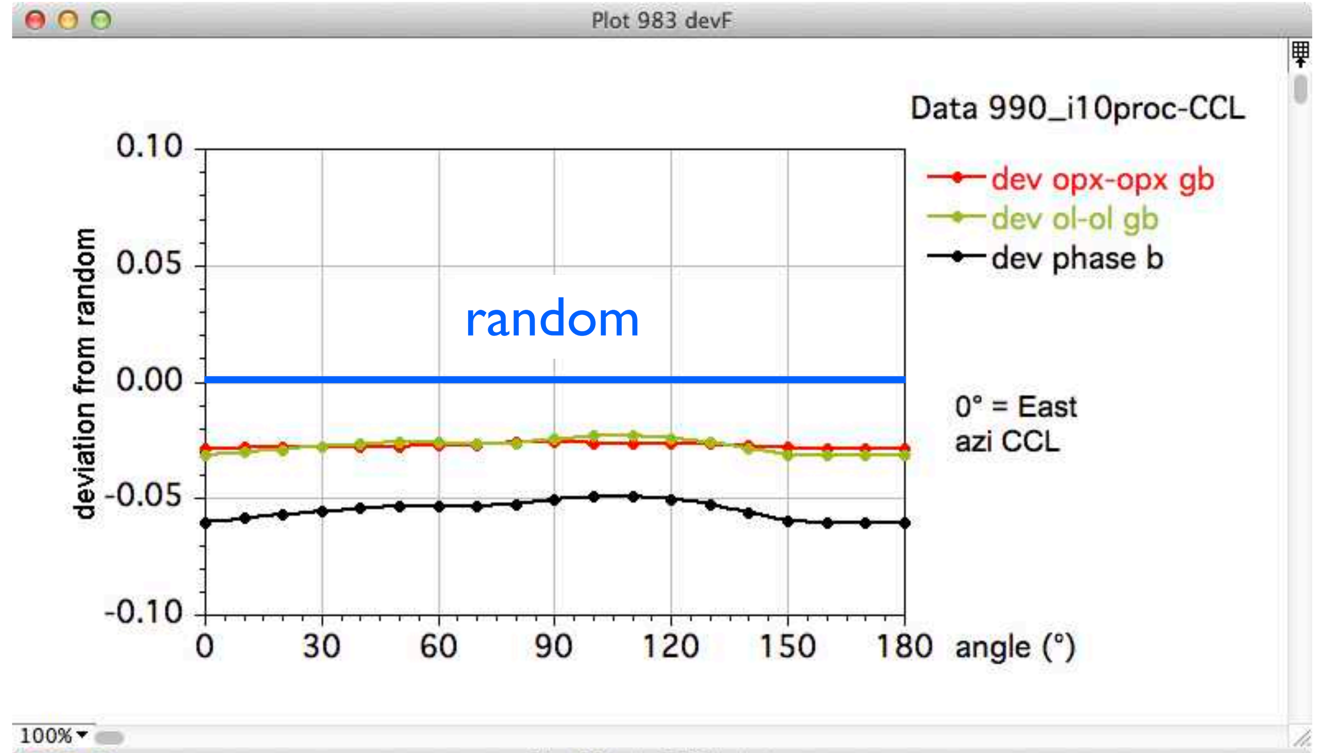
(= rectangular version of surfor rose diagram)

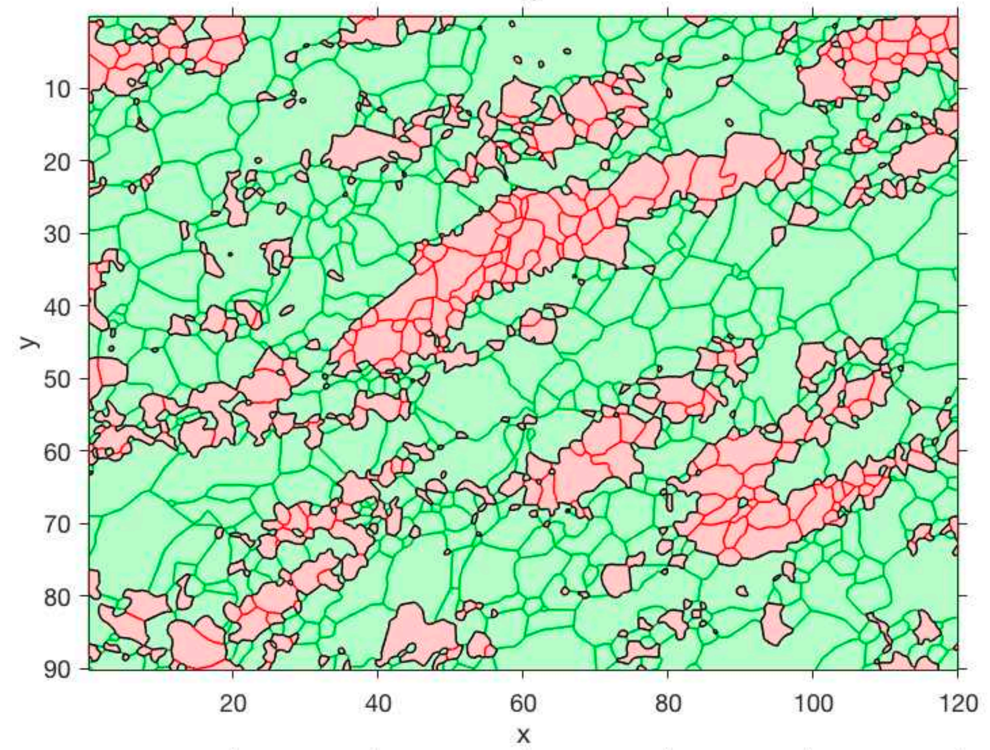
comparison of clustering ordering directions with strain



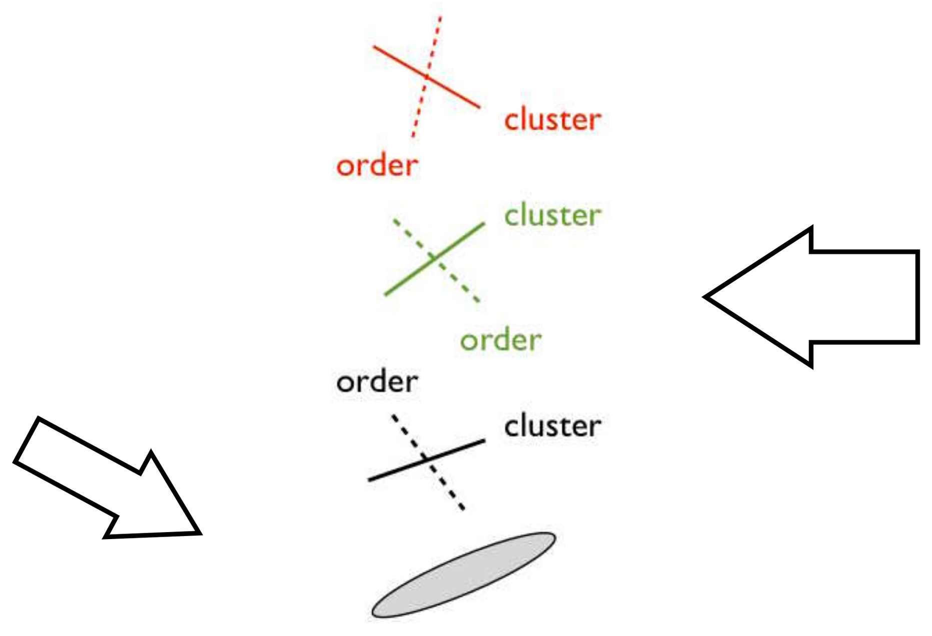
gamma = 0
⇒ strain ellipse
a/b = 1.0
φ = (45°)

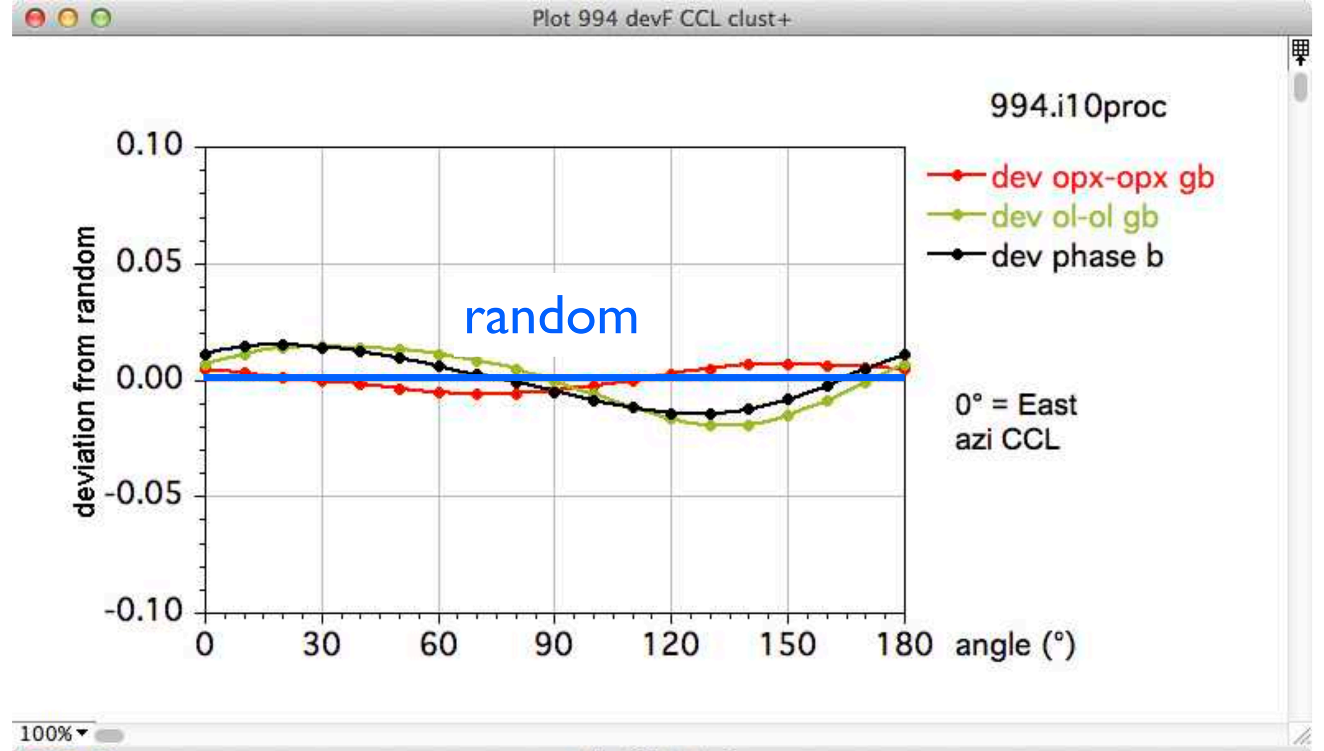


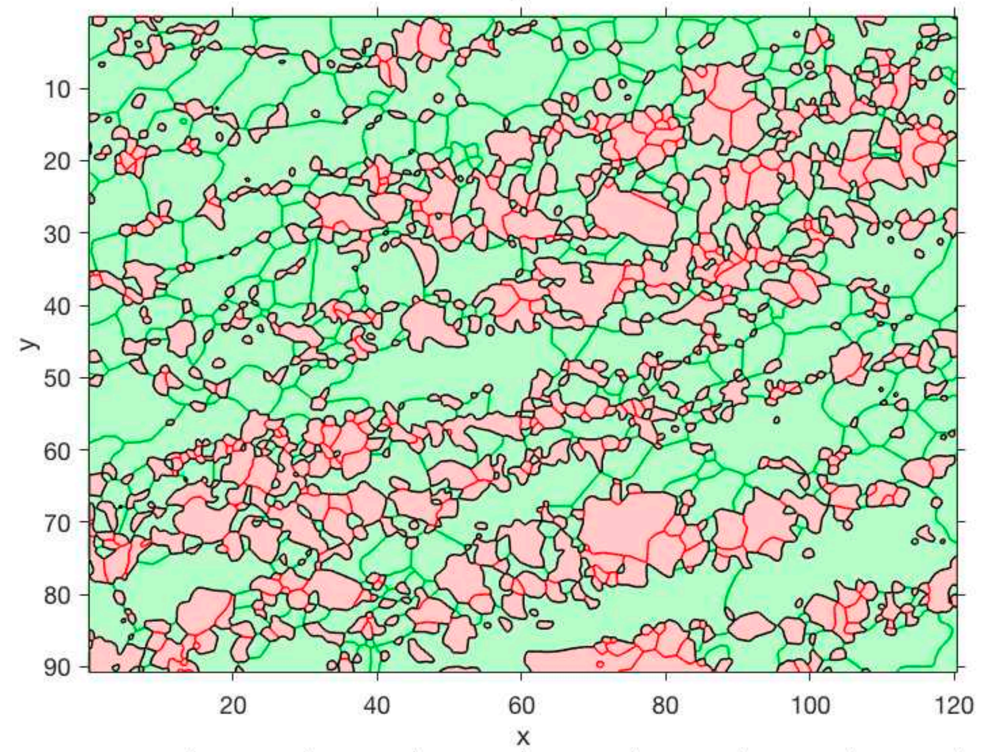




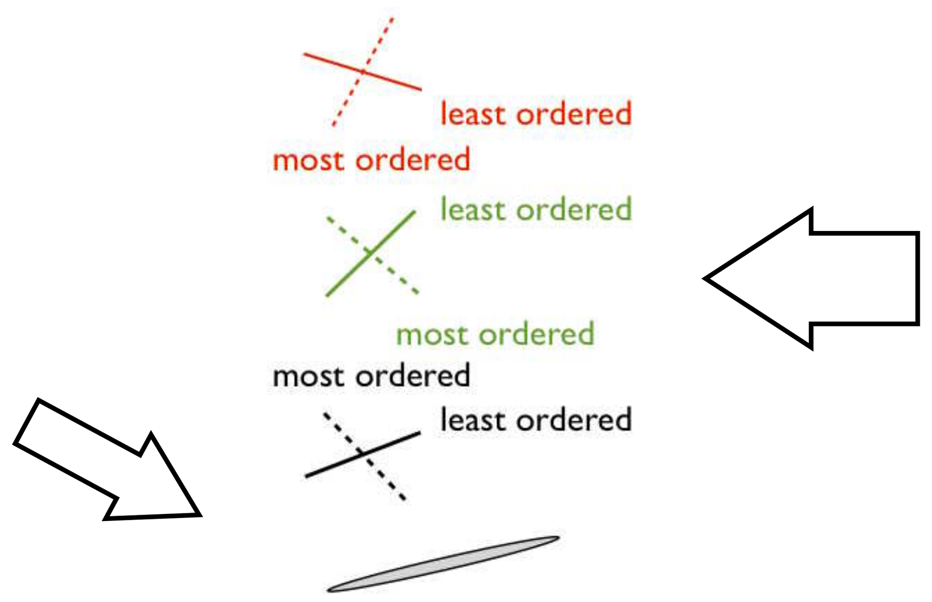
gamma = 1.9
⇒ strain ellipse
a/b = 5.4
φ = 23°

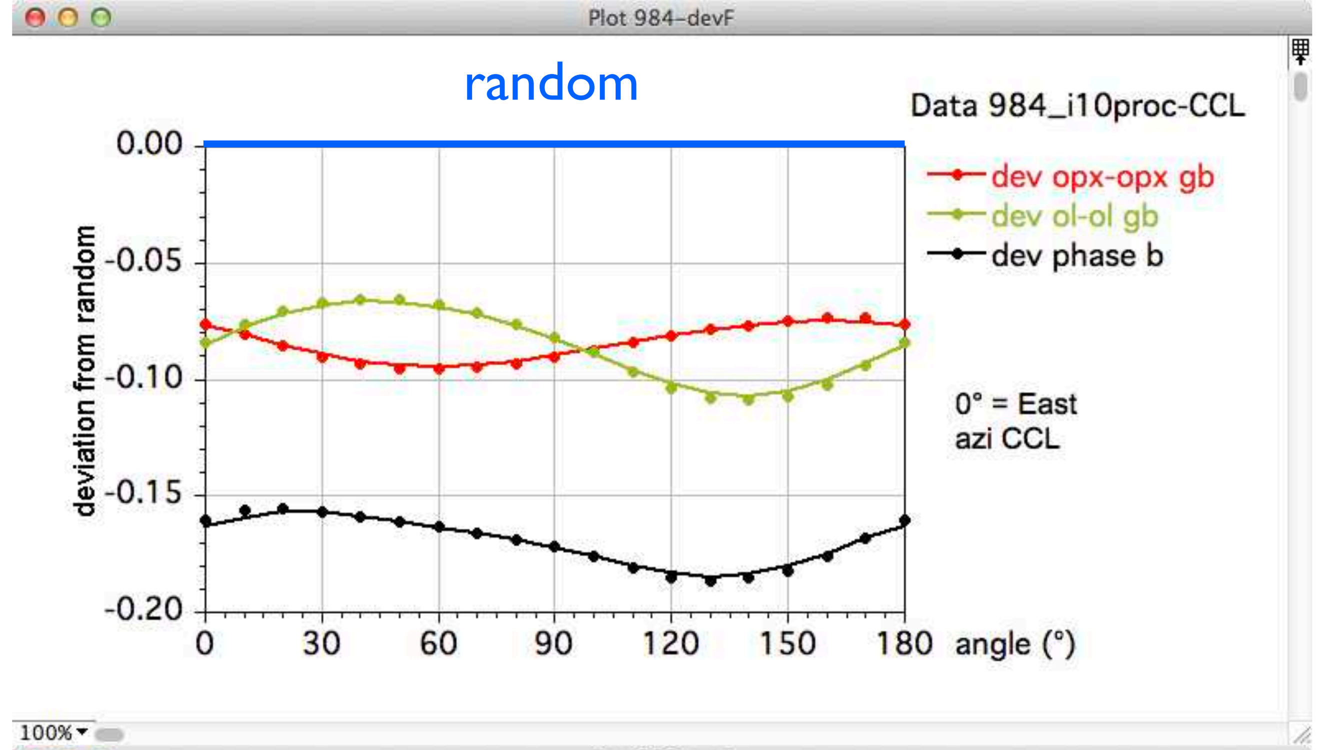


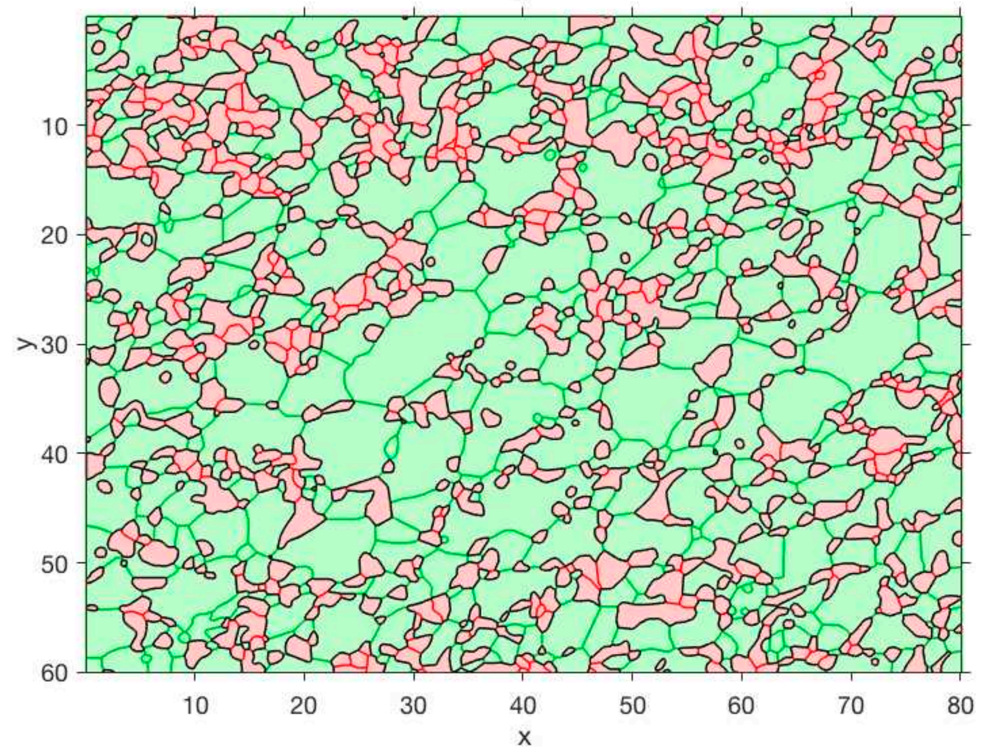




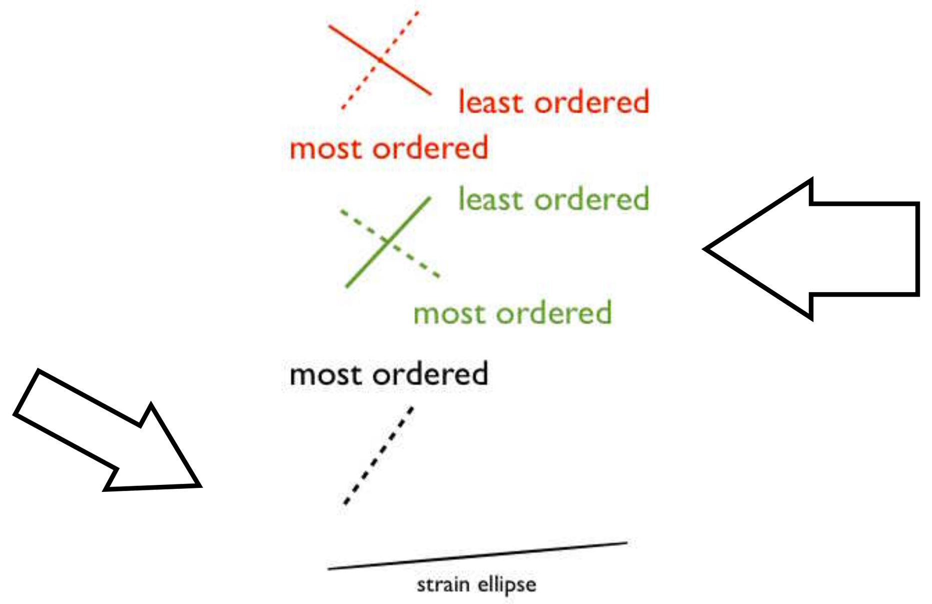
gamma = 4.2
⇒ strain ellipse
a/b = 19.6
φ = 13°

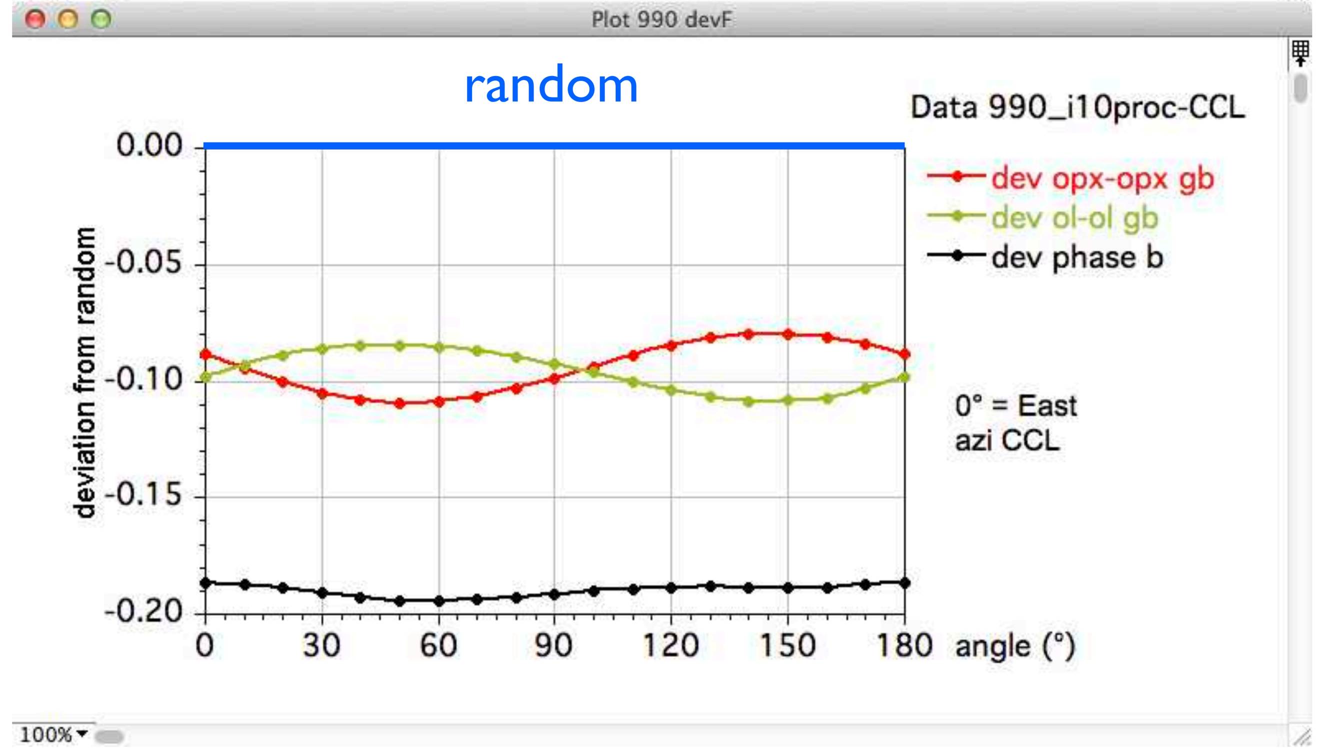






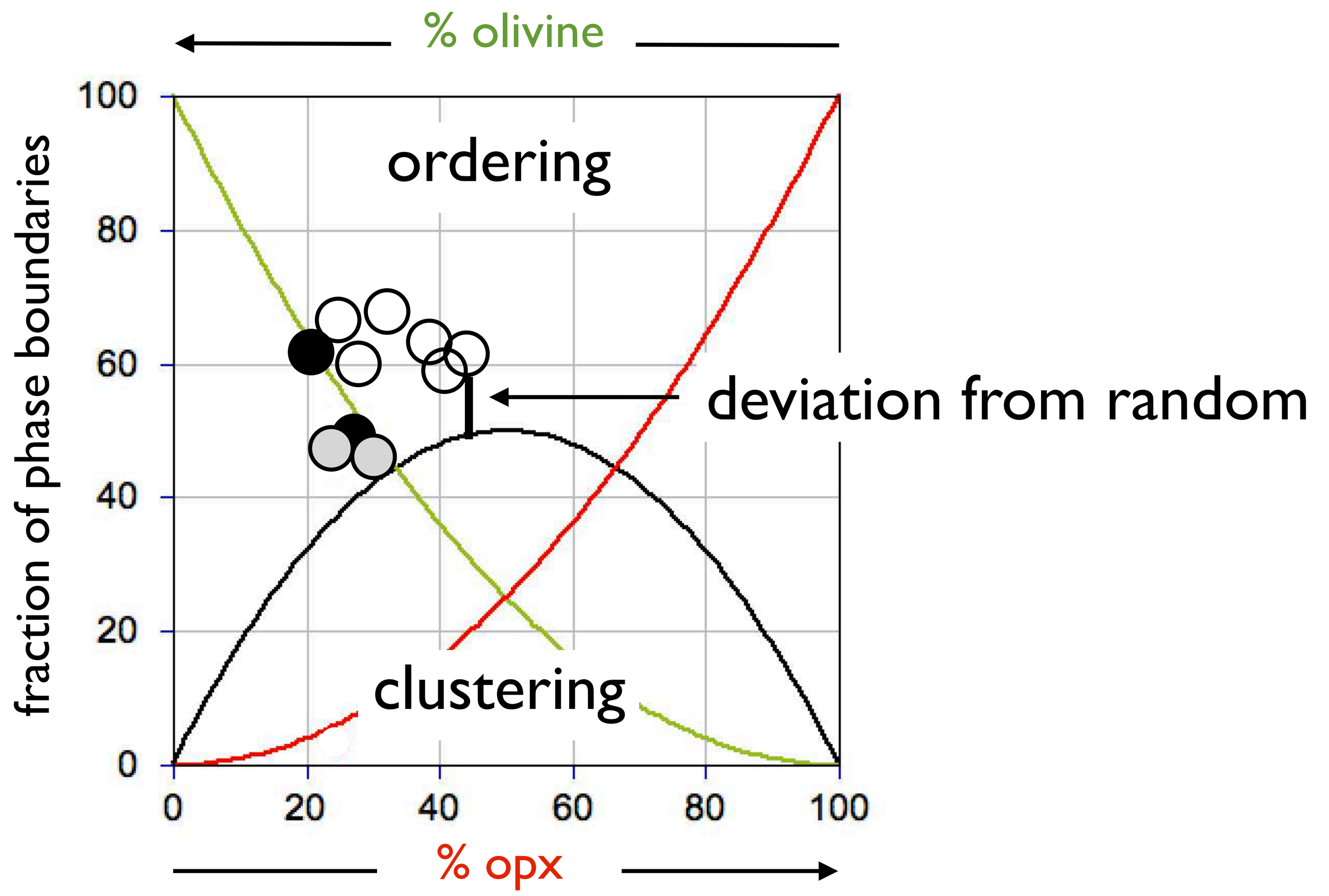
gamma = 17.3
⇒ strain ellipse
a/b = 301.3
φ = 5°

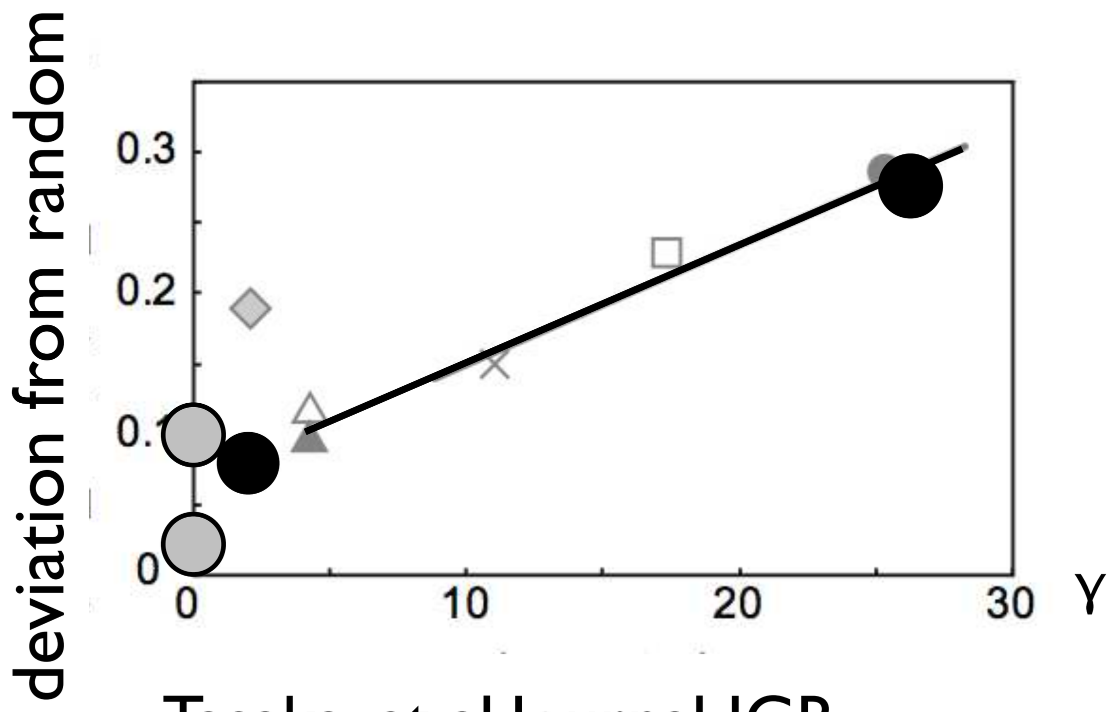




Deviation from random

for phase: dev = random - observed
for opx and ol: dev = observed - random
if dev > 0 ⇒ clustering
if dev < 0 ⇒ ordering





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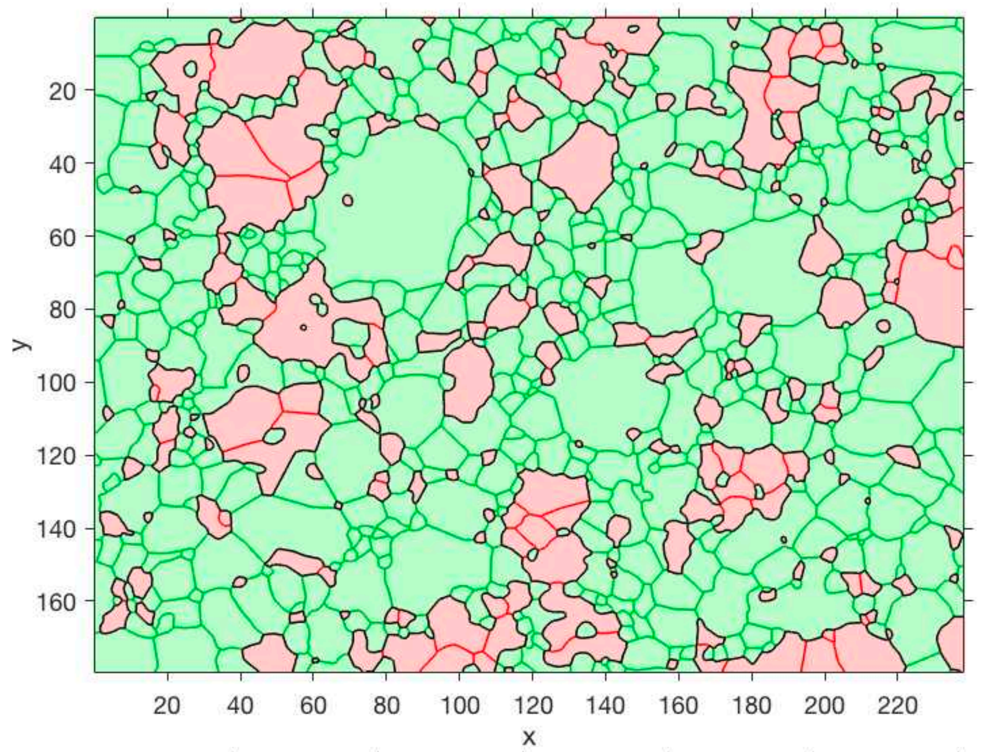
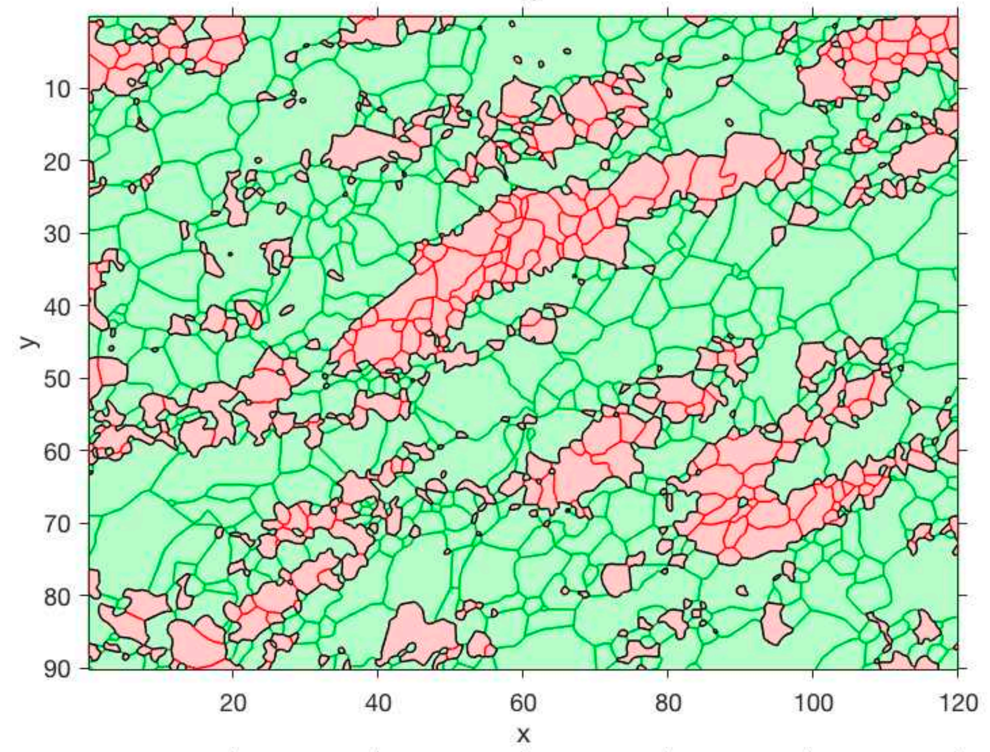
development of ordering anisotropy



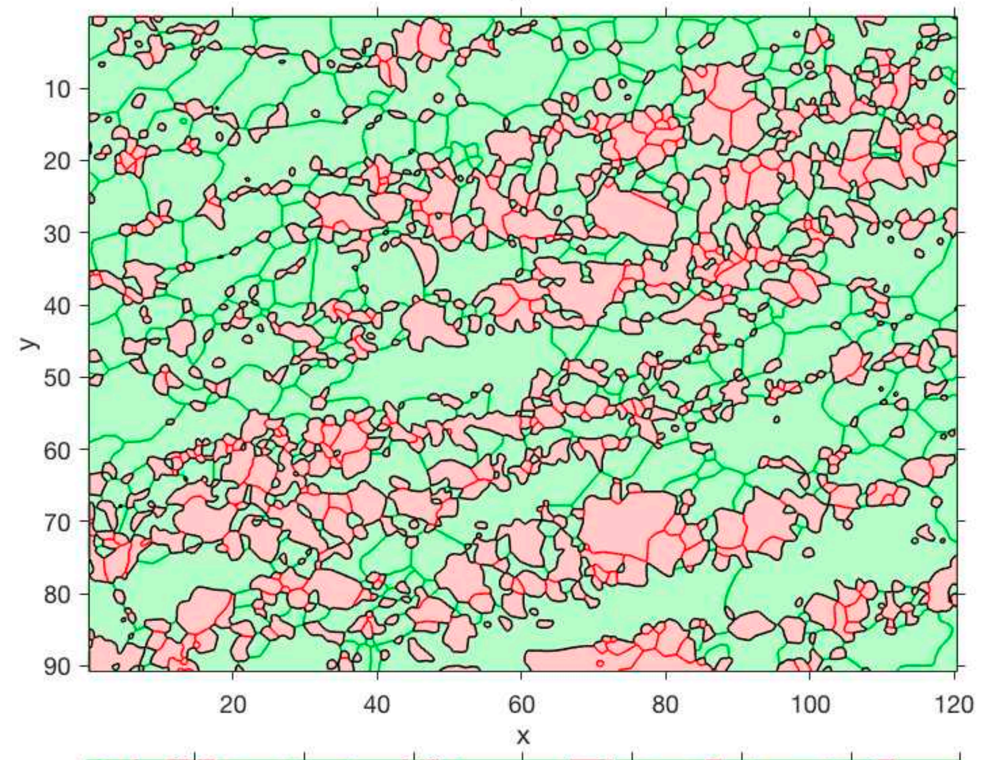
gamma = 0   a/b = 1.0   phi = (45°)

opx least ordering = ~105° (-0.022)
ol least ordering = ~constant (-0.026)
phase least ordering = ~105° (-0.049)



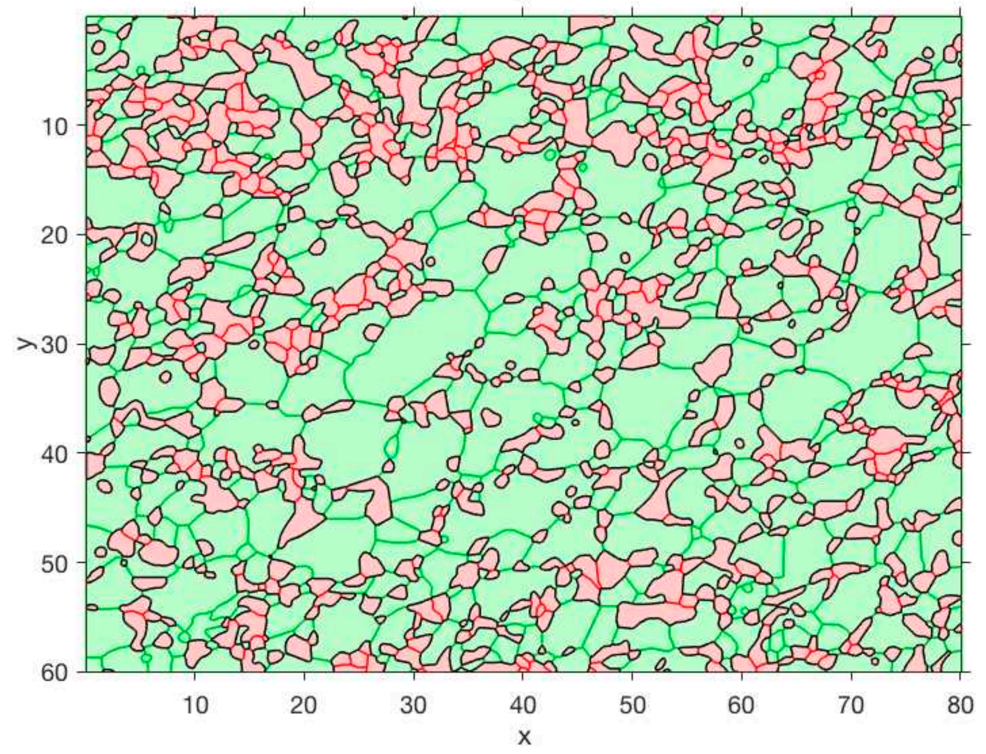
gamma = 1.9   a/b = 5.4   phi = 23°

opx most clustered = 150° (+0.007)   most ordered = 77° (-0.007)
ol most clustered = 36° (+0.014)   most ordered = 136° (-0.020)
phase most clustered = 19° (+0.016)   most ordered = 127° (-0.015)



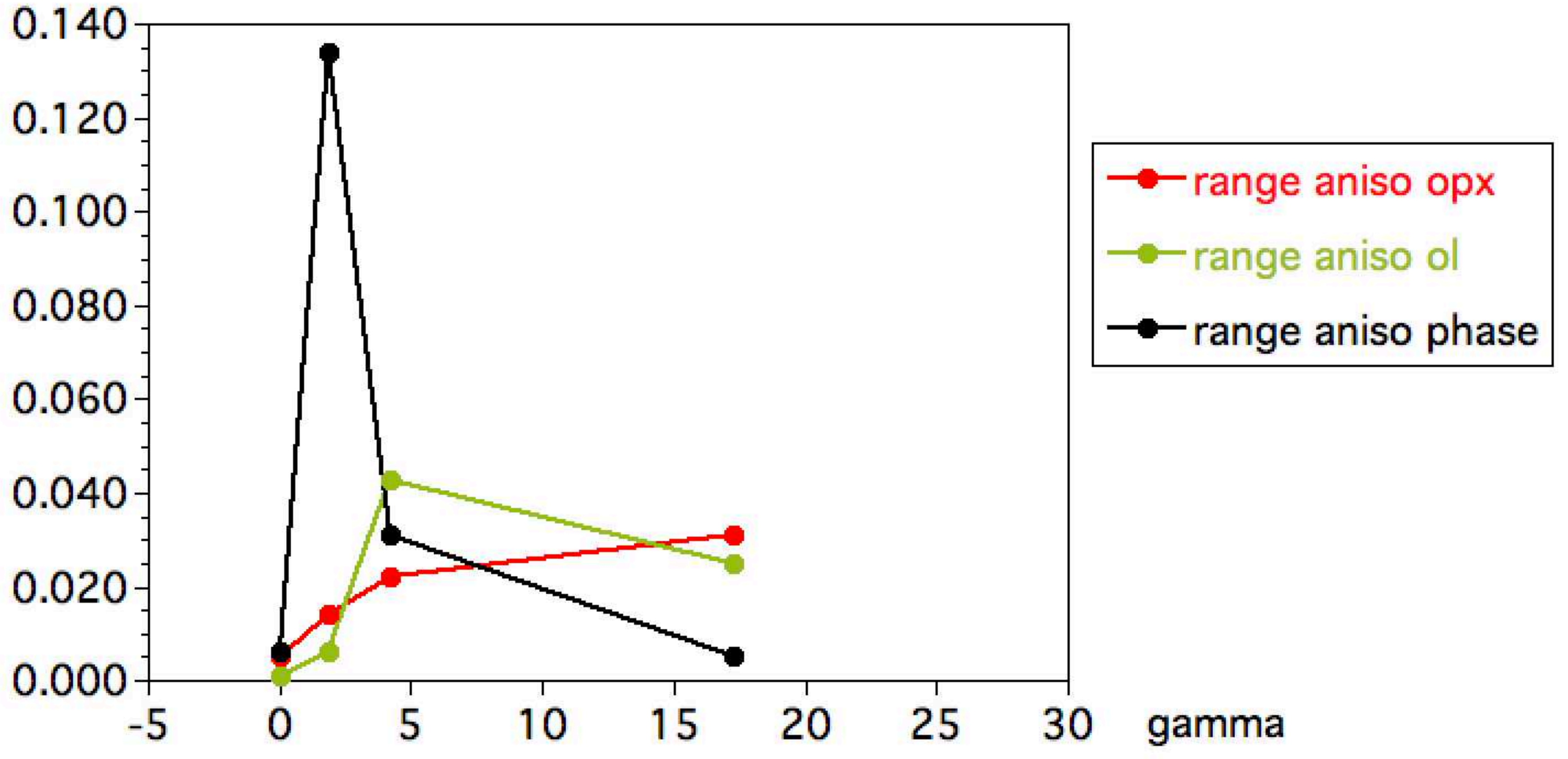
gamma = 4.2   a/b = 19.6   phi = 13°

opx least ordered = 163° (-0.074)   most ordered = 61° (-0.096)
ol least ordered = 44° (-0.066)   most ordered = 140° (-0.109)
phase least ordered = 22° (-0.156)   most ordered = 133° (-0.187)



gamma = 17.3   a/b = 301.3   phi = (5°)

opx least ordered = 146° (-0.079)   most ordered = 52° (-0.110)
ol least ordered = 47° (-0.083)   most ordered = 146° (-0.108)
phase least ordered = -° (-0.189)   most ordered = 55° (-0.194)



at high shrear strains

anisotropy of opx grows due to layering (?)
anisotropy of ol and phase decreases

<< to overview

overview

the story

the published data

further development of analysis:

1. using surface fractions
2. adding opx-opx and ol-ol data
3. consider grain size
4. directional ordering - clustering

additional info

(1) background for contact surface analysis

(2) procedure for analyisis usinh Image SXM

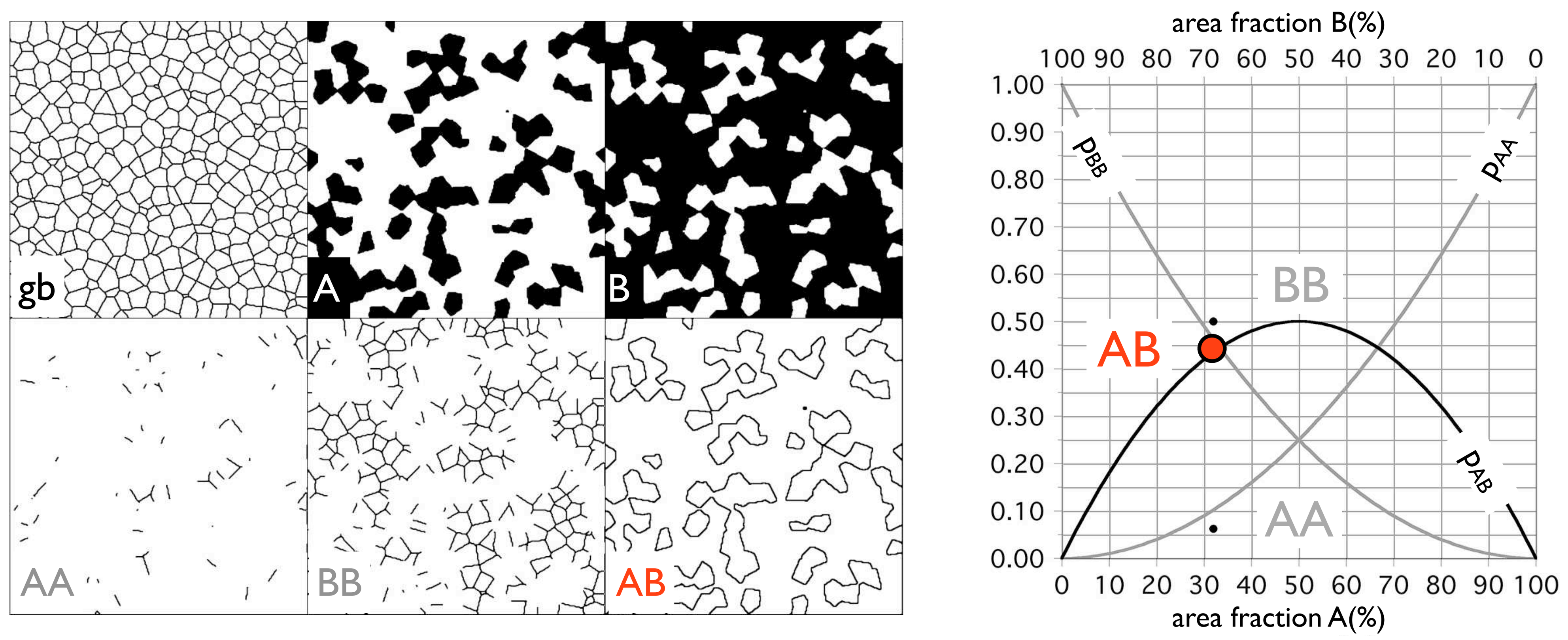
(3) testing the method

(4) grain size measurements

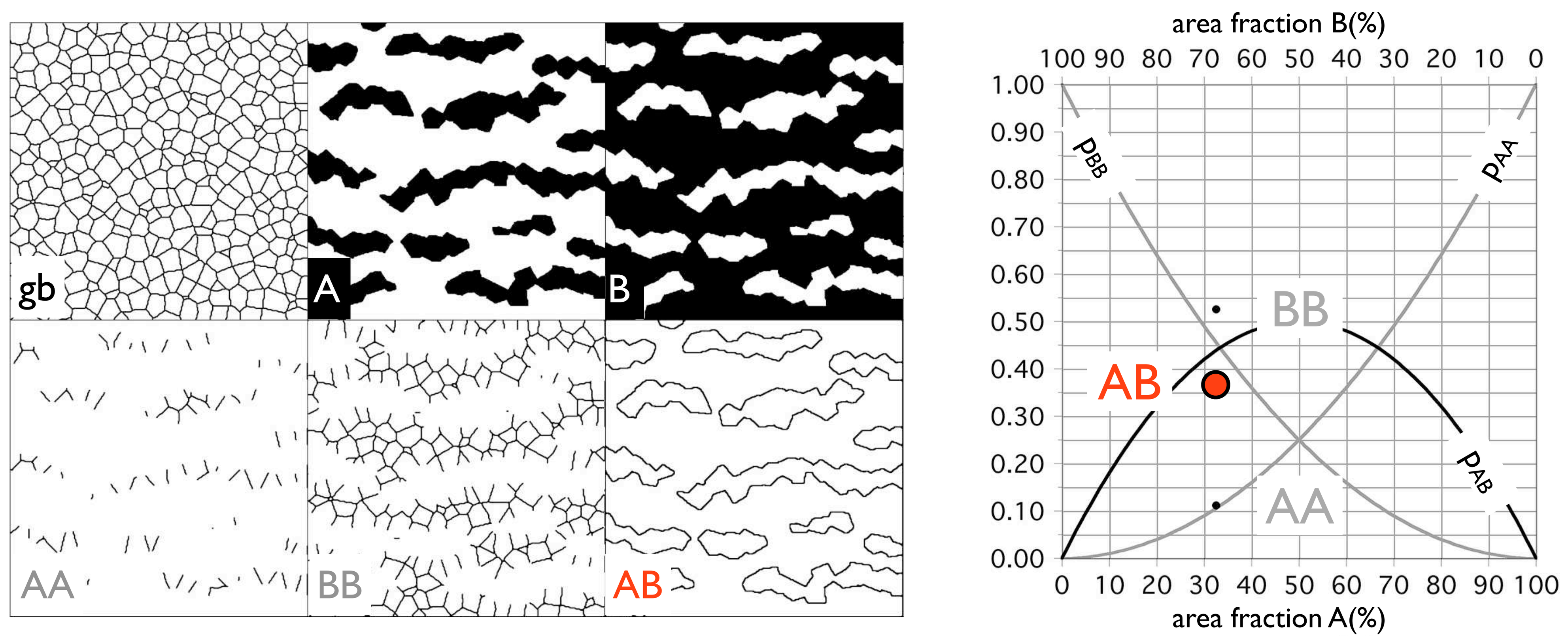
additional info (1)

background for contact surface analysis

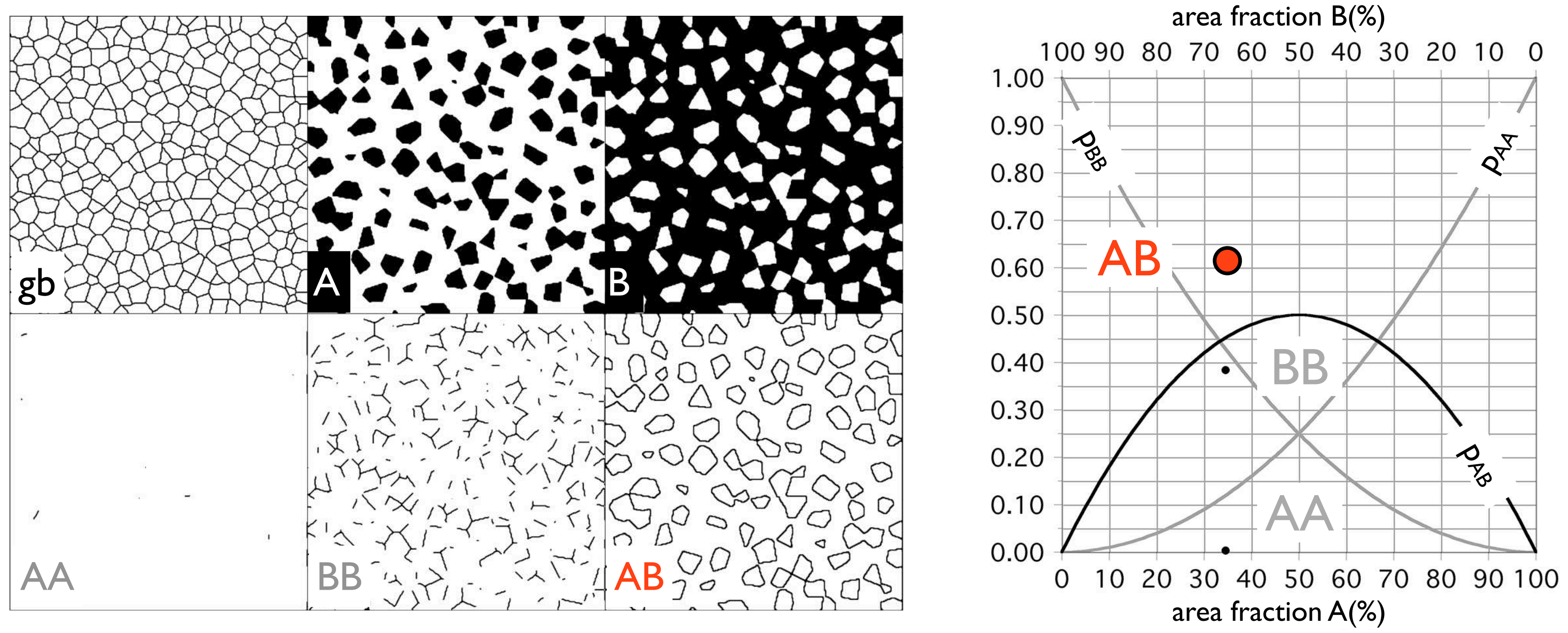
random



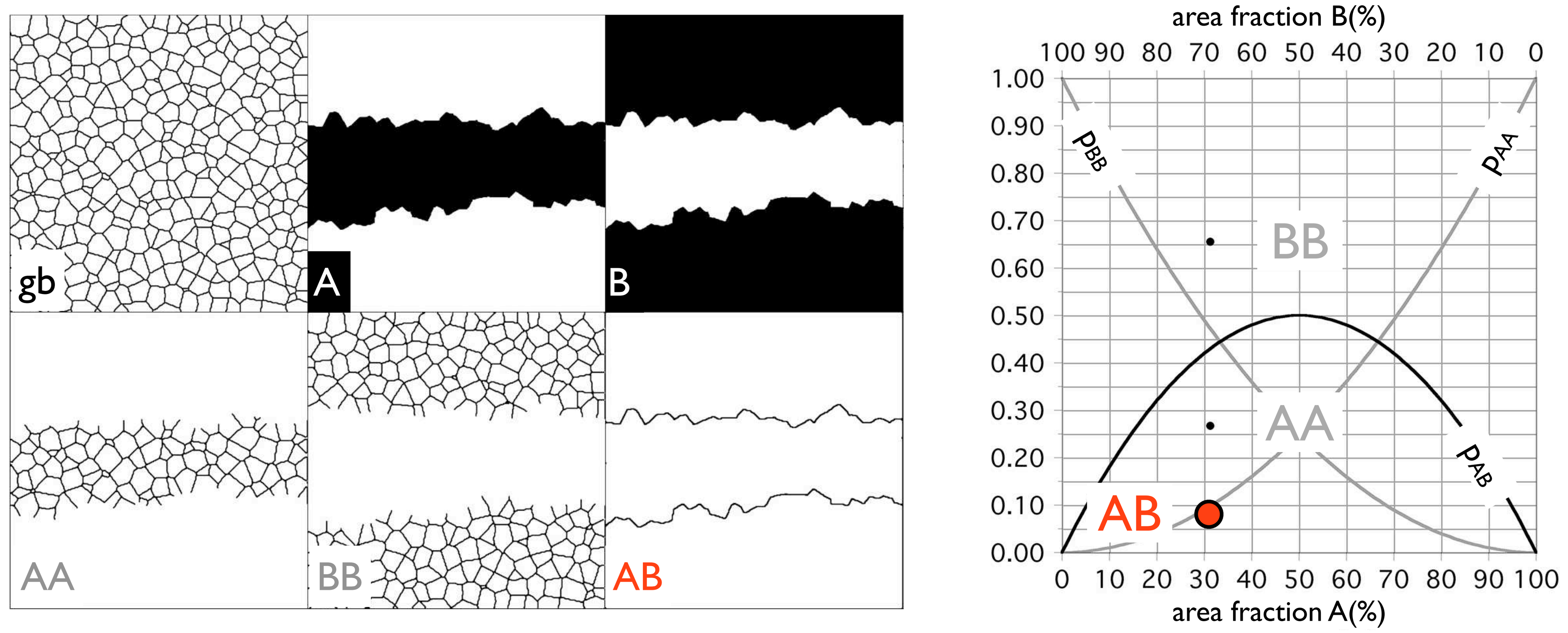
clustered



ordered



strongly clustered

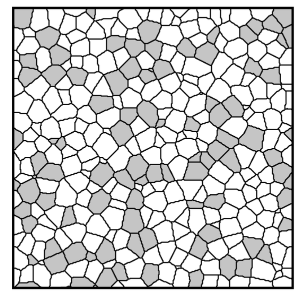


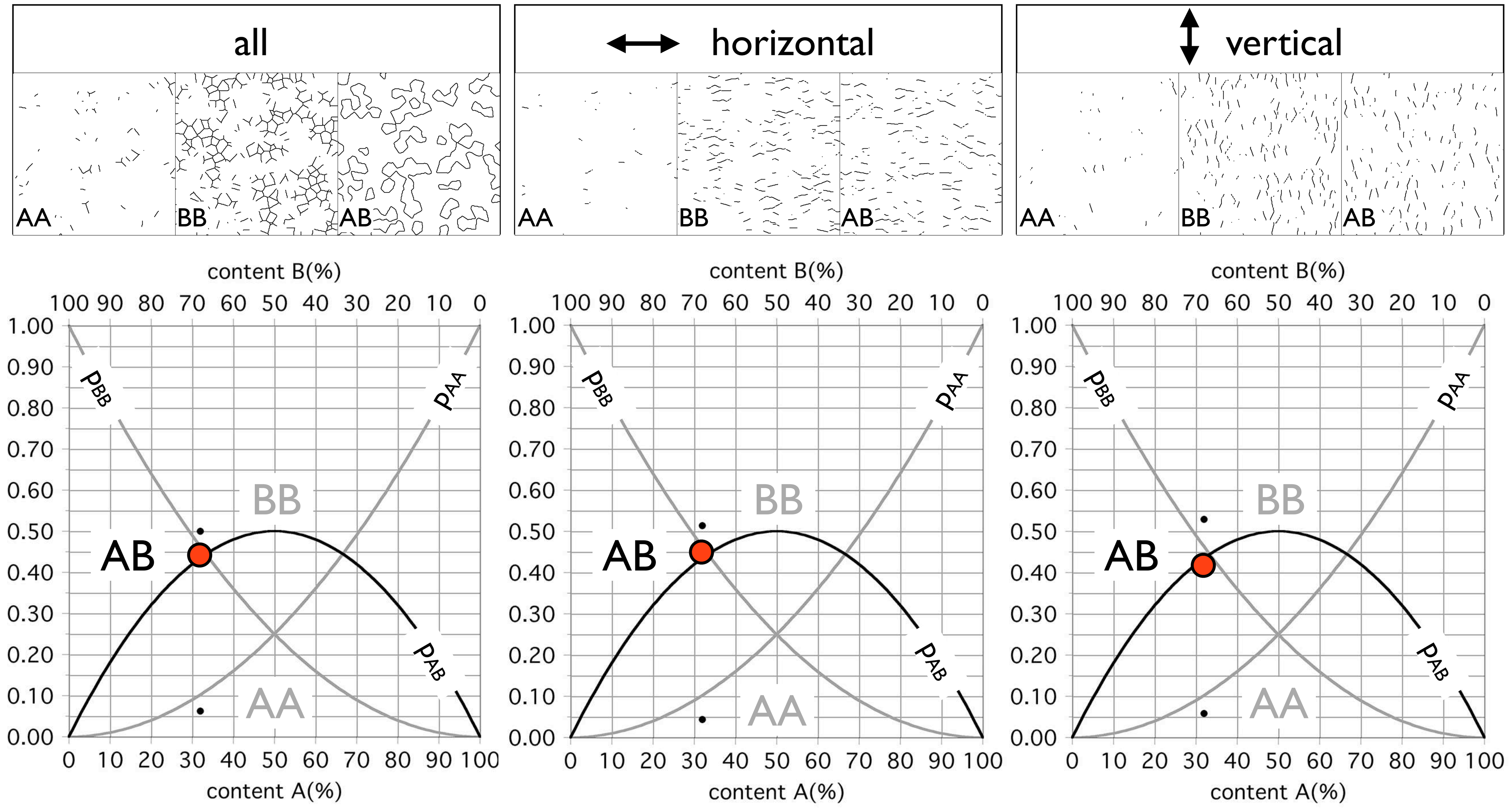
to overview >>

additional info (1)

anisotropic cases

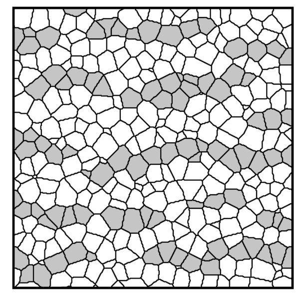
random

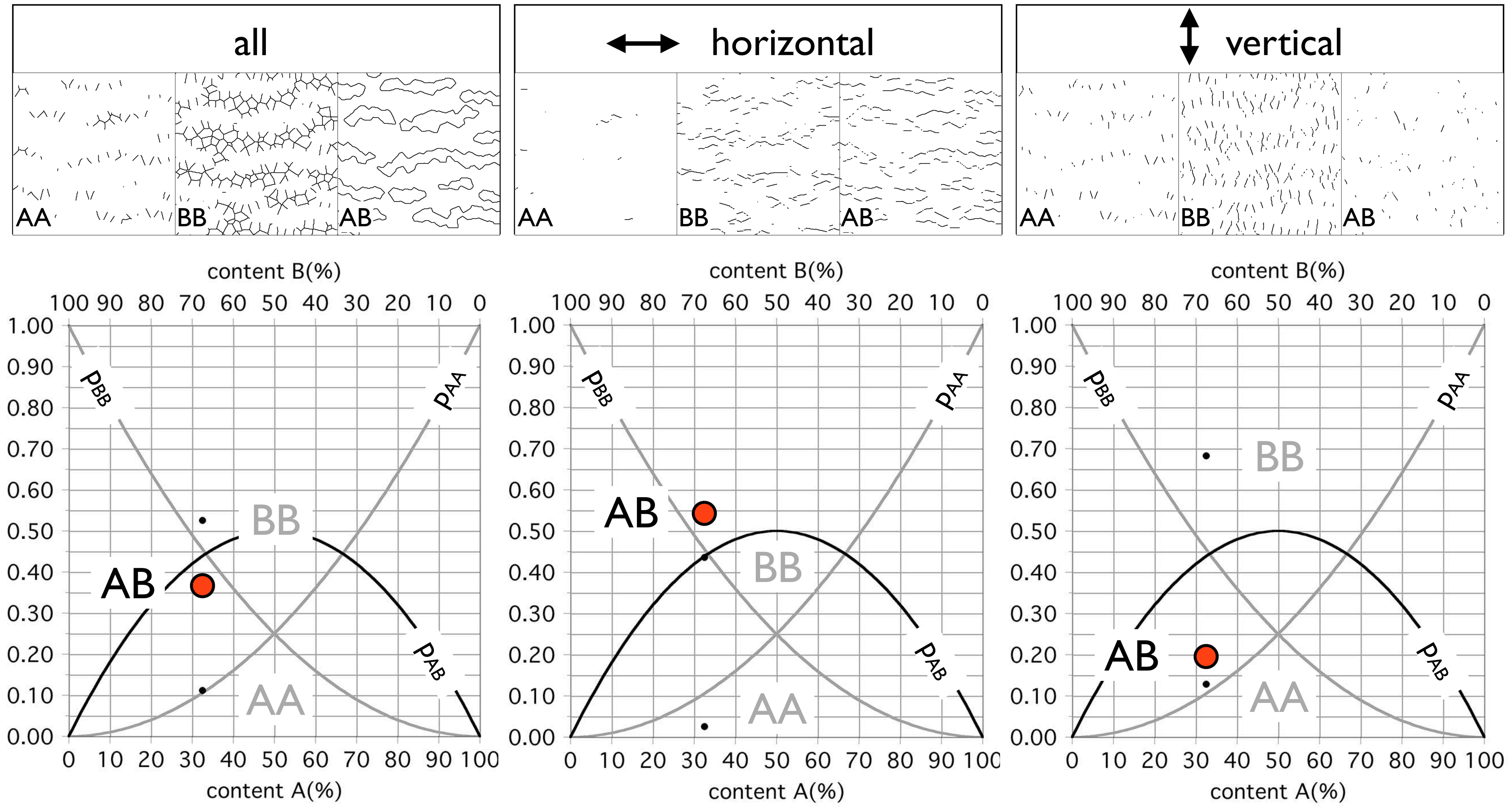




isotropic random

clustered



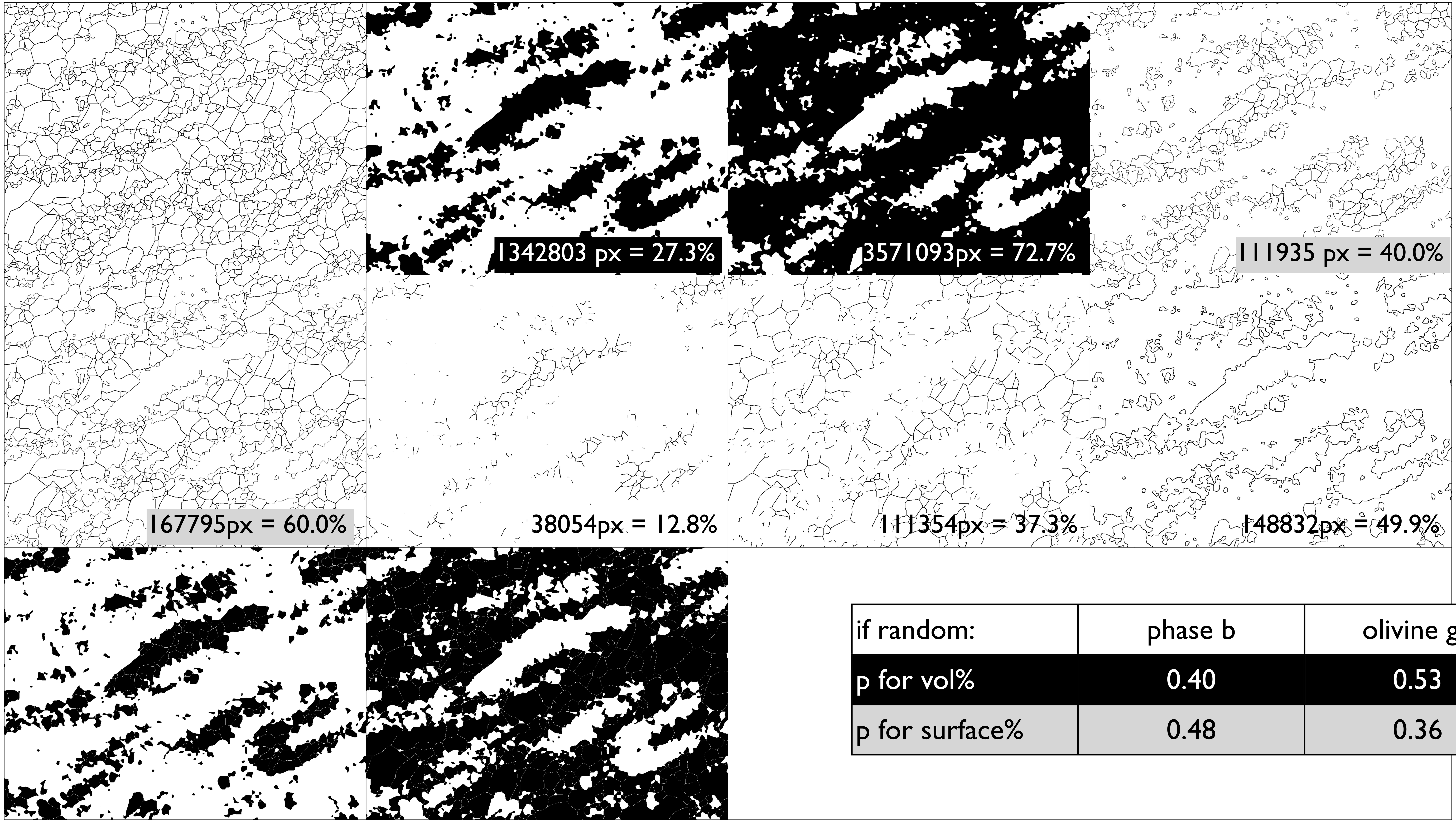


anisotropic clustered

<< to overview

additional info (2)

analyzing contact surfaces using Image SXM / Lazy contacts



if random:	phase b	olivine gb	opx gb
p for vol%	0.40	0.53	0.07
p for surface%	0.48	0.36	0.16

cf: Heilbronner R. & Barrett S. (2014)Image Analysis in Earth Sciences, Springer Verlag Heidelberg

to overview

additional info (3)

testing the method:

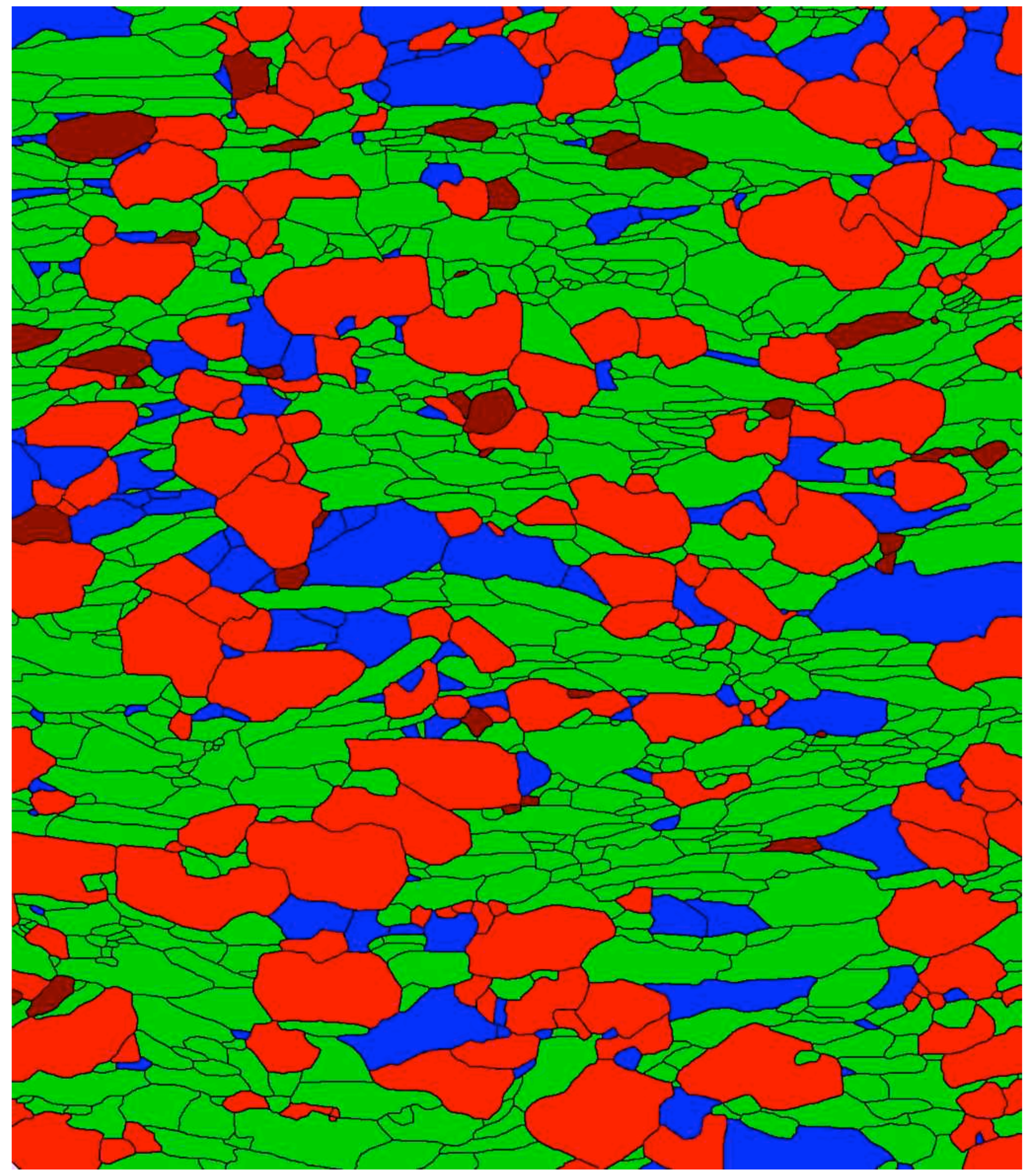
1. using different maps of same area
2. testing 1 phase against rest
3. testing two phases without rest

James Horst Tjerk Luca Victoria Nynke

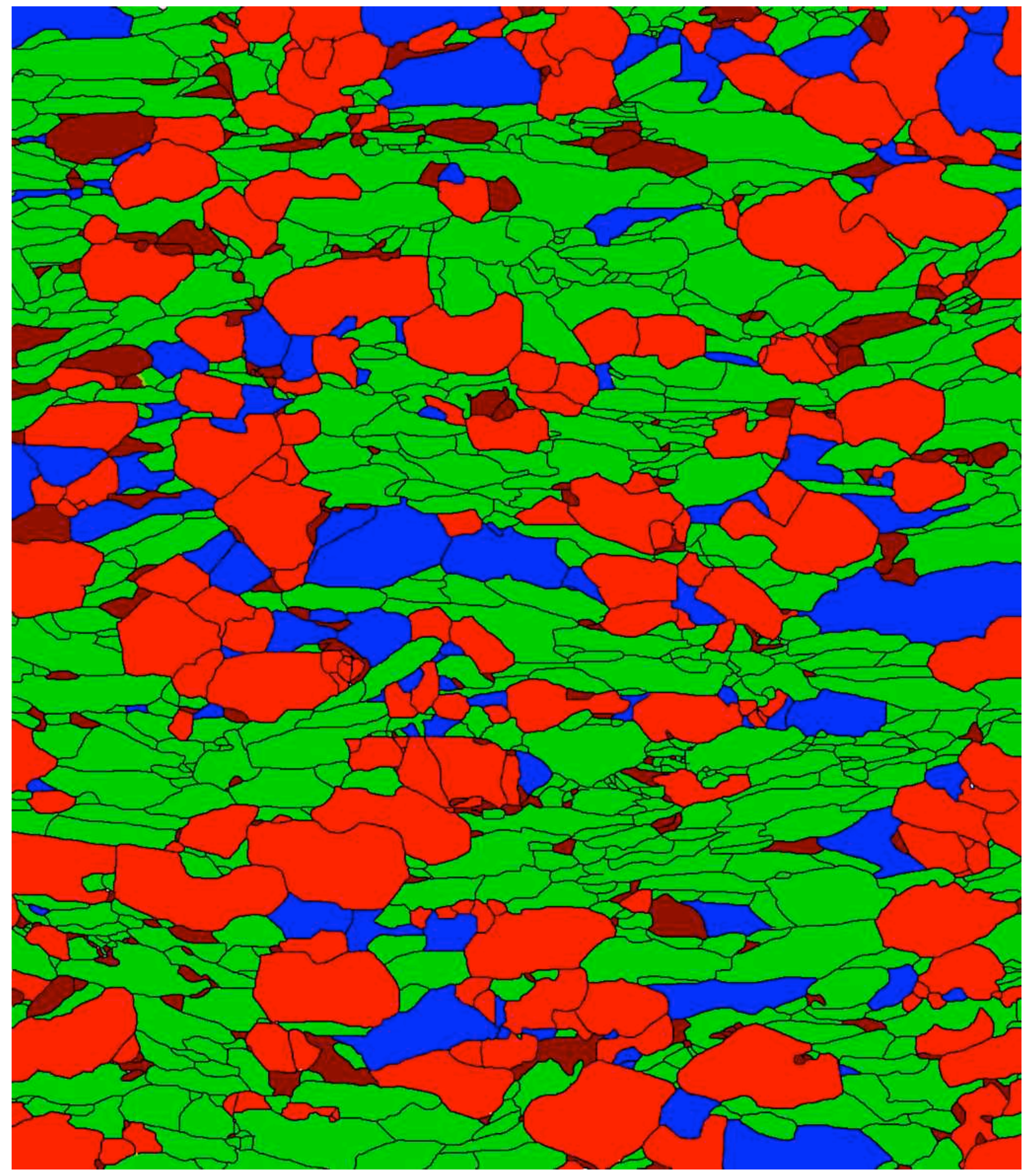
the famous M3 party

Members were asked by James to manually outline grains. They all got the same SEM/BS image ... and came up with slightly different interpretations:

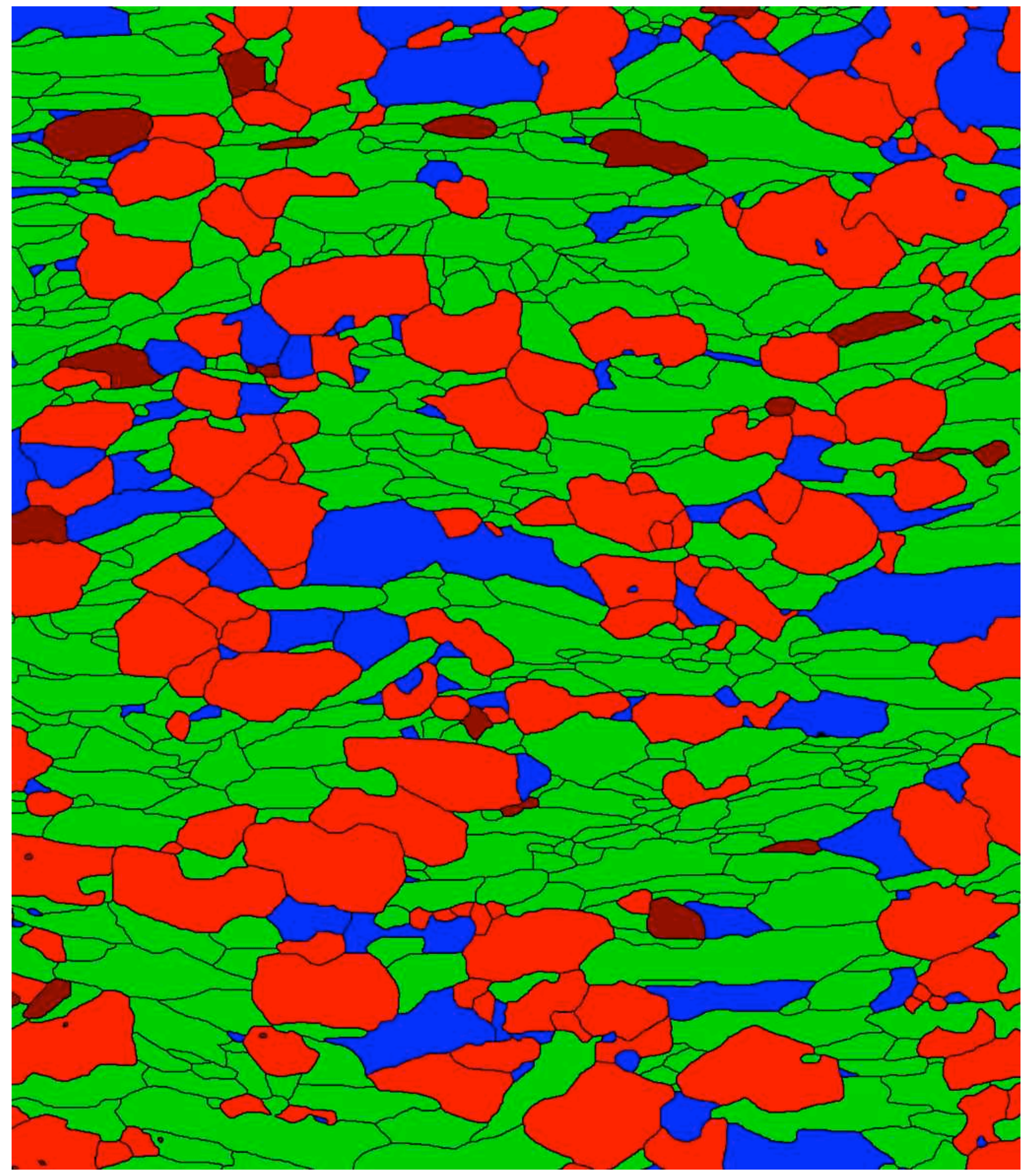
- garnet
- omphacite
- quarz
- unidentified



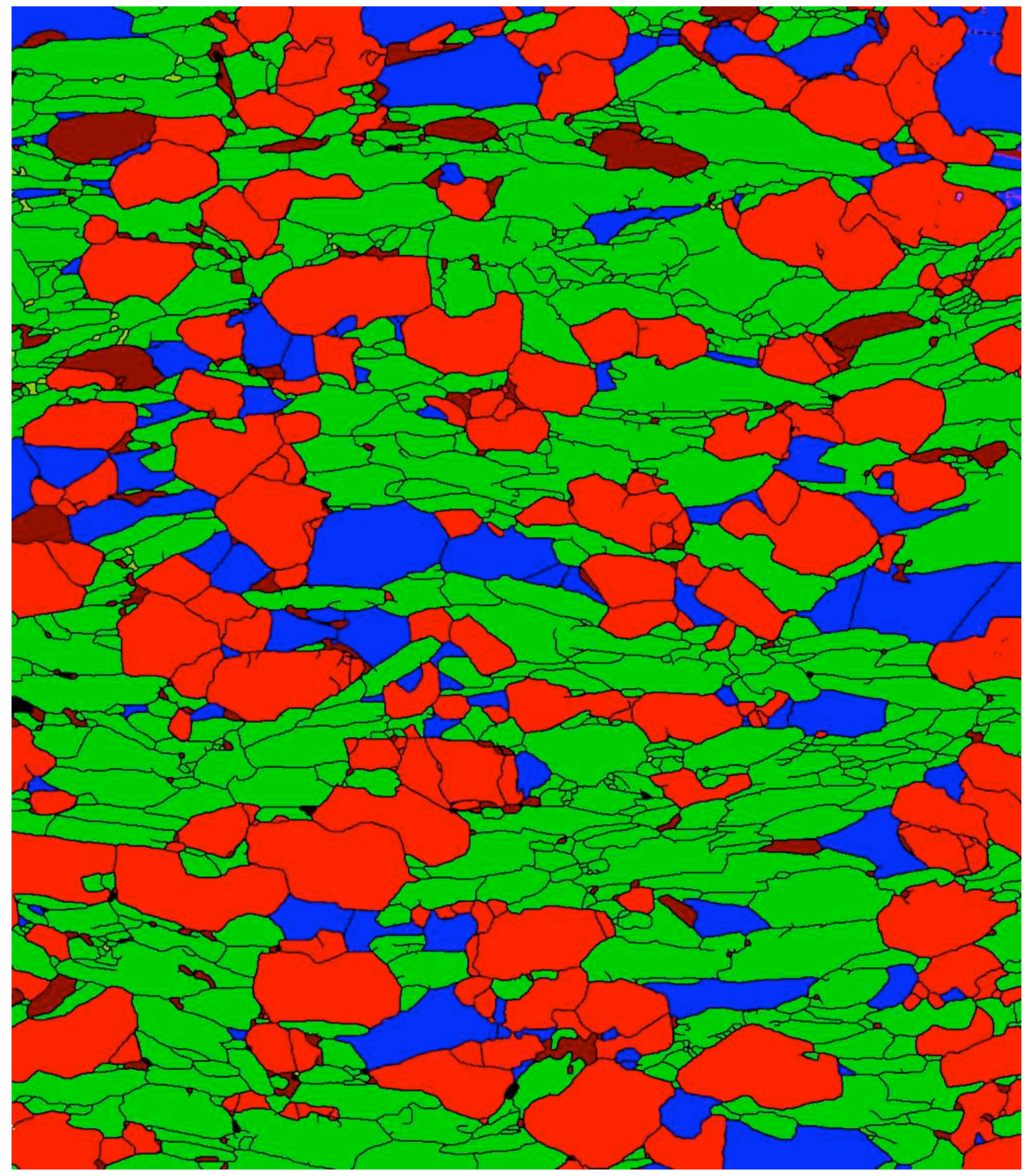
James XZ (M3)



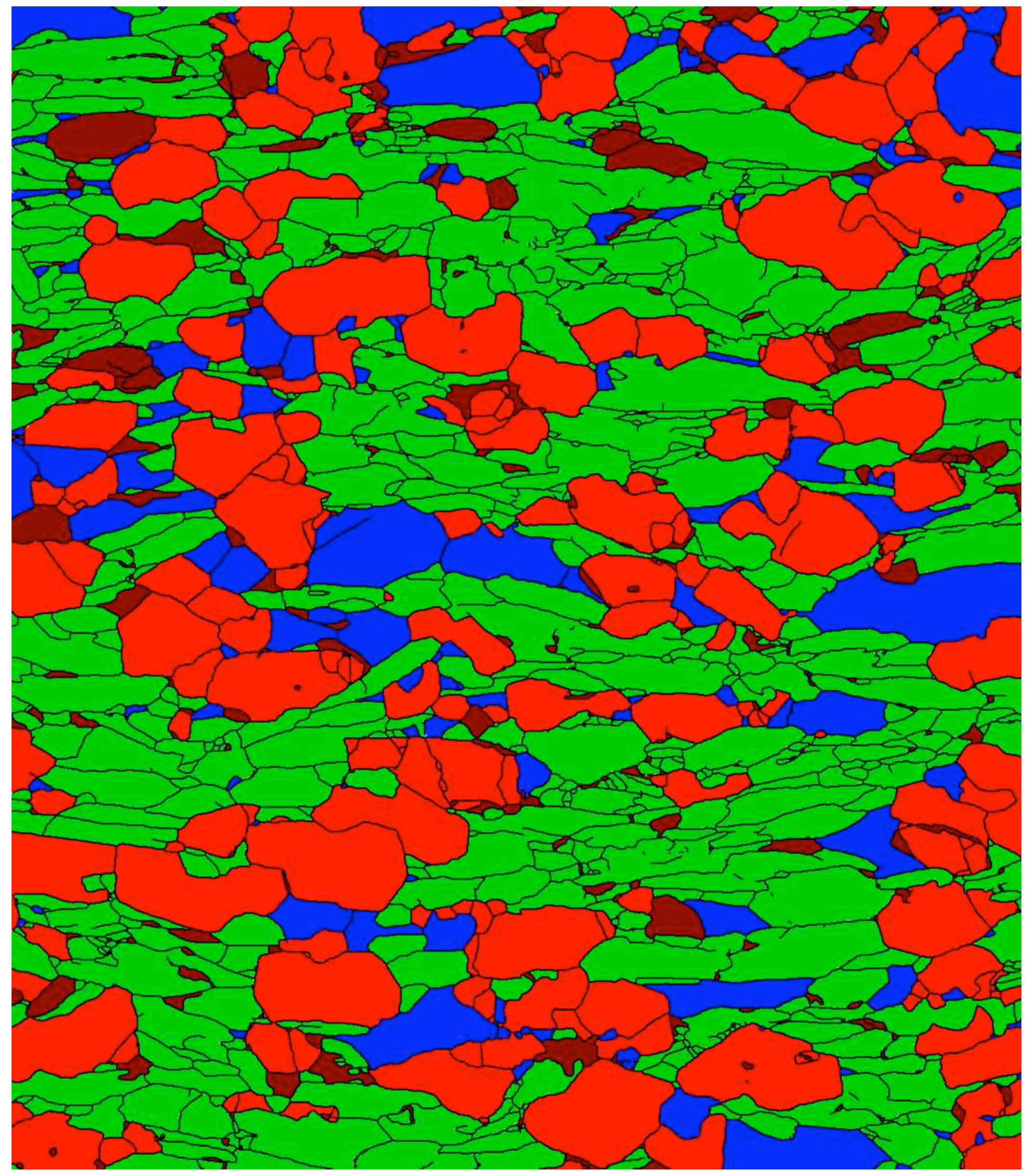
Horst



Luca



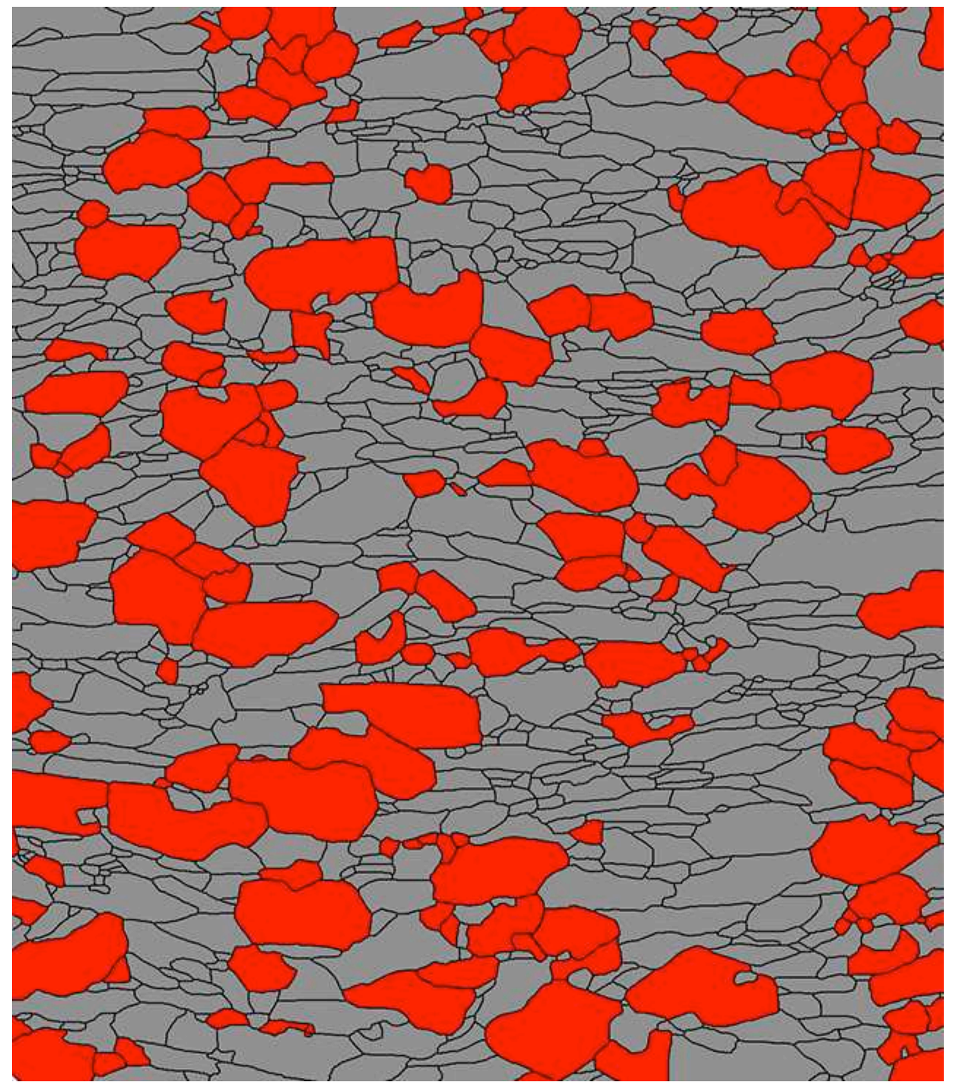
Victoria



Nynke

to overview >>

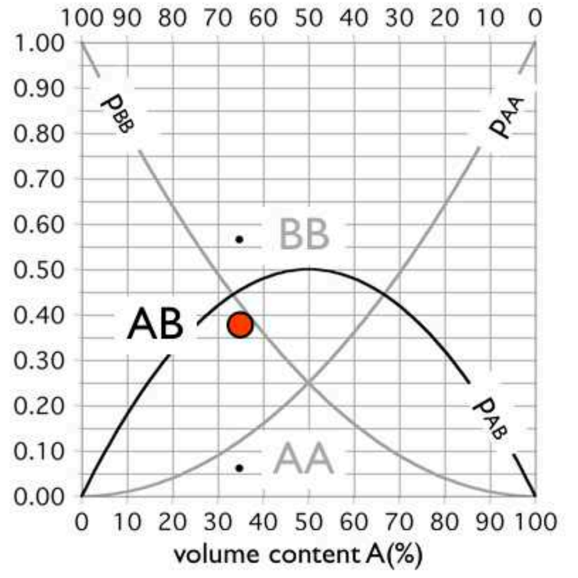
additional info (3)



garnet in eclogite

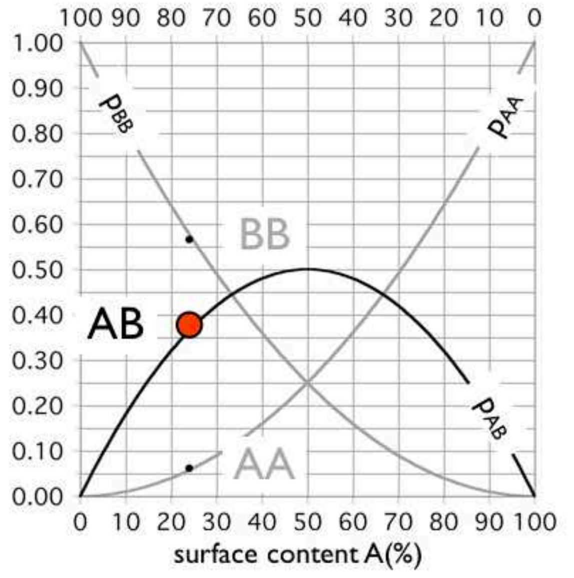
Note:
Same volume fraction
different surface fraction.
⇒ Importance of choosing
the right definition for
'fraction'

vol%



in terms of volume proportions

surf%

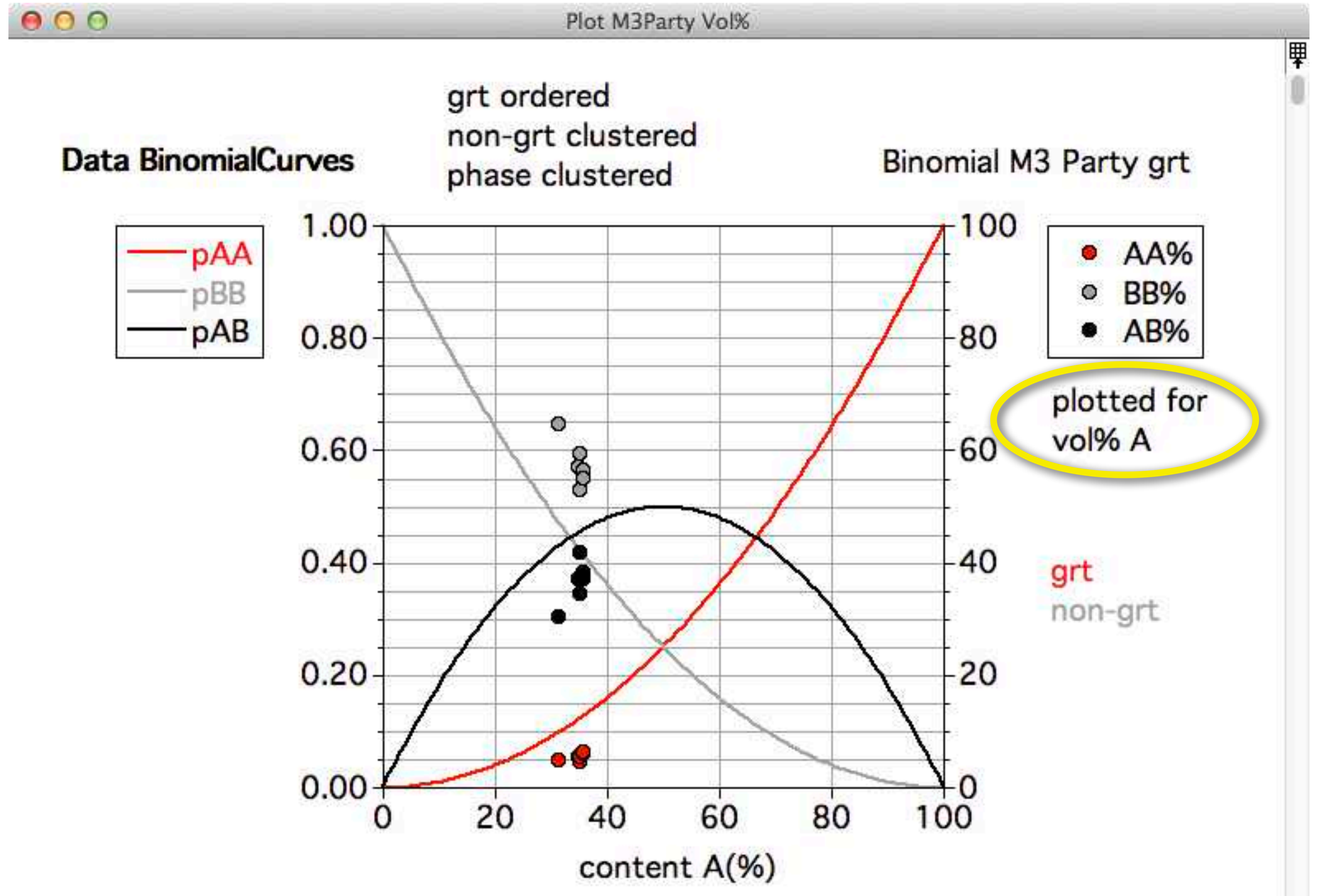


in terms of surface proportions

interpretation:

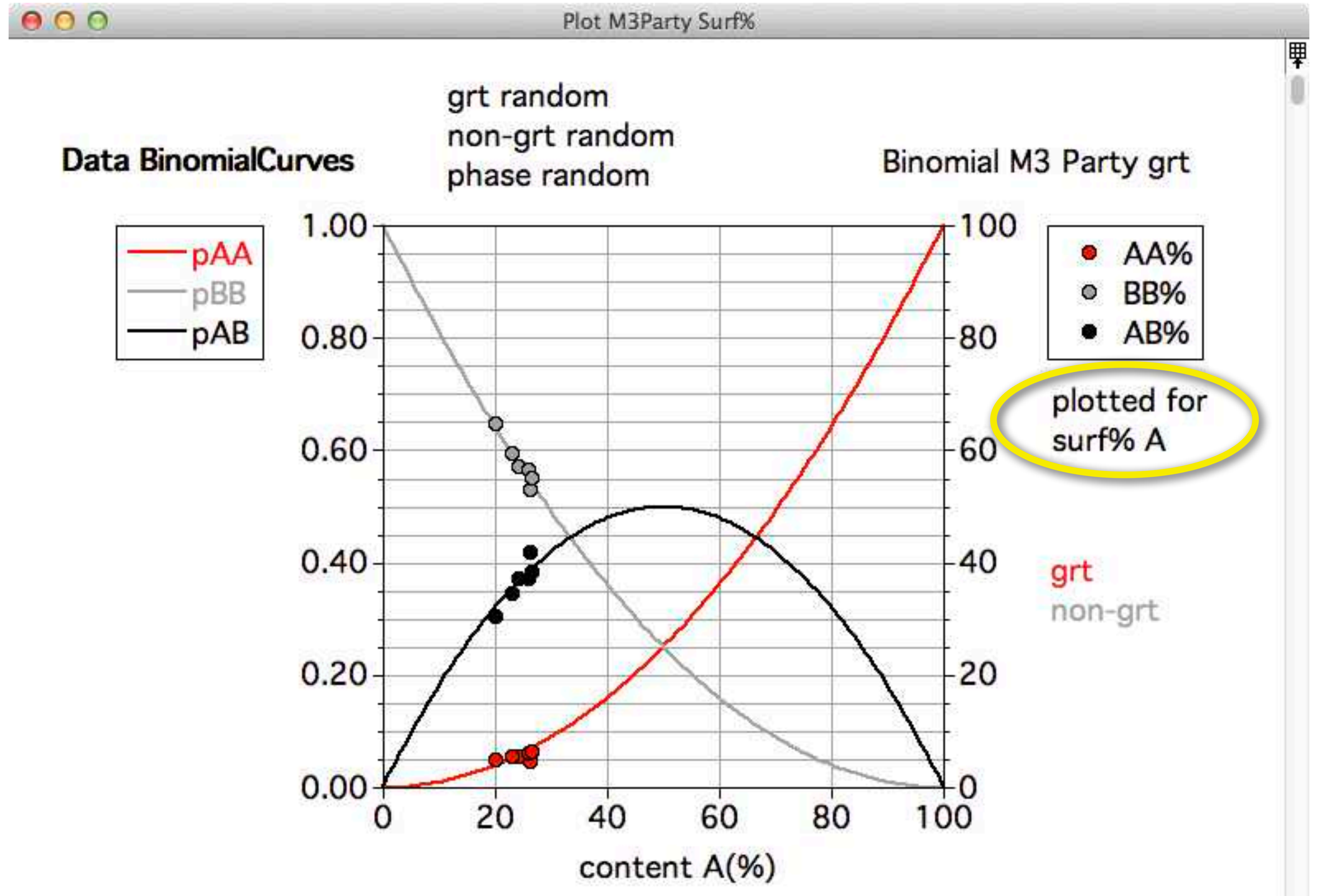
vol%	surf%
AB ~ random - clustered	AB random
AA anticlustered	AA random
BB clustered	BB random

plotting for volume %



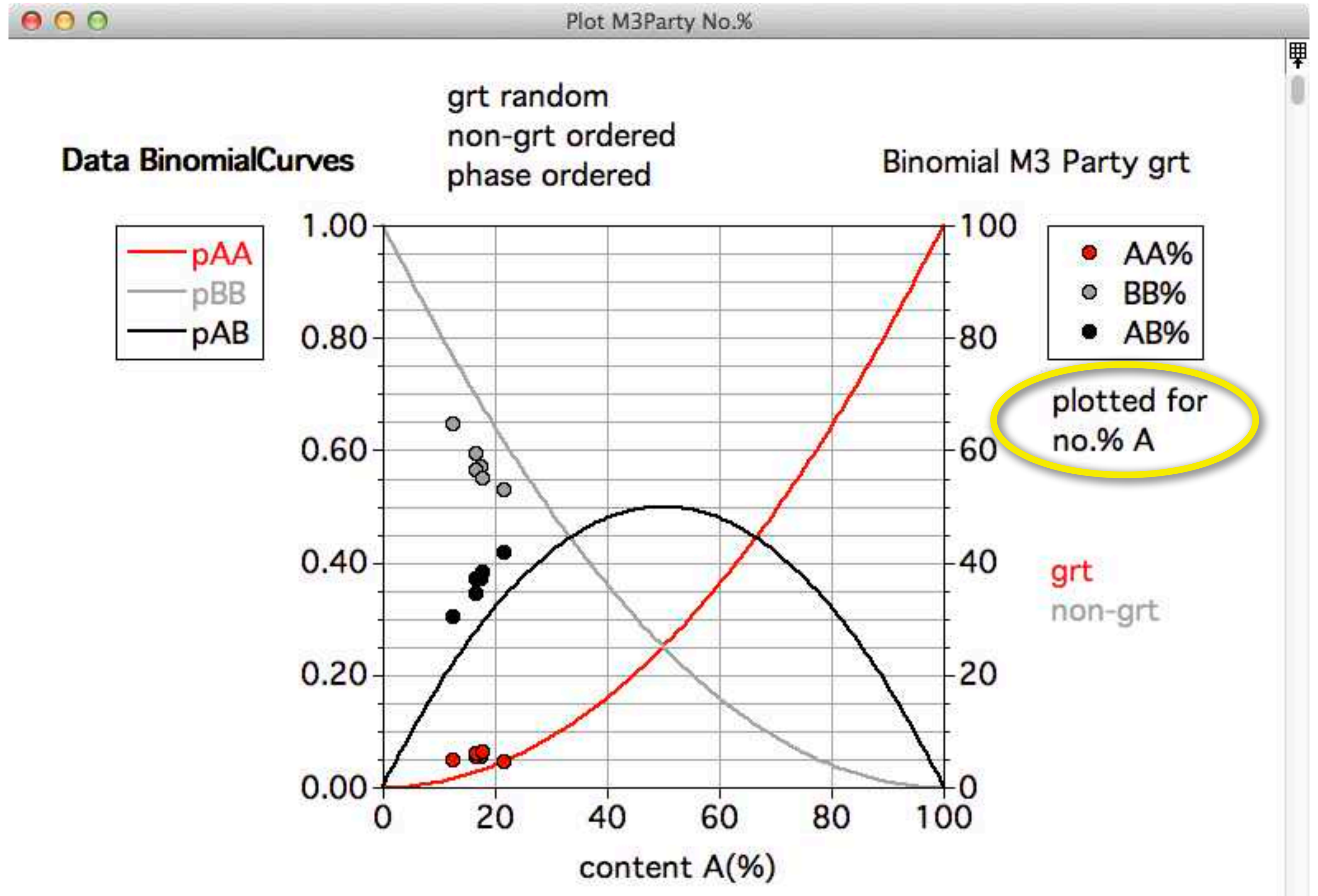
⇒ clustering

plotting for surface %



fit on random curves

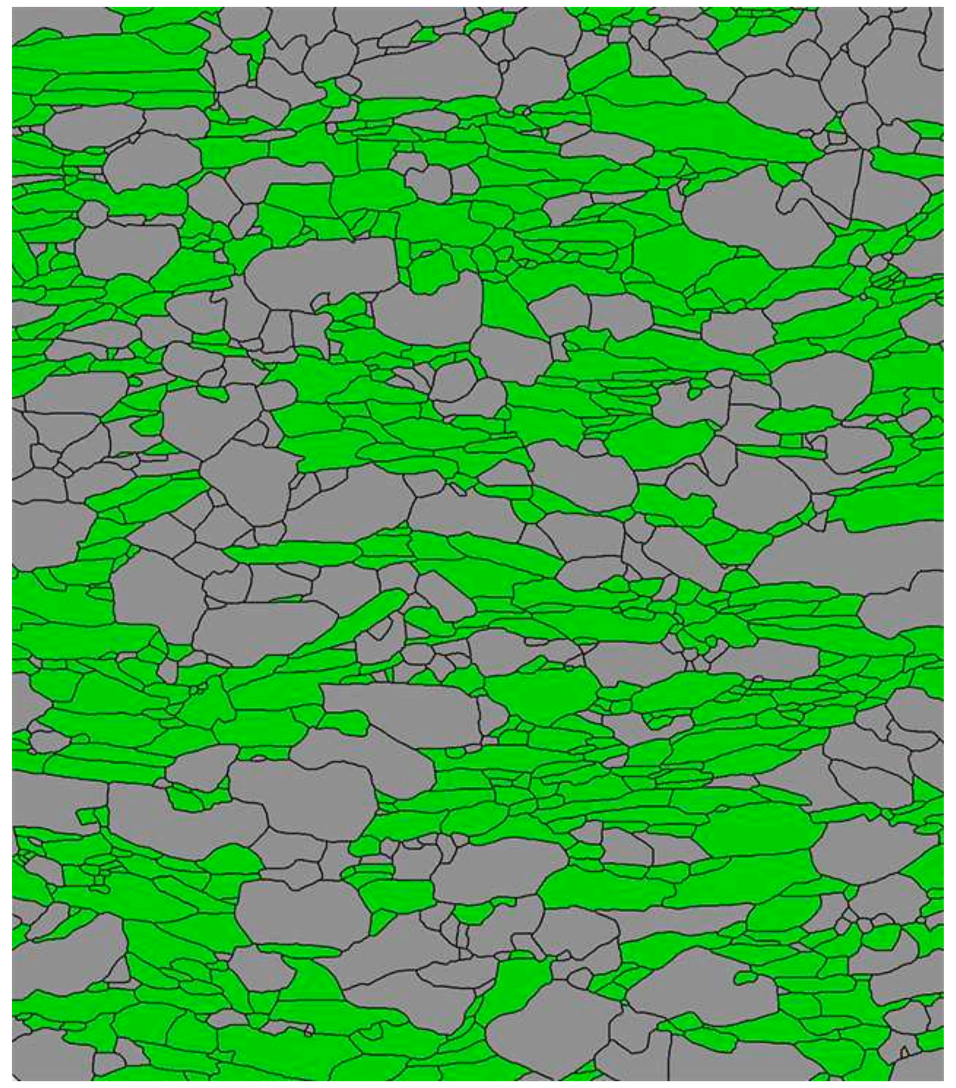
plotting for number %



⇒ ordering ?

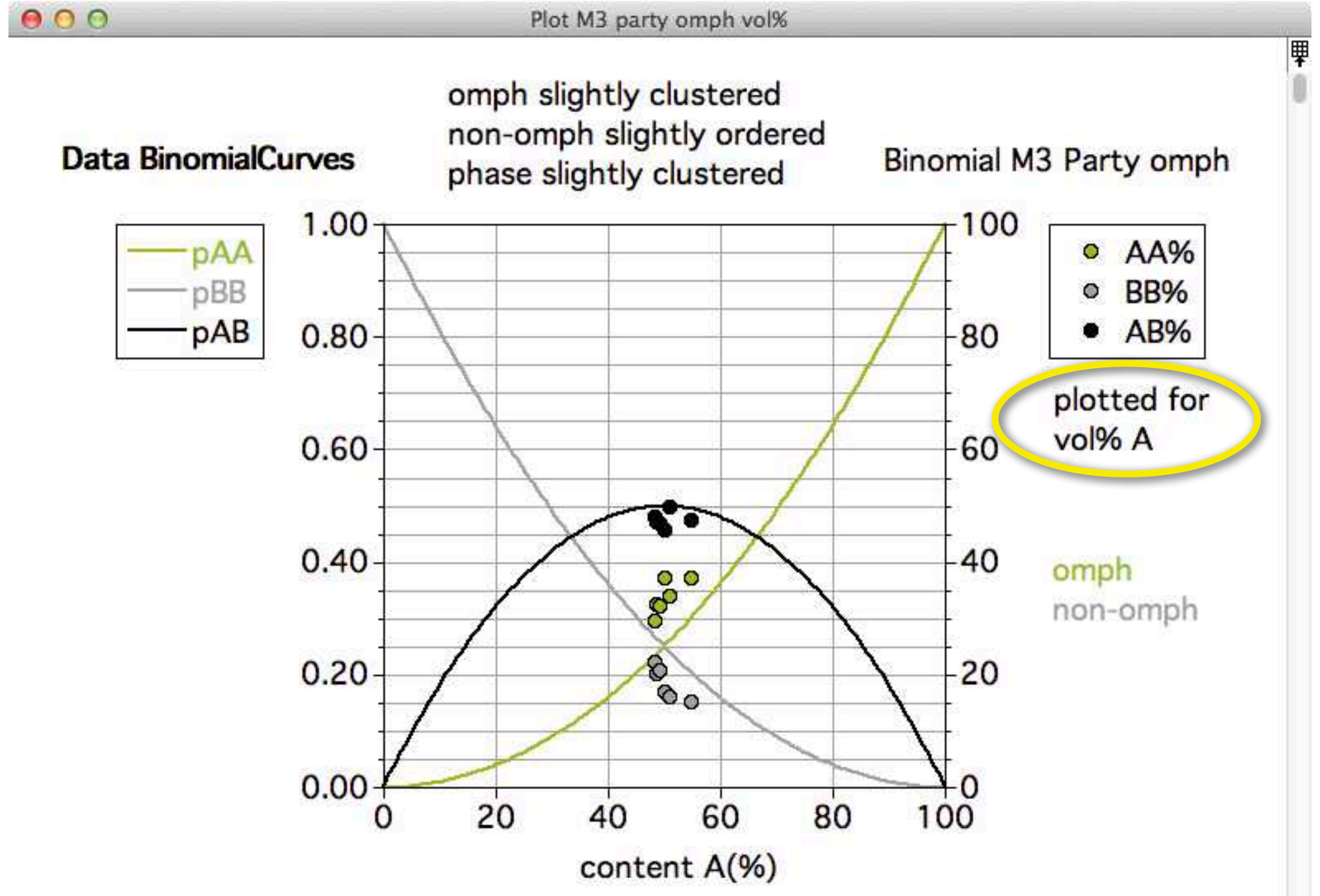
<< to overview >>

additional info (3)



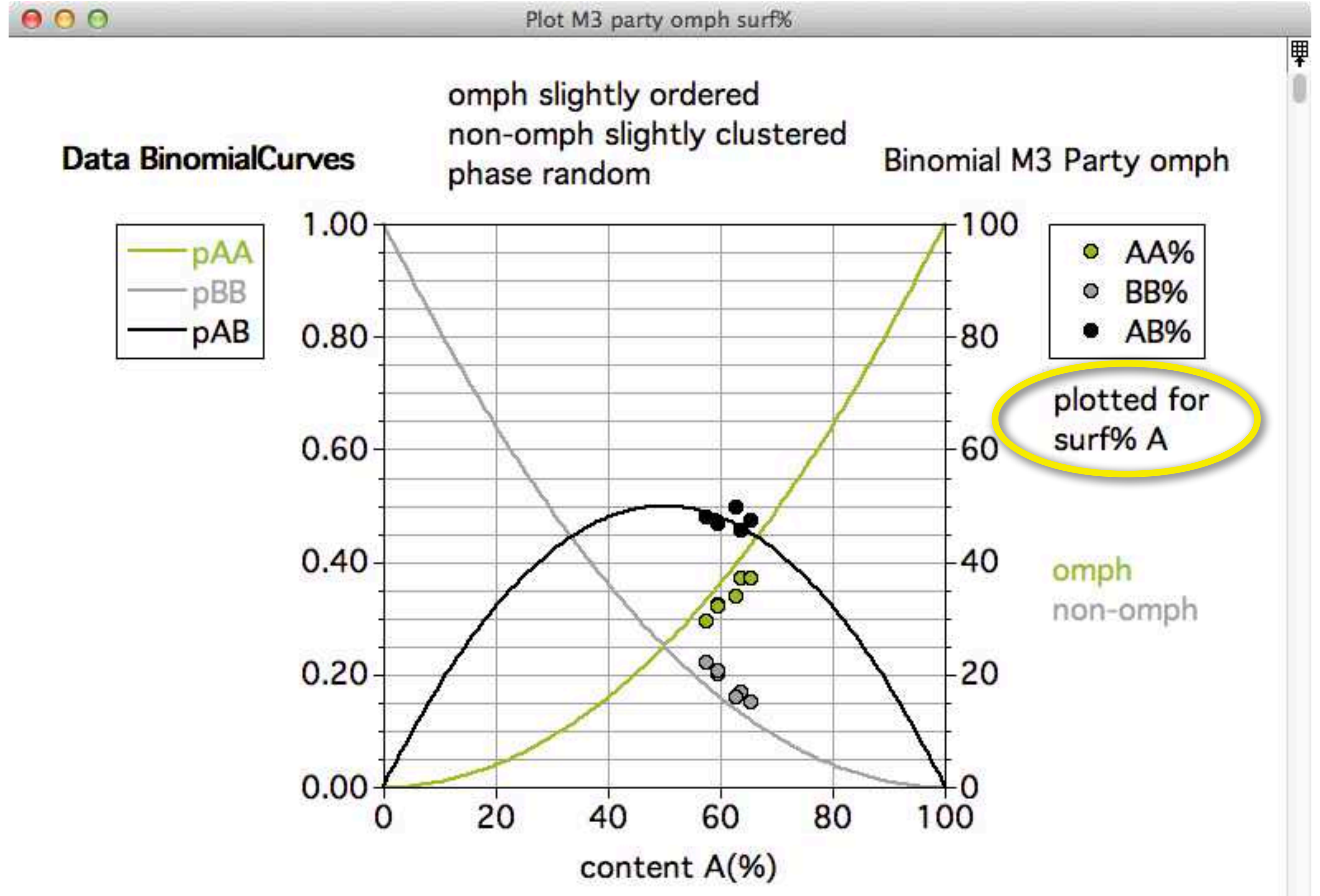
omphacite in eclogite

plotting for volume %



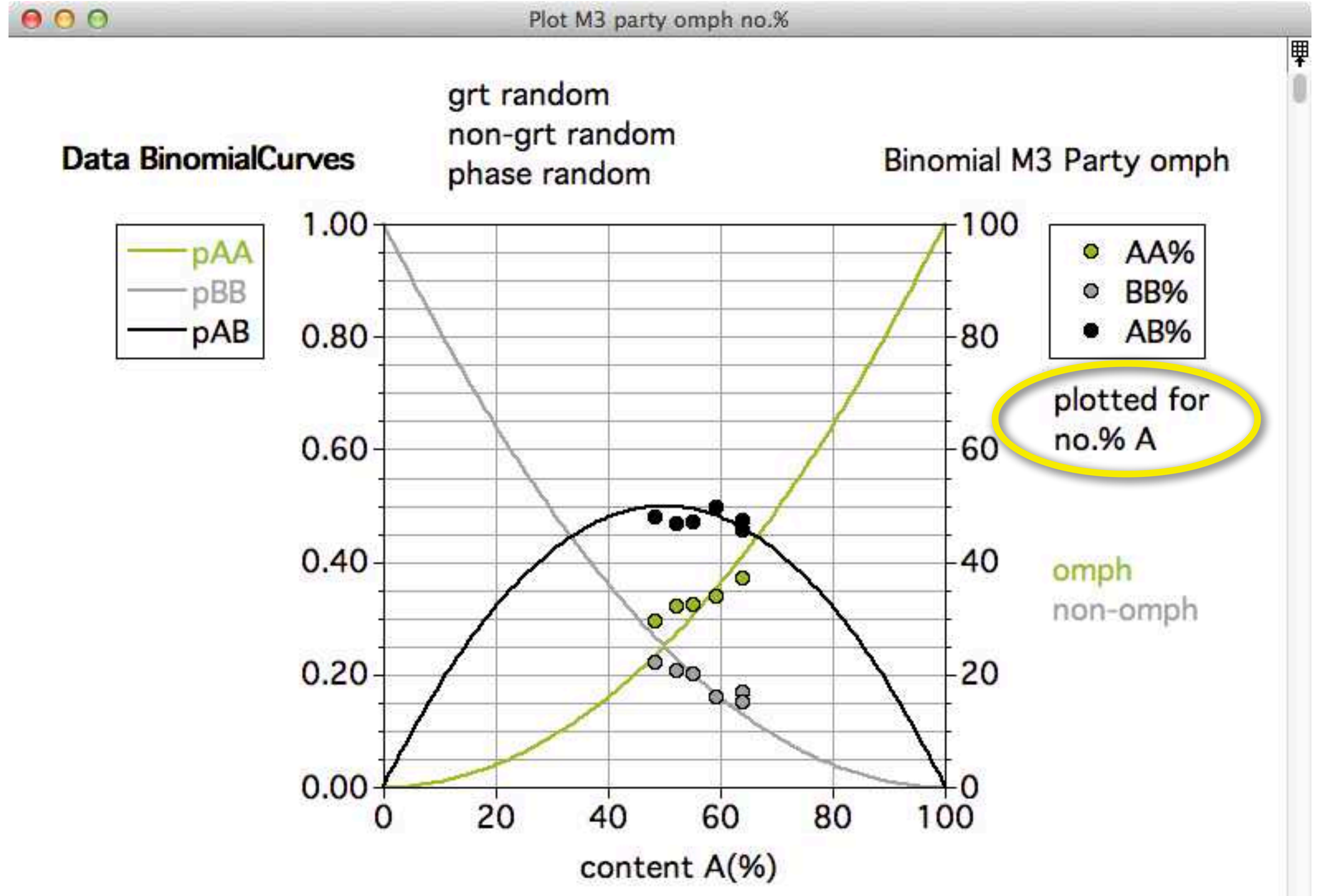
⇒ contradictory

plotting for surface %



± fit on random curves

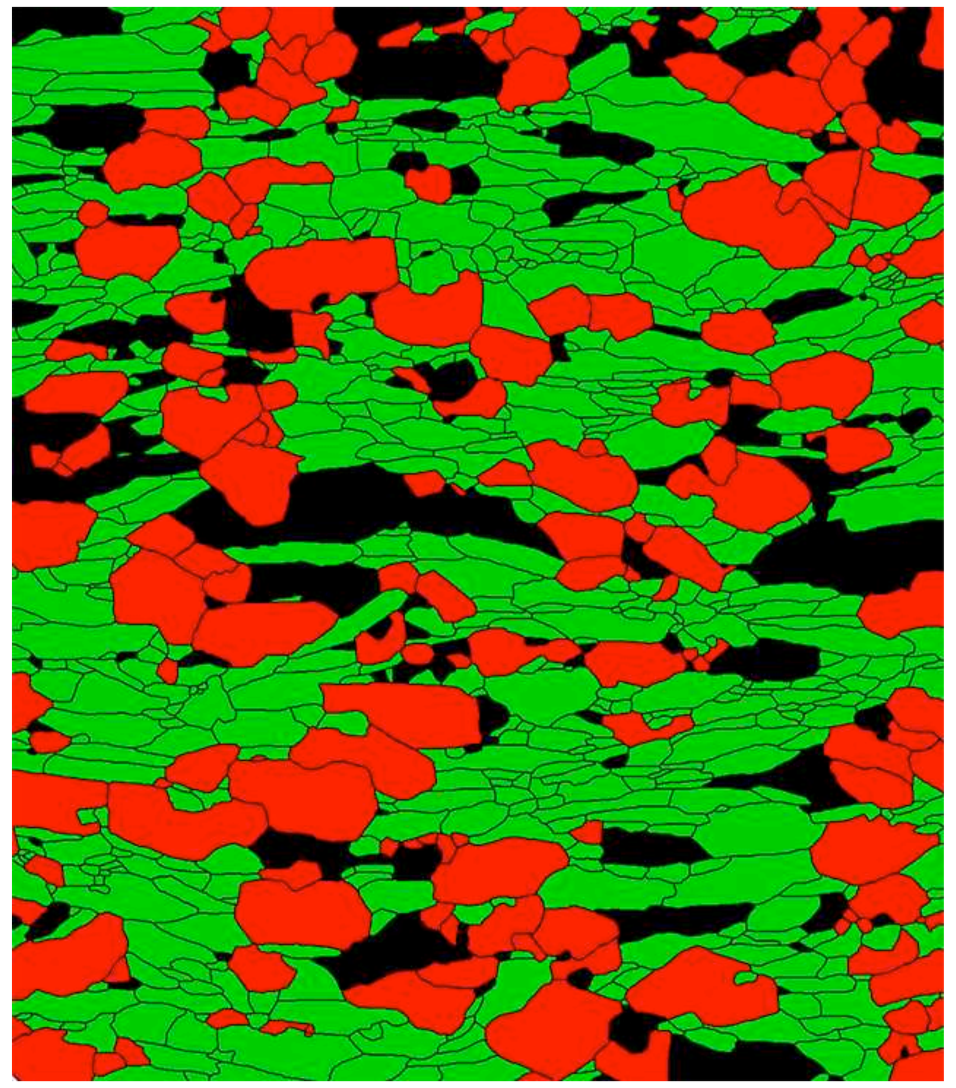
plotting for number %



± fit on random curves

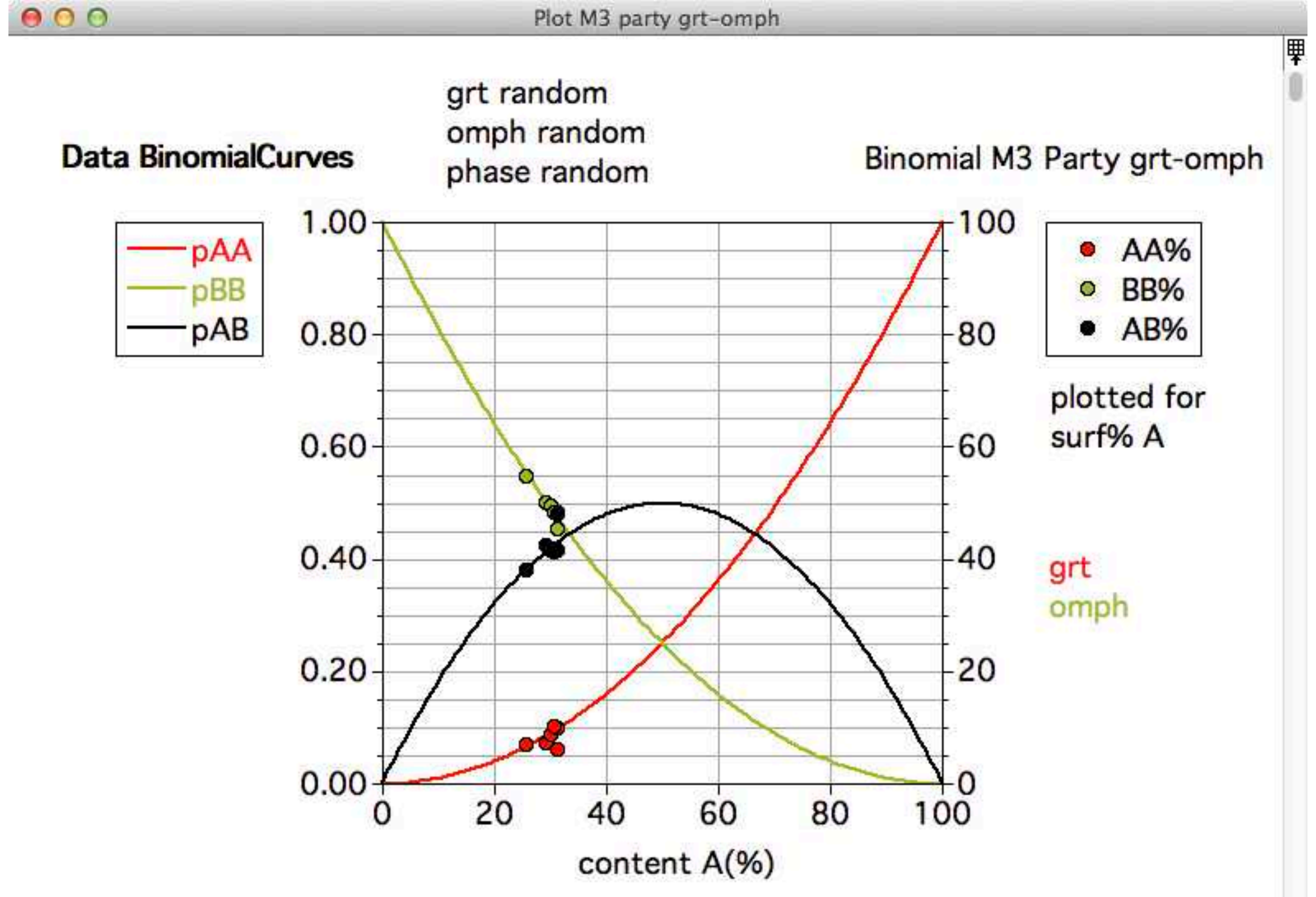
<< to overview >>

additional info (3)

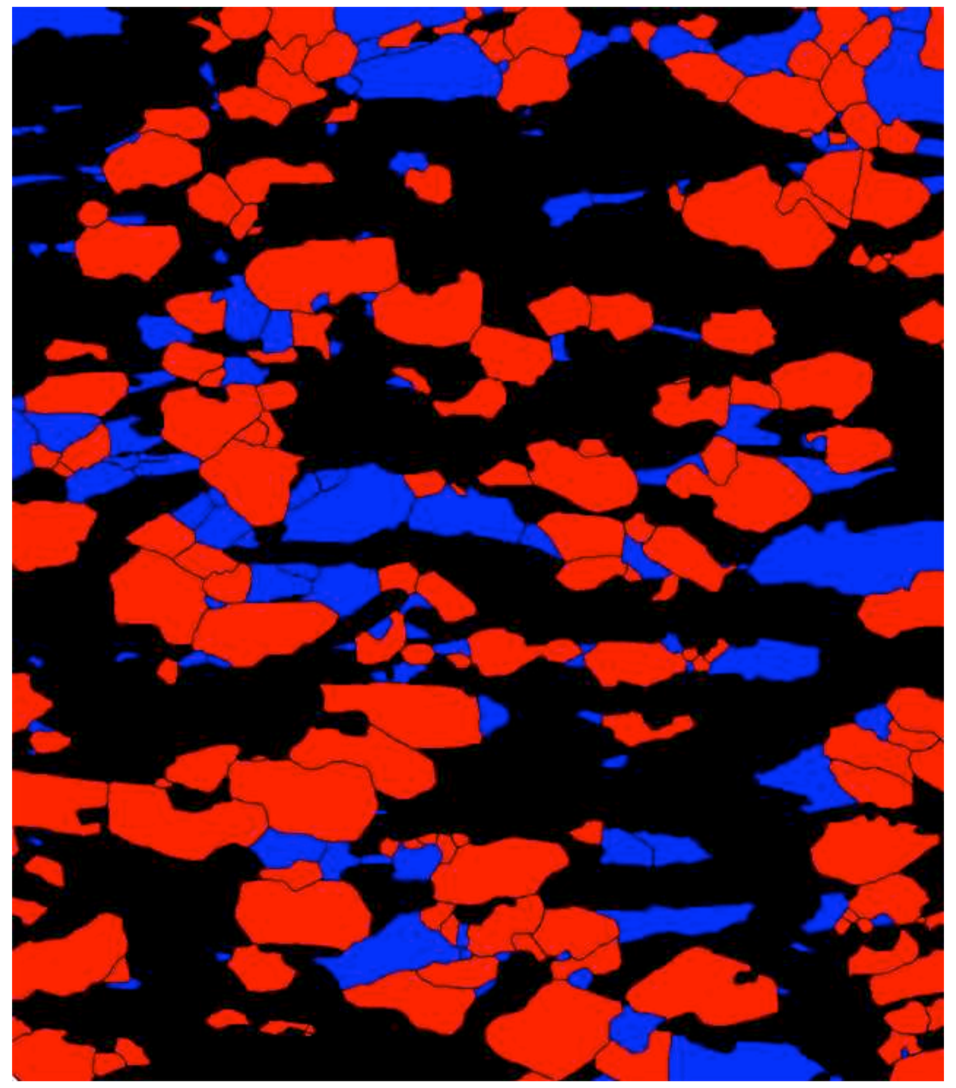


garnet and omphacite

plotting for surface %

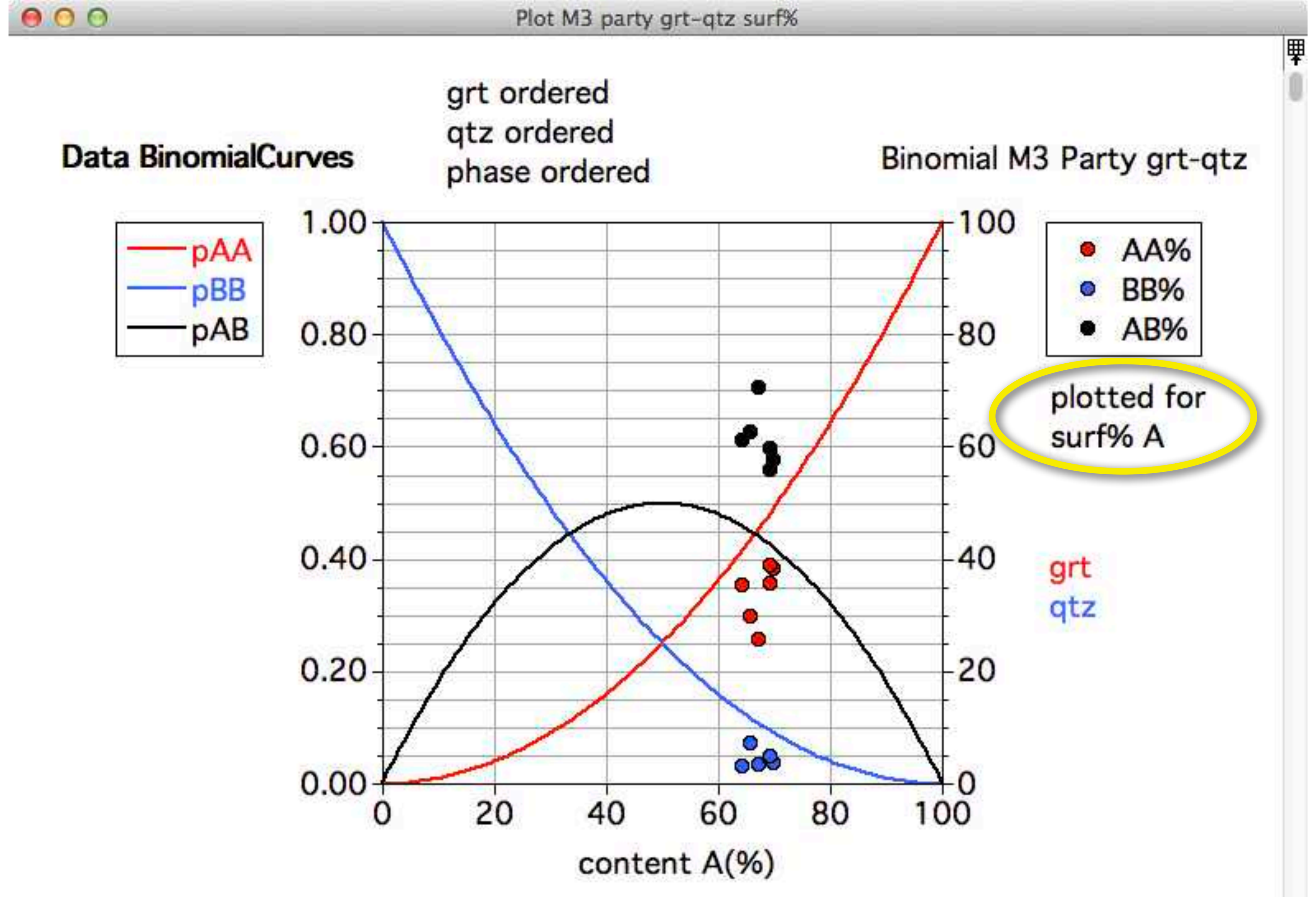


random



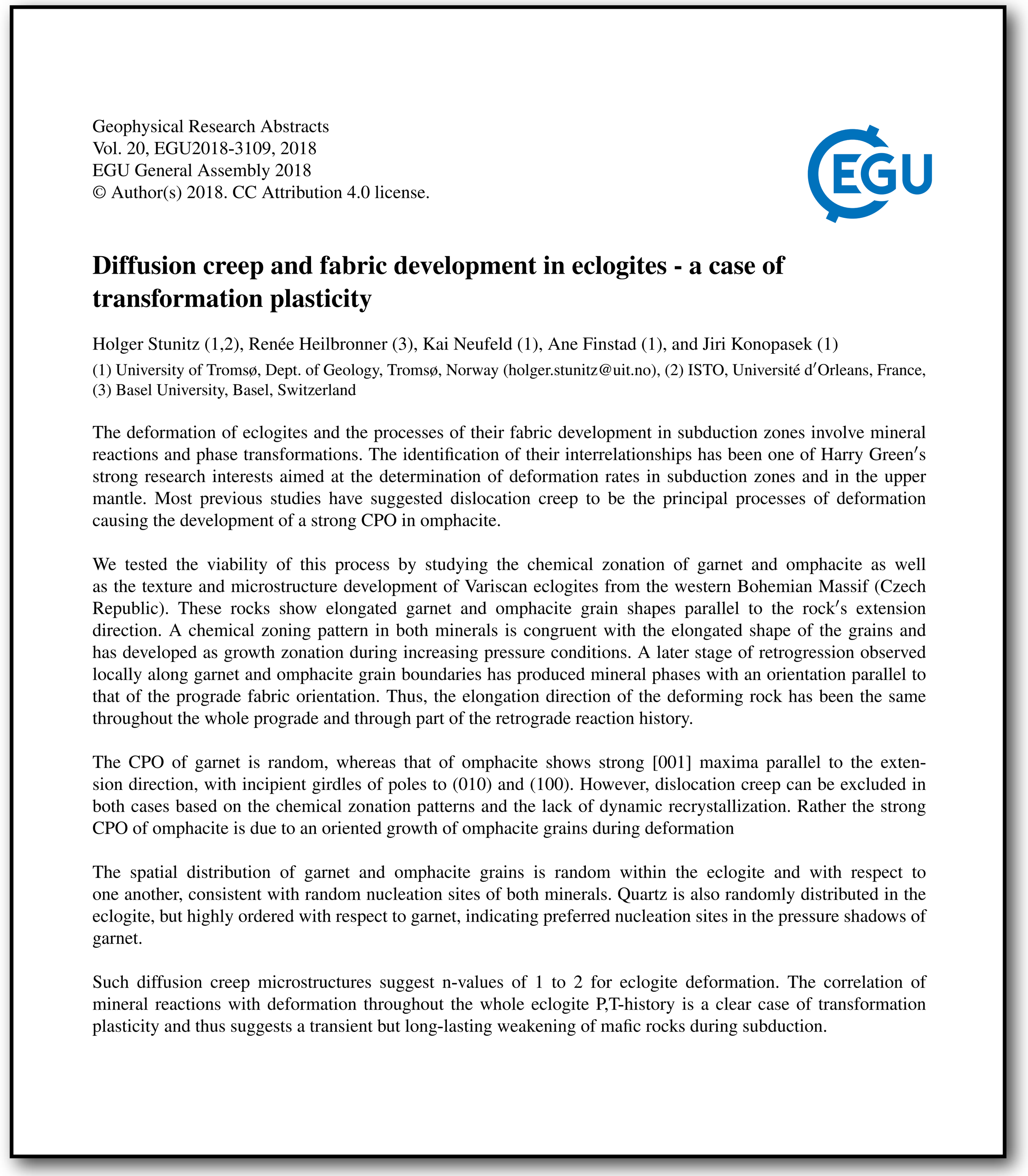
garnet and quartz

plotting for surface %



ordered

see also EGU2018-3109
Poster session EMPR1.8 / SM2.19 / TS3.11
Hall X2 Monday 17:30 - 19:00



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Diffusion creep and fabric development in eclogites - a case of transformation plasticity

Holger Stunitz (1,2), Renée Heilbronner (3), Kai Neufeld (1), Ane Finstad (1), and Jiri Konopasek (1)
(1) University of Tromsø, Dept. of Geology, Tromsø, Norway (holger.stunitz@uit.no), (2) ISTO, Université d'Orleans, France, (3) Basel University, Basel, Switzerland

The deformation of eclogites and the processes of their fabric development in subduction zones involve mineral reactions and phase transformations. The identification of their interrelationships has been one of Harry Green's strong research interests aimed at the determination of deformation rates in subduction zones and in the upper mantle. Most previous studies have suggested dislocation creep to be the principal processes of deformation causing the development of a strong CPO in omphacite.

We tested the viability of this process by studying the chemical zonation of garnet and omphacite as well as the texture and microstructure development of Variscan eclogites from the western Bohemian Massif (Czech Republic). These rocks show elongated garnet and omphacite grain shapes parallel to the rock's extension direction. A chemical zoning pattern in both minerals is congruent with the elongated shape of the grains and has developed as growth zonation during increasing pressure conditions. A later stage of retrogression observed locally along garnet and omphacite grain boundaries has produced mineral phases with an orientation parallel to that of the prograde fabric orientation. Thus, the elongation direction of the deforming rock has been the same throughout the whole prograde and through part of the retrograde reaction history.

The CPO of garnet is random, whereas that of omphacite shows strong [001] maxima parallel to the extension direction, with incipient girdles of poles to (010) and (100). However, dislocation creep can be excluded in both cases based on the chemical zonation patterns and the lack of dynamic recrystallization. Rather the strong CPO of omphacite is due to an oriented growth of omphacite grains during deformation

The spatial distribution of garnet and omphacite grains is random within the eclogite and with respect to one another, consistent with random nucleation sites of both minerals. Quartz is also randomly distributed in the eclogite, but highly ordered with respect to garnet, indicating preferred nucleation sites in the pressure shadows of garnet.

Such diffusion creep microstructures suggest n-values of 1 to 2 for eclogite deformation. The correlation of mineral reactions with deformation throughout the whole eclogite P,T-history is a clear case of transformation plasticity and thus suggests a transient but long-lasting weakening of mafic rocks during subduction.

<< to overview

additional info (4)

determination of mode by Gaussian fit

opx

ol

Table 1
Summary of the Experiments

	Undeformed sample		Deformed sample							
Experiment #	PT-983	991	PT-994	996	984	998	1024	990	1006	1012
Flow Stress (MPa)	-	-	108	82	96	118	99	93	76	72
Strain Rate (10^{-4} s^{-1})	-	-	2.47	0.32	1.90	4.64	2.30	1.65	2.13	4.62
Shear Strain	-	-	1.9	2.0	4.2	4.2	10.9	17.3	26.2	25.3
d_{EA_ol} (μm)	6.5	5.8	2.9	4.5	2.9	1.7	1.4	2.3	2.3	1.9
d_{EA_px} (μm)	5.2	4.1	1.7	2.4	1.9	1.1	1.1	1.3	1.3	1.0
d_{ol} (μm)	8.3	7.4	3.7	5.7	3.6	2.2	1.8	2.9	2.8	2.4
d_{px} (μm)	6.6	5.3	2.3	3.1	2.4	1.4	1.4	1.7	1.6	1.3
μ_{h_ol} (μm)	7.8	4.6	3.2	3.0	3.2	1.3	1.7	1.7	2.5	1.4
μ_{h_px} (μm)	6.5	2.7	2.7	2.0	2.8	1.0	1.6	1.3	1.8	1.0
μ_{v_ol} (μm)	16.1	14.0	8.5	12.8	9.3	4.5	4.1	5.2	4.6	3.8
μ_{v_px} (μm)	14.5	12.6	4.4	5.6	4.9	2.6	2.2	2.1	2.3	1.6
N_{ol}	2643	881	1450	364	1319	290	2008	343	1300	527
N_{px}	1337	488	1504	566	2070	570	2175	640	1552	743
f_{px}	0.27	0.25	0.25	0.28	0.35	0.41	0.33	0.33	0.25	0.25

Note. N_{ol} and N_{px}: The number of analyzed olivine and pyroxene grain.

= 3D mode

compare

Check: Tasaka, M., Zimmerman, M. E., Kohlstedt, D. L., Stünitz, H., & Heilbronner, R. (2017). Rheological weakening of olivine + orthopyroxene aggregates due to phase mixing: Part 2. Microstructural development. Journal Geophysical Research: Solid Earth, 122, 7597–7612. https://doi.org/10.1002/ 2017JB014311

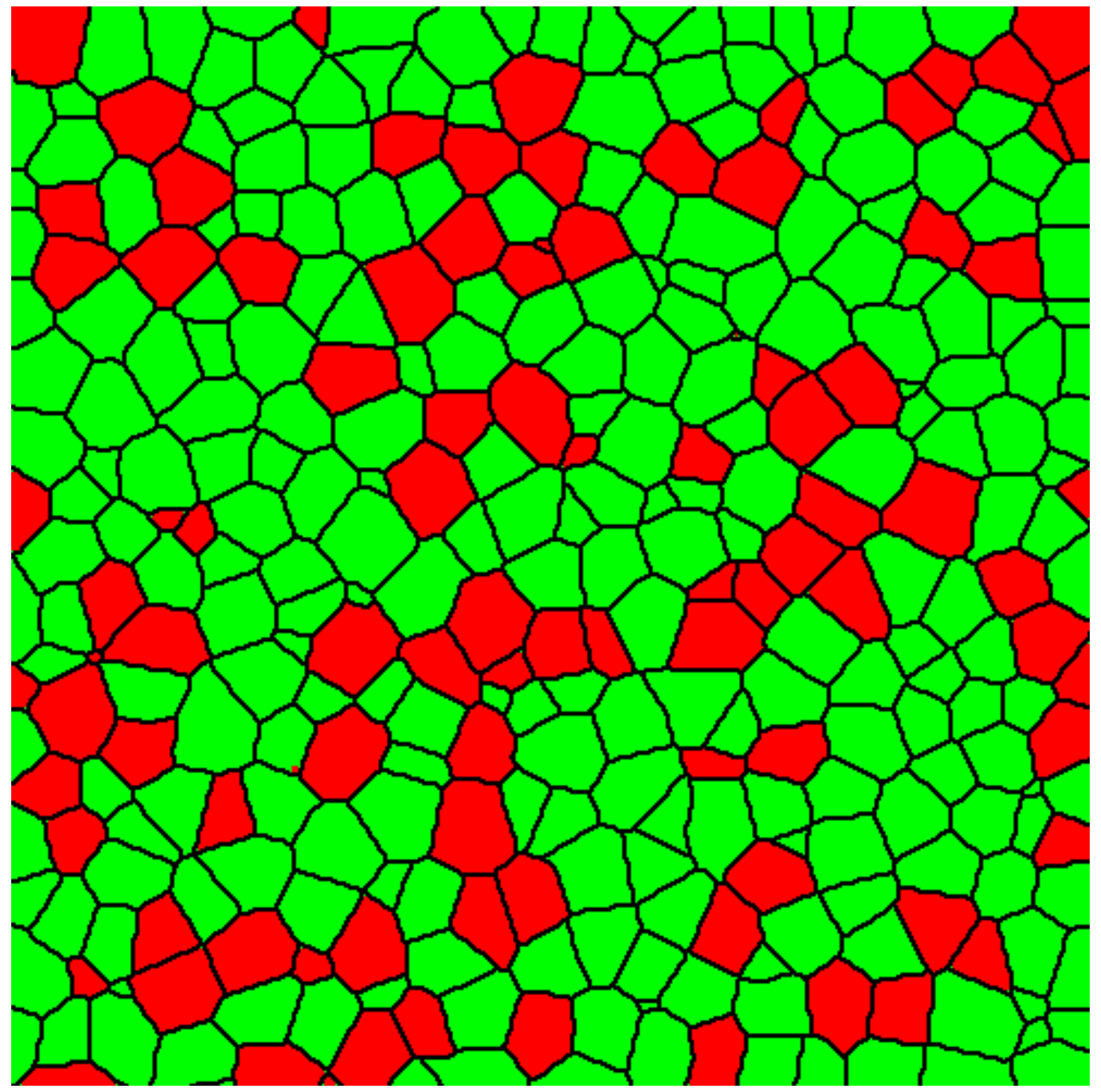
to overview

Anisotropic spatial clustering and ordering of olivine and orthopyroxene during rheological weakening conditions

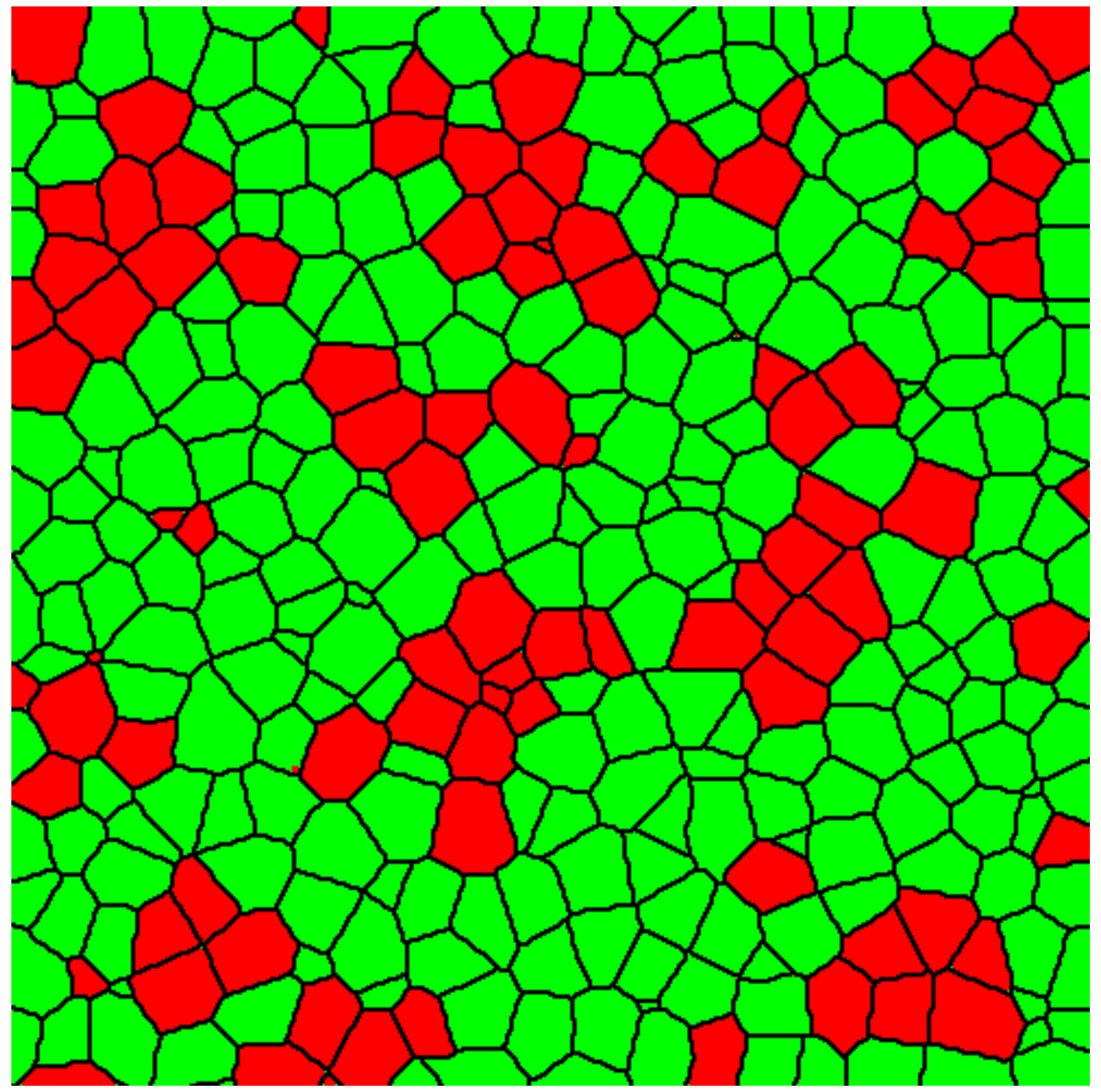
EGU2018-6888

Renée Heilbronner (1) and Miki Tasaka (2)
(1) Geological Institute, Basel University, Switzerland, (renee.heilbronner@unibas.ch),
(2) Department of Geoscience, Shimane University, Shimane, Japan

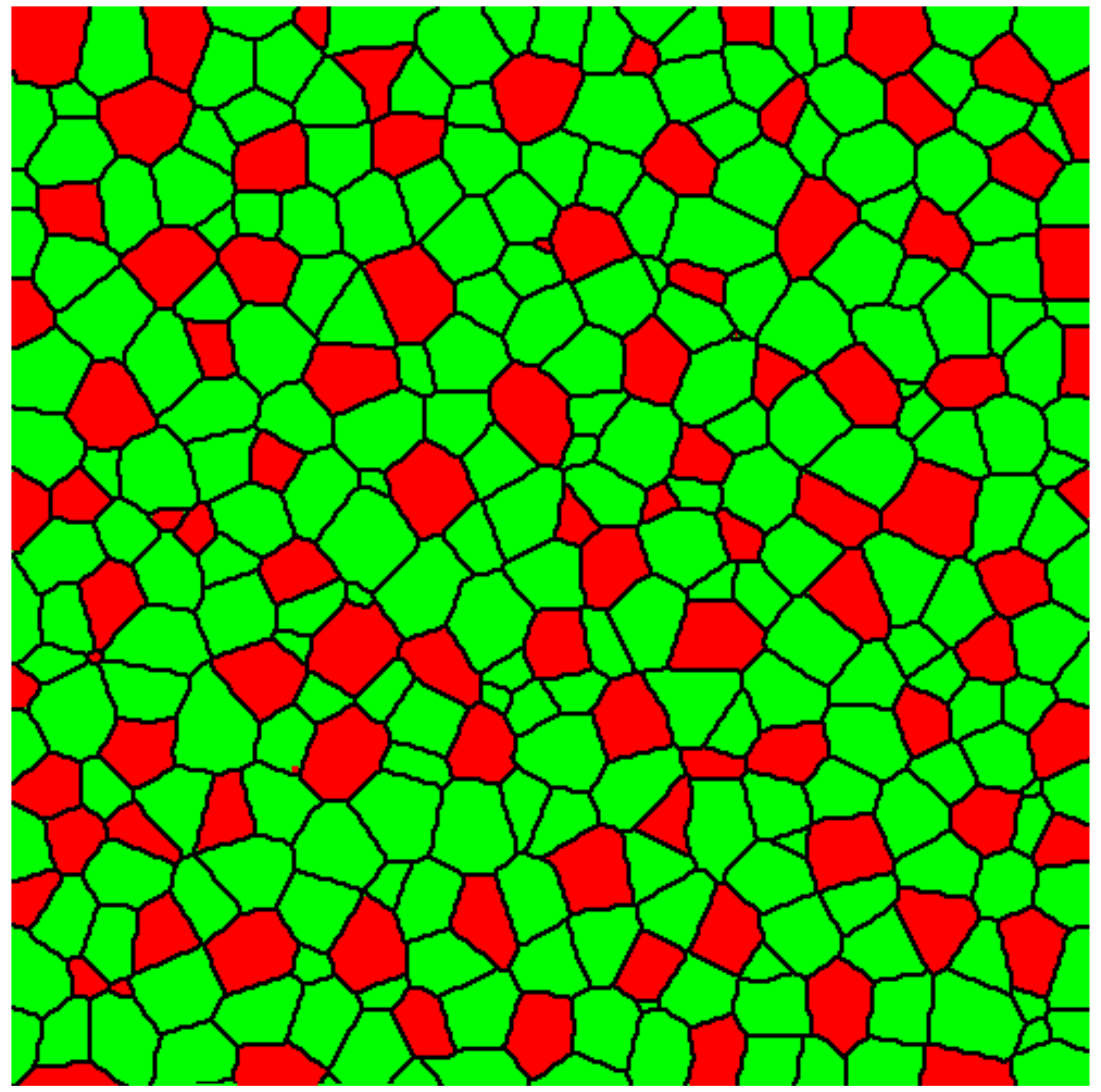
10 µm



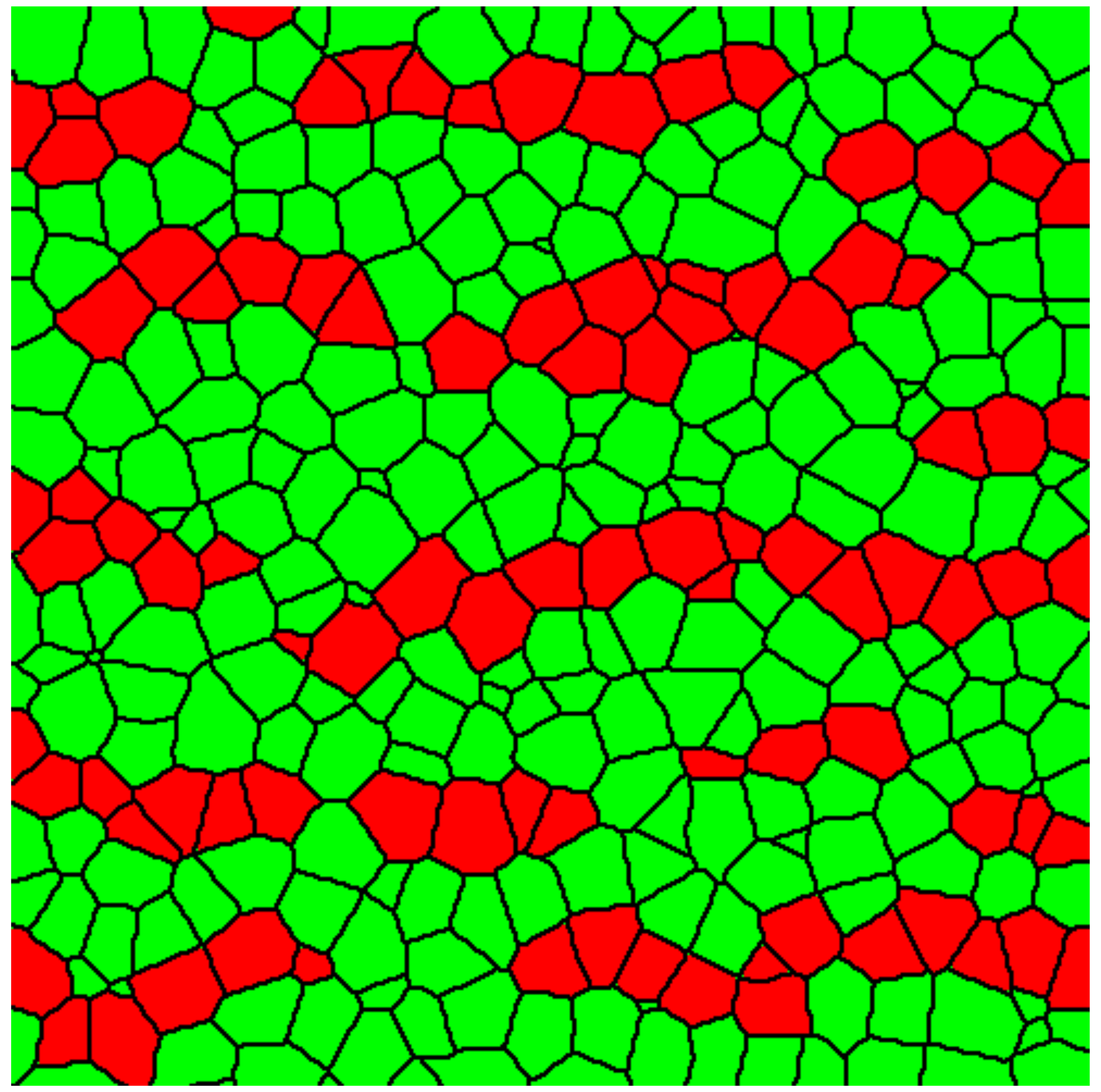
random



clustered



ordered



horizontally clustered
vertically ordered

Check: Tasaka, M., Zimmerman, M. E., Kohlstedt, D. L., Stünitz, H., & Heilbronner, R. (2017). Rheological weakening of olivine + orthopyroxene aggregates due to phase mixing: Part 2. Microstructural development. Journal Geophysical Research: Solid Earth, 122, 7597–7612. https://doi.org/10.1002/ 2017JB014311