the geometry of diffusion creep: what the microstructures of the Troms nappe eclogites can tell us about fast exhumation

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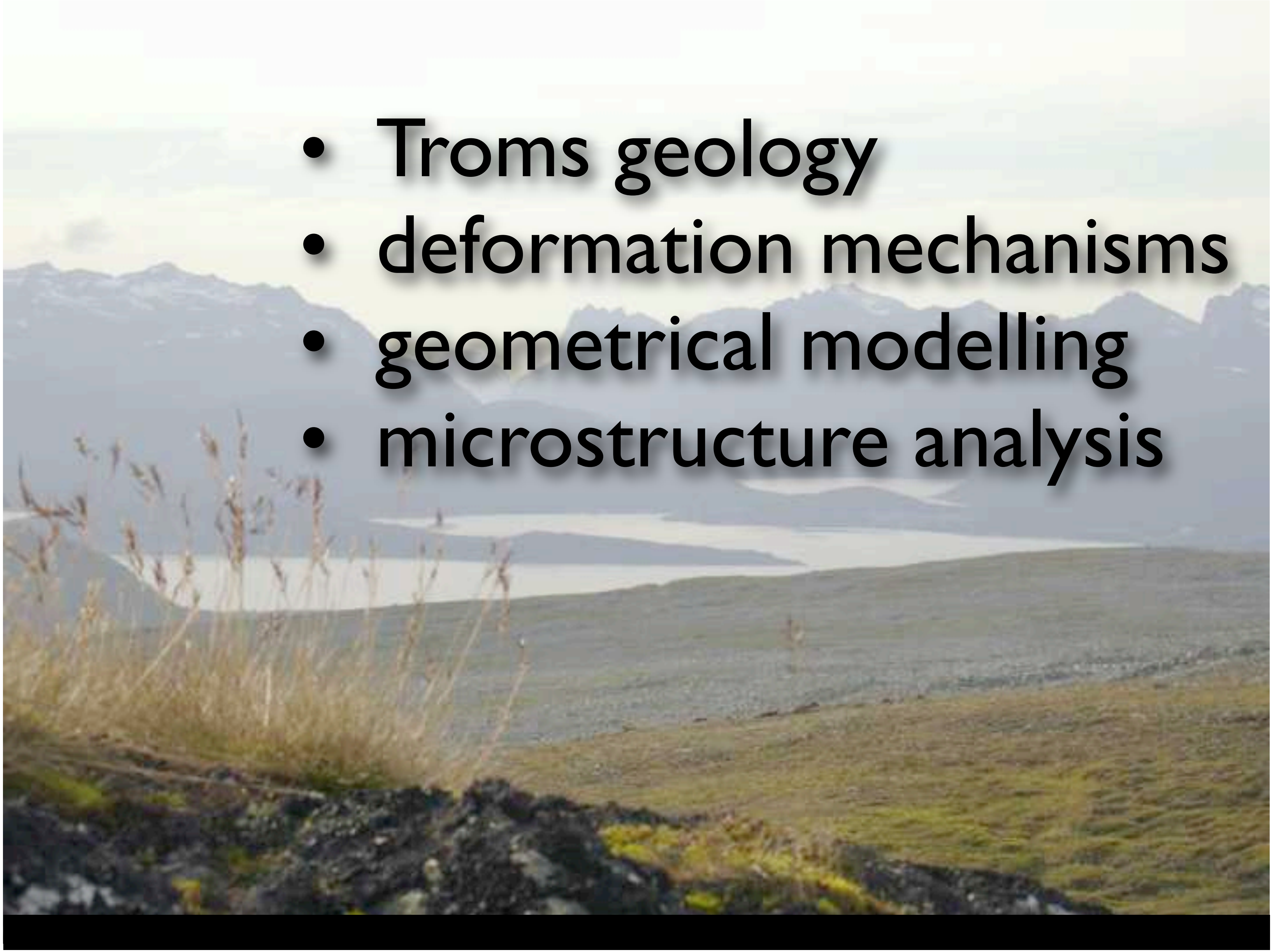
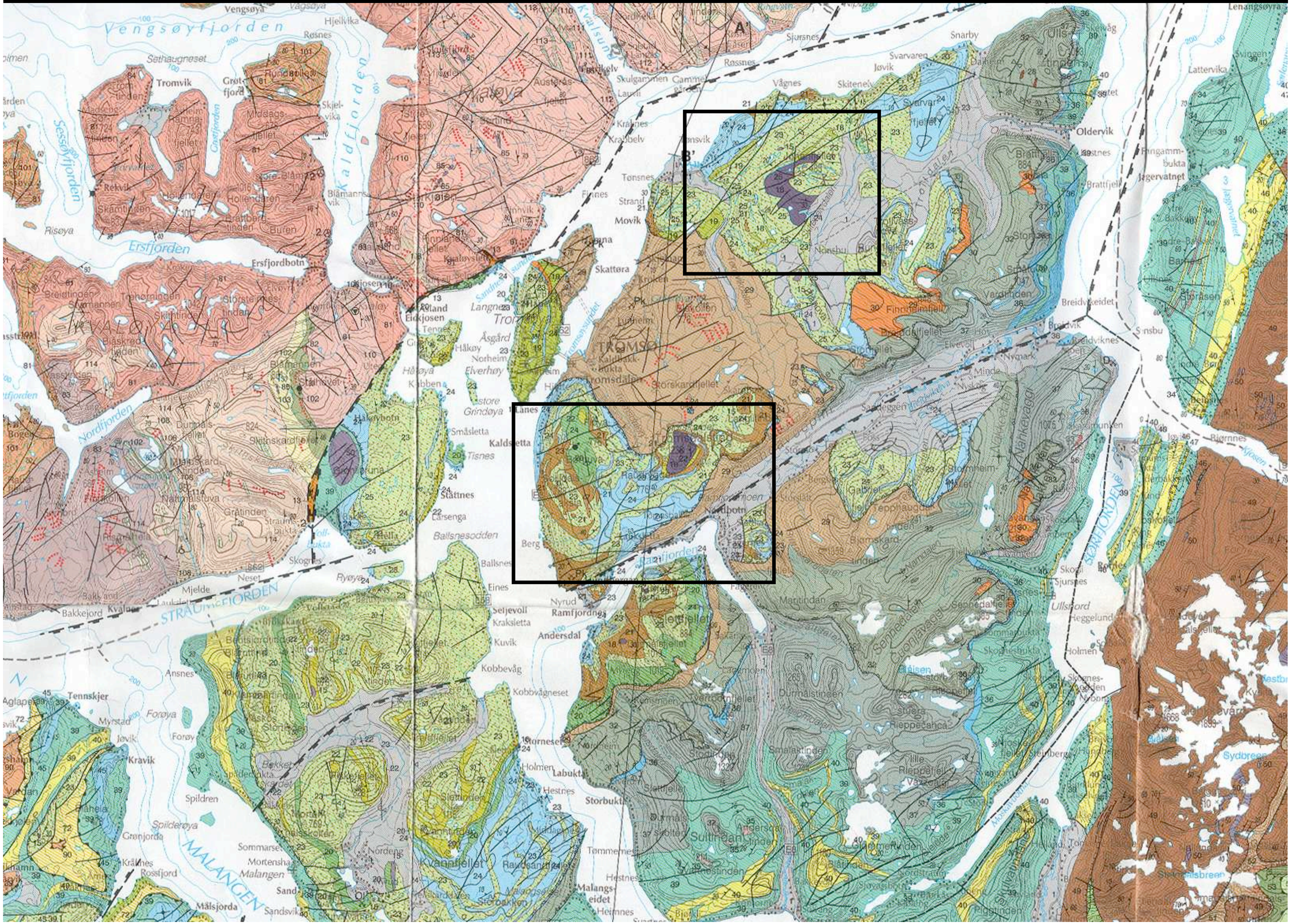
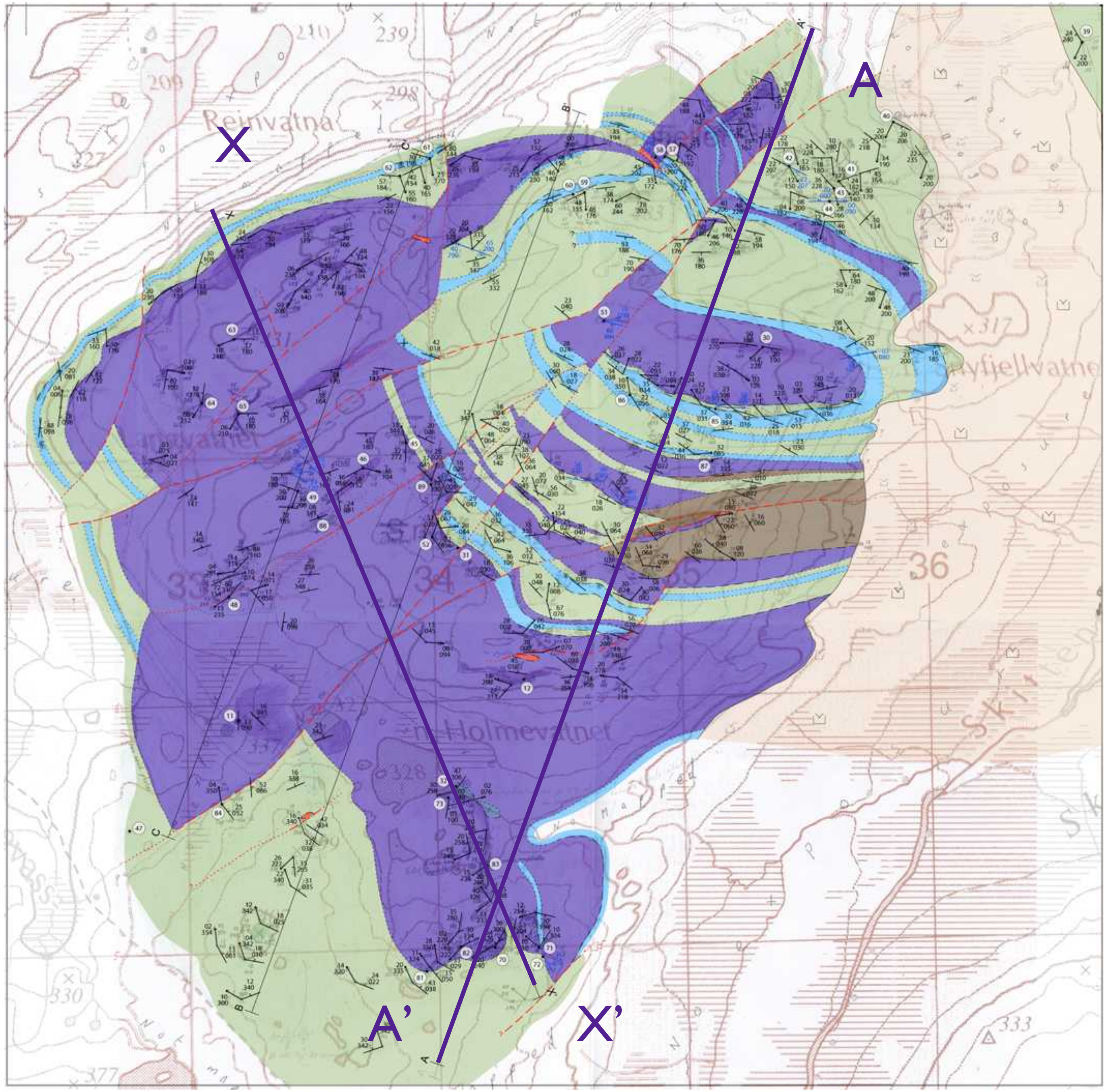

• Troms geology
• deformation mechanisms
• geometrical modelling
• microstructure analysis

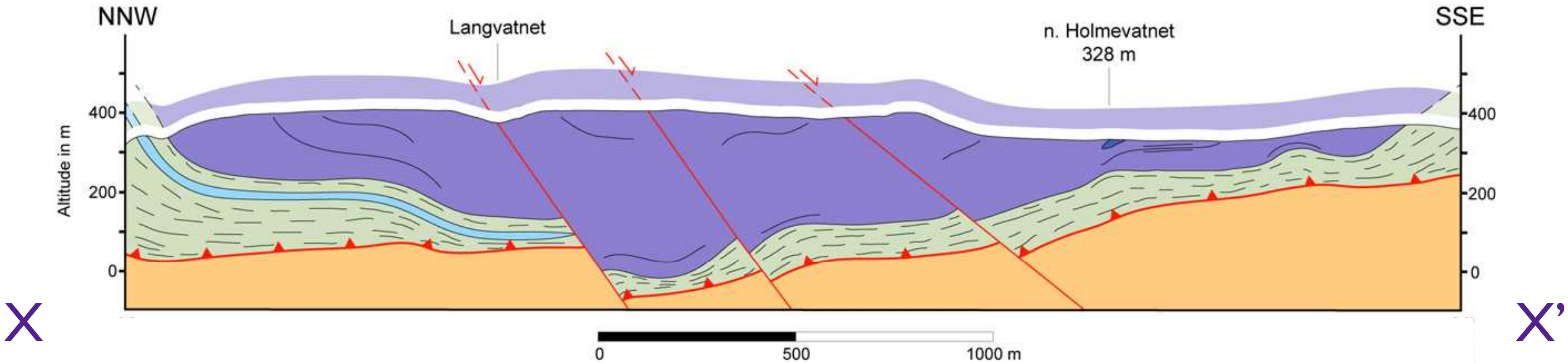
modified after Bergh & Andresen (1985)

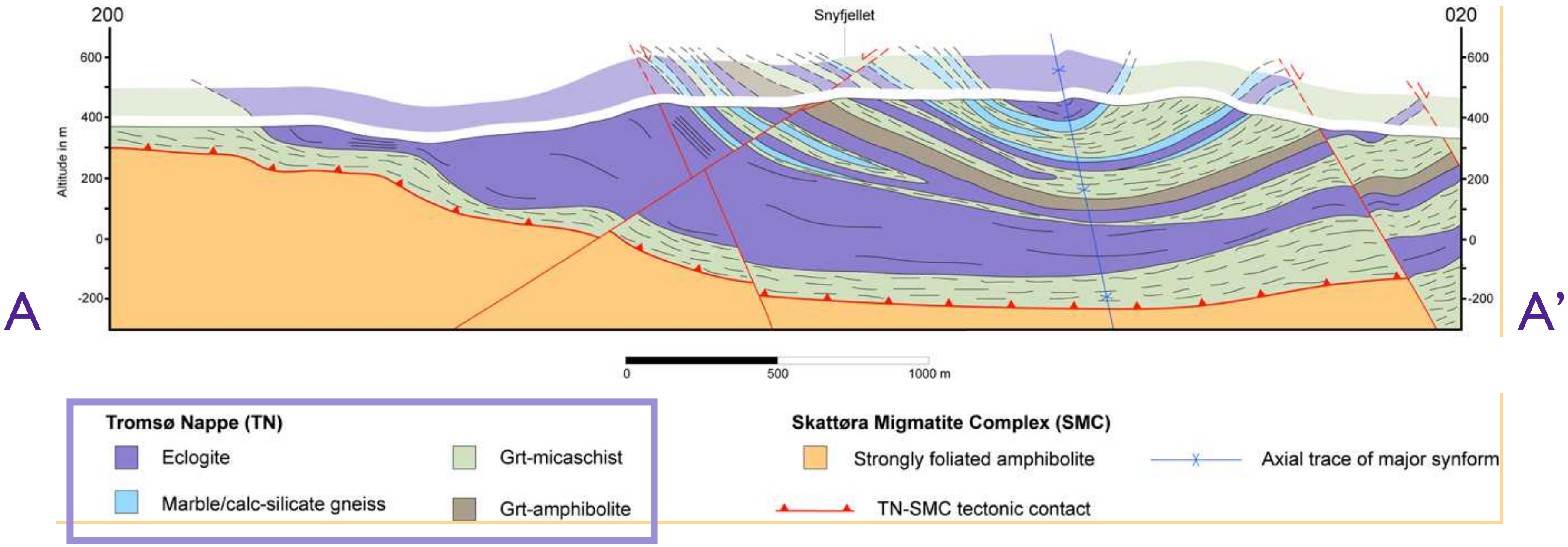


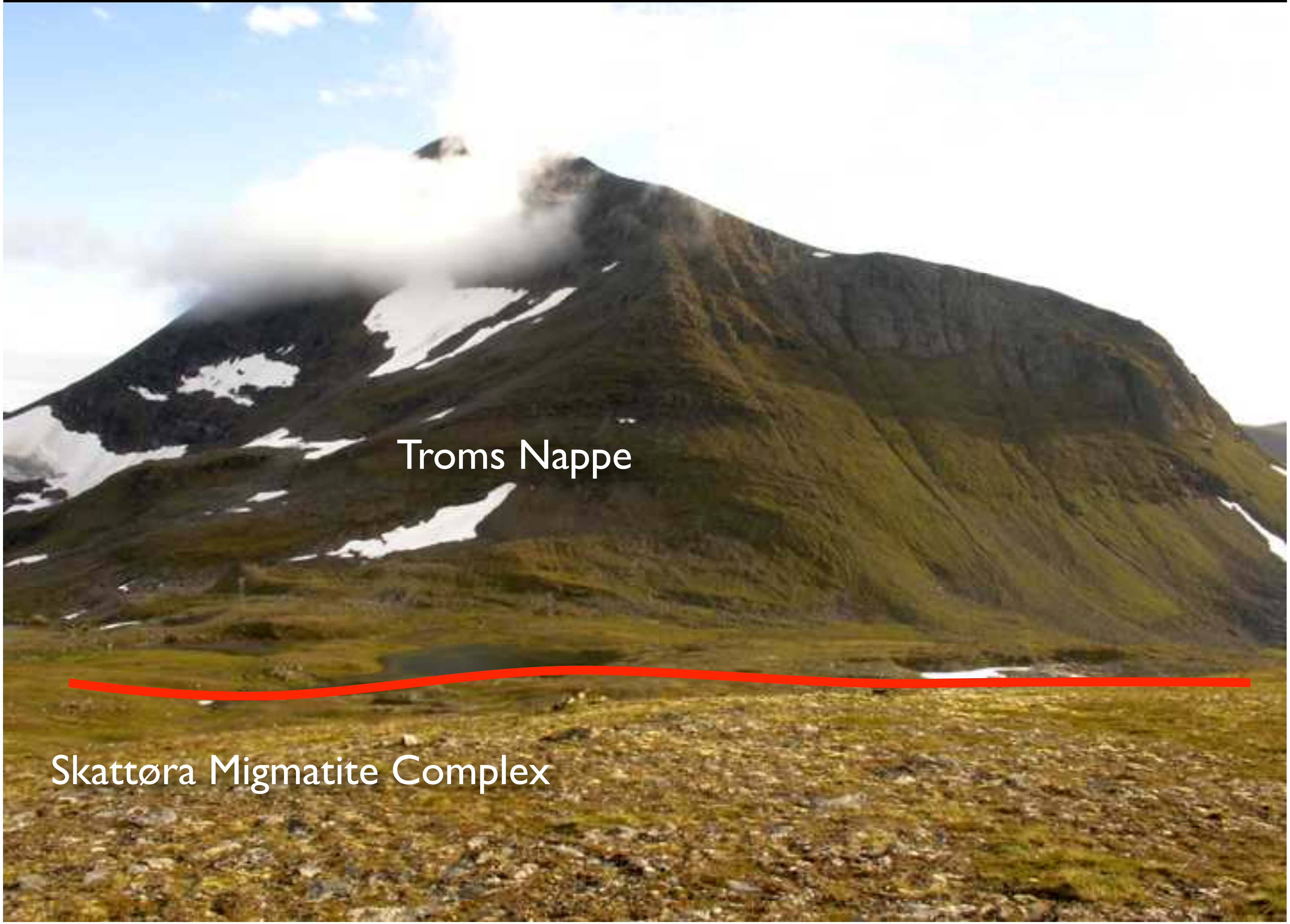
James Mackenzie

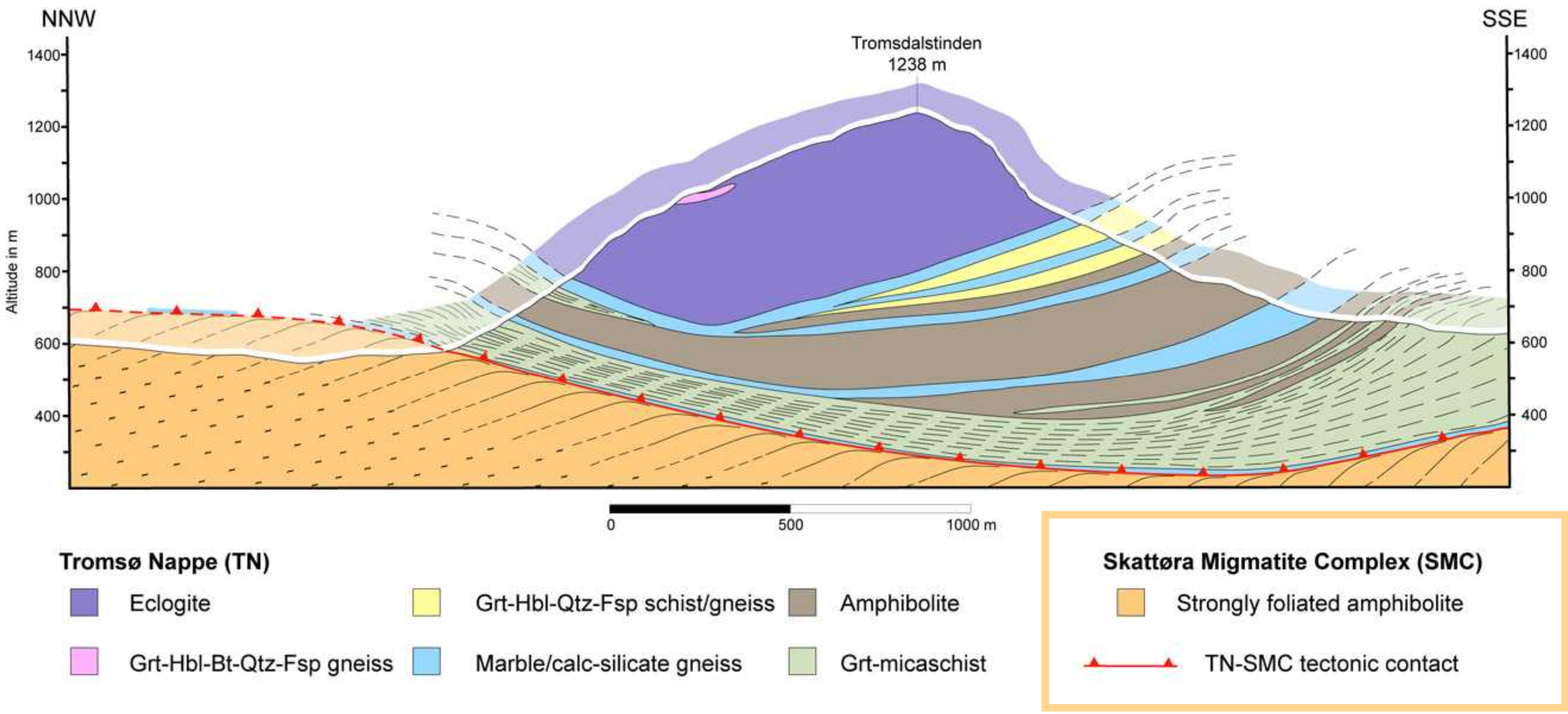


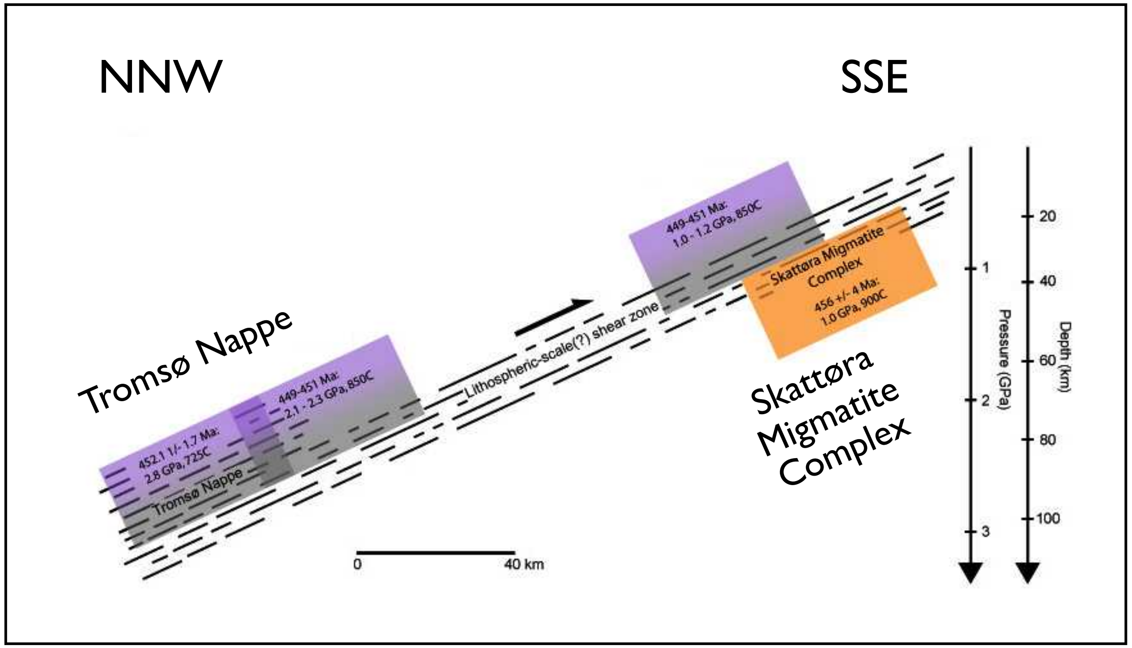
1 km


X
X'
NNW
SSE
Langvatnet
n. Holmevatnet
328 m
Altitude in m
400
200
0
0
500
1000 m

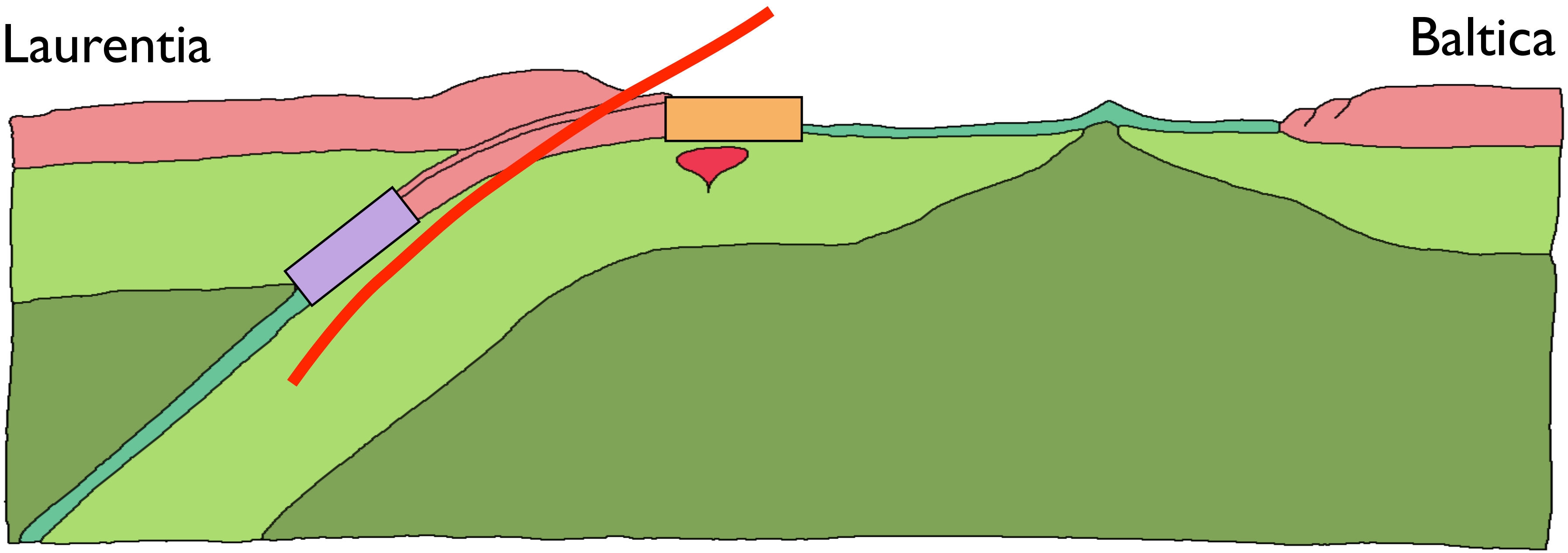

A
A'
200
020
Snyfjellet
Altitude in m
600
400
200
0
-200
0
500
1000 m
Tromsø Nappe (TN)
Eclogite
Grt-micaschist
Marble/calc-silicate gneiss
Grt-amphibolite
Skattøra Migmatite Complex (SMC)
Strongly foliated amphibolite
Axial trace of major synform
TN-SMC tectonic contact


Troms Nappe
Skattøra Migmatite Complex

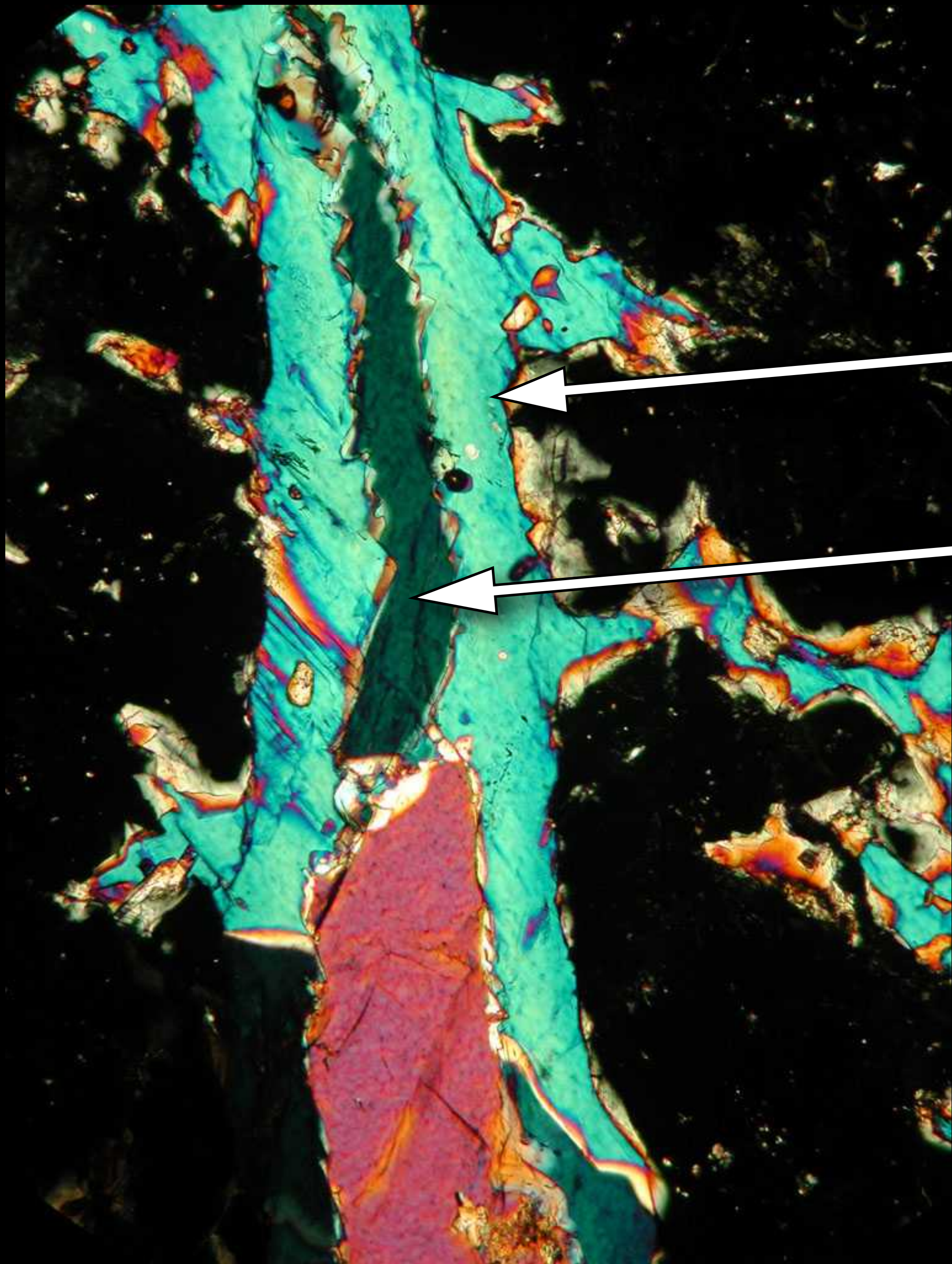

NNW
SSE
Tromsdalstinden
1238 m
Altitude in m
1400
1200
1000
800
600
400
0
500
1000 m
Tromsø Nappe (TN)
Eclogite
Grt-Hbl-Bt-Qtz-Fsp gneiss
Grt-Hbl-Qtz-Fsp schist/gneiss
Marble/calc-silicate gneiss
Amphibolite
Grt-micaschist
Skattøra Migmatite Complex (SMC)
Strongly foliated amphibolite
TN-SMC tectonic contact



James Mackenzie
+
Holger Stünitz
+
Kåre Kullerud
Steffen Bergh
Erling Ravna



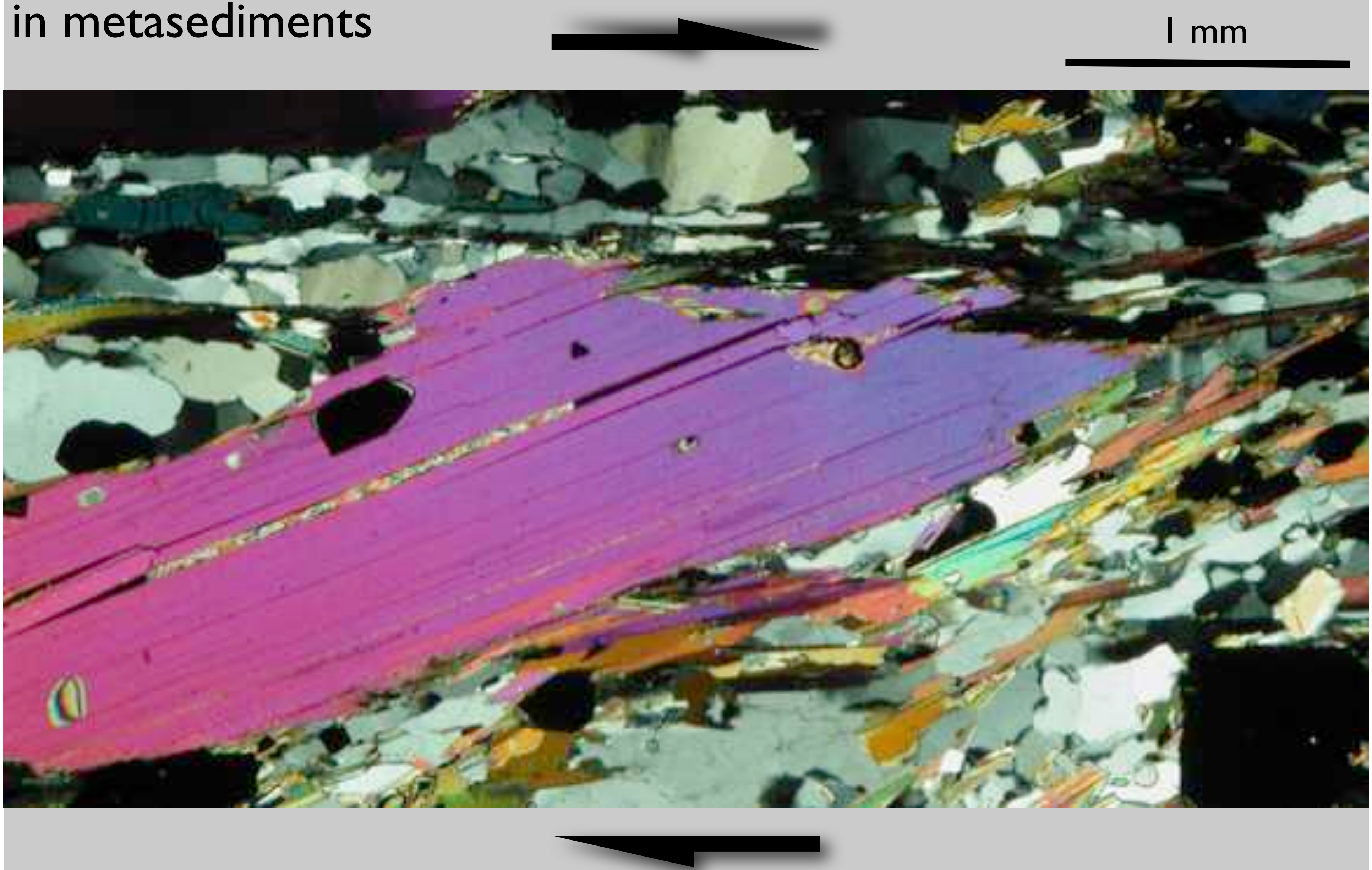
crack-seal veins in garnet

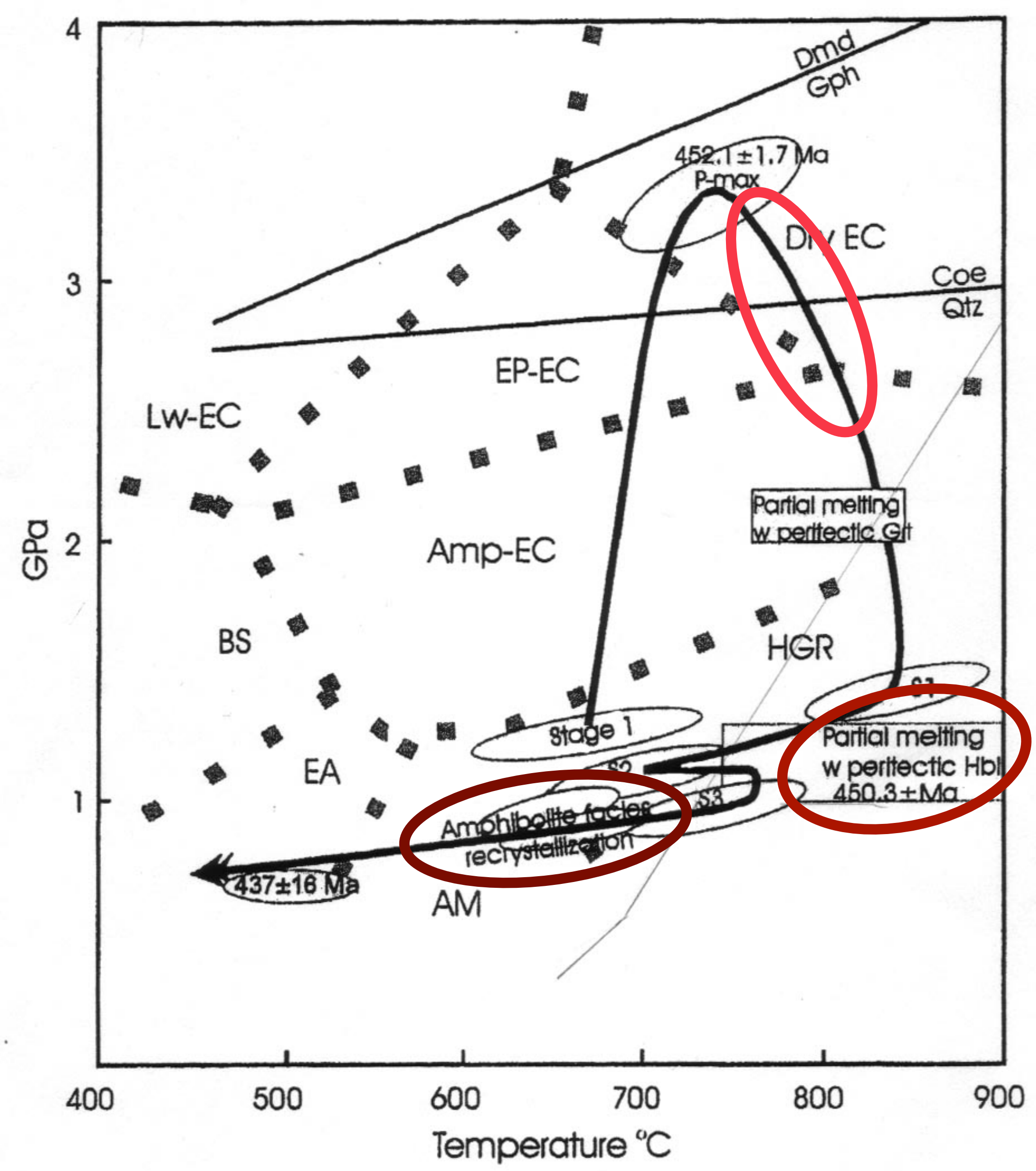


omphacite 1

omphacite 2
(lower jadeite
content)

shear sense top SE during retrograde overprint in metasediments





452 Ma

Decreasing pressure conditions:
omphacite 1 ⟶ omphacite 2

450 Ma
437 Ma

Ravna & Roux (2006)
Corfu et al. (2003)

Time: 452 Ma - 449 Ma = 3 Ma
(Corfu et al., 2003)

$3\ \text{Ma} = 3 \cdot 10^6 \cdot 365 \cdot 24 \cdot 60 \cdot 60 \approx 10^{14}\ \text{s}$

Pressure difference: 3 GPa - 2 GPa = 1 GPa
(Ravna & Roux, 2006)

Vertical displacement ≈ 30 km
Shear displacement ≈ 100 km
Thickness of shear zone ≈ 1 km
Shear strain $\gamma \approx 100$

Shear strain rate $\dot{\gamma} \approx 100 / 10^{14}\text{s} \approx 10^{-12}\ \text{s}^{-1}$

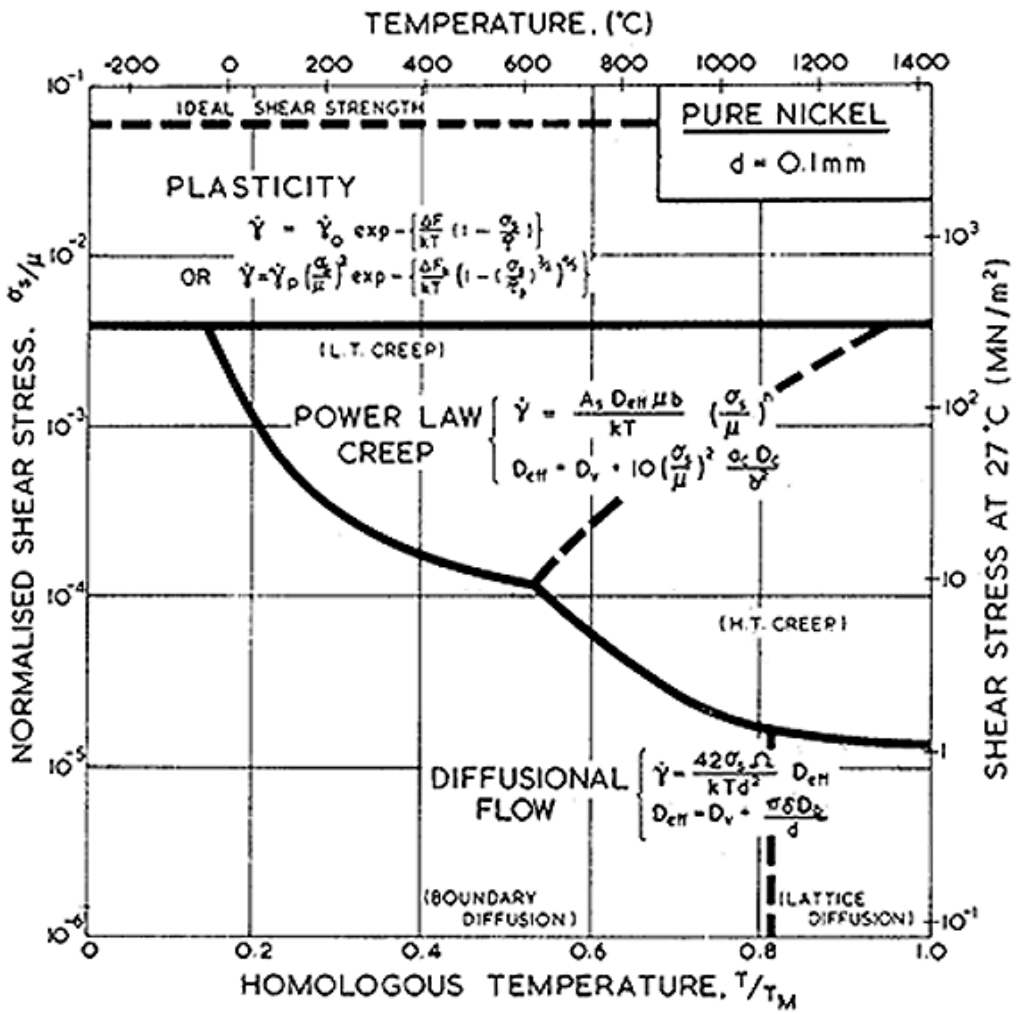
Localized shear: $\dot{\gamma} \approx 10^{-11}\ \text{s}^{-1}$ to $10^{-10}\ \text{s}^{-1}$

fast exhumation

high shear strain rates

which deformation mechanism?

deformation mechanism maps - flow laws



ideal strength

plasticity

power law creep

low temperature

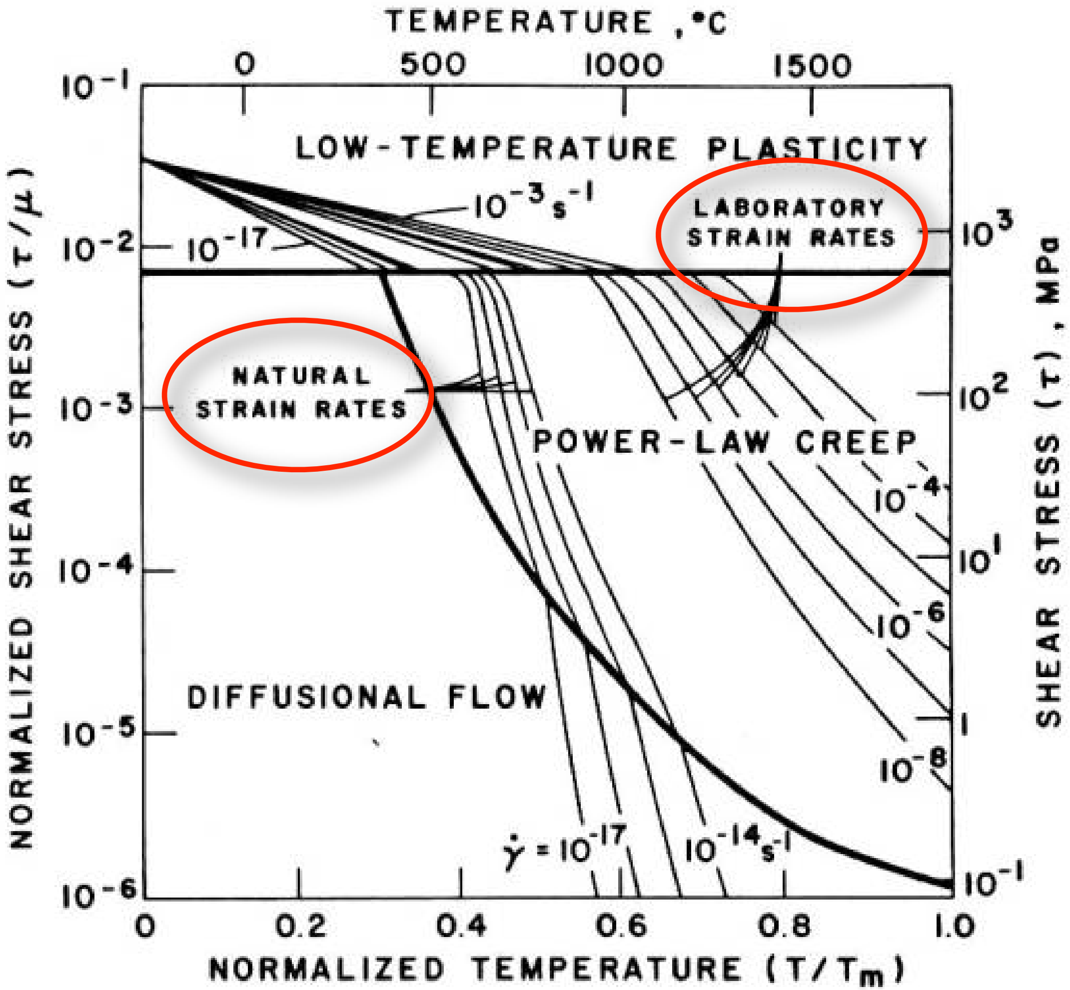
high temperature

diffusional flow

boundary diffusion

lattice diffusion

deformation mechanism maps - rheologies



ideal strength

plasticity

power law creep

low temperature

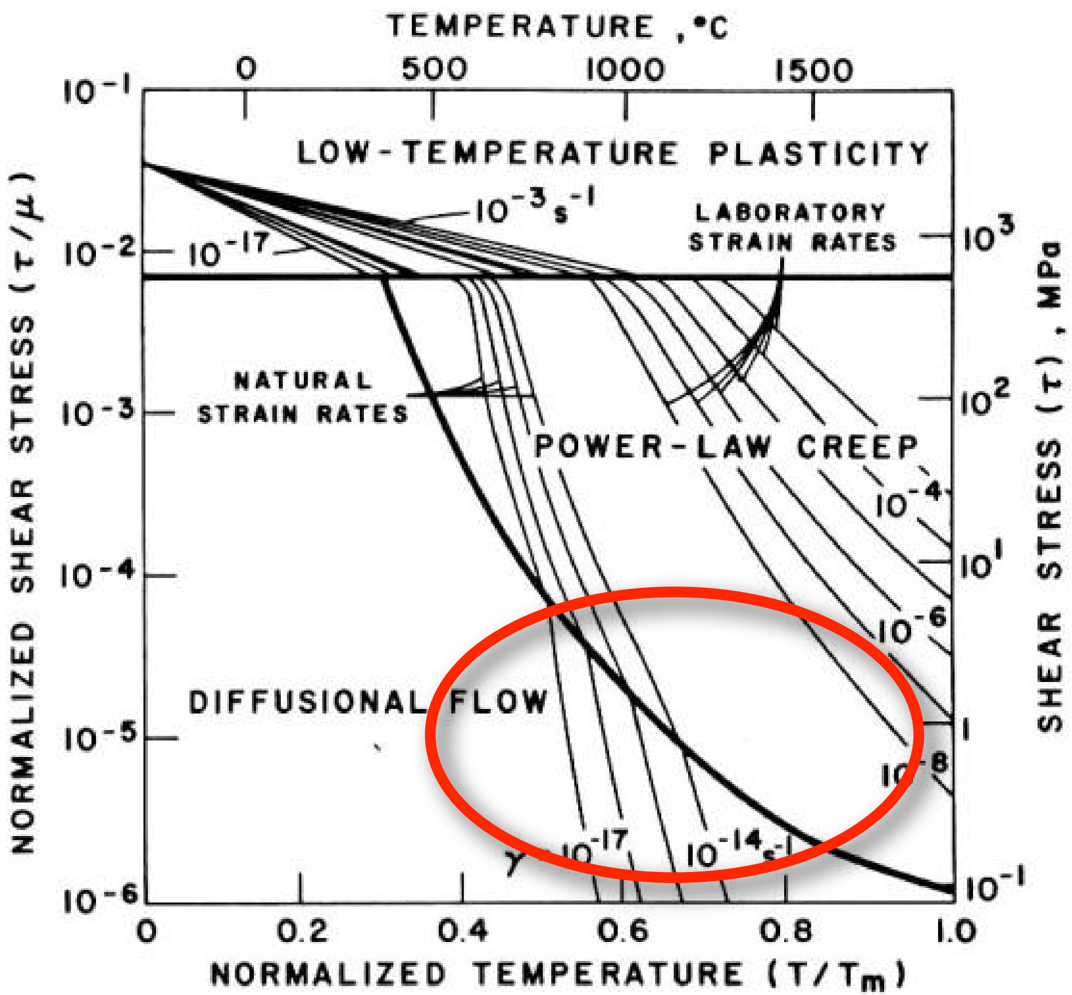
high temperature

diffusional flow

boundary diffusion

lattice diffusion

deformation mechanism maps - regimes



fracture

dislocation glide

dislocation creep

low n

high n

diffusion creep

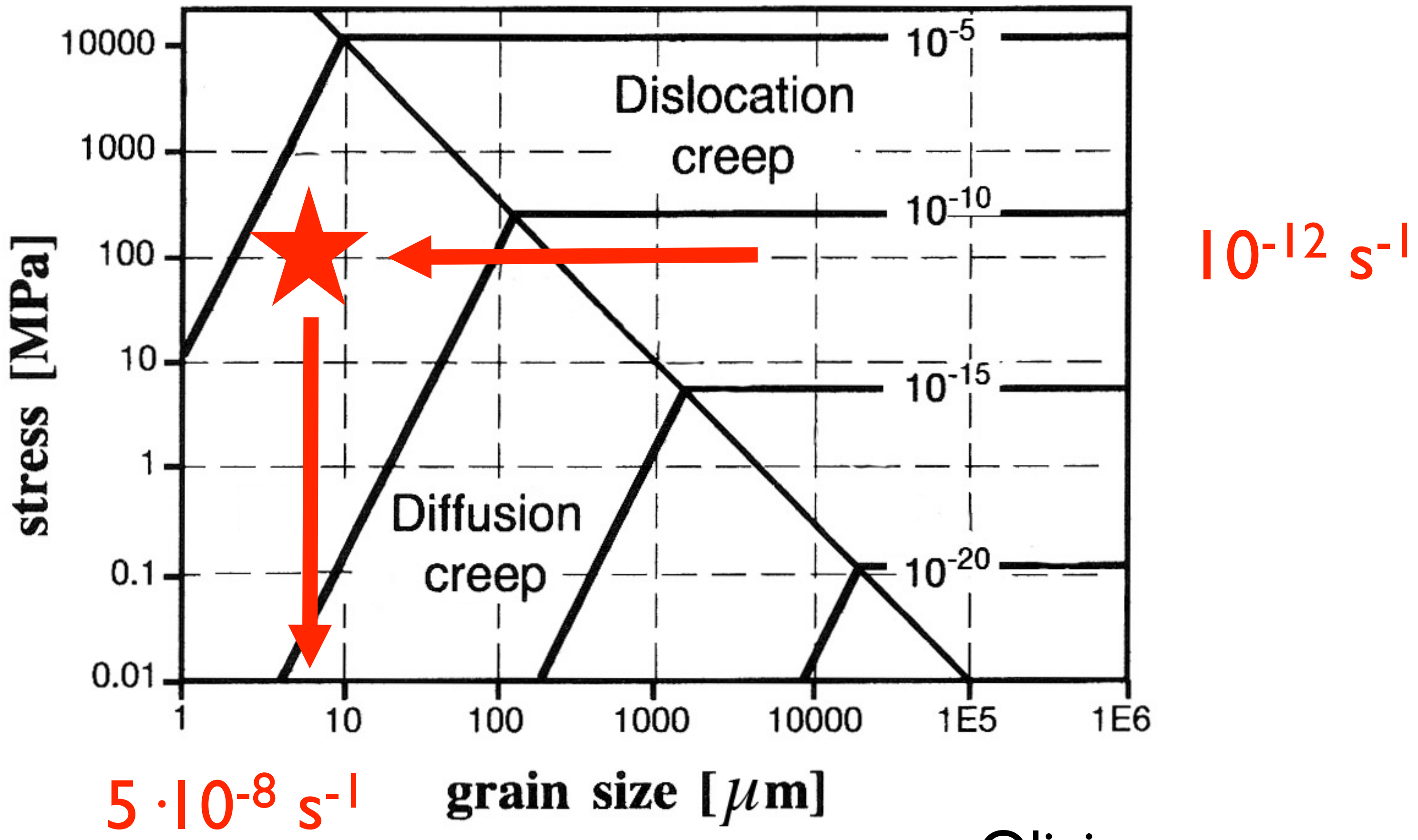
boundary diffusion

lattice diffusion

low stress - high T

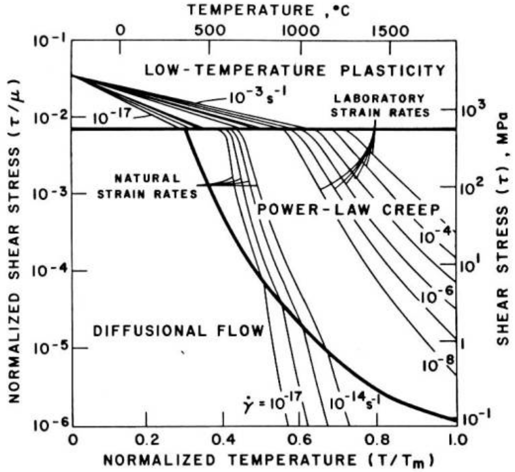
deformation mechanism maps - grain size

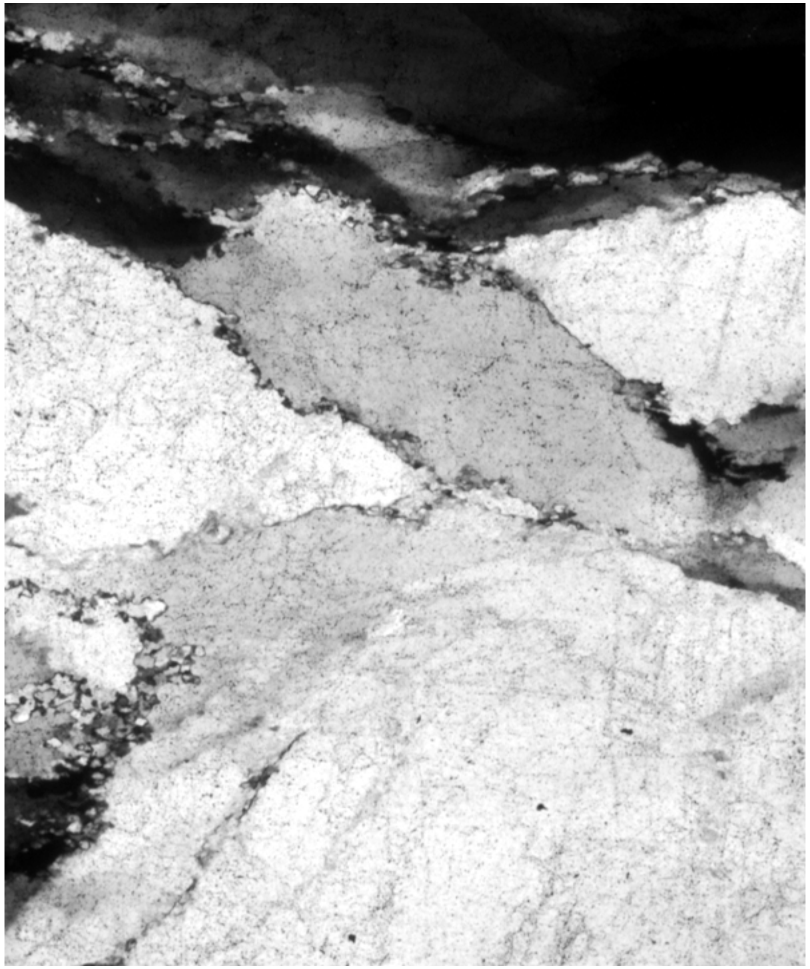
T = constant



Olivine
after De Bresser et al. 1998

microstructures

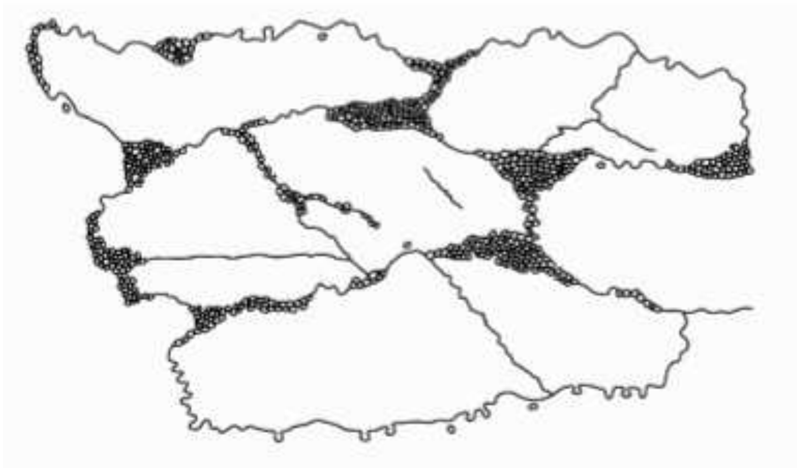




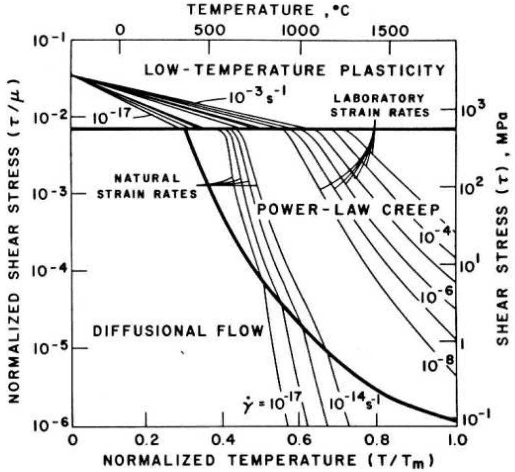
100 µm

bulging recrystallization

dislocation creep



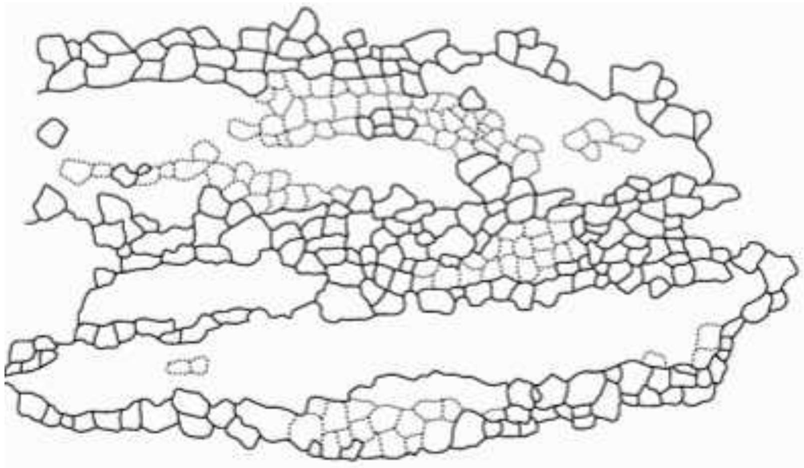
microstructures



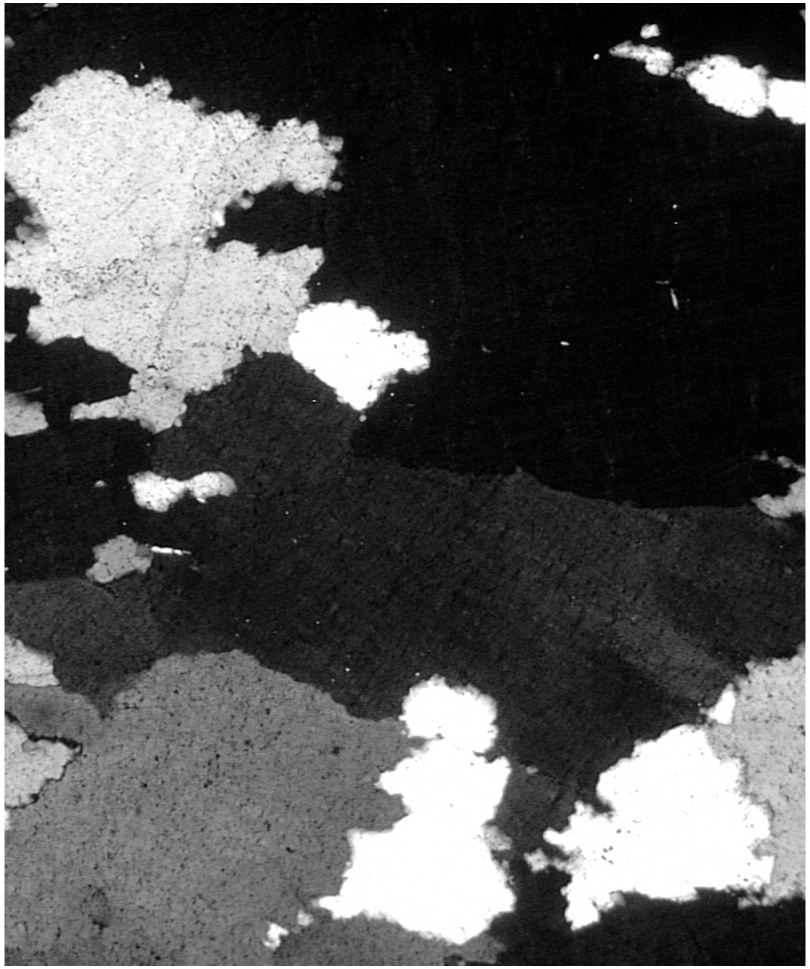
100 μm

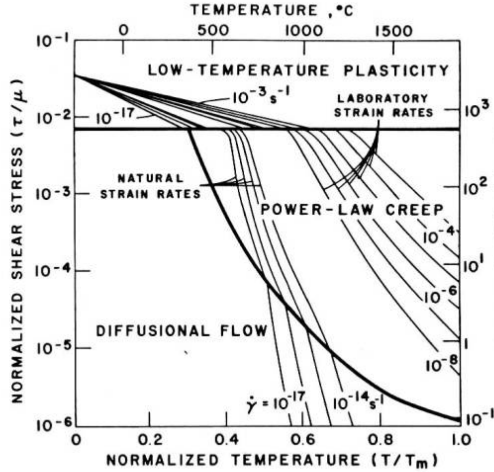
subgrain rotation
recrystallization

dislocation creep



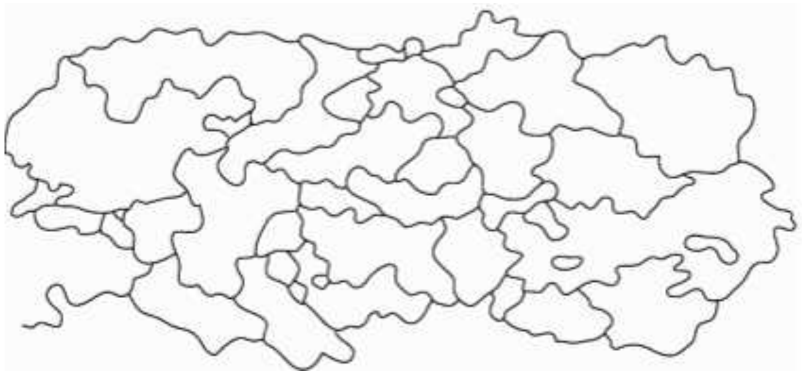
microstructures





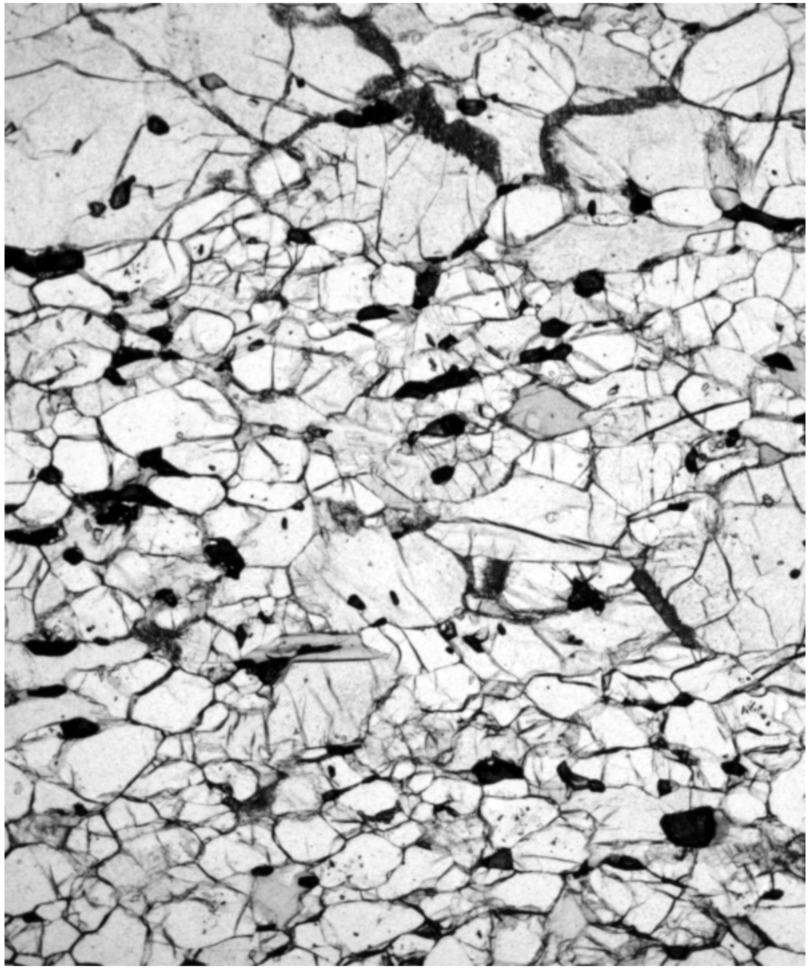
grain boundary migration
recrystallization

dislocation creep

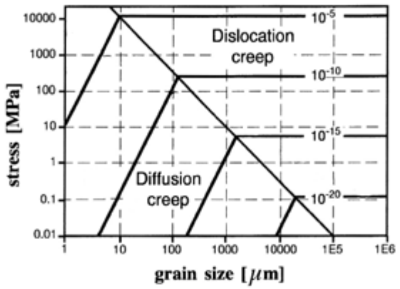


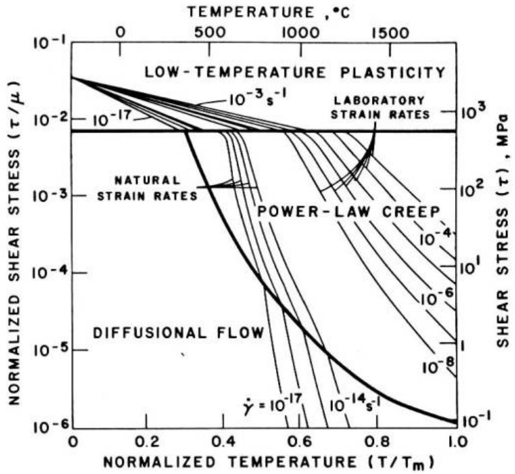
100 µm

microstructures



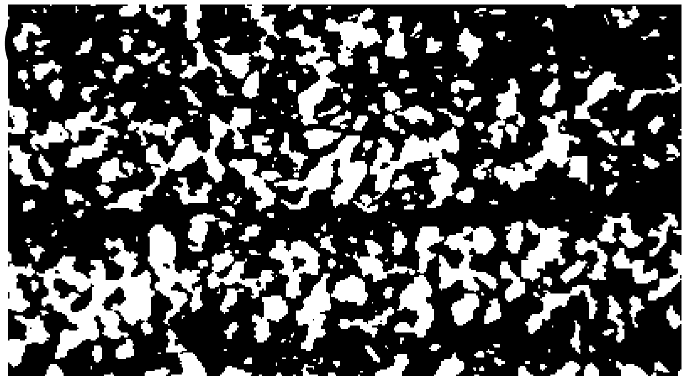
500 μm





grain boundary sliding
solution precipitation

diffusion creep



deformation mechanism
= diffusion creep

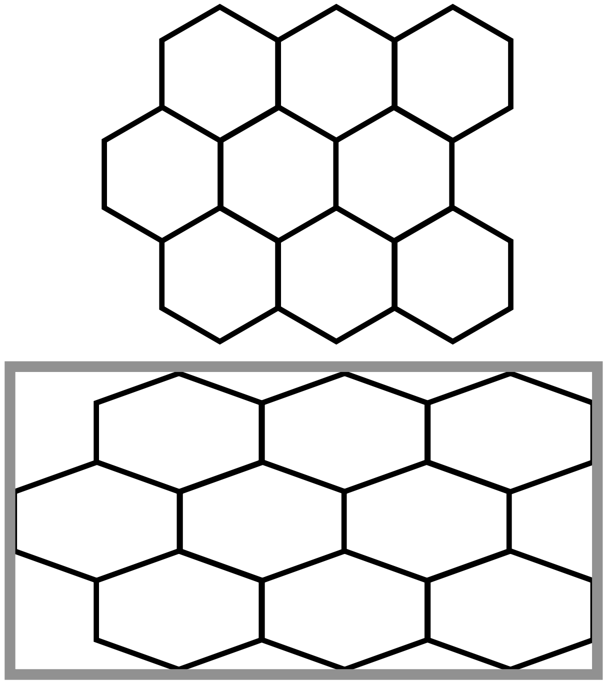
how to recognize it ?

micromechanical models

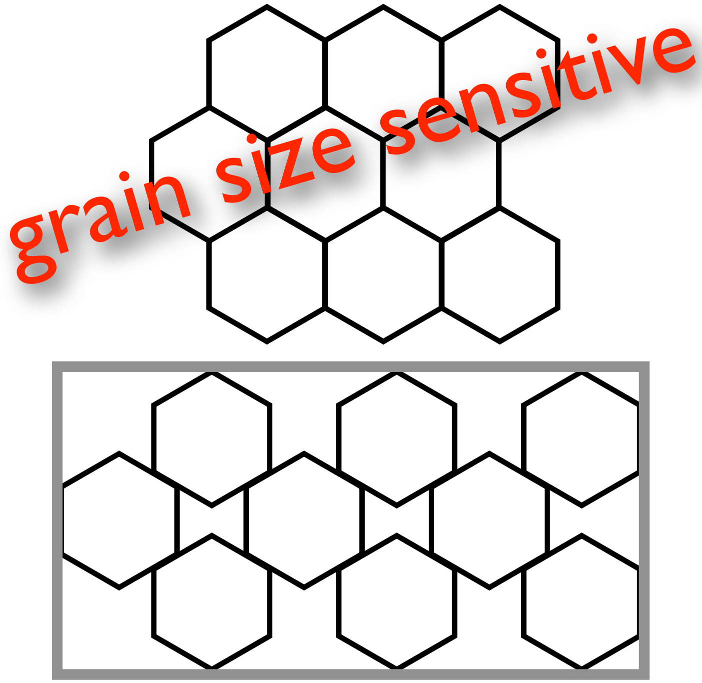
intracrystalline plasticity
dislocation glide
(facilitated by:)

granular flow
grain boundary sliding
pressure solution

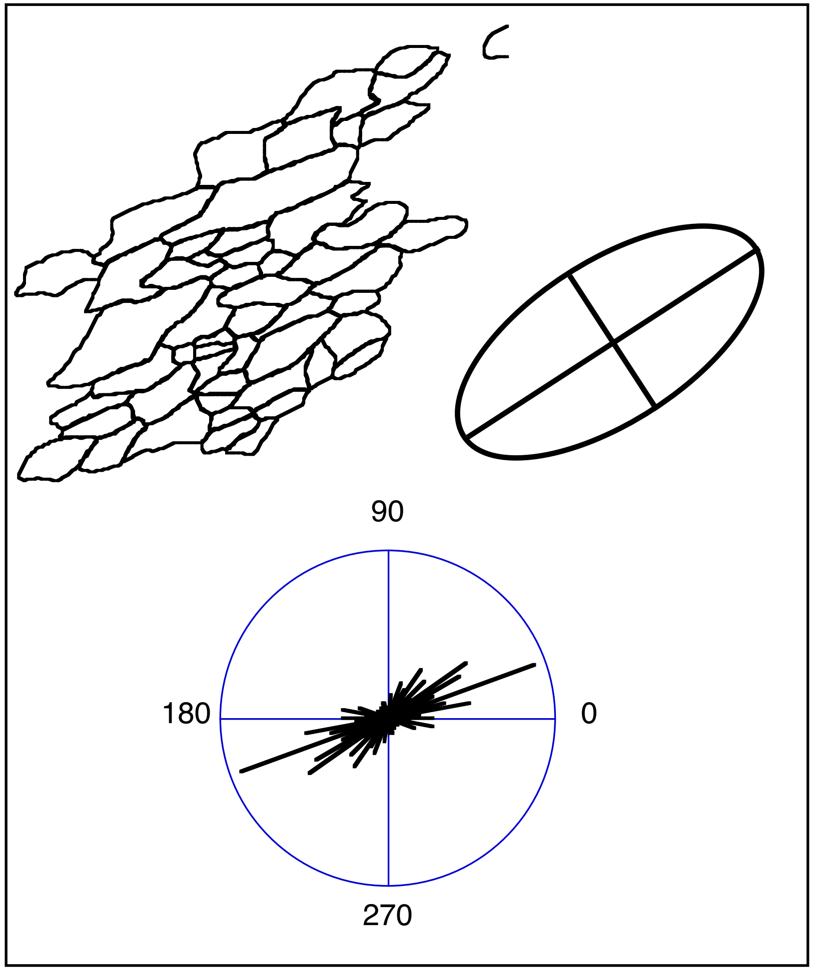
dislocation creep



diffusion creep



geometrical models

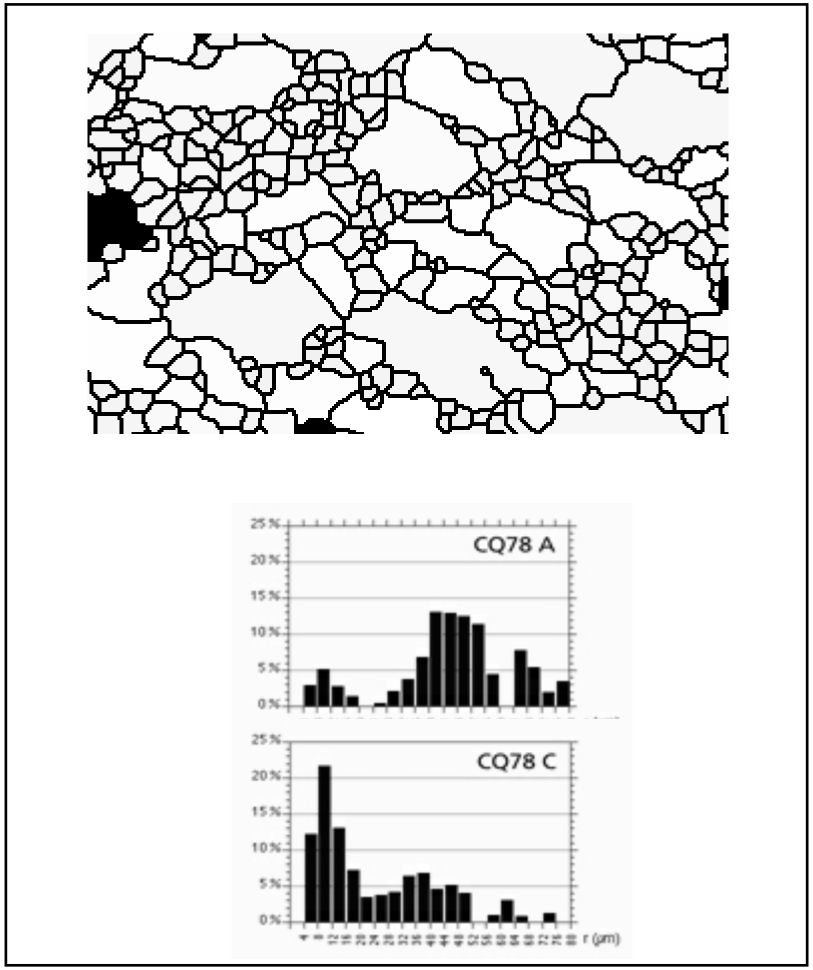


shape change = strain
strain markers,
homogeneous
deformation

intracyrstalline plasticity
dislocation glide with 5
slips systems (van Mises)

surfor paror
(Panozzo, 1984, 1983)

geometrical models

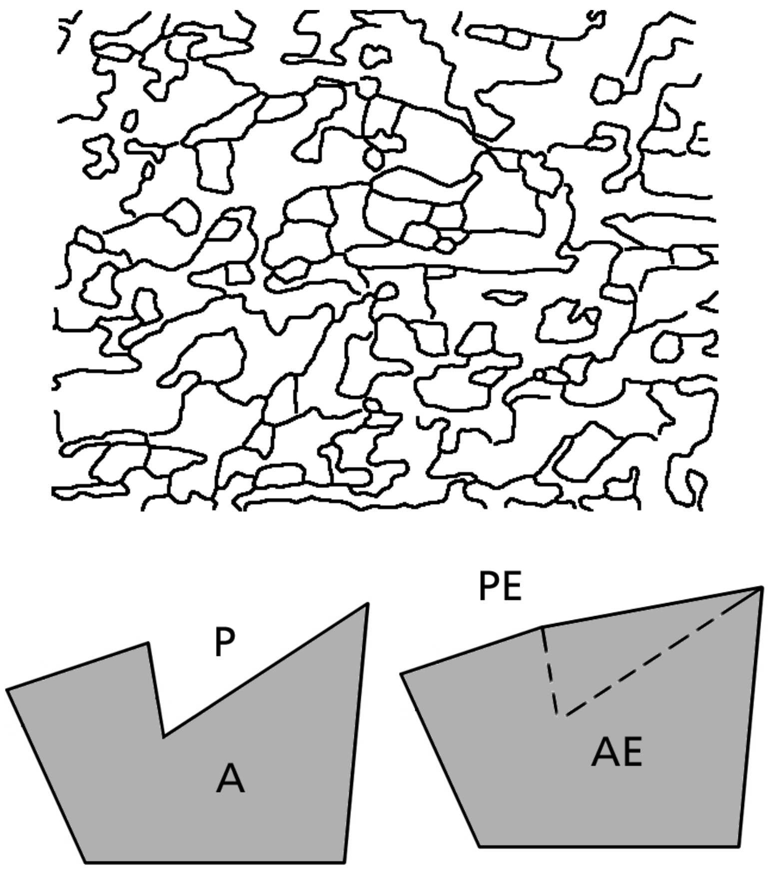


change of size
grain size distribution

recrystallization, grain growth, nucleation

stripstar
Heilbronner & Bruhn (1998)

geometrical models



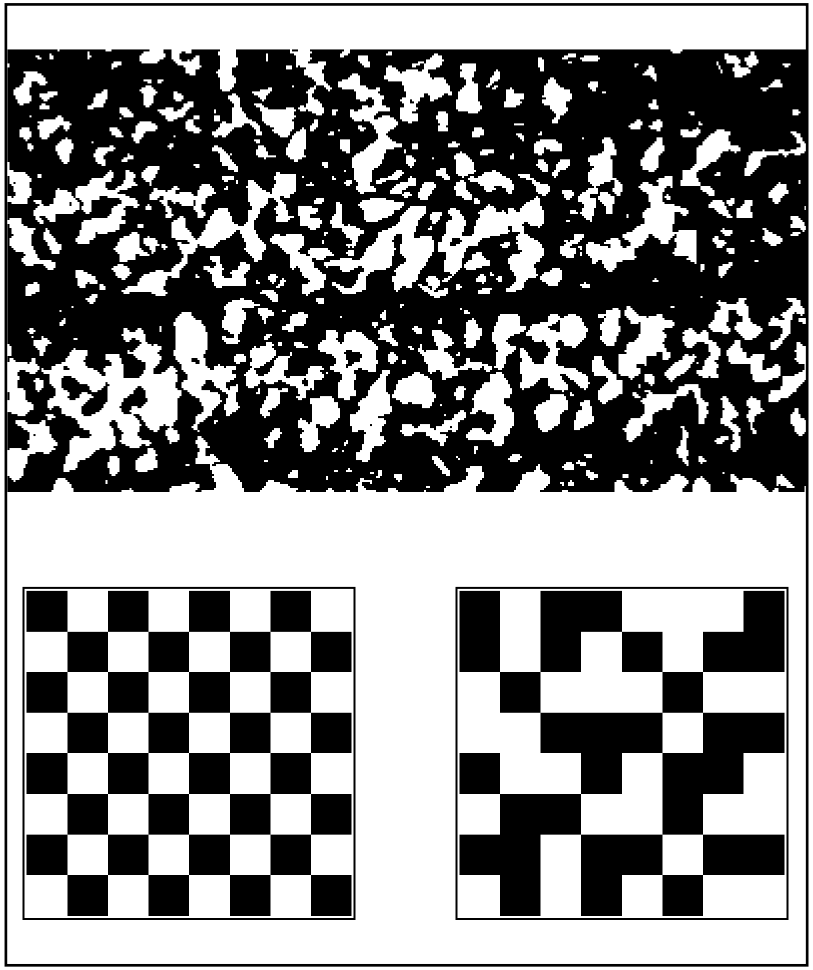
PARIS(%) factor = 2 · ((P-E) / E) · 100

shape change ≠ strain
lobate boundaries
convex-concave
angularity, etc.

grain boundary migration
annealing, cataclasis

ishapes
(Heilbronner & Keulen, 2006)

geometrical models



spatial distribution
grain contact frequency

grain boundary sliding
granular flow
heterogeneous nucleation

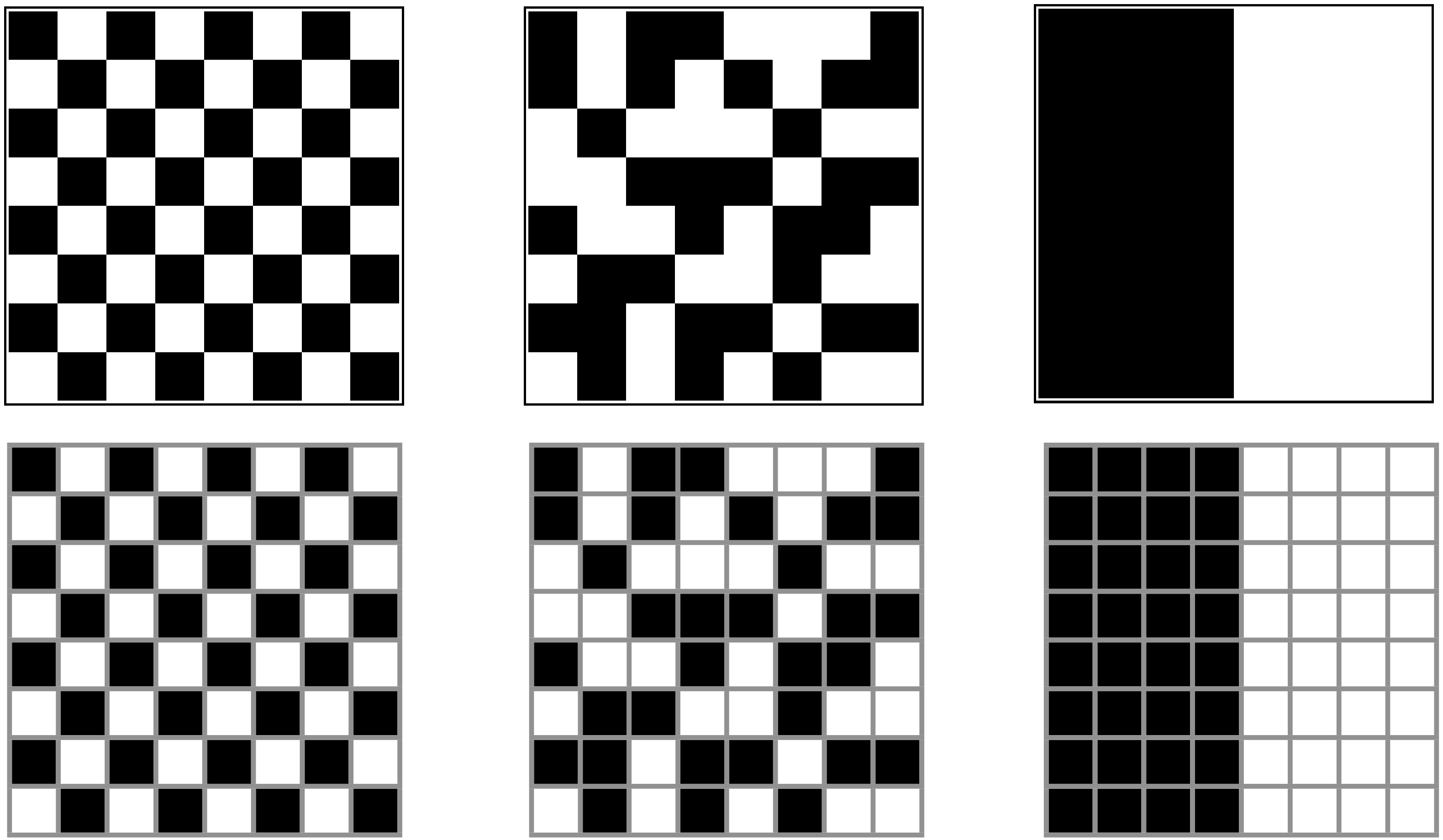
transition frequency
(Kretz, 1969)

new definition of old model

$\neq$ Markov chain on 2-D

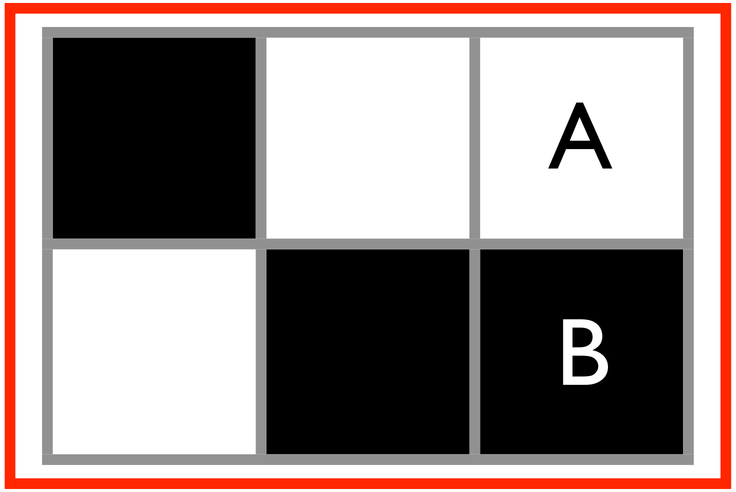
3-D model analyzed in 2-D

conceptual model

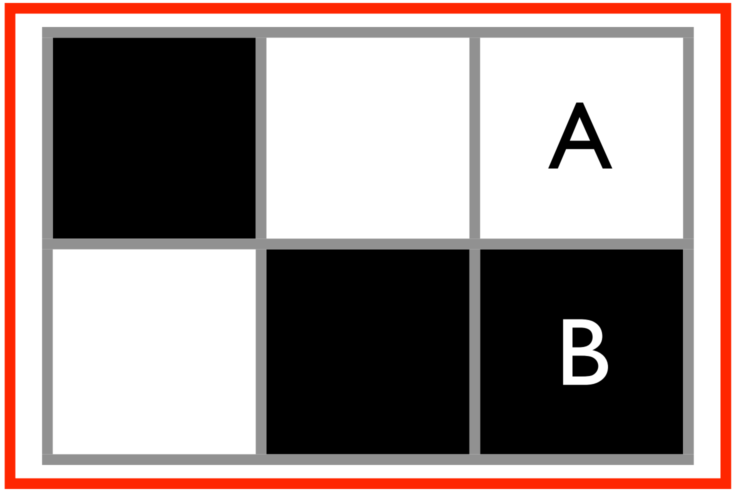


anticlustered random clustered

conceptual model



conceptual model

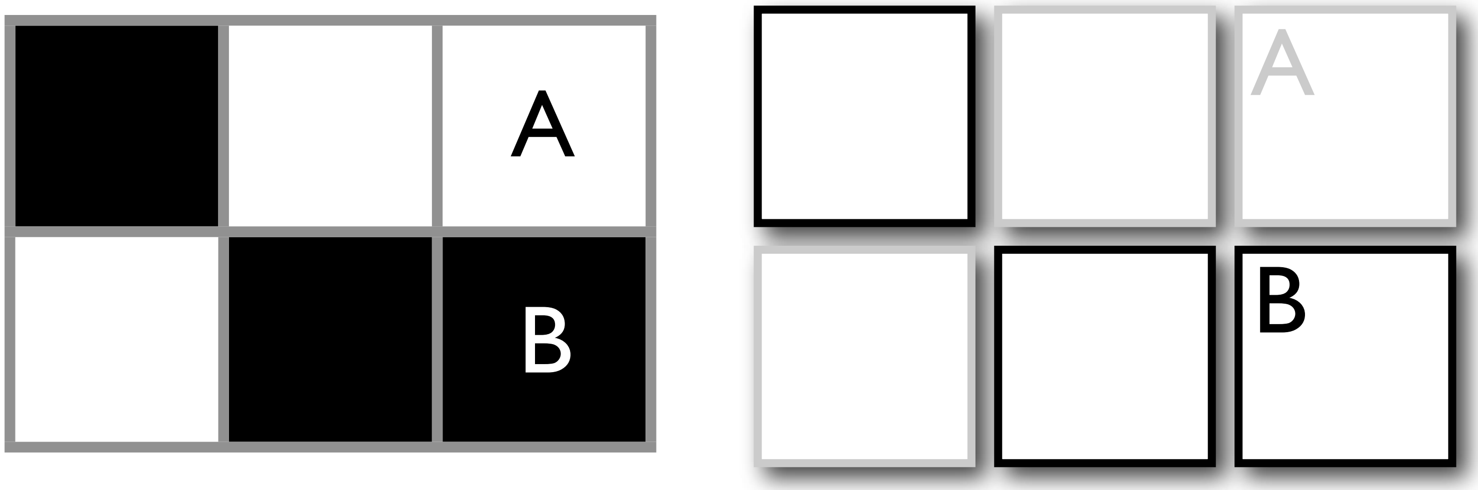


2 types of grains:

A = white
B = black

no. of grains (A) = no. of grains (B)
grain size (A) = grain size (B)

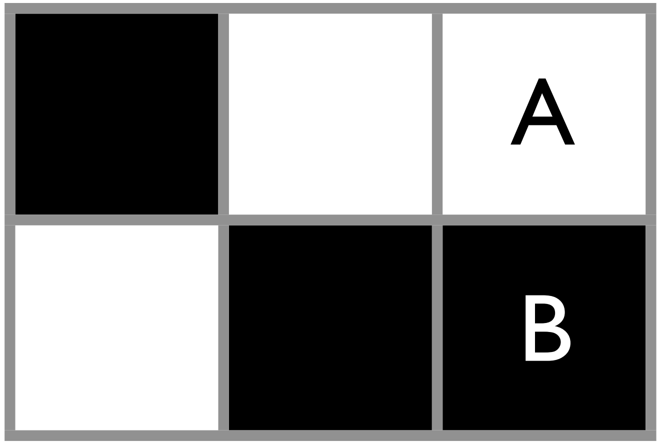
conceptual model

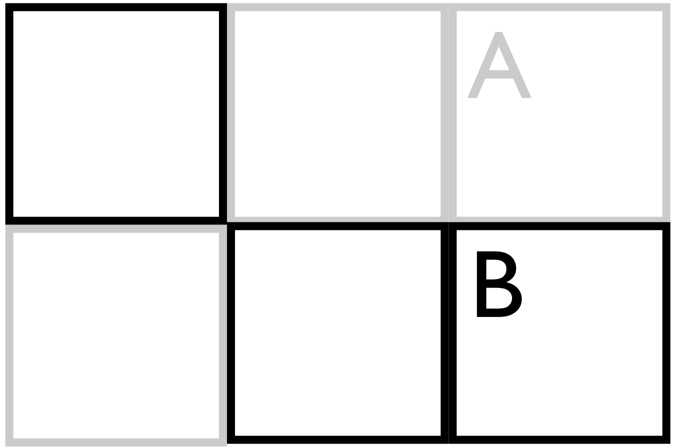


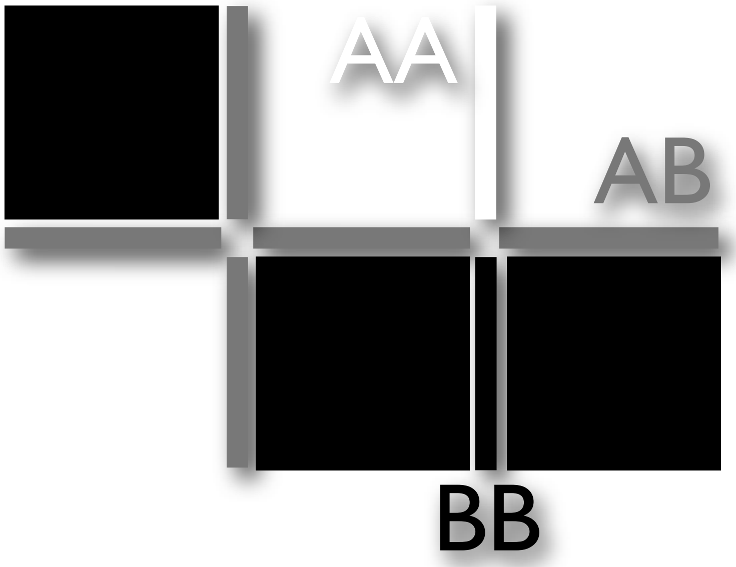
two types of grain boundary surface S

surface % (A) = surface % (B)

conceptual model

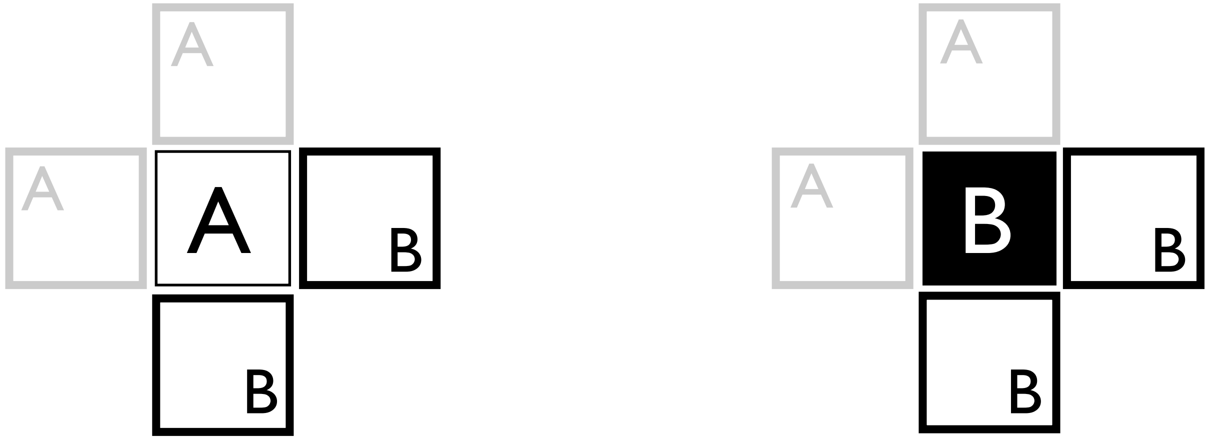






3 types of grain contact surface
AA, BB, AB (= BA)

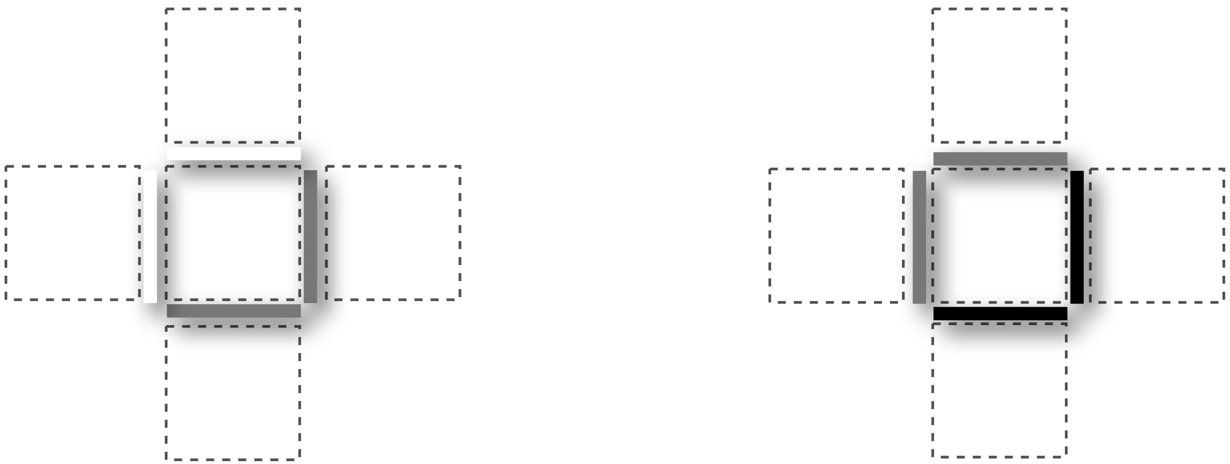
conceptual model



for any given grain A, B, ...
the chance pA, pB, ... of sharing
grain boundary surface with grains A, B, ...
is proportional to the surface fraction[1)] of A, B, ...

1) surface (phase) / total grain boundary surface

conceptual model



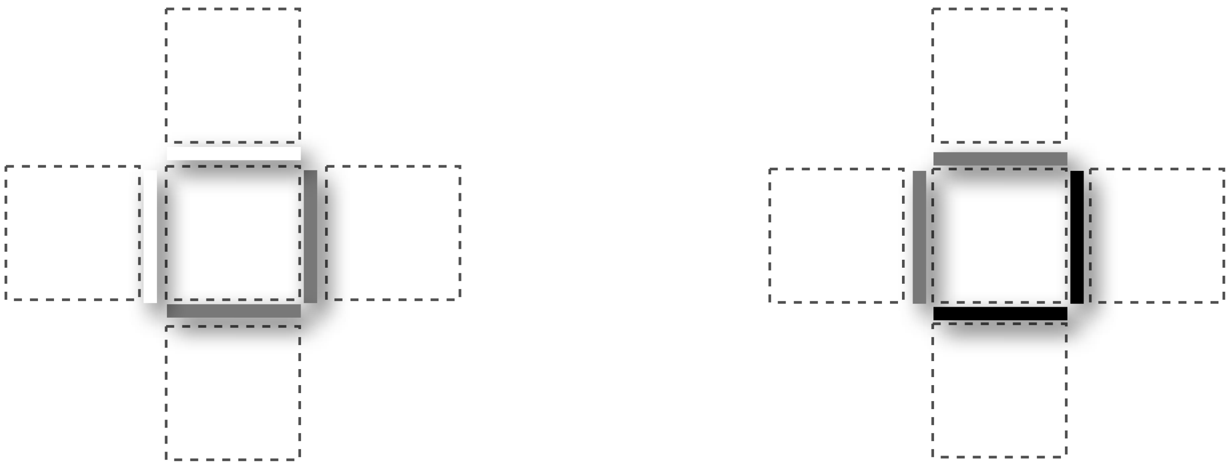
the resulting distributions of contact surface

AA , AB , ... BA , BB ,...

follow the

binomial (polynomial) distribution

conceptual model



$$AA = pA \cdot pA = pA^2$$

$$BB = pB \cdot pB = (1-pA)^2$$

$$AB = BA = pA \cdot pB + pB \cdot pA = 2 \cdot pA \cdot (1-pA)$$

conceptual model

Binomial distribution

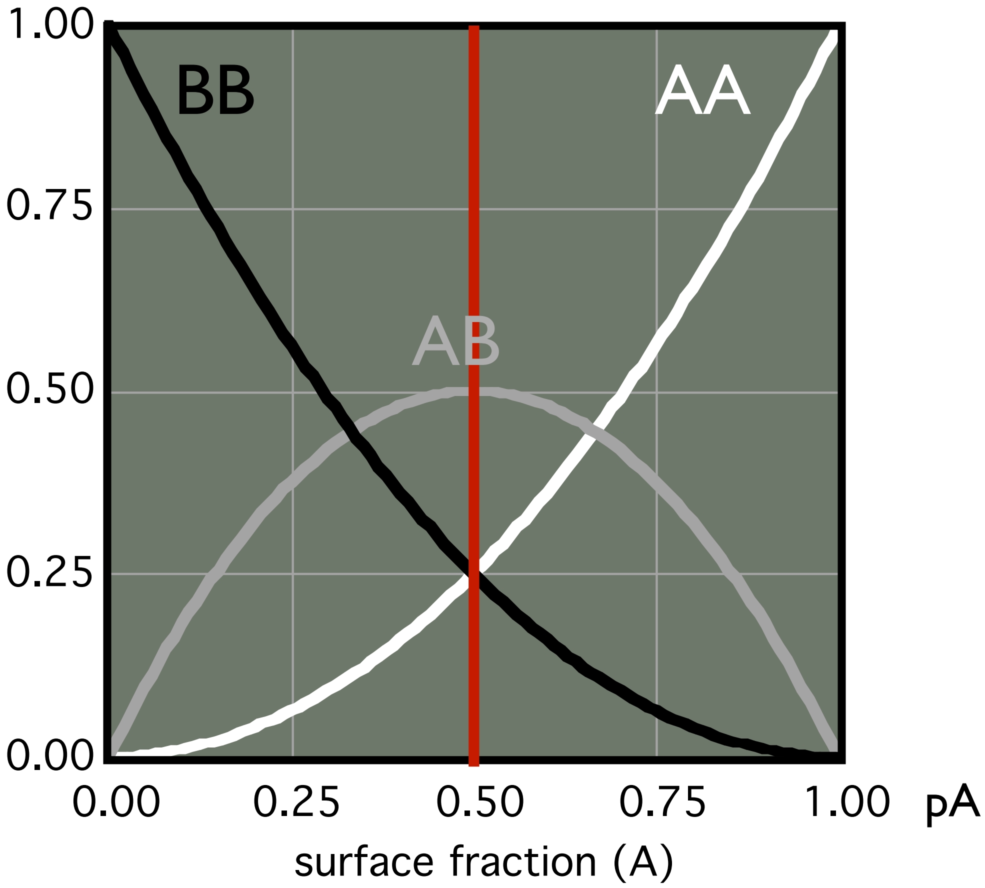
@ pA = pB = 0.5

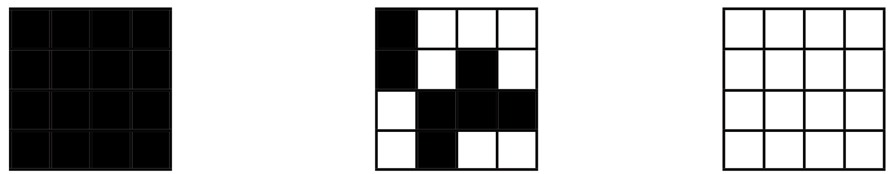
$AA = pA^2 = 0.25$

$AB = 2pA(1-pA) = 0.50$

$BB = (1-pA)^2 = 0.25$

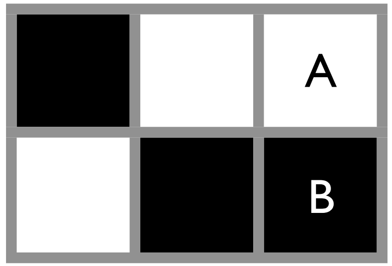
@ pA = pB = 0.5



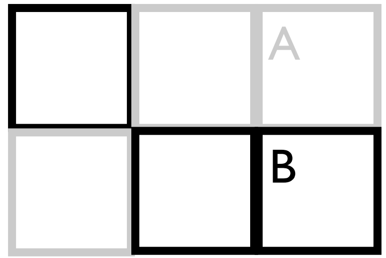


stereology

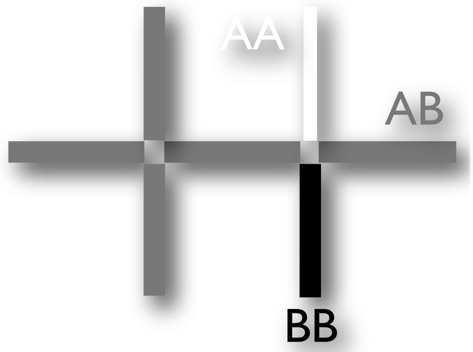
volume % (phase) = area % (phase)
$= A(\text{phase}) / A_{tot}$
$= A_A$ (phase)



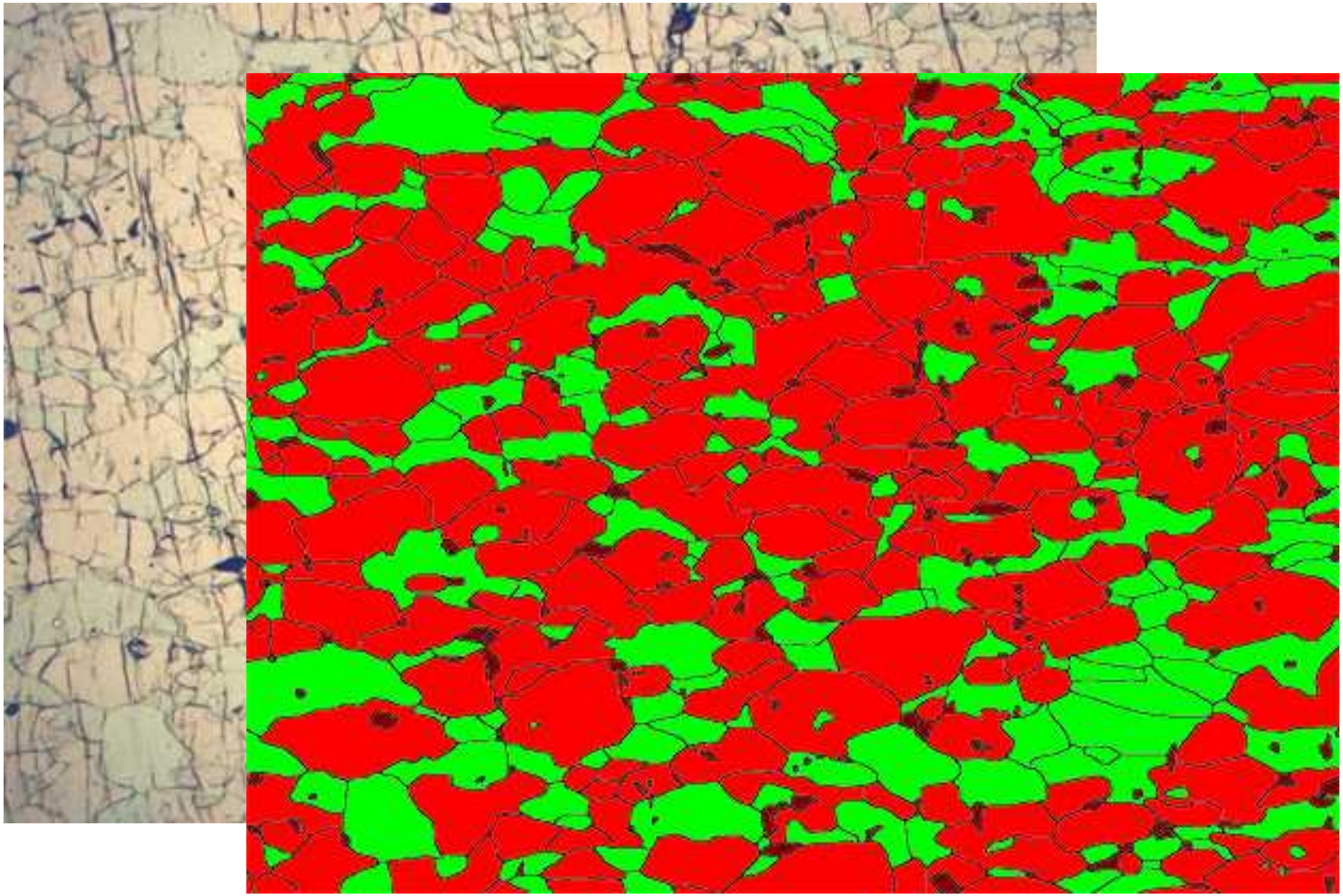
surface % (phase) = outline % (phase)
$= L(\text{phase}) / L_{tot}$
$= L_L$(phase)



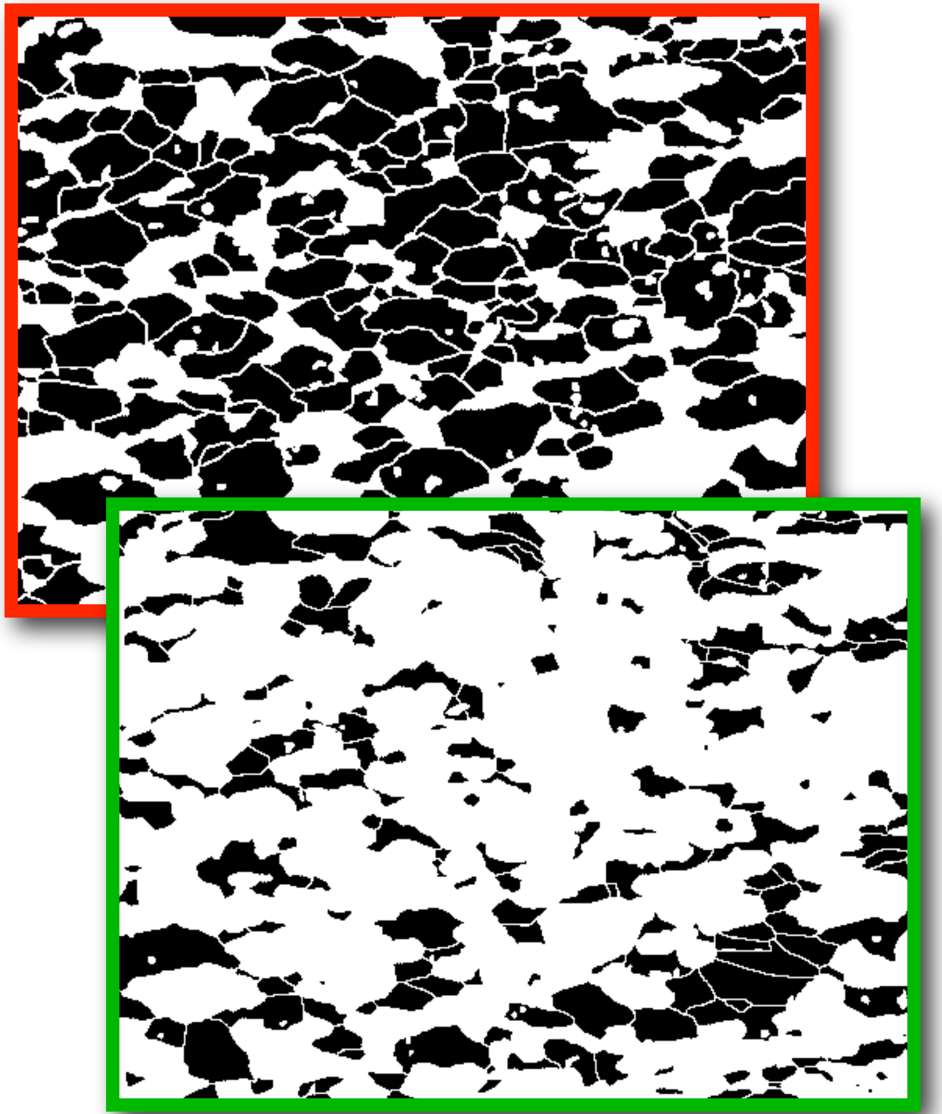
surface % (contact) = line % (contact)
$= L(\text{contact}) / L_{tot}$
$= L_L$(contact)

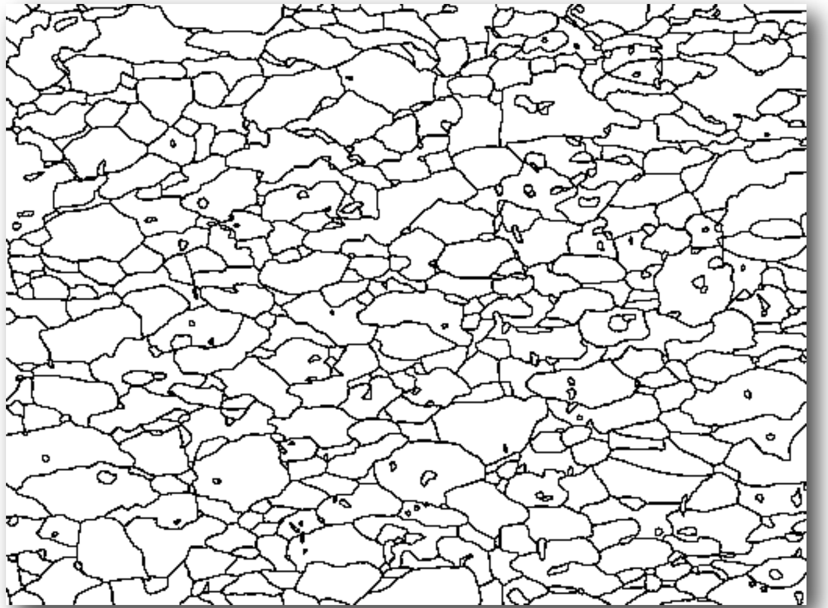


how to measure volume and surface in 2-D



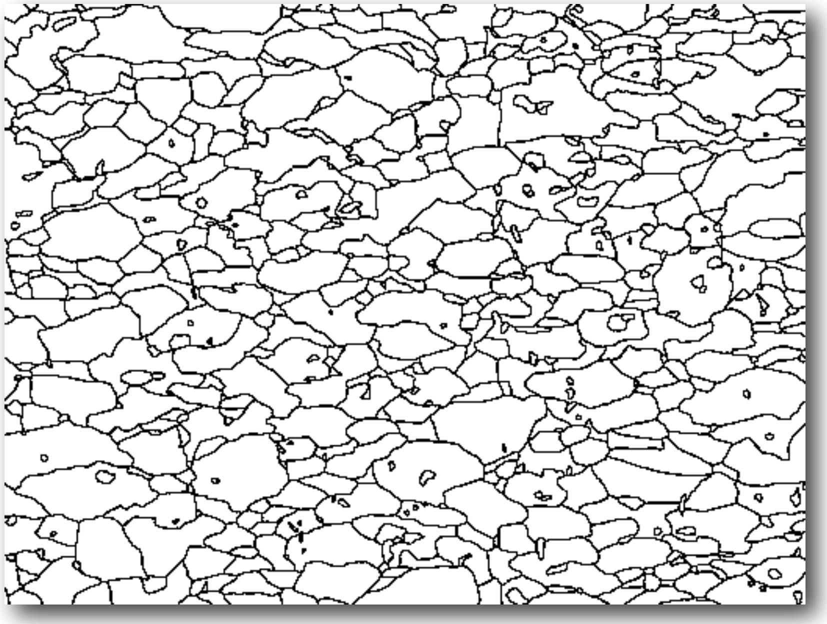
3-D volume% = area%

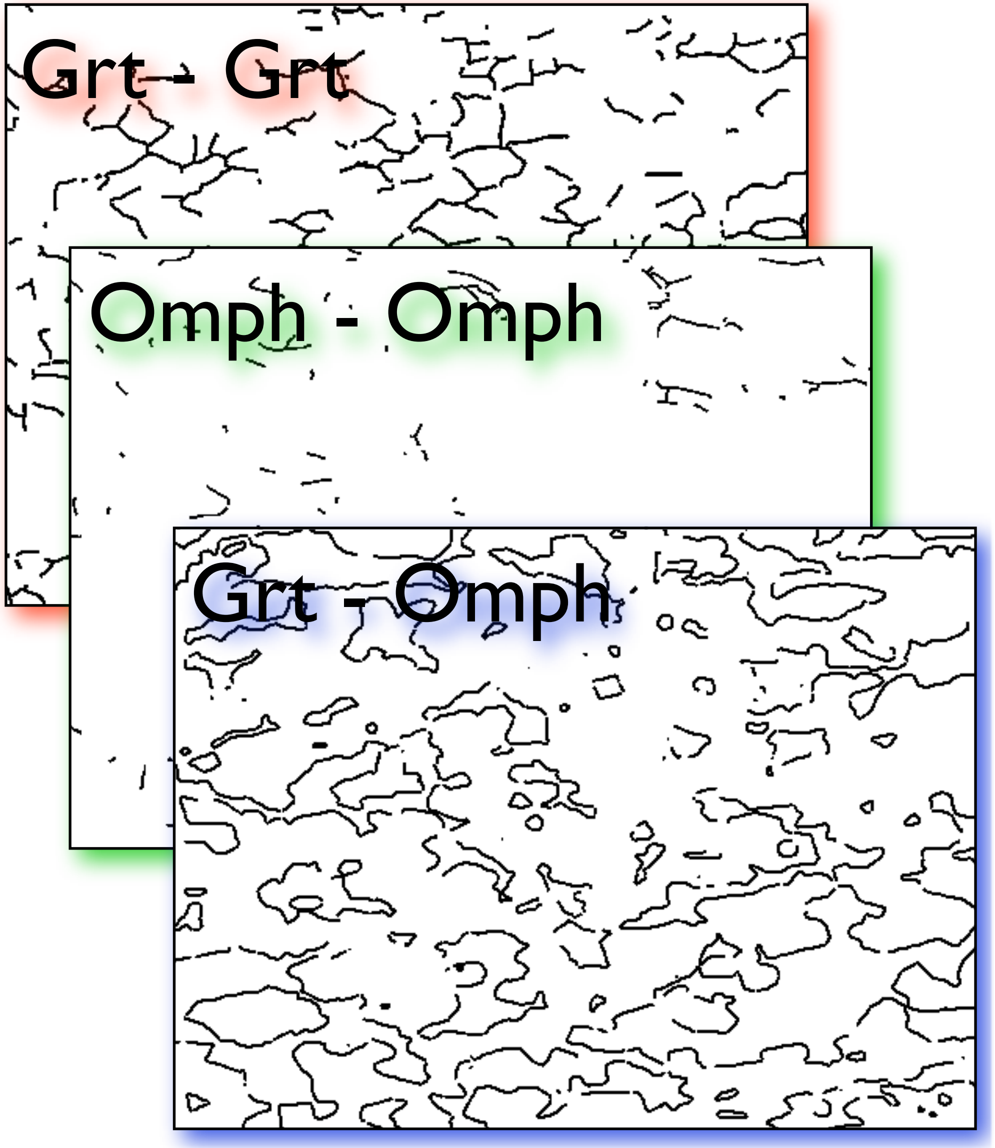




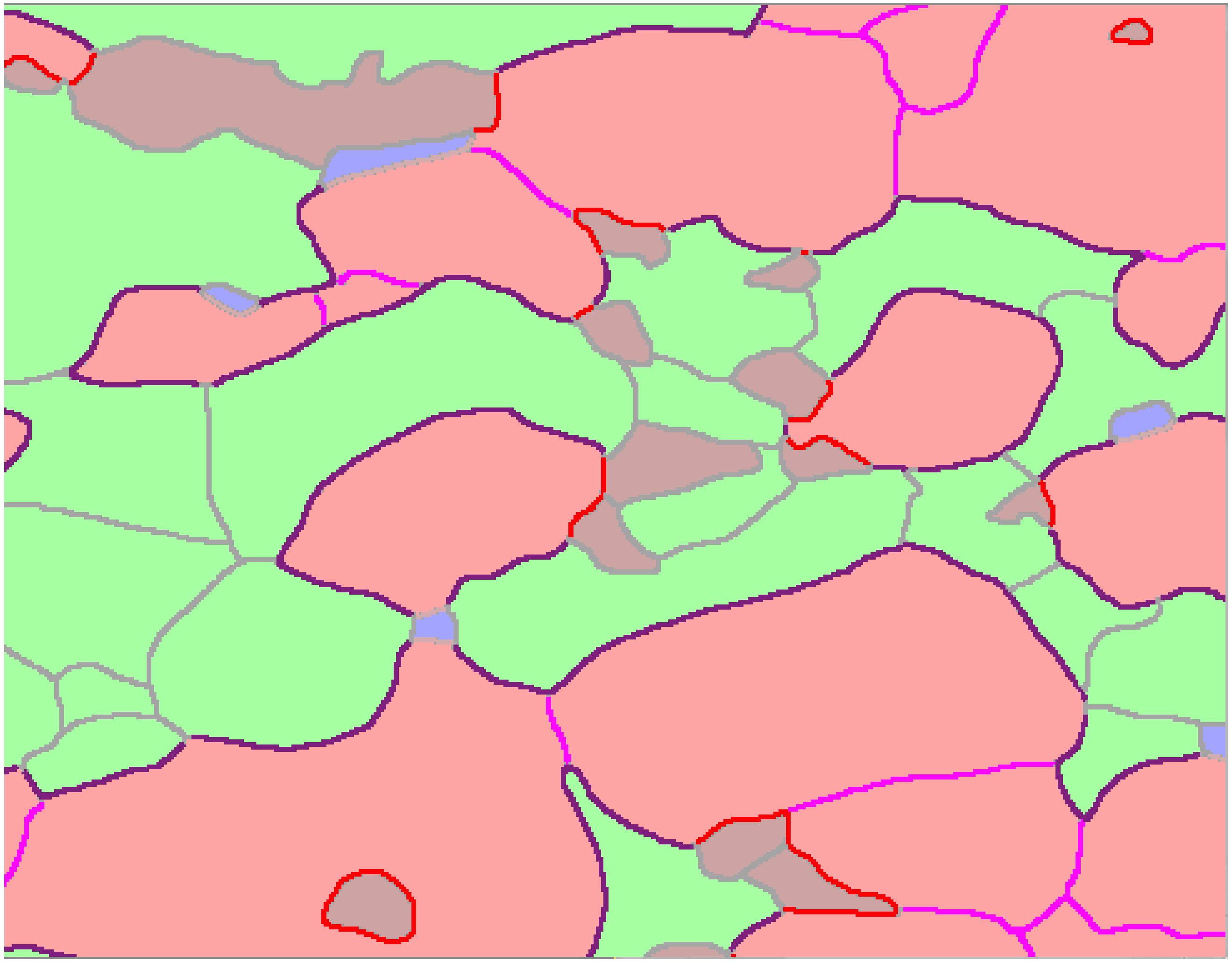
3-D grain surface%
= boundary outline %

3-D contact surface% = contact line%





how to find contact surfaces in 2-D



micrograph

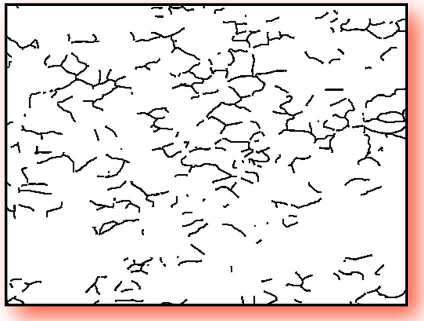
grain boundary map

phases

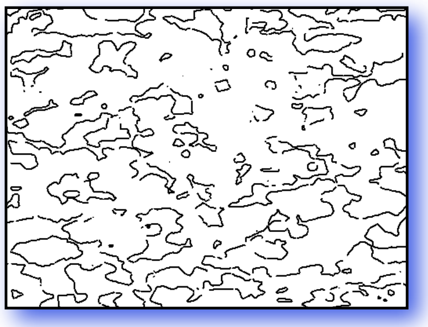
boundary of phases

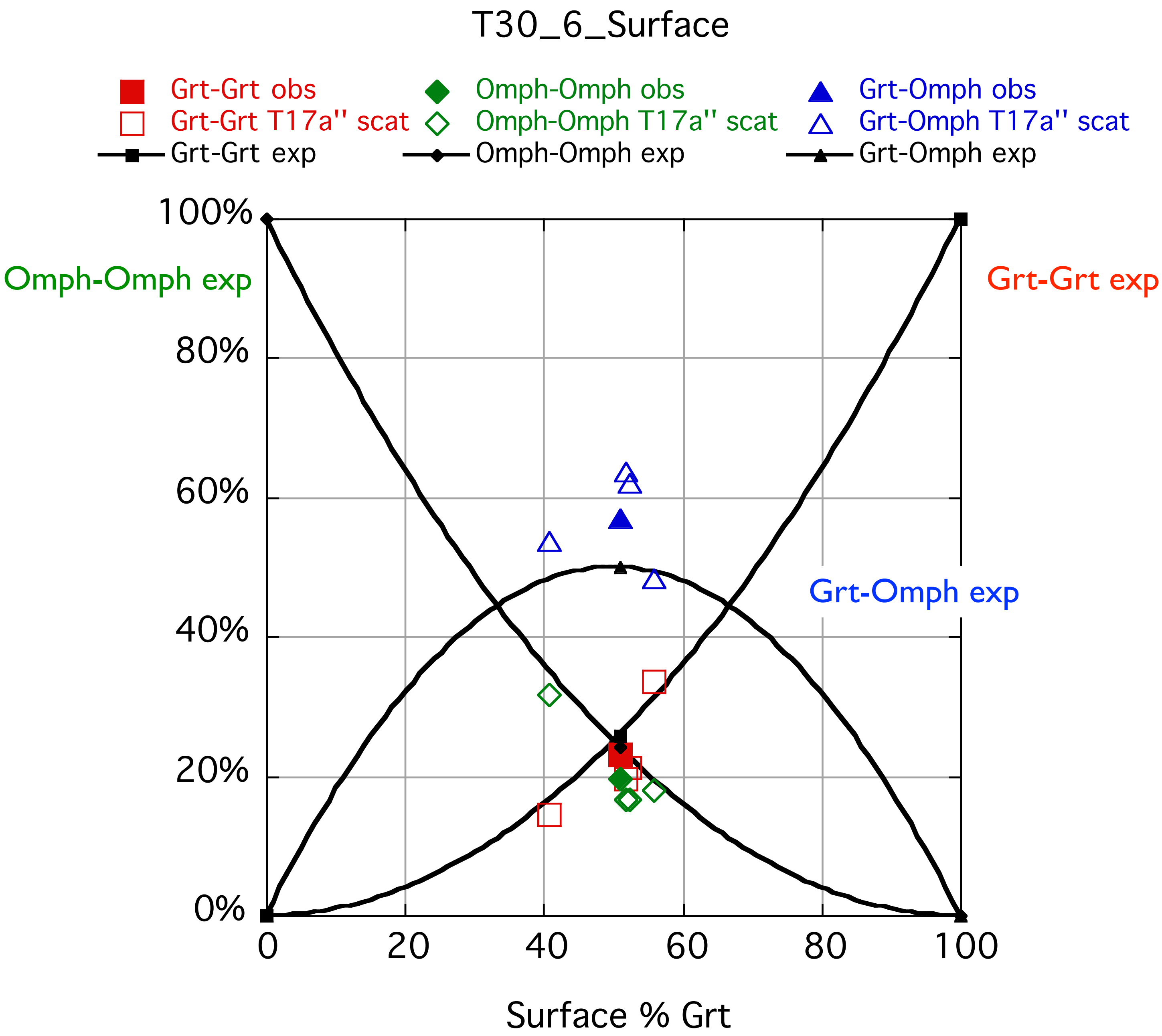
overlap of phases
=> contact types

grain boundaries

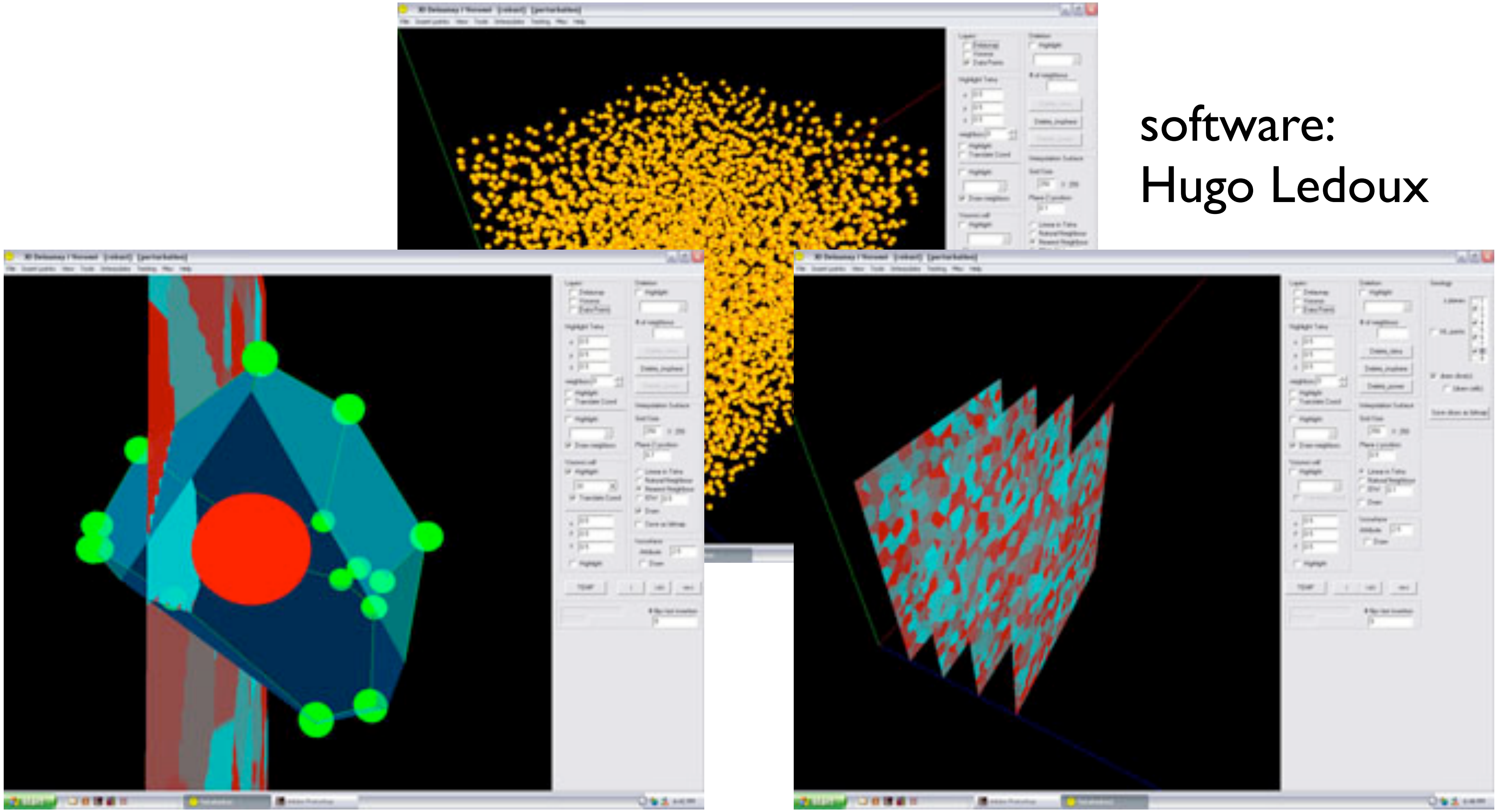


phase boundaries



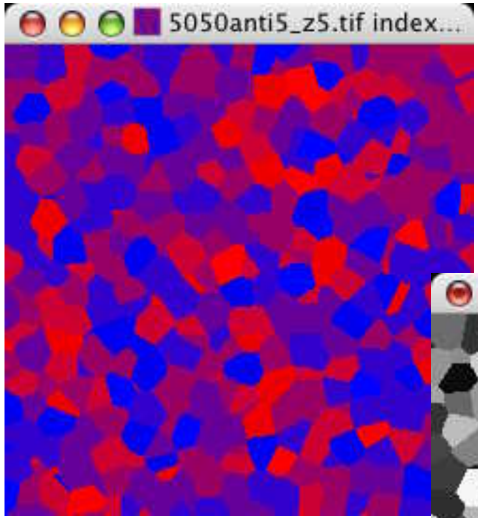


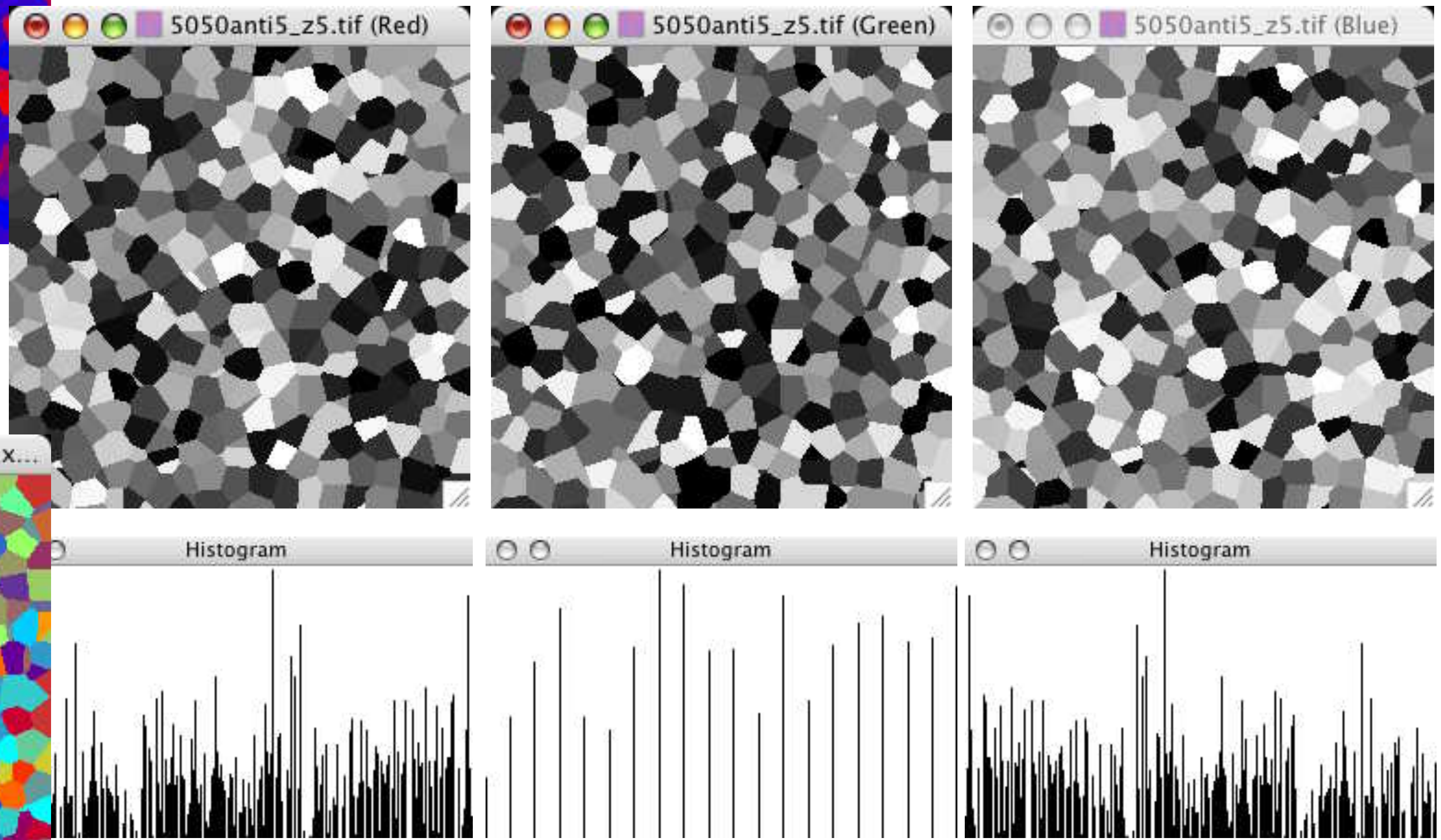
3-D numerical simulations

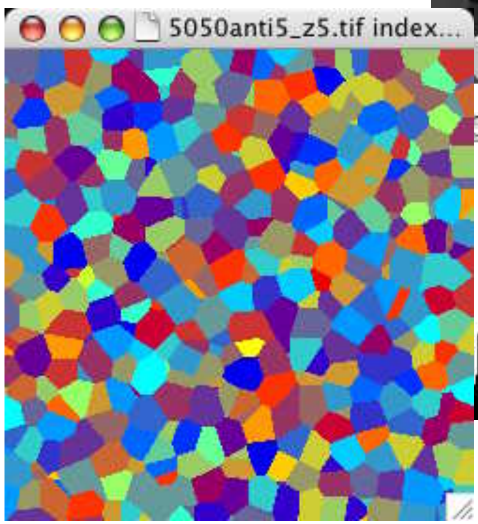


software:
Hugo Ledoux

Lazy voronoi macro: create phase maps

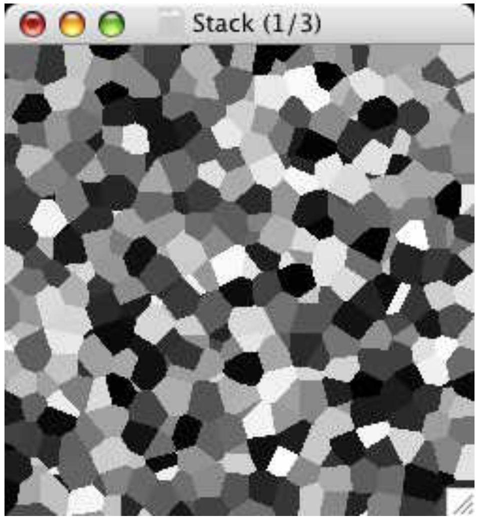


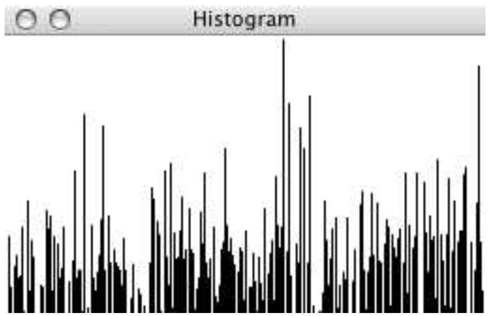


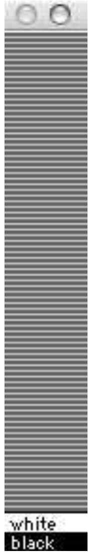


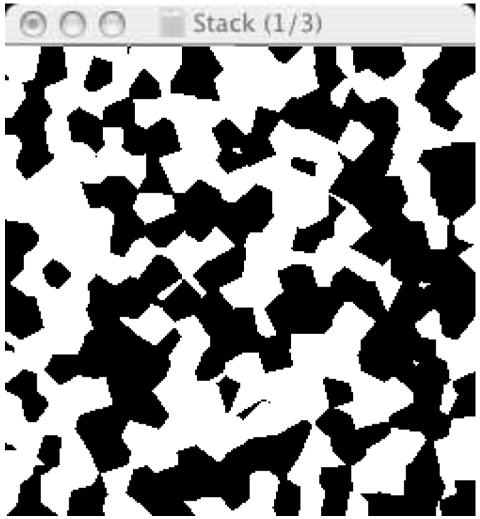
(0<R<255) (0<G<20) B = 255-R

Lazy voronoi macro: create phase maps

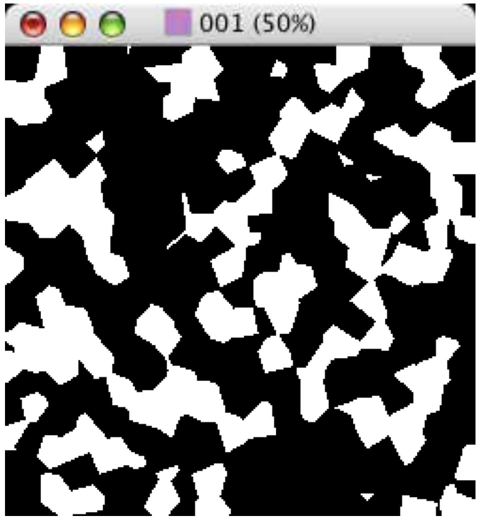




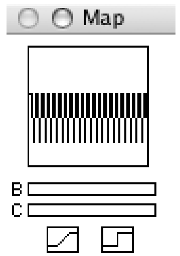




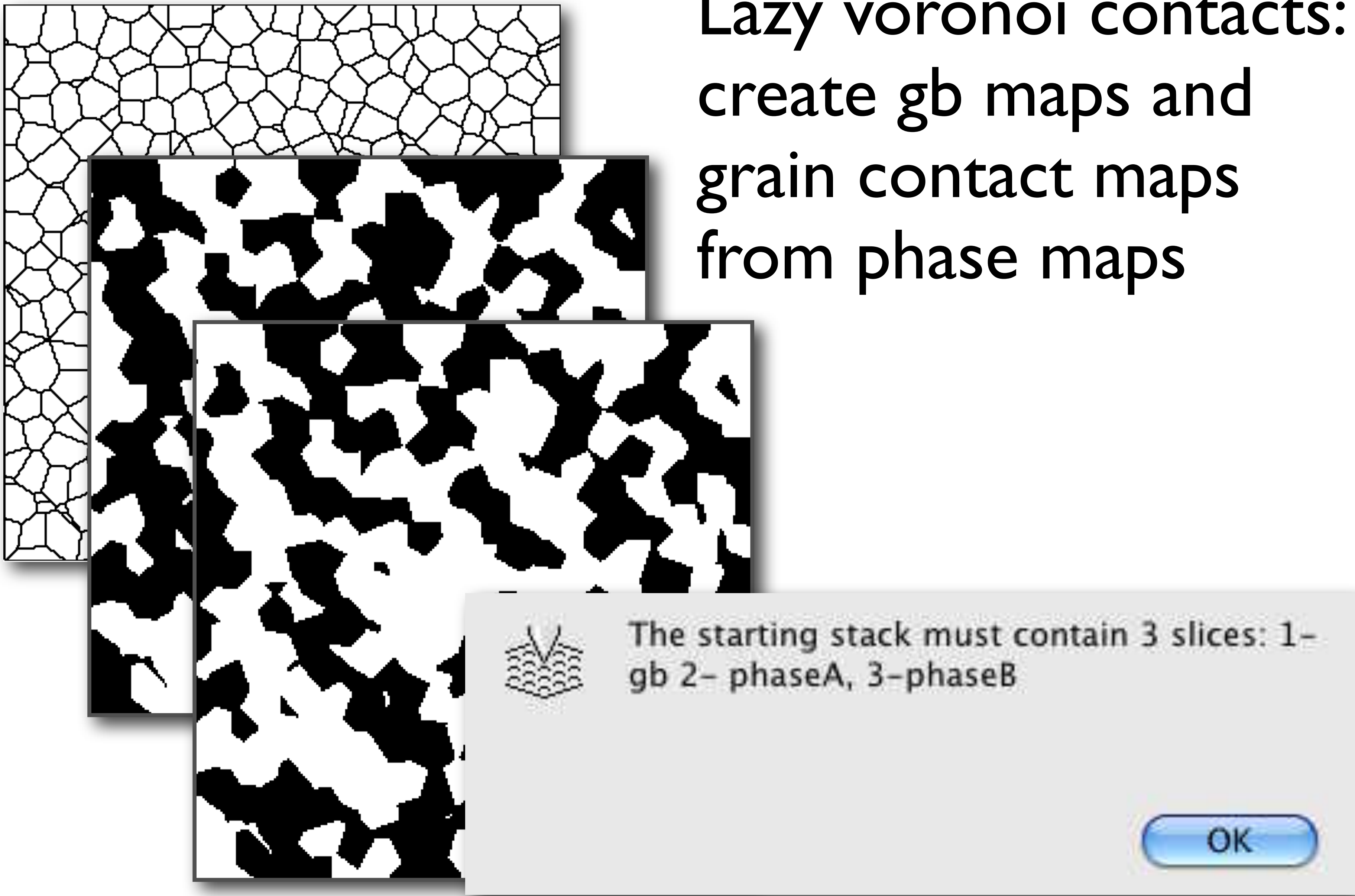
every 2nd



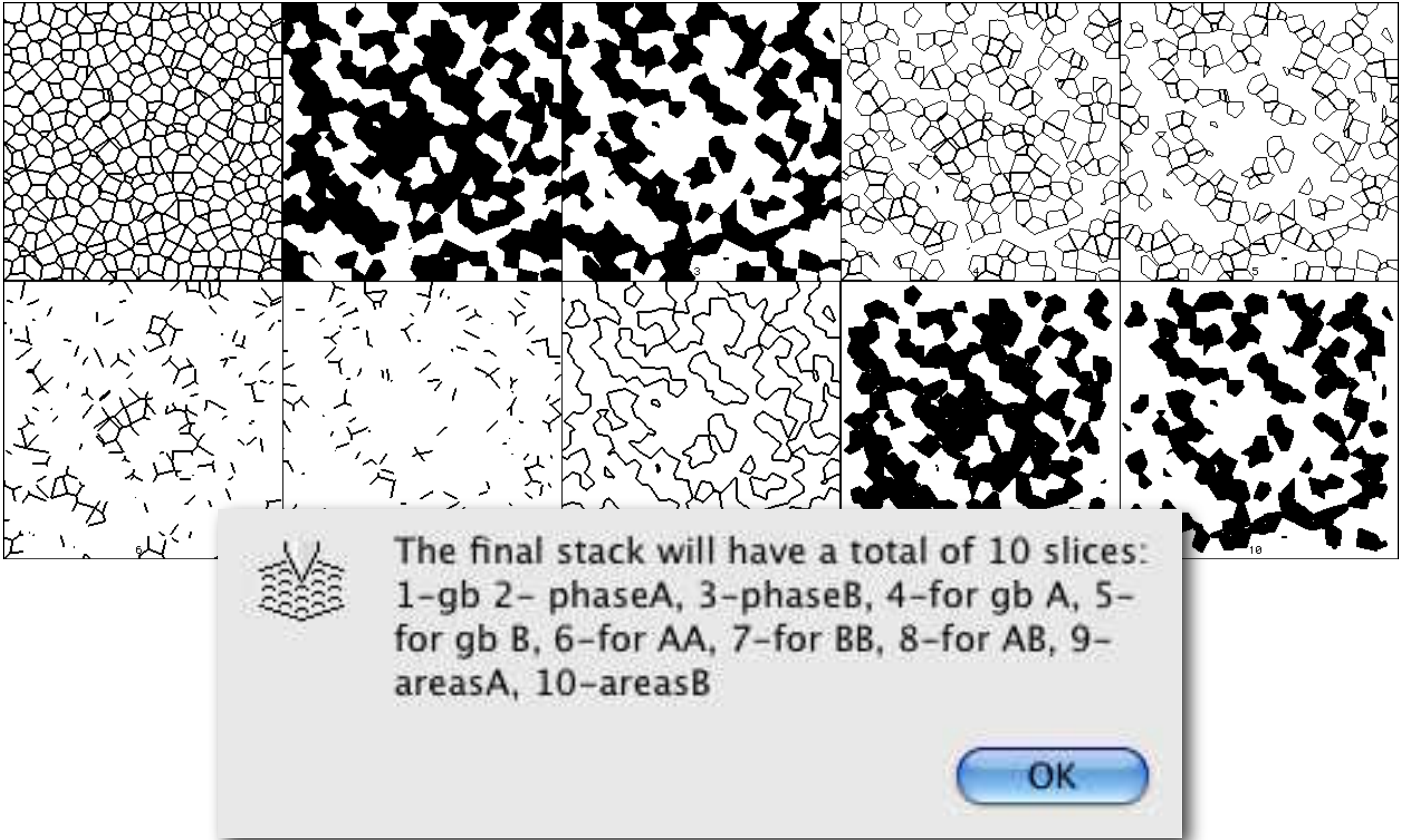
every 3rd

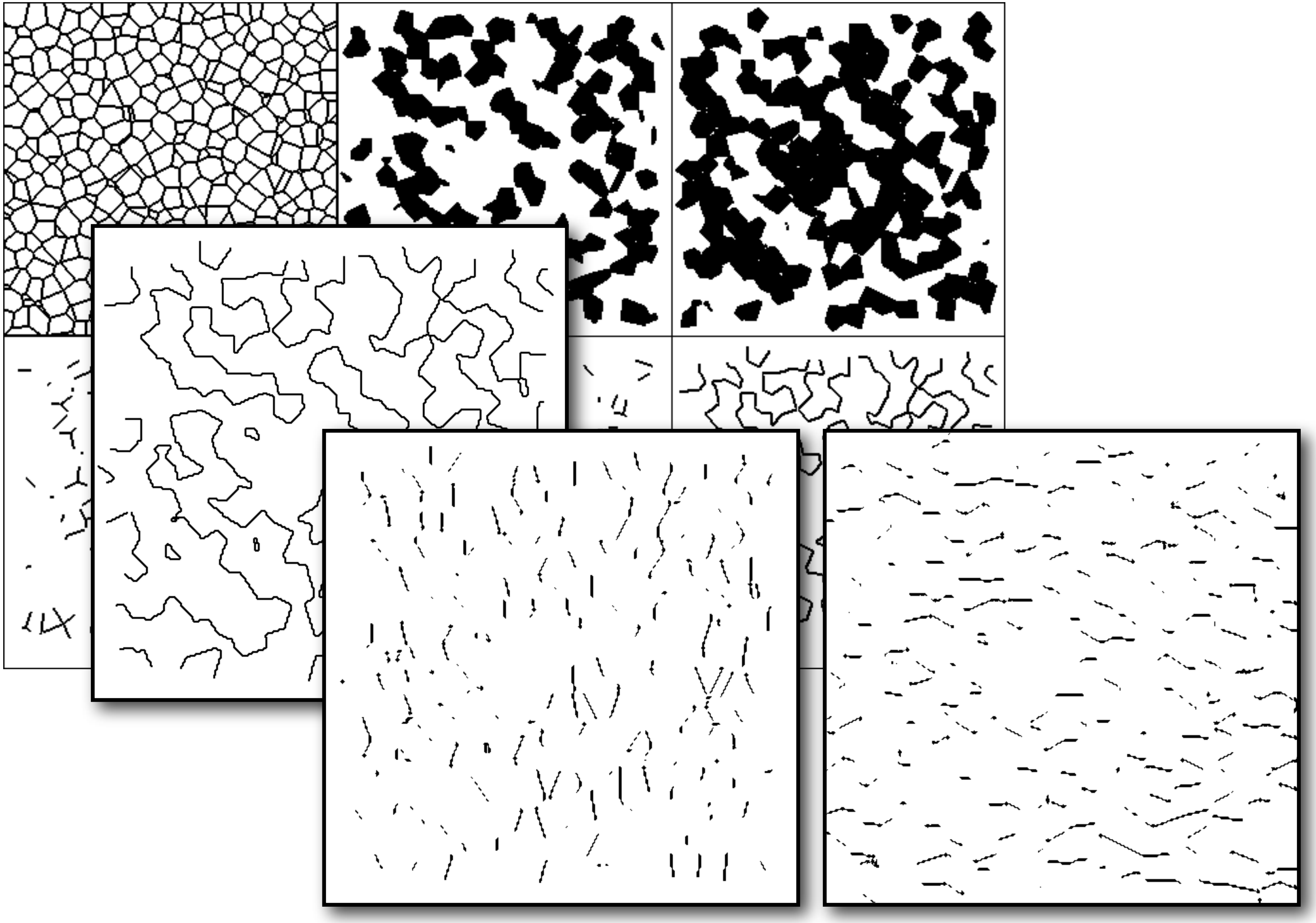


Lazy voronoi contacts: create gb maps and grain contact maps from phase maps

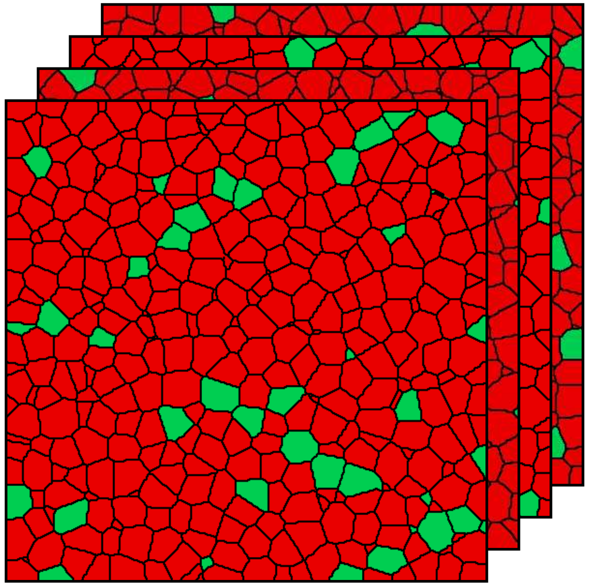


Lazy voronoi contacts

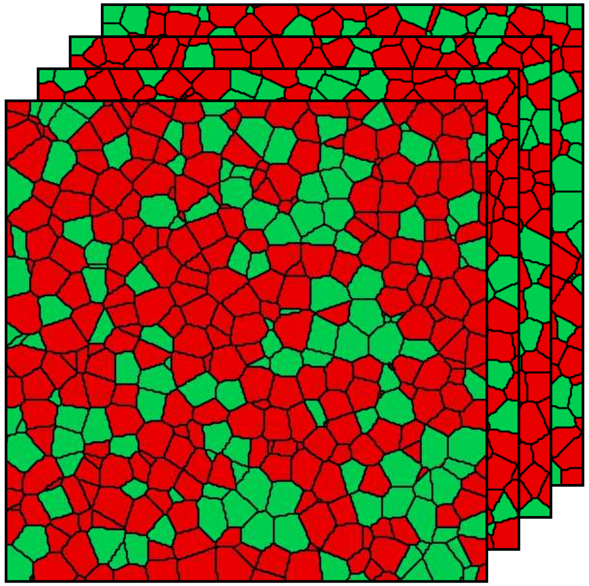




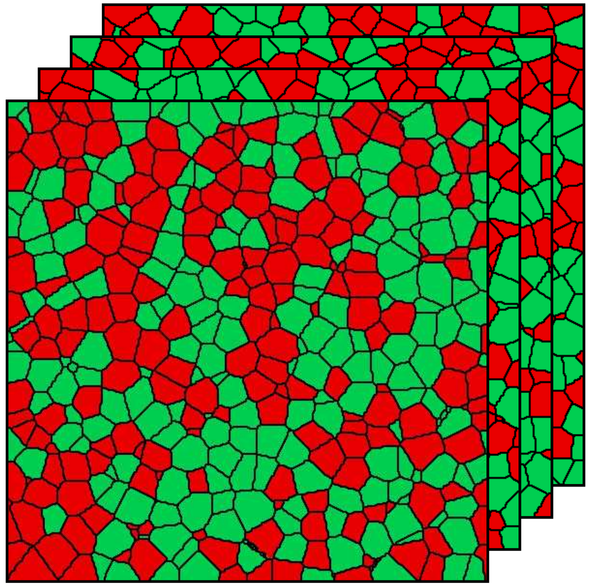
3-D numerical simulations



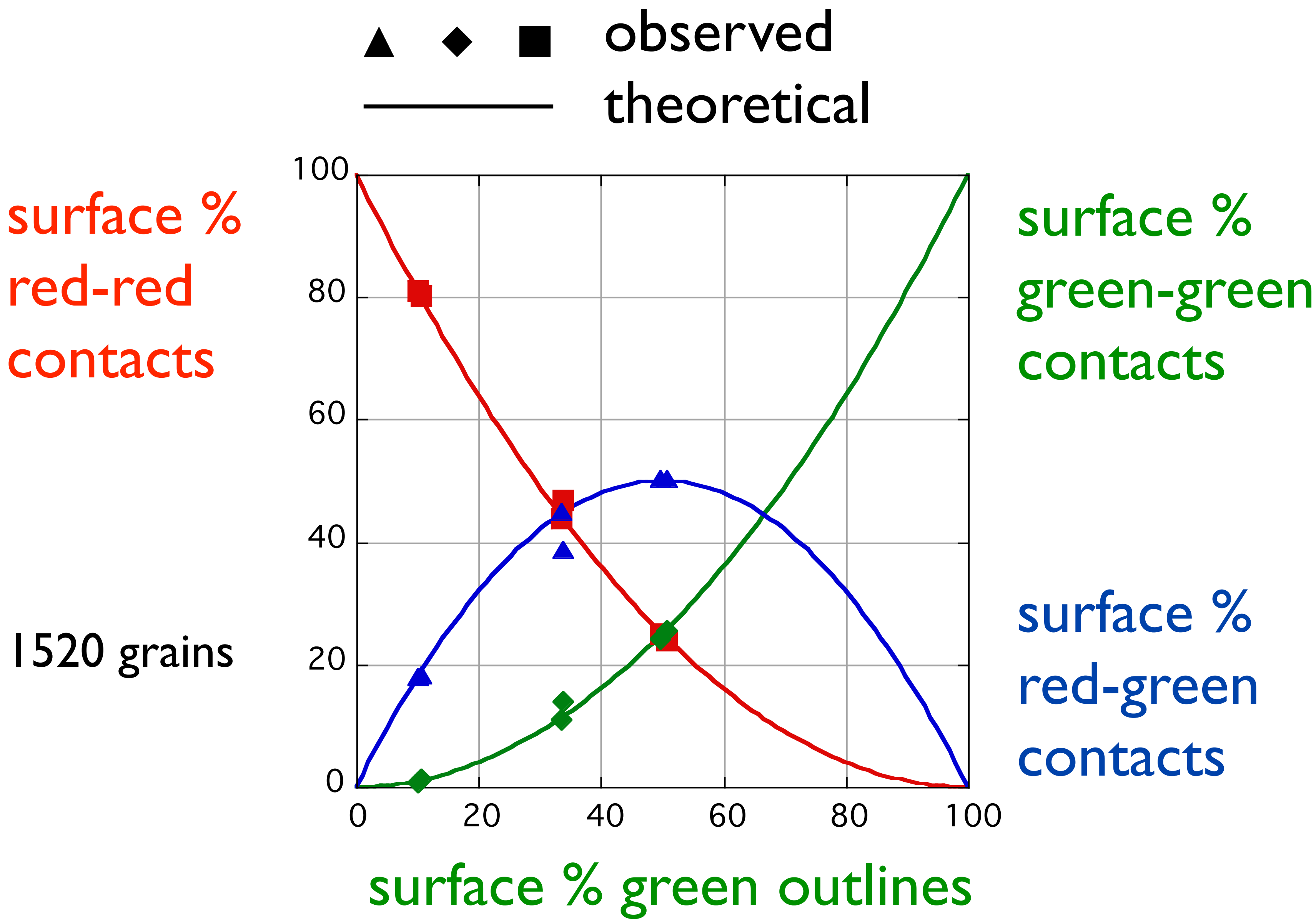
10:90



33:66



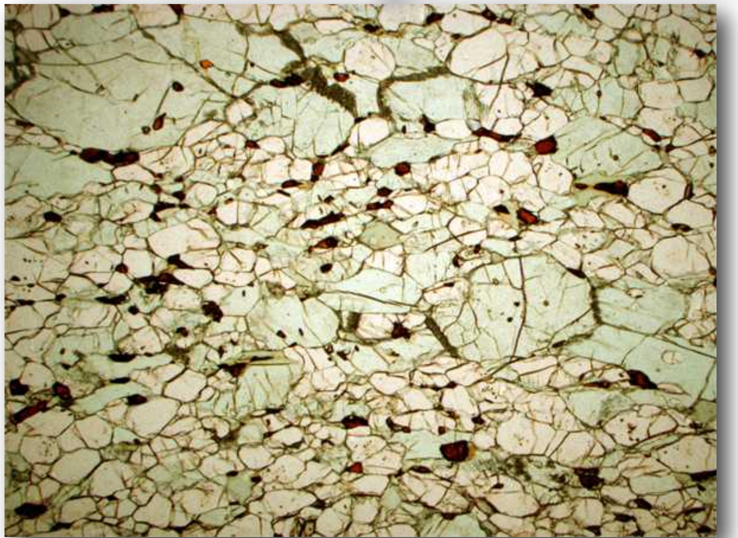
50:50


observed
theoretical
surface %
red-red
contacts
surface %
green-green
contacts
surface %
red-green
contacts
1520 grains
0
20
40
60
80
100
surface % green outlines

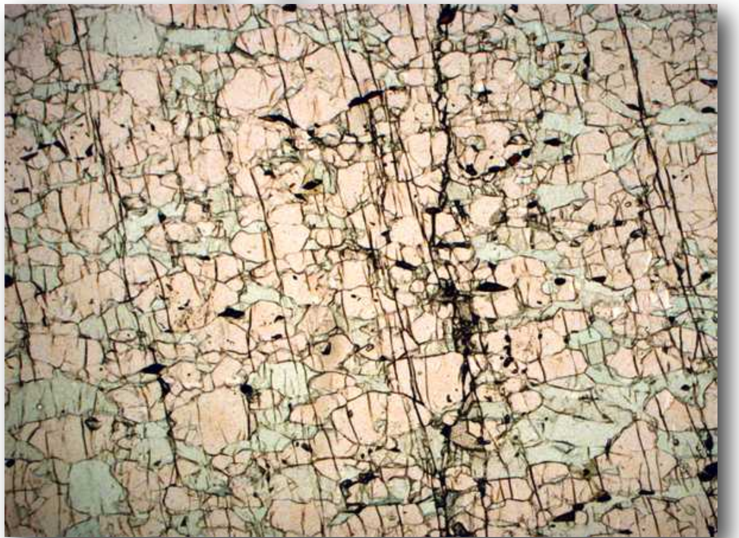
Troms Nappe eclogites

T21: low garnet content

T30: medium garnet content

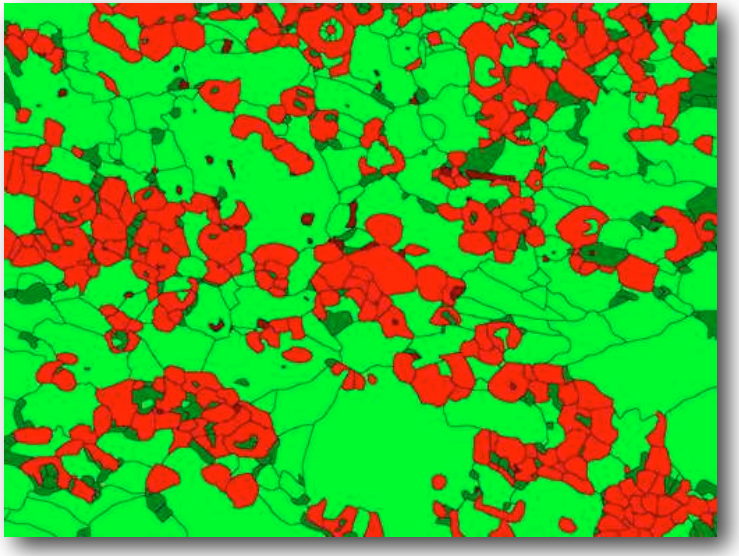


T17: high garnet content

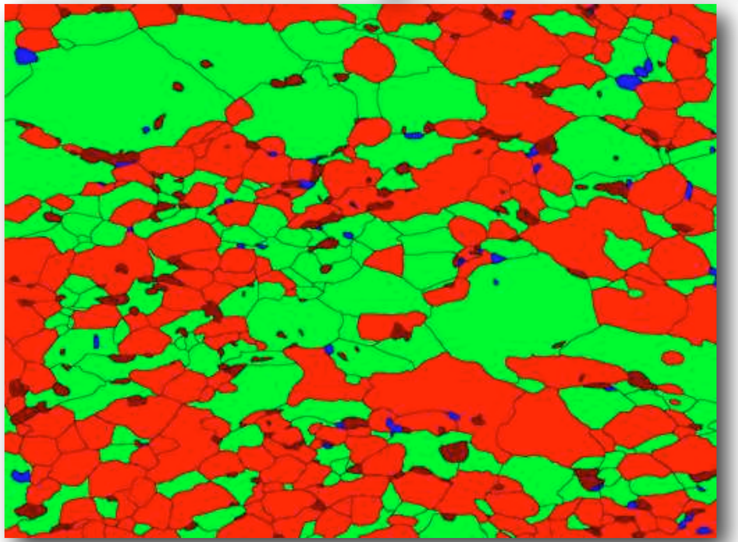


Troms Nappe eclogites

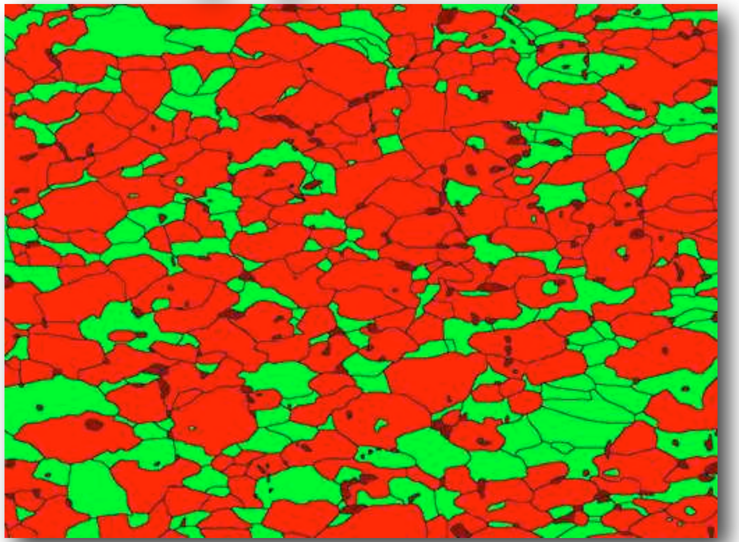
T21: low garnet content

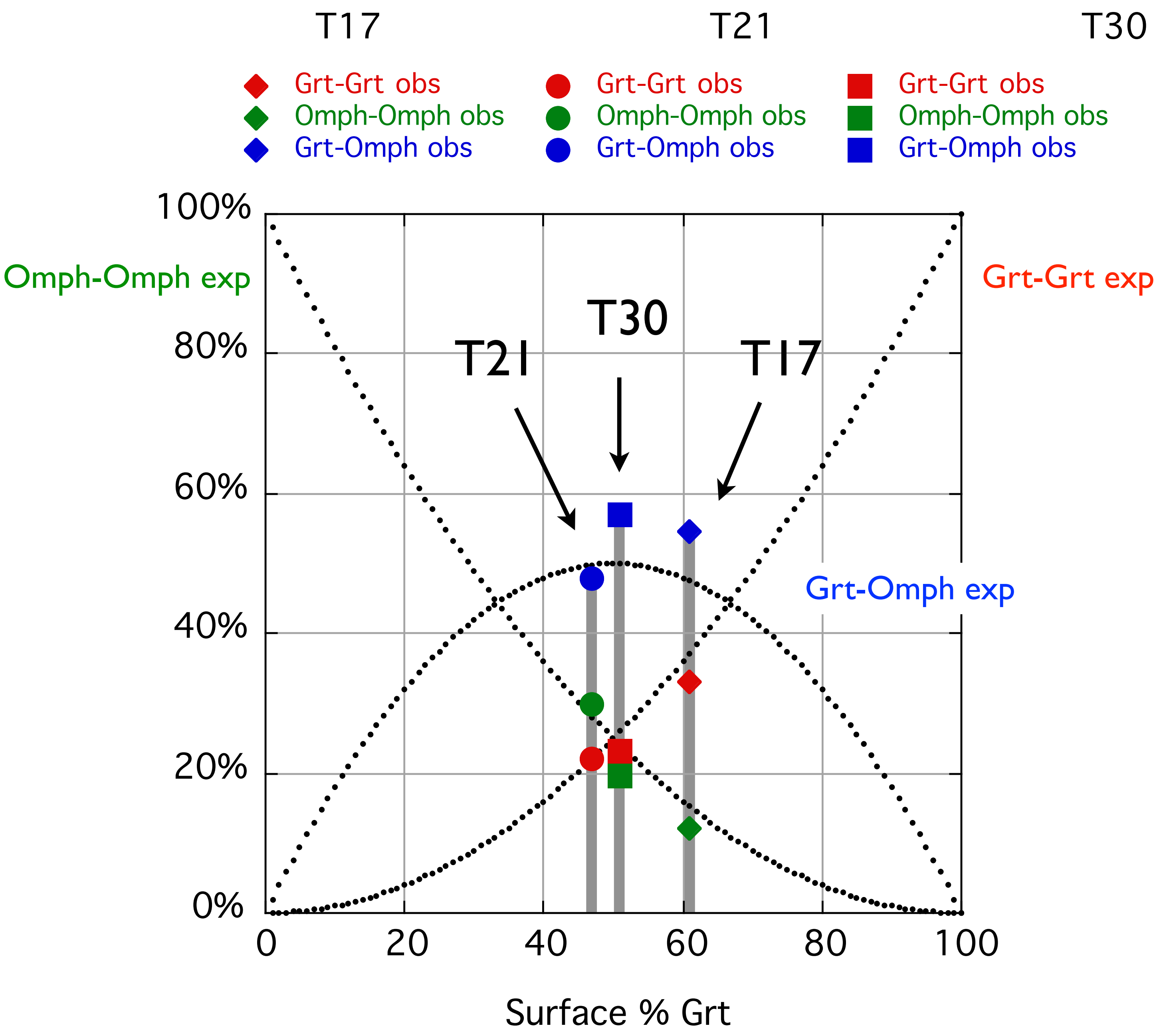


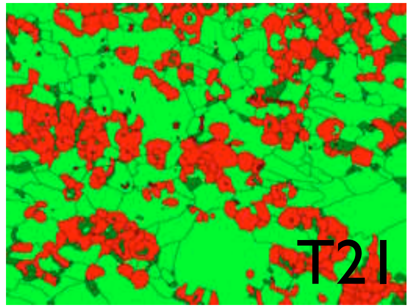
T30: medium garnet content

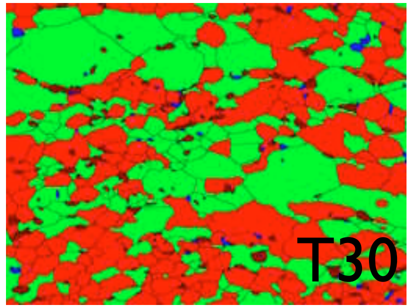


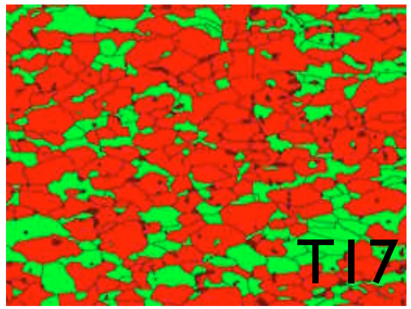
T17: high garnet content

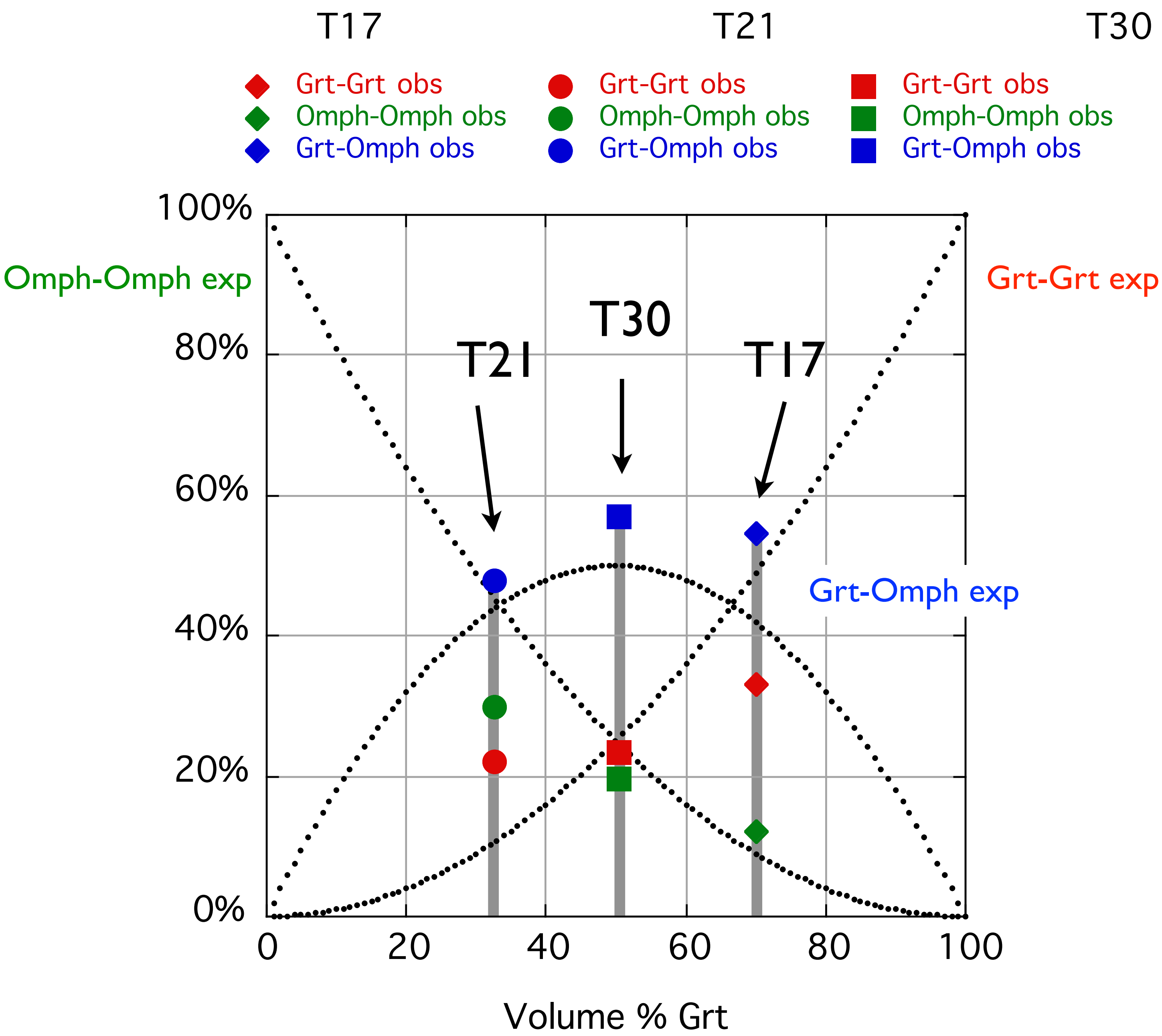


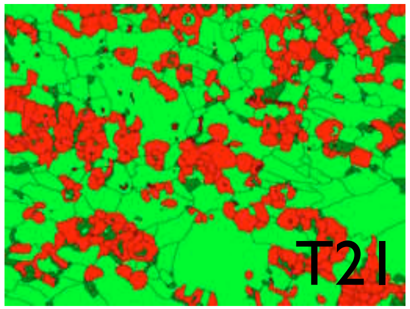

T17
T21
T30
Grt-Grt obs
Omph-Omph obs
Grt-Omph obs
Grt-Grt obs
Omph-Omph obs
Grt-Omph obs
Grt-Grt obs
Omph-Omph obs
Grt-Omph obs
100%
80%
60%
40%
20%
0%
Omph-Omph exp
Grt-Grt exp
Grt-Omph exp
T21
T30
T17
0
20
40
60
80
100
Surface % Grt

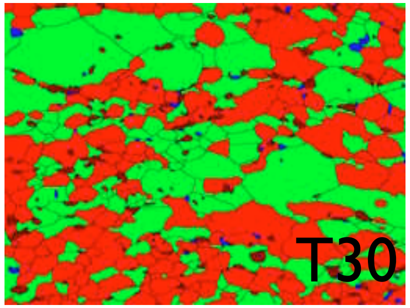

T21

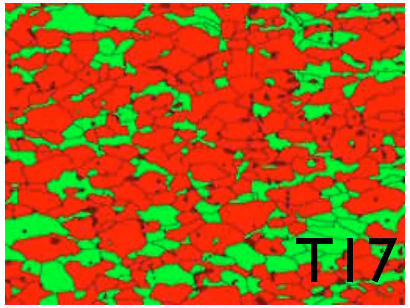

T30

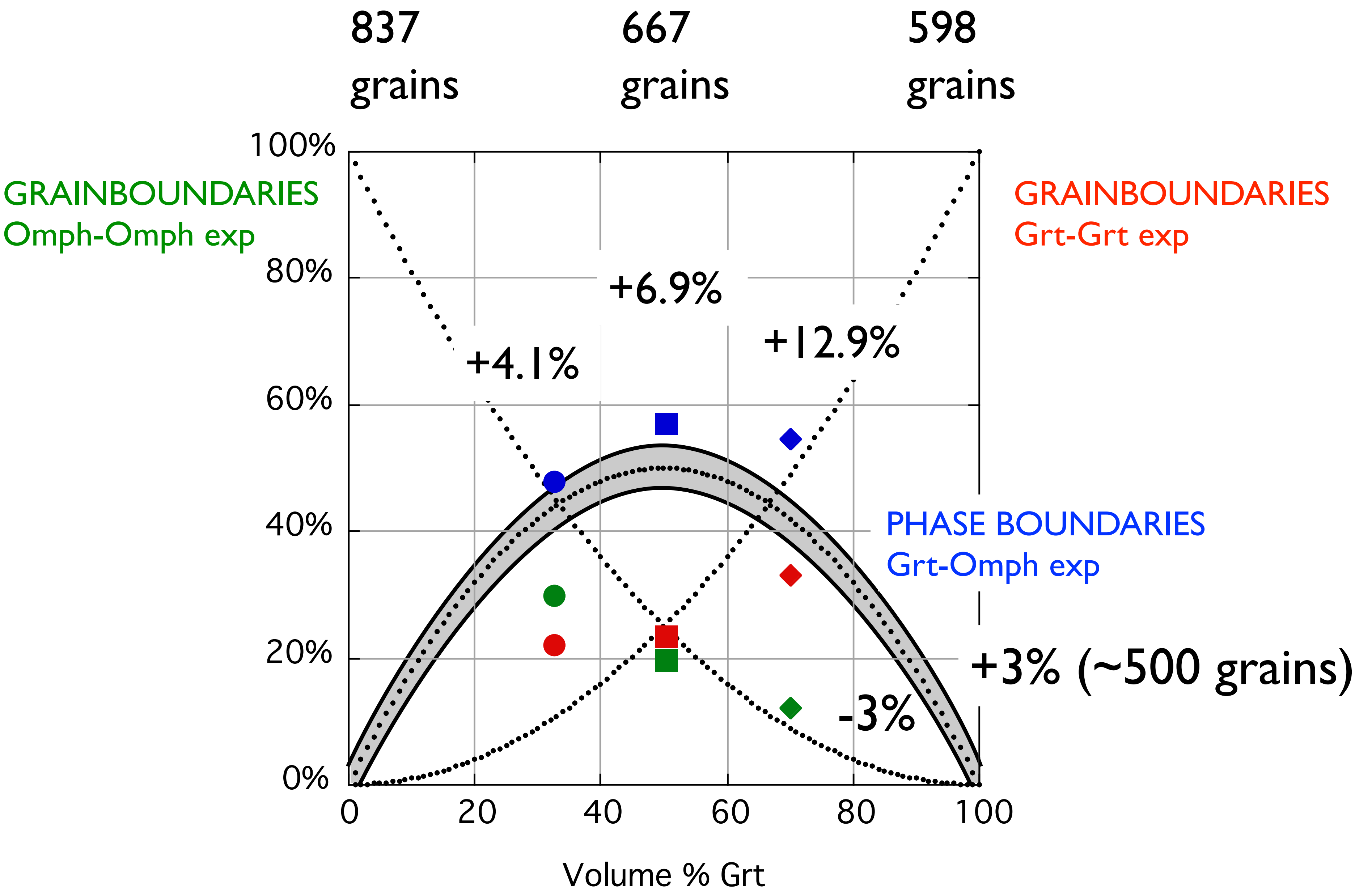

T17


T17
T21
T30
Grt-Grt obs
Omph-Omph obs
Grt-Omph obs
Grt-Grt obs
Omph-Omph obs
Grt-Omph obs
Grt-Grt obs
Omph-Omph obs
Grt-Omph obs
100%
80%
60%
40%
20%
0%
Omph-Omph exp
Grt-Grt exp
Grt-Omph exp
T21
T30
T17
0
20
40
60
80
100
Volume % Grt


T21


T30

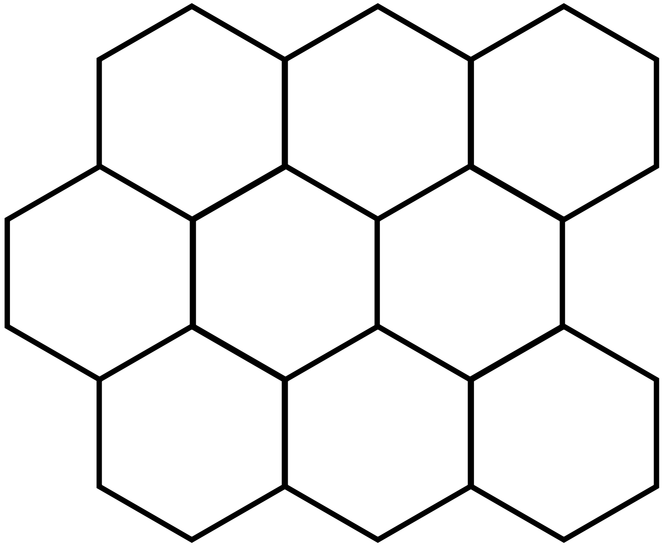

T17


837 grains
667 grains
598 grains
100%
80%
60%
40%
20%
0%
GRAINBOUNDARIES
Omph-Omph exp
GRAINBOUNDARIES
Grt-Grt exp
PHASE BOUNDARIES
Grt-Omph exp
+6.9%
+4.1%
+12.9%
+3% (~500 grains)
-3%
0
20
40
60
80
100
Volume % Grt

spatial distribution
= diffusion creep

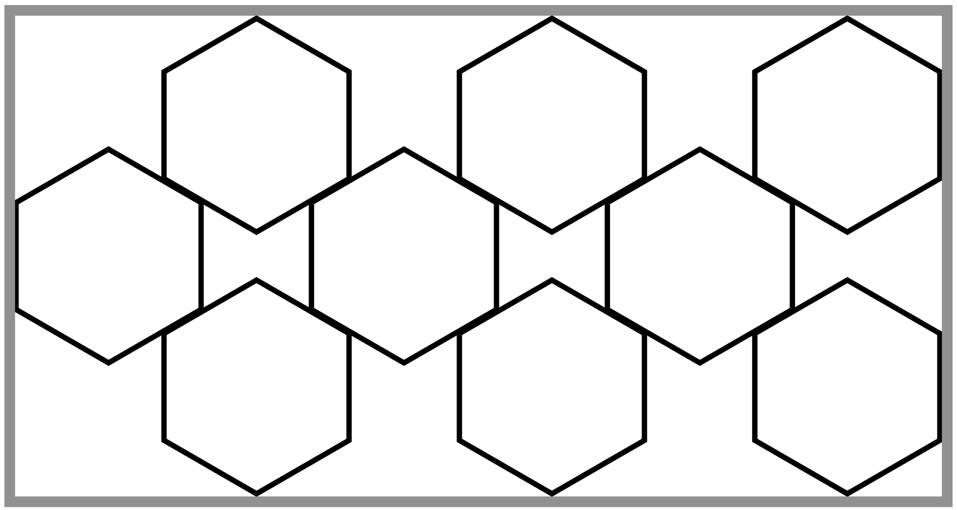
process ?

micromechanical models



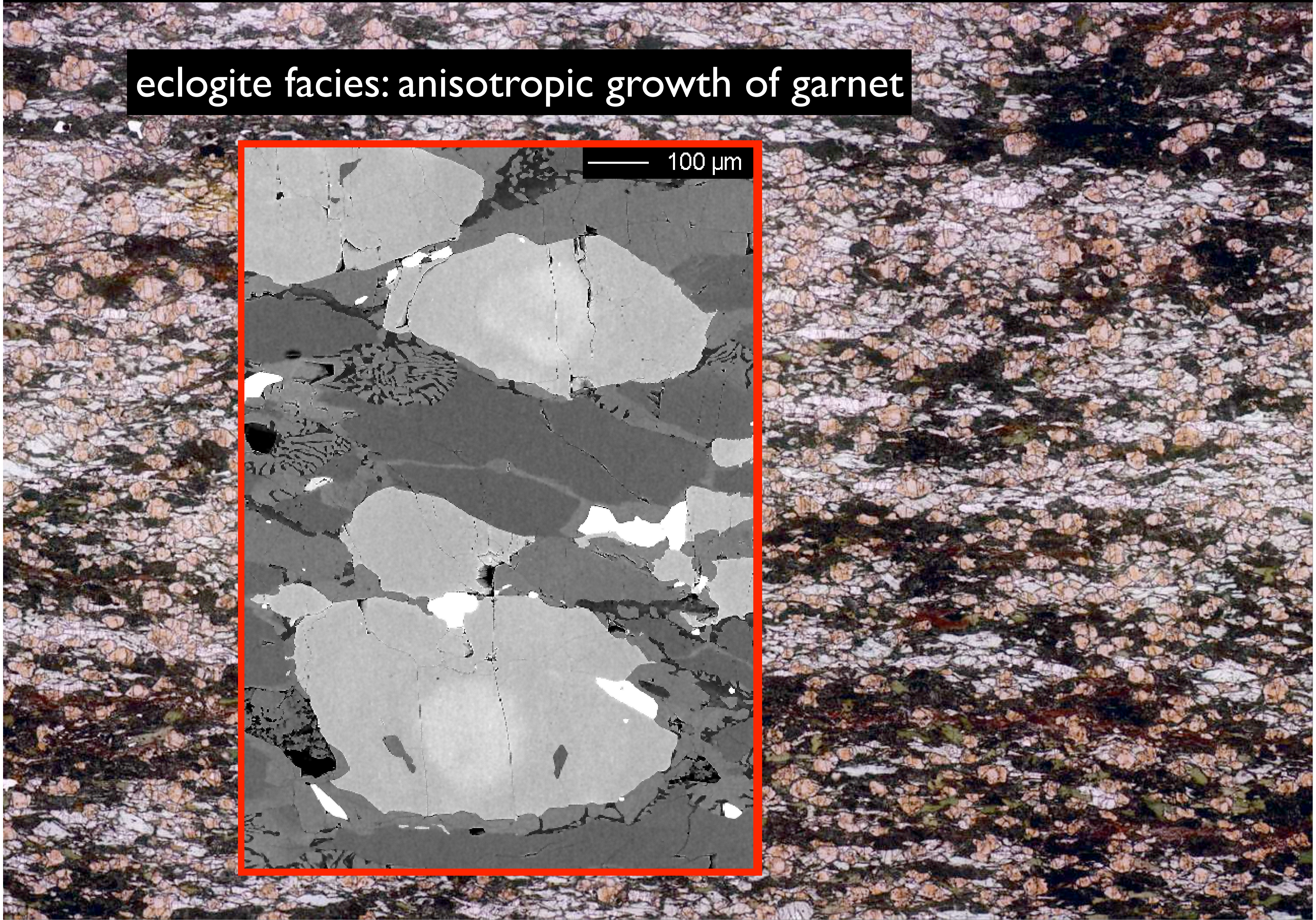
mass flux

diffusion creep
- through solid
- along boundary



granular flow
grain boundary sliding
pressure solution

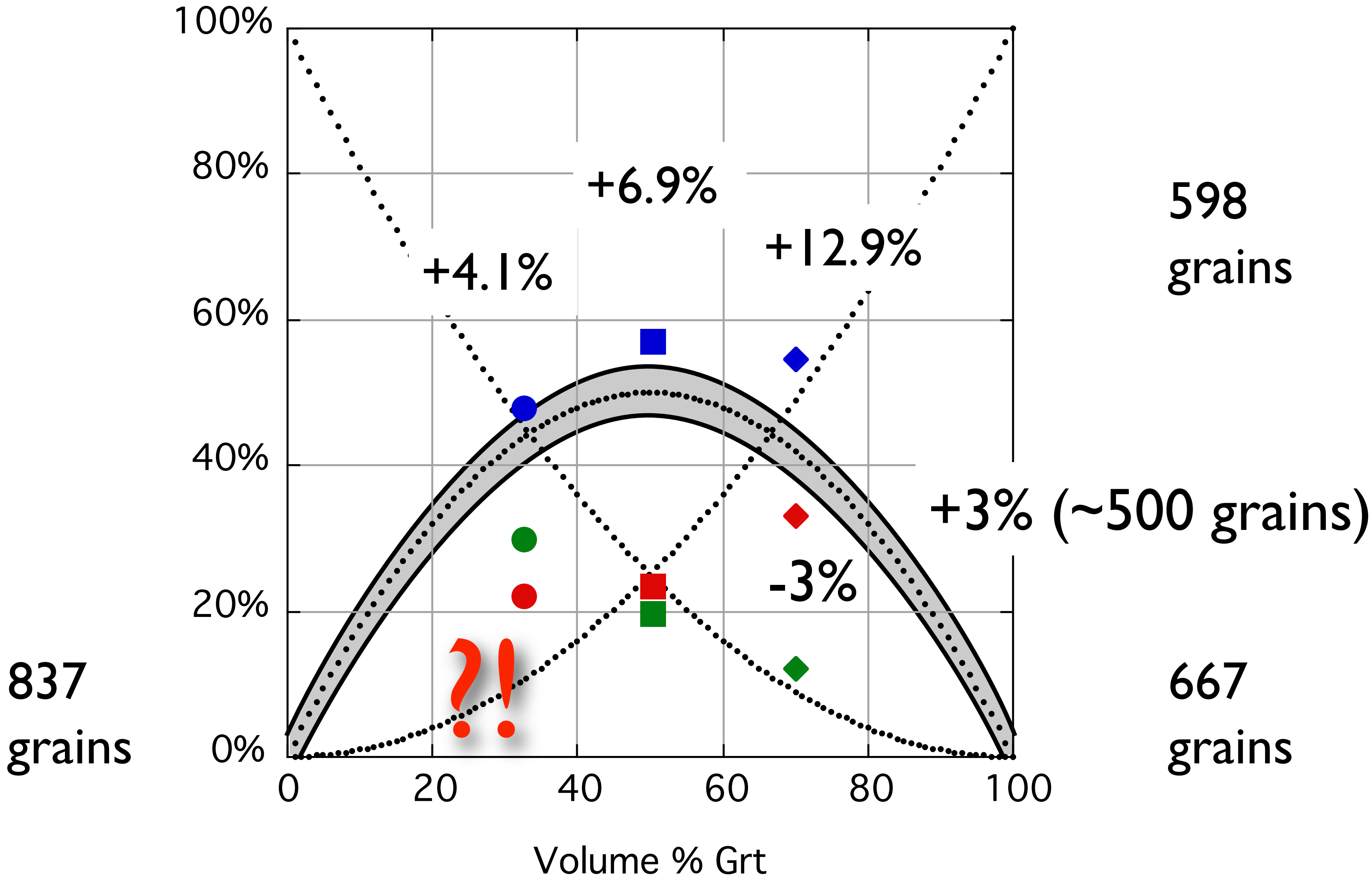
eclogite facies: anisotropic growth of garnet



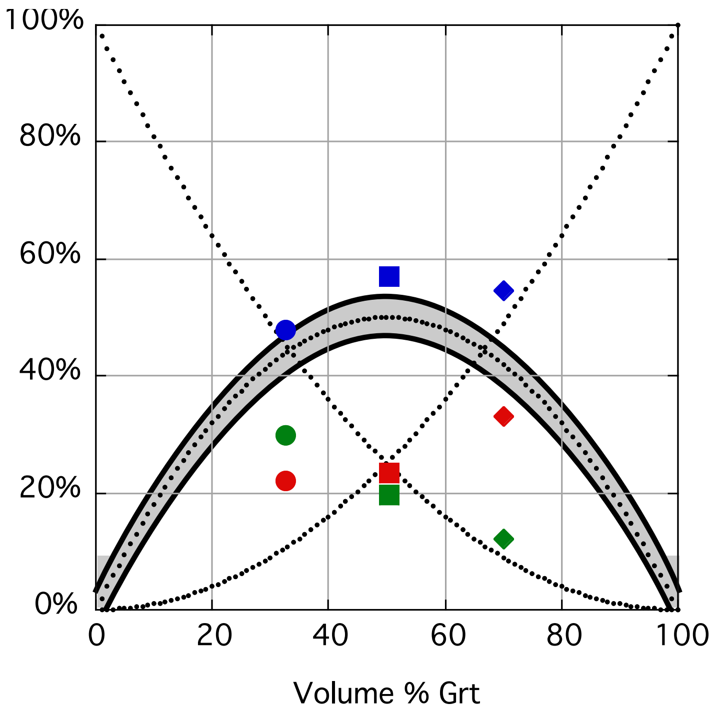
1. fast exhumation, high shear strain rates
2. deformation mechanism = diffusion creep
3. geometrical model
   ≠ strain ≠ shape ≠ gs
   = spatial distribution
4. model: 3-D, 2-D section
   stereology 2-D > 3-D (≠ Kretz)
5. to get errors: simulations
   (3-D Voronoi by Ledoux)

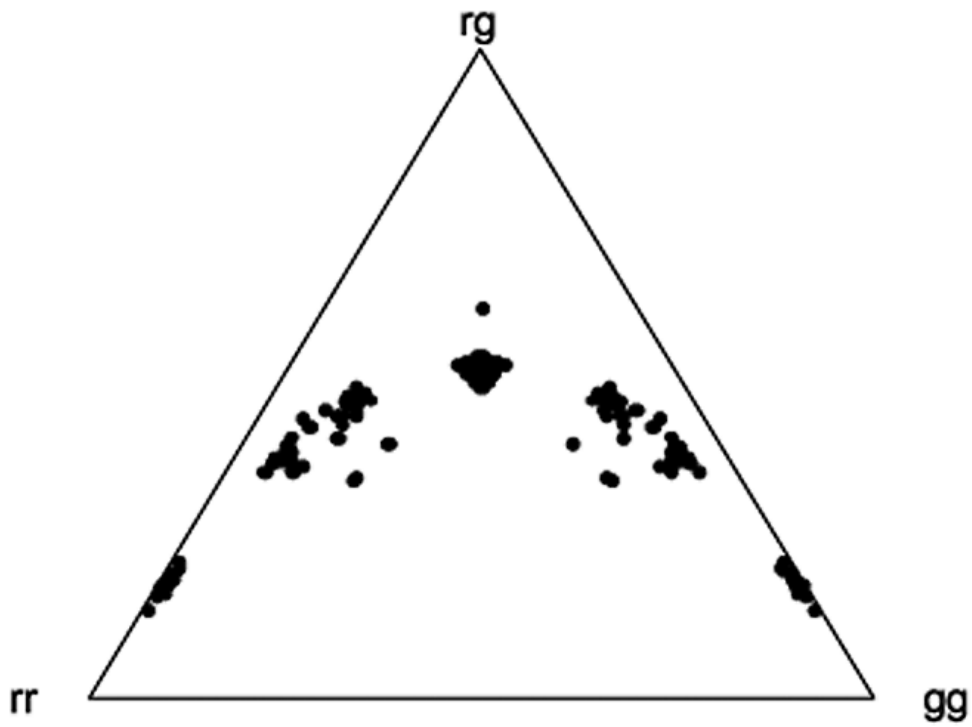
... future work ?

errors?


100%
80%
60%
40%
20%
0%
0
20
40
60
80
100
Volume % Grt
+6.9%
+4.1%
+12.9%
598
grains
+3% (~500 grains)
-3%
837
grains
667
grains
?!

errors?





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... 6. beer ...