Using grain boundary irregularity to quantify dynamic recrystallization in ice

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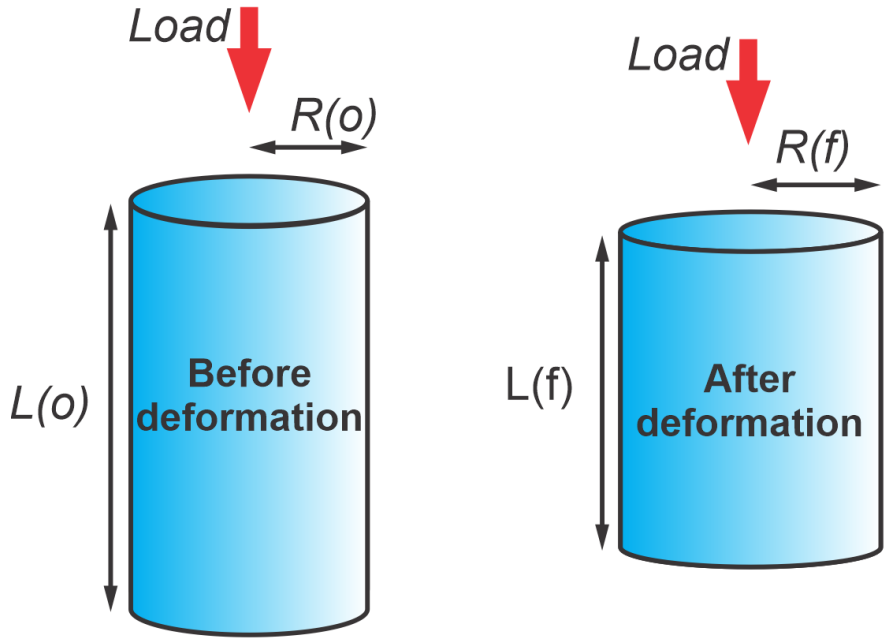
Background: Mount Erebus, Antarctica. Photo by: S. Fan

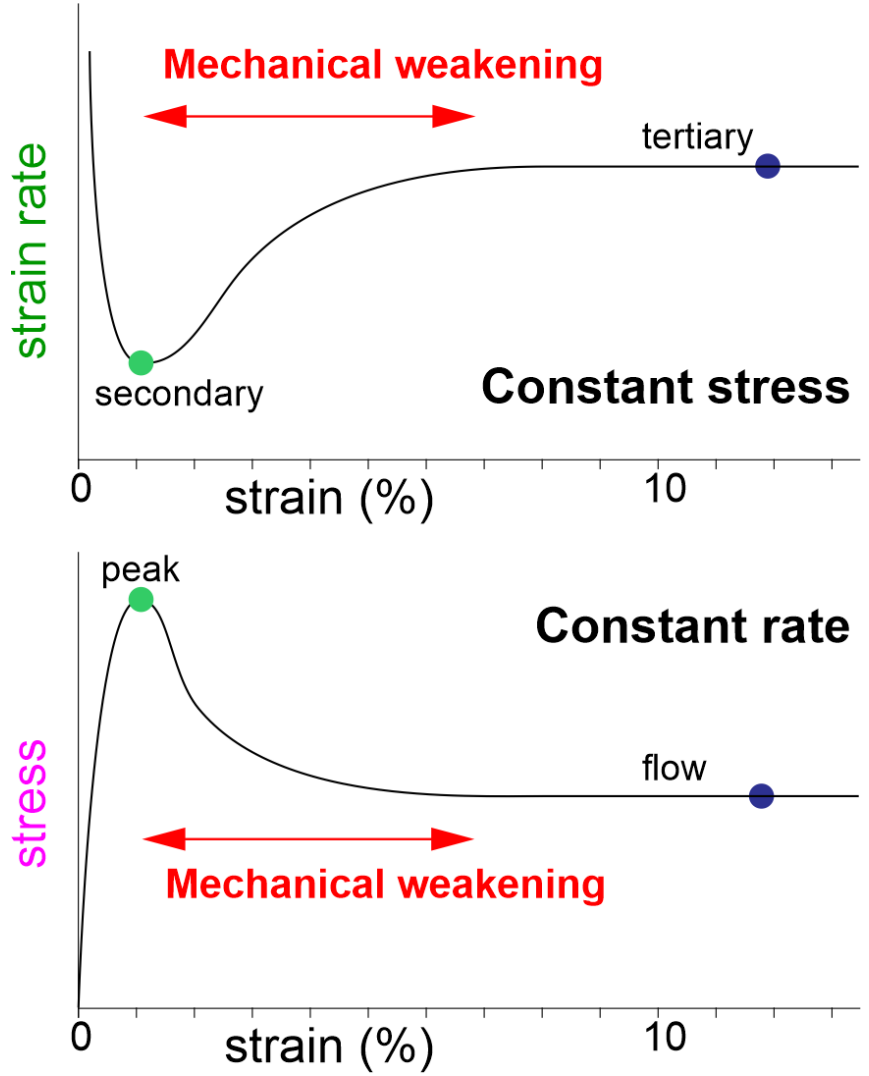
Ice becomes mechanically weaker during deformation

The weakening (enhancement) of ice is tightly correlated with dynamic recrystallization processes

Geometry of polycrystalline ice sample before and after deformation

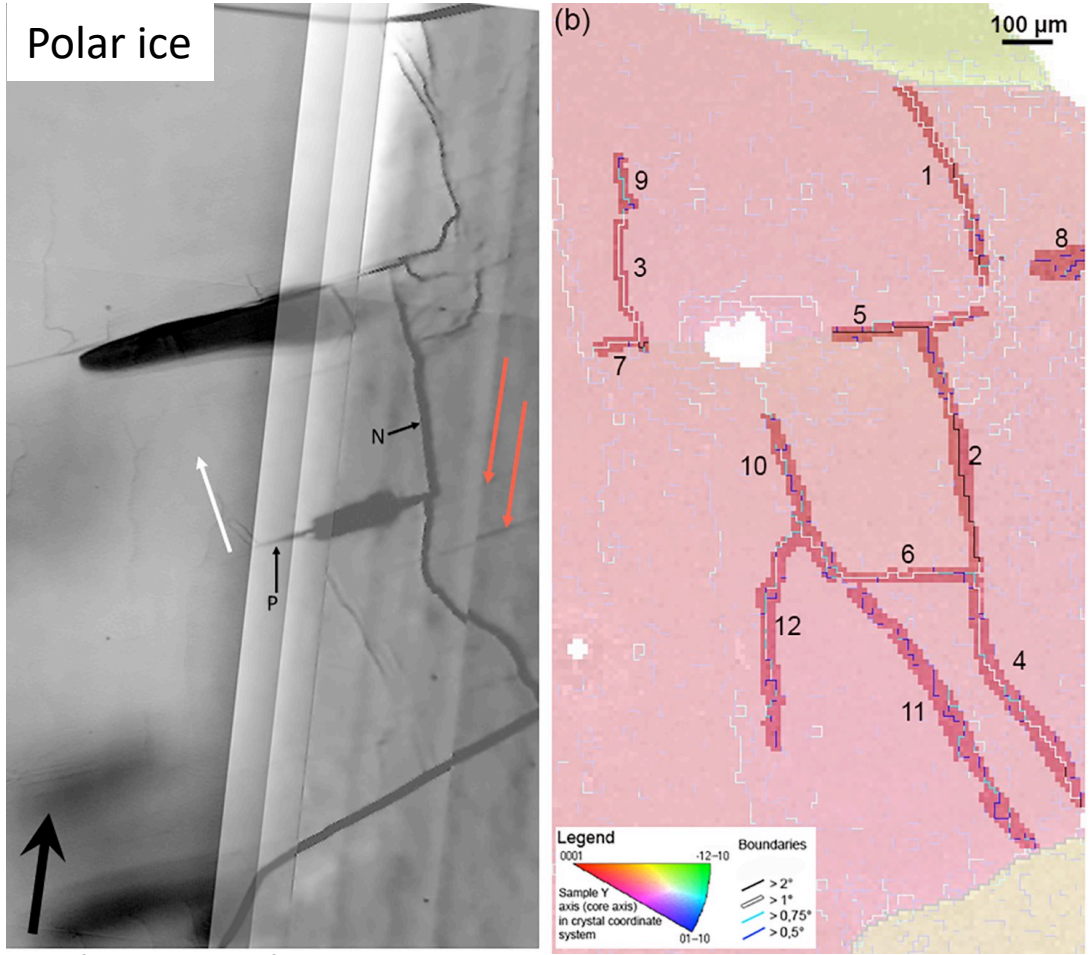


strain = -ln(*L(f)*/*L(o)*)



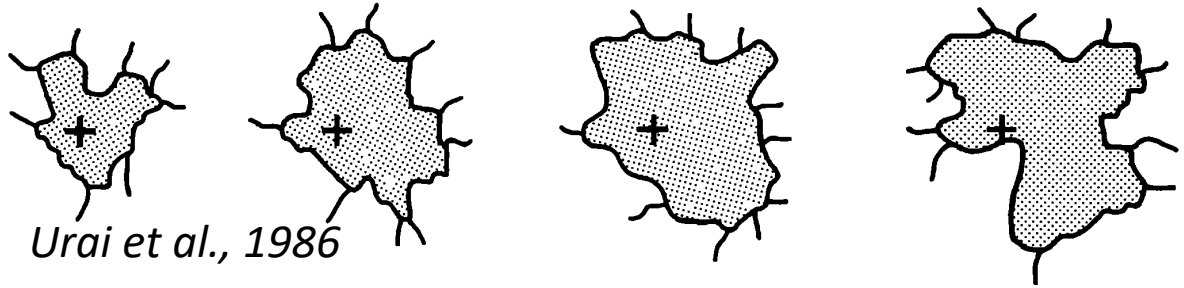
Dynamic recrystallization = formation/migration of grain boundaries

Intragranular boundaries: recovery of dislocations



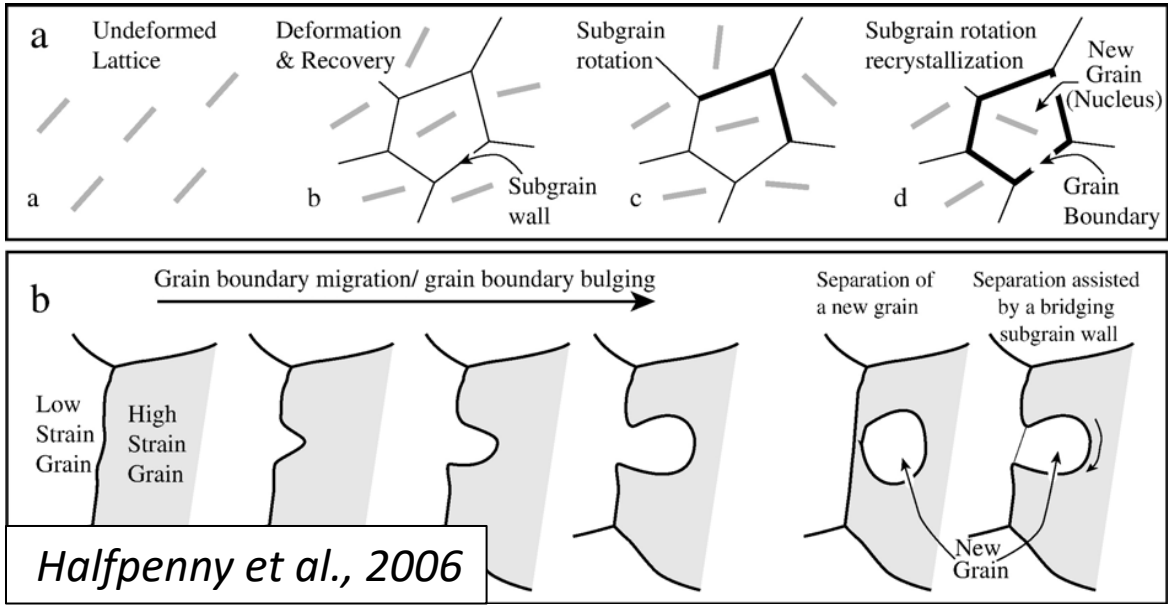
Weikusat et al., 2017

Dynamic grain growth—grain boundary migration



Urai et al., 1986

Nucleation— subgrain rotation/bulging



Halfpenny et al., 2006

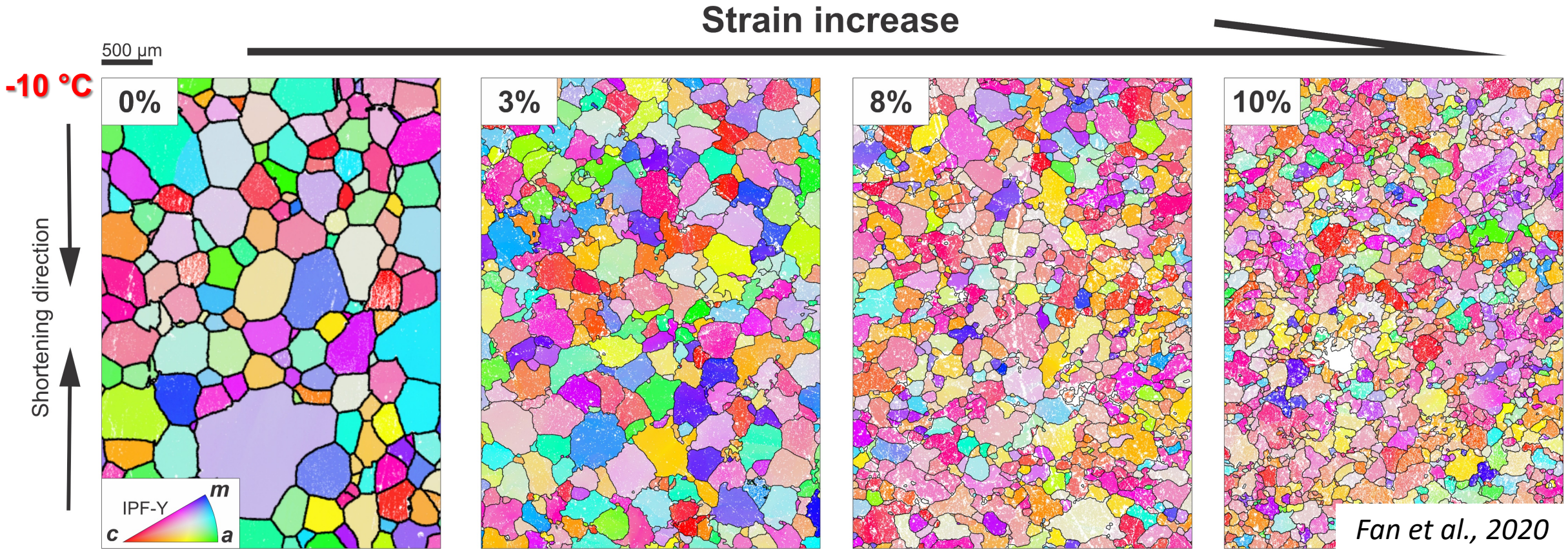
Weikusat, Ilka, et al. "EBSD analysis of subgrain boundaries and dislocation slip systems in Antarctic and Greenland ice." Solid Earth 8.5 (2017): 883-898.

Urai, J. L., W. D. Means, and G. S. Lister. "Dynamic recrystallization of minerals." Mineral and rock deformation: laboratory studies. Vol. 36. Washington, DC: AGU, 1986. 161-199.

Halfpenny, Angela, David J. Prior, and John Wheeler. "Analysis of dynamic recrystallization and nucleation in a quartzite mylonite." Tectonophysics 427.1-4 (2006): 3-14.

We know DRX is active during high T deformation

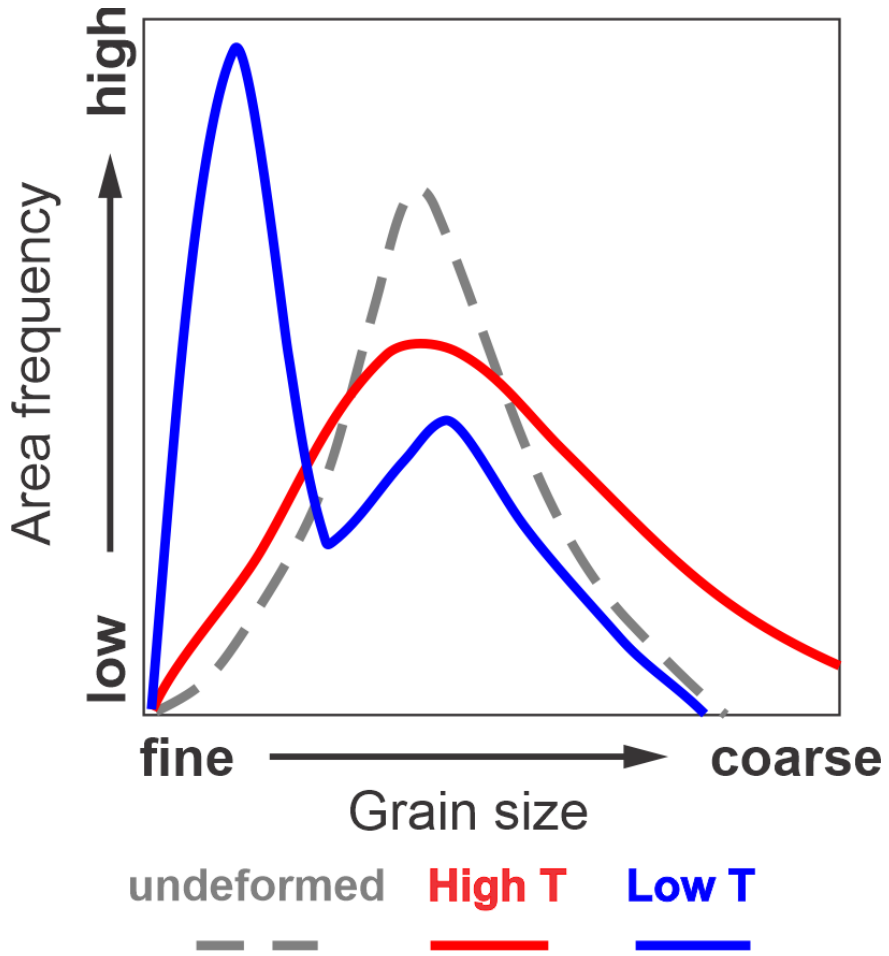
BUT, the quantification of DRX remains challenging

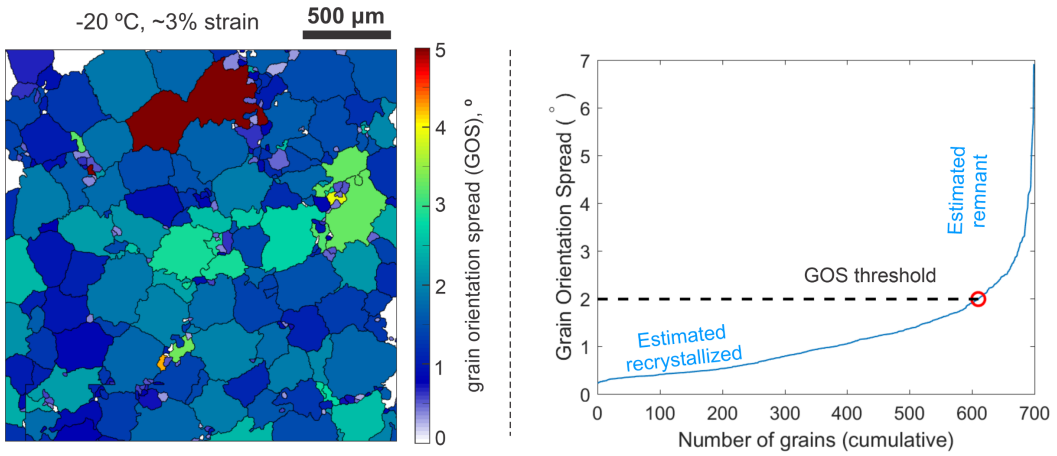


Fan, Sheng, et al. "Temperature and strain controls on ice deformation mechanisms: insights from the microstructures of samples deformed to progressively higher strains at− 10,− 20 and− 30° C." The Cryosphere 14.11 (2020): 3875-3905.

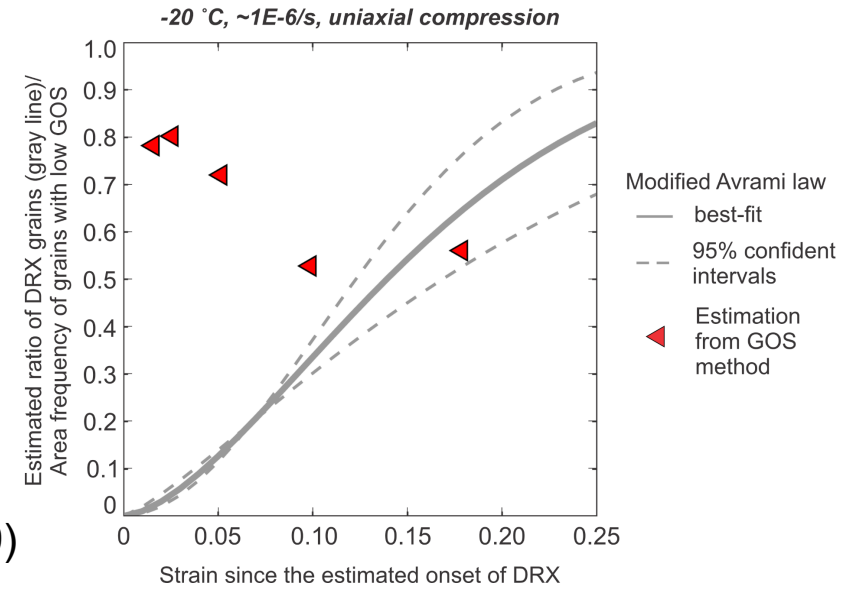
Ideal ways of segregating DRX grains at low *T* do not work at high *T*

Grain size method



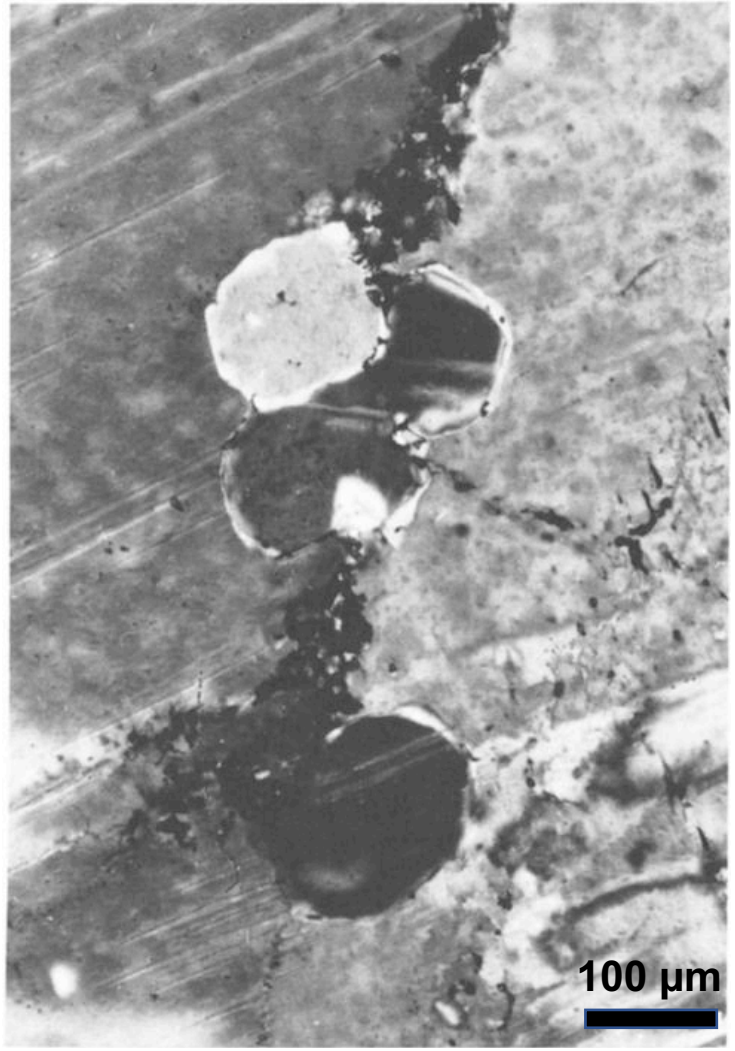


Internal distortion method (Cross et al., 2017; Cross & Skemer, 2019)

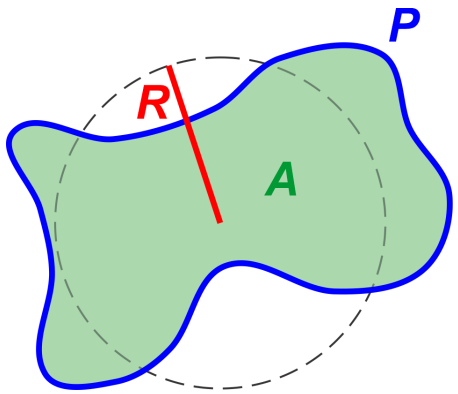


Cross, A. J., et al. "The recrystallized grain size piezometer for quartz: An EBSD-based calibration." Geophysical Research Letters 44.13 (2017): 6667-6674.
Cross, A. J., and P. Skemer. "Rates of dynamic recrystallization in geologic materials." Journal of Geophysical Research: Solid Earth 124.2 (2019): 1324-1342.

Grain boundary irregularity: segregate recrystallized grains from remnant grains

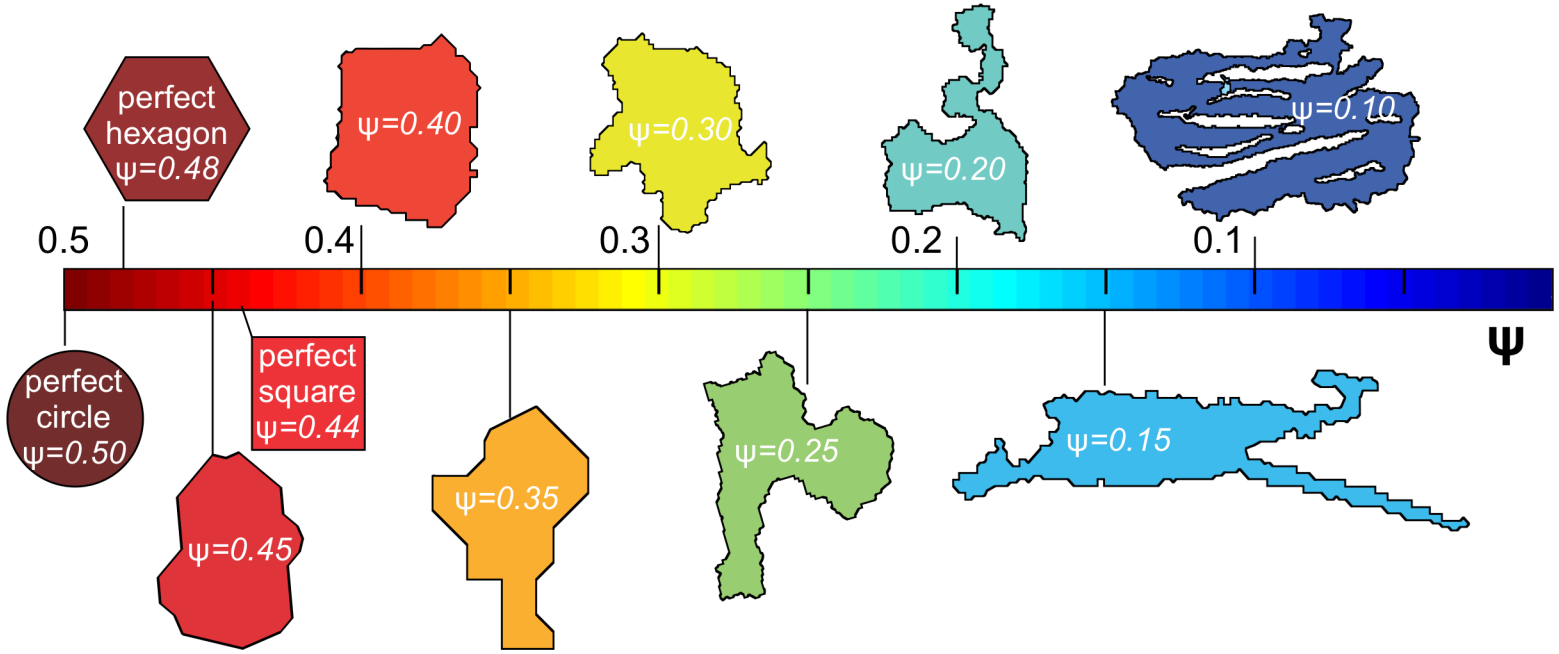


Urai et al., 1986

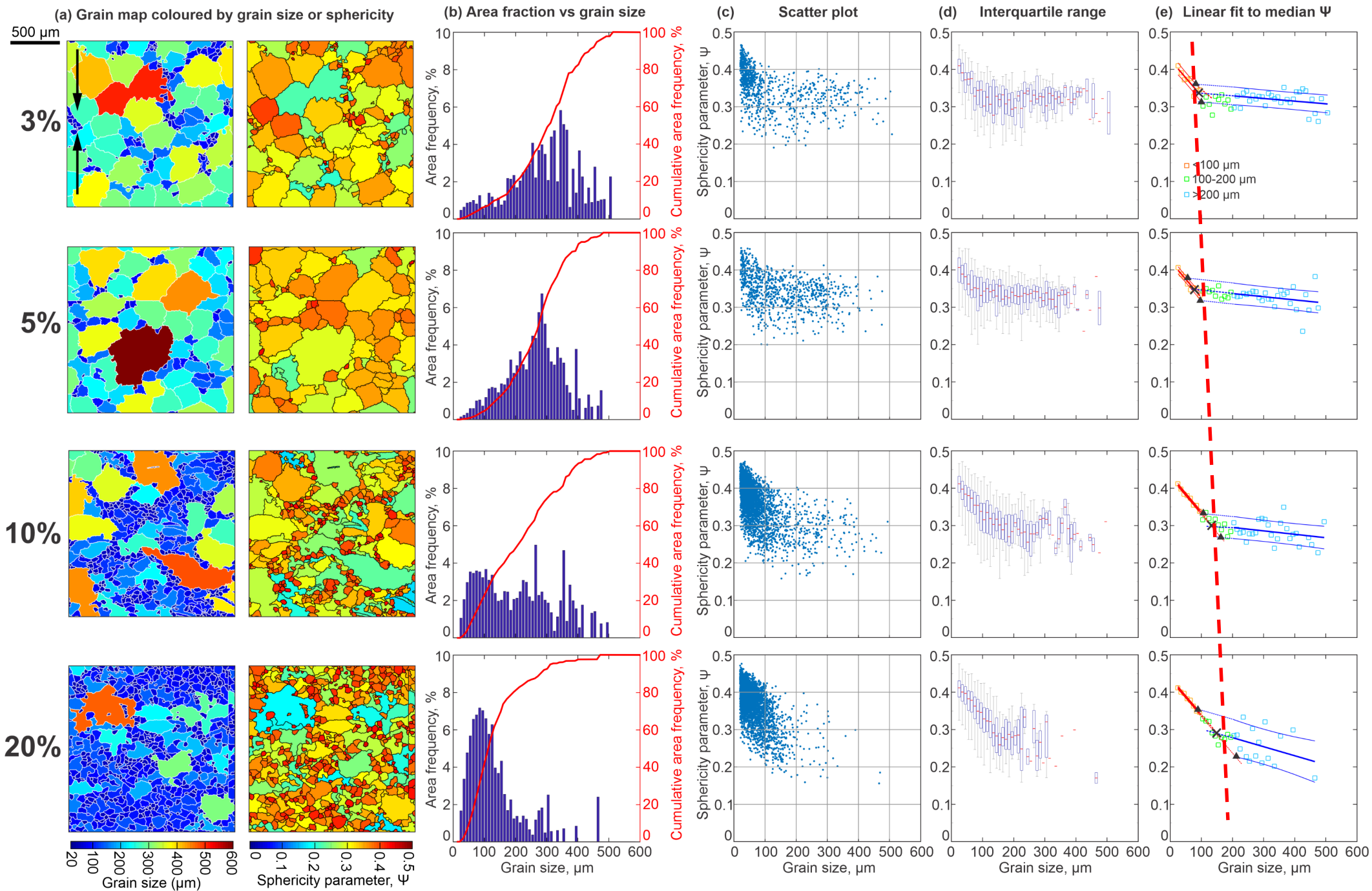


$$\Psi = \frac{P}{A \times R}$$

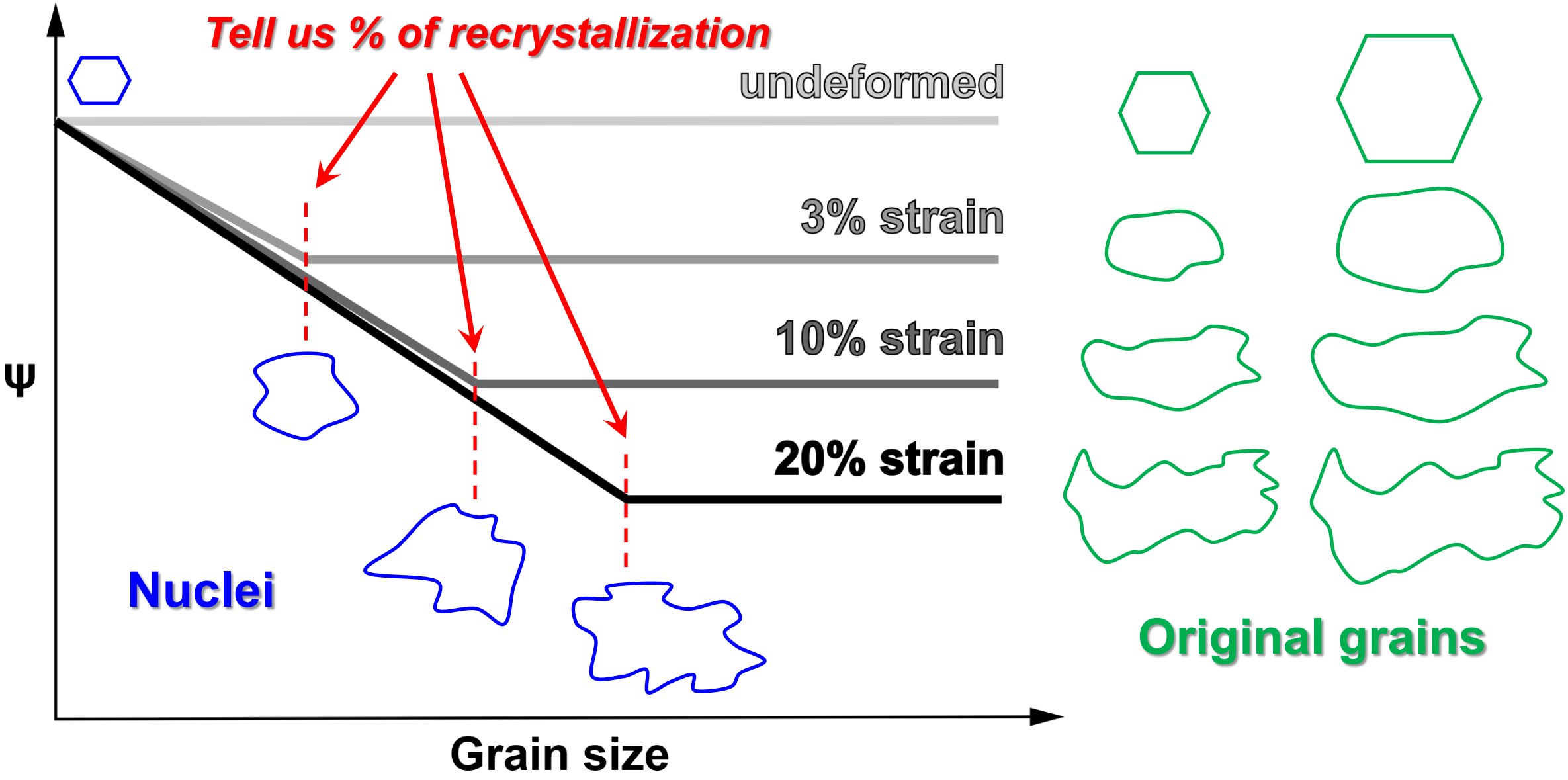
Grain boundary irregularity = $1/\Psi$

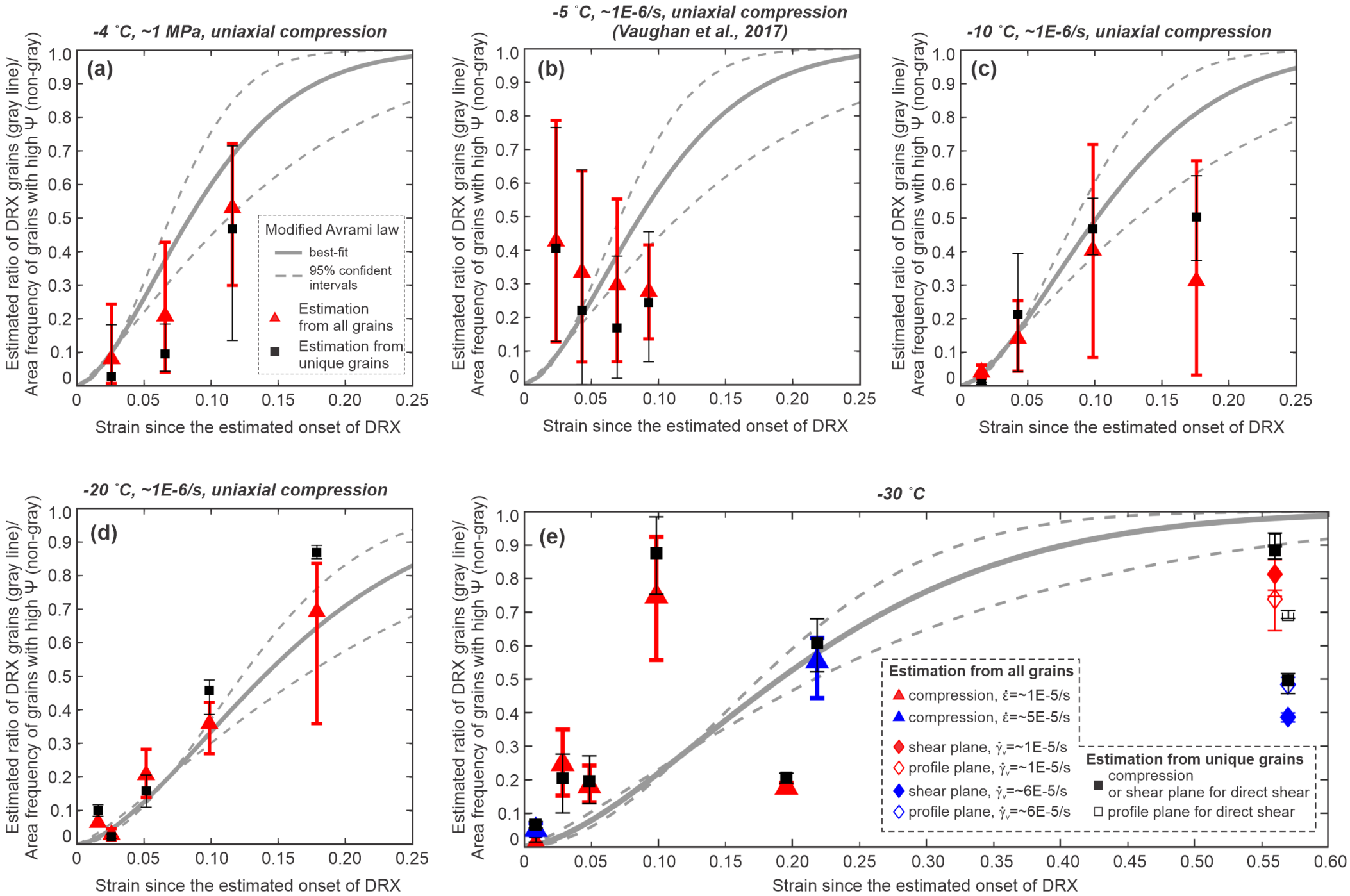


Urai, J. L., W. D. Means, and G. S. Lister. "Dynamic recrystallization of minerals." Mineral and rock deformation: laboratory studies. Vol. 36. Washington, DC: AGU, 1986. 161-199.

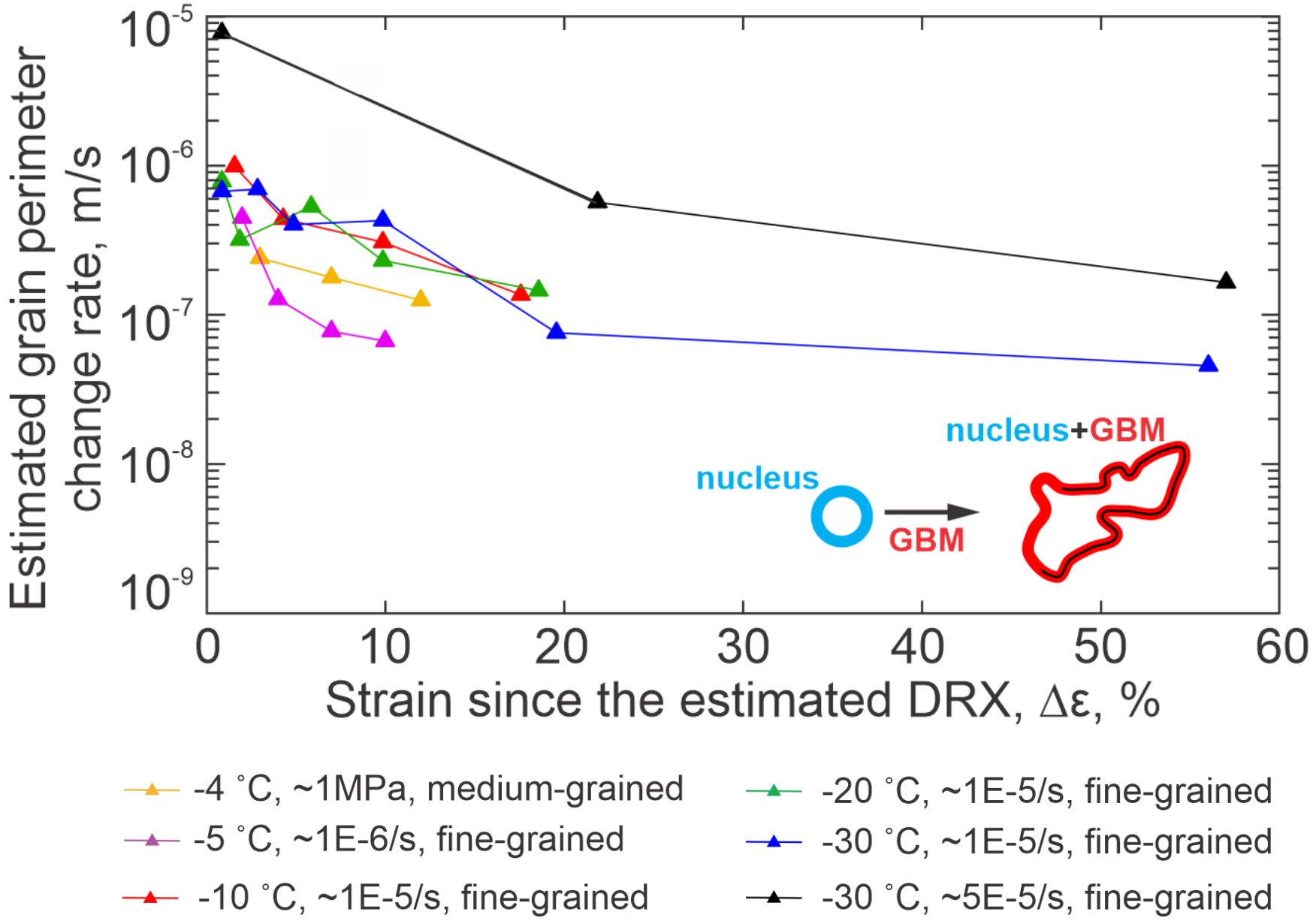

-20 °C
(a) Grain map coloured by grain size or sphericity
500 μm
3%
5%
10%
20%
Grain size (μm)
Sphericity parameter, Ψ
(b) Area fraction vs grain size
Area frequency, %
Cumulative area frequency, %
Grain size, μm
(c) Scatter plot
Sphericity parameter, ψ
(d) Interquartile range
(e) Linear fit to median Ψ
<100 μm
100-200 μm
>200 μm

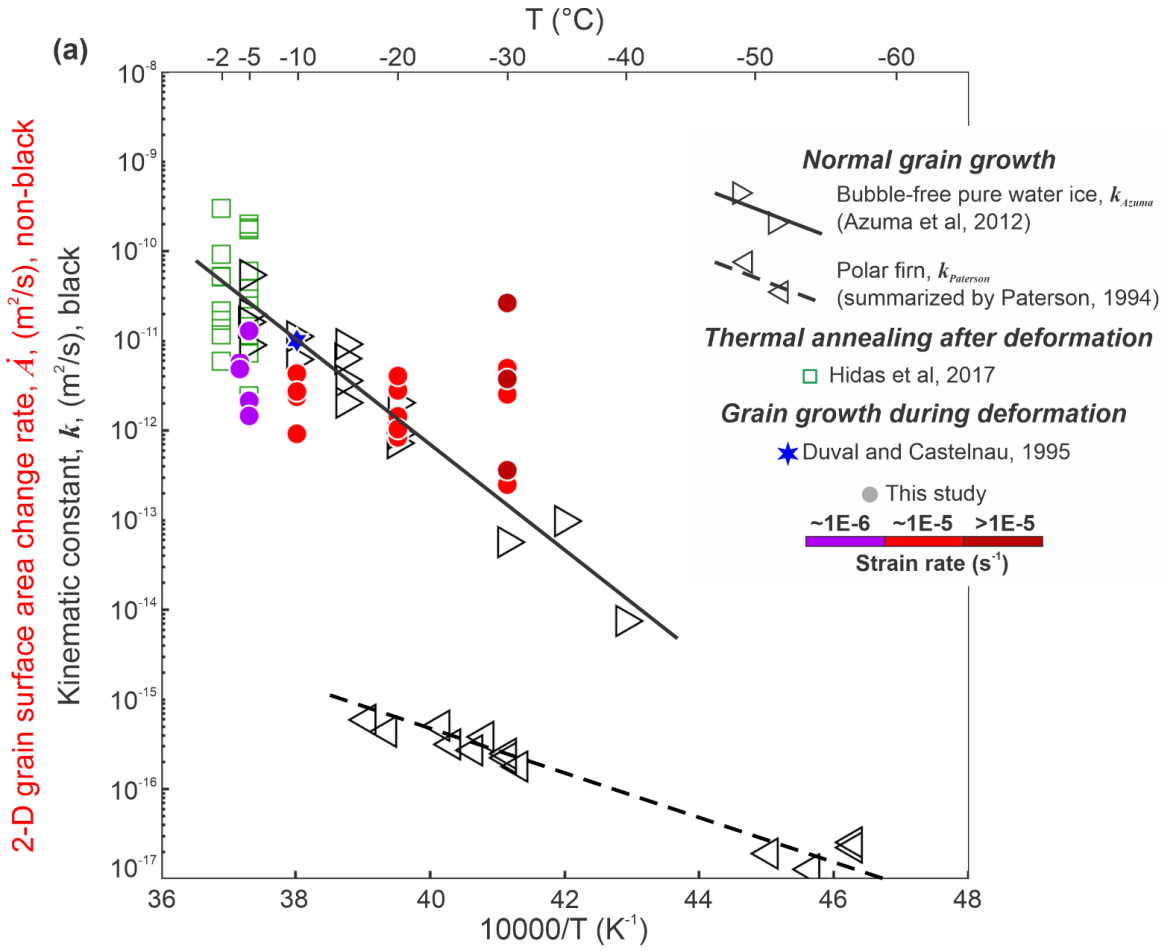
Sphericity vs. grain size: segregate recrystallized and remnant grains

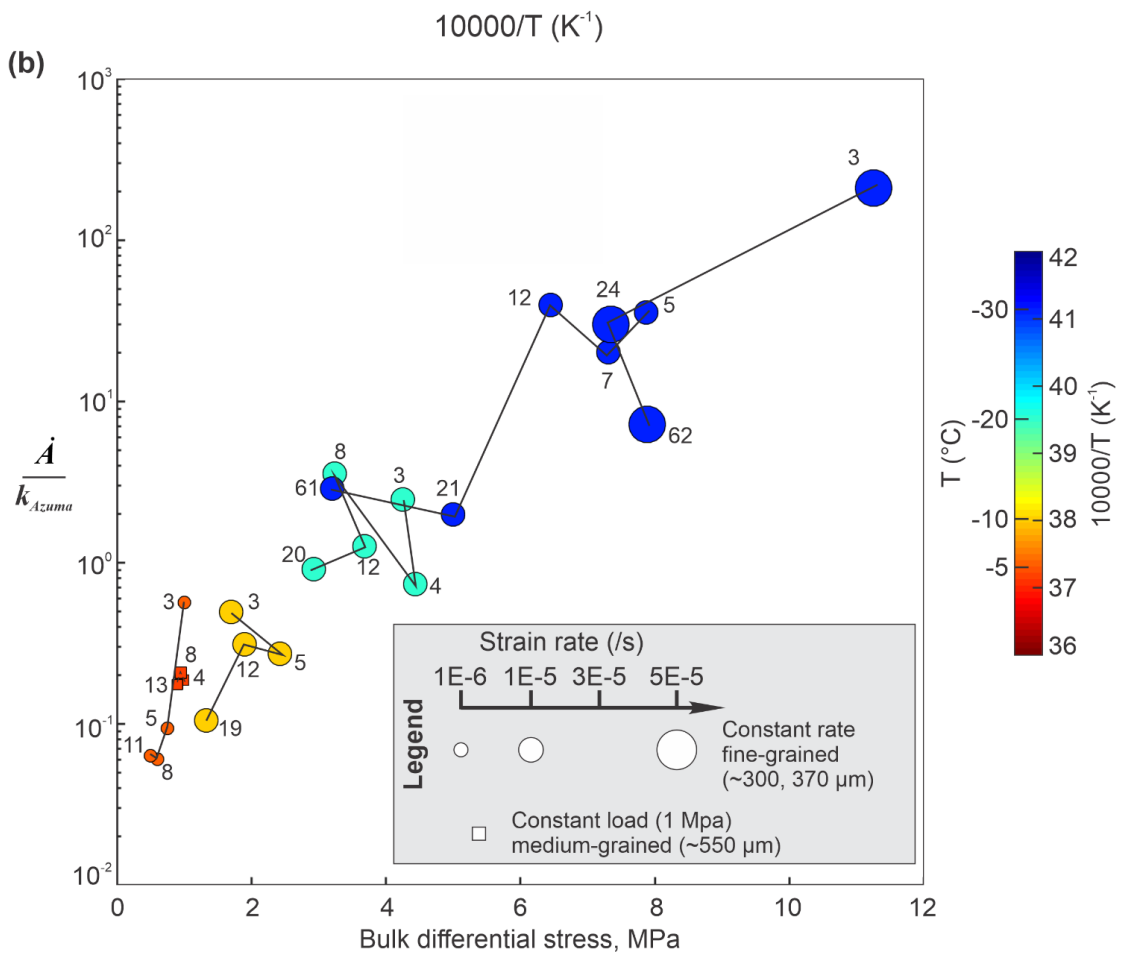



-4 ˚C, ~1 MPa, uniaxial compression
(a)
-5 ˚C, ~1E-6/s, uniaxial compression
(Vaughan et al., 2017)
(b)
-10 ˚C, ~1E-6/s, uniaxial compression
(c)
-20 ˚C, ~1E-6/s, uniaxial compression
(d)
-30 ˚C
(e)
Estimated ratio of DRX grains (gray line)/
Area frequency of grains with high Ψ (non-gray)
Strain since the estimated onset of DRX
Modified Avrami law
best-fit
95% confident intervals
Estimation from all grains
Estimation from unique grains
Estimation from all grains
compression, ε̇=~1E-5/s
compression, ε̇=~5E-5/s
shear plane, γ̇v=~1E-5/s
profile plane, γ̇v=~1E-5/s
shear plane, γ̇v=~6E-5/s
profile plane, γ̇v=~6E-5/s
Estimation from unique grains
compression
or shear plane for direct shear
profile plane for direct shear

GBM rate is similar at high and low temperature



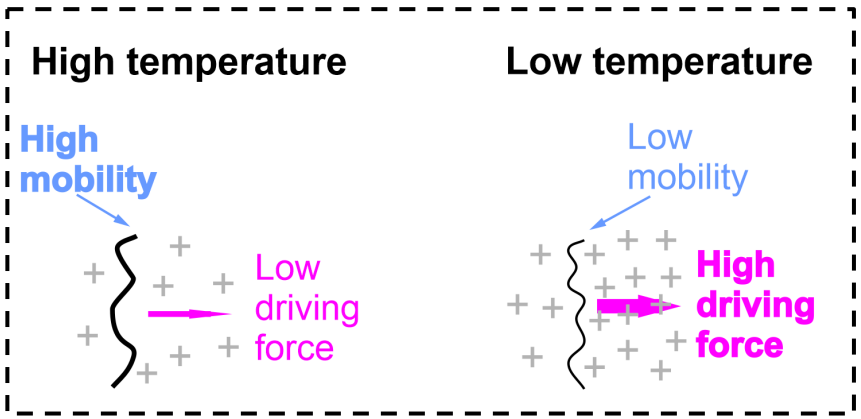




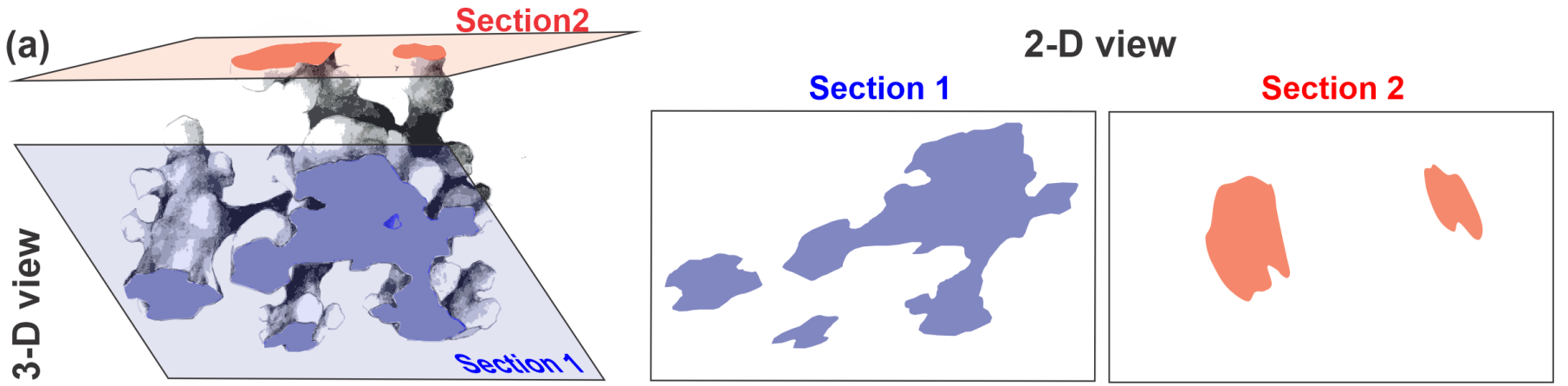
GBM rate =

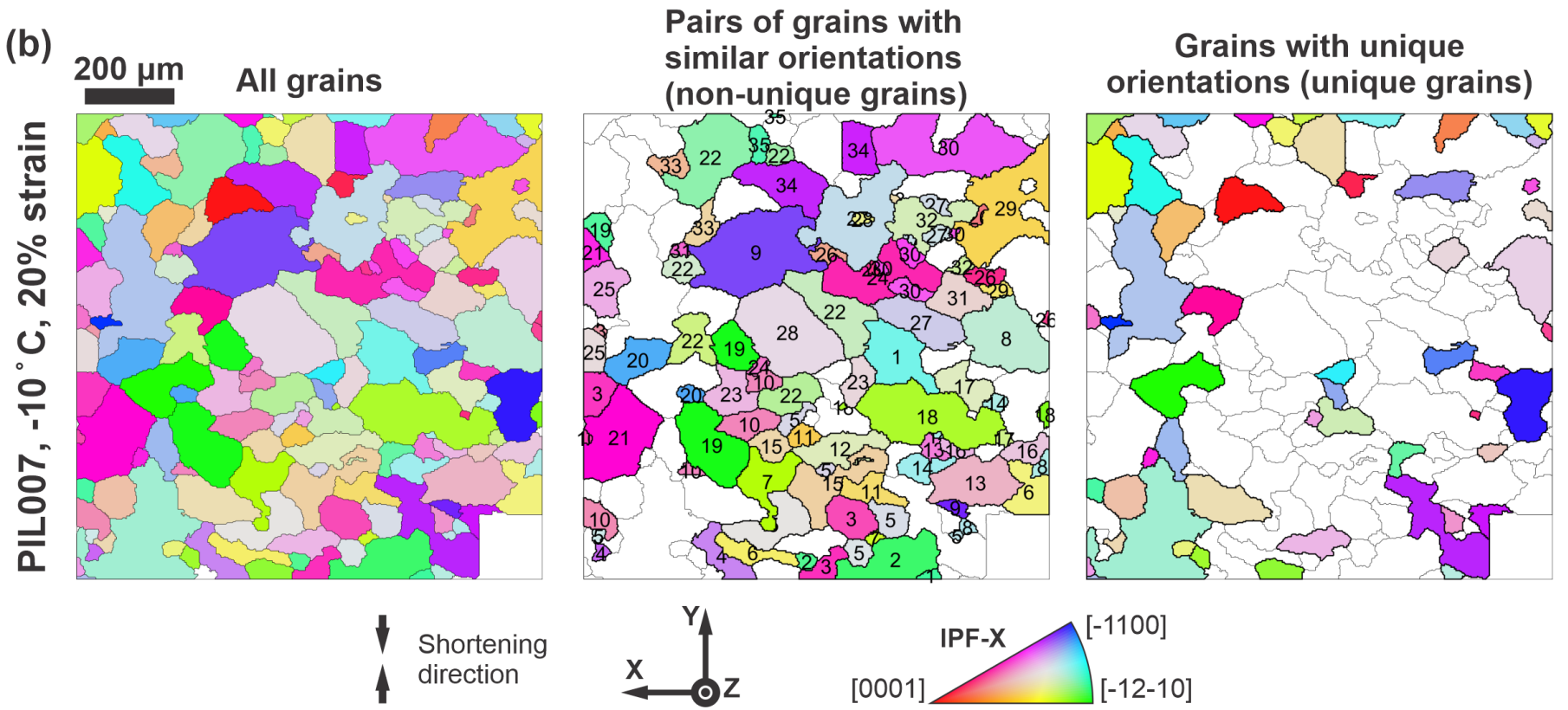
grain boundary mobility × **driving force**

k_{Azuma} **Stress**



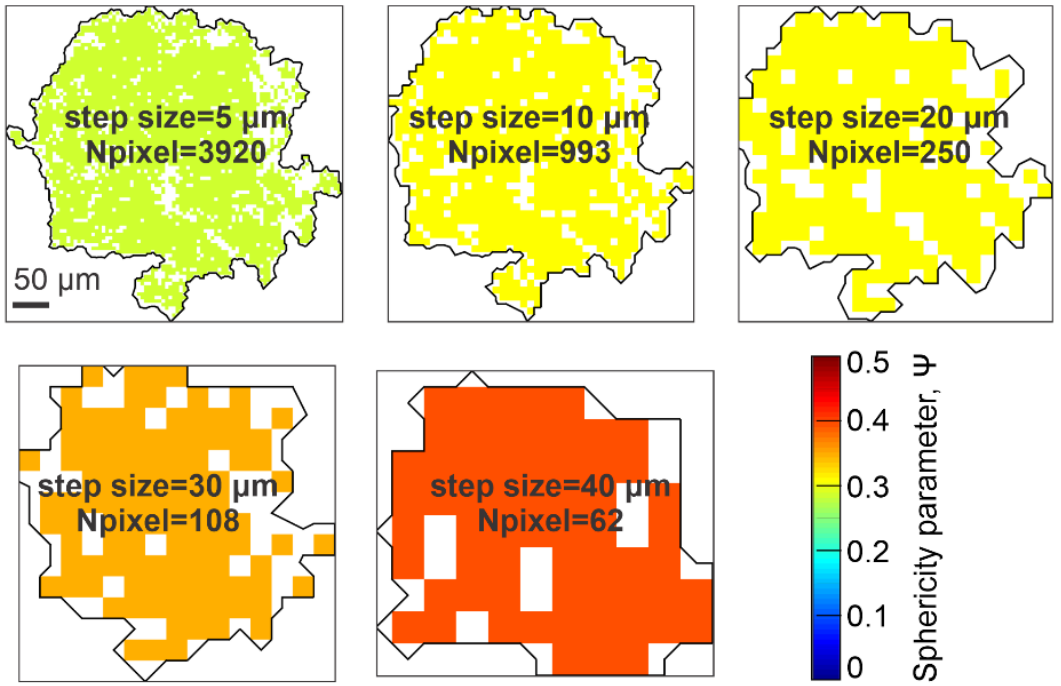
Oversampling of highly irregular grains in 2-D sections



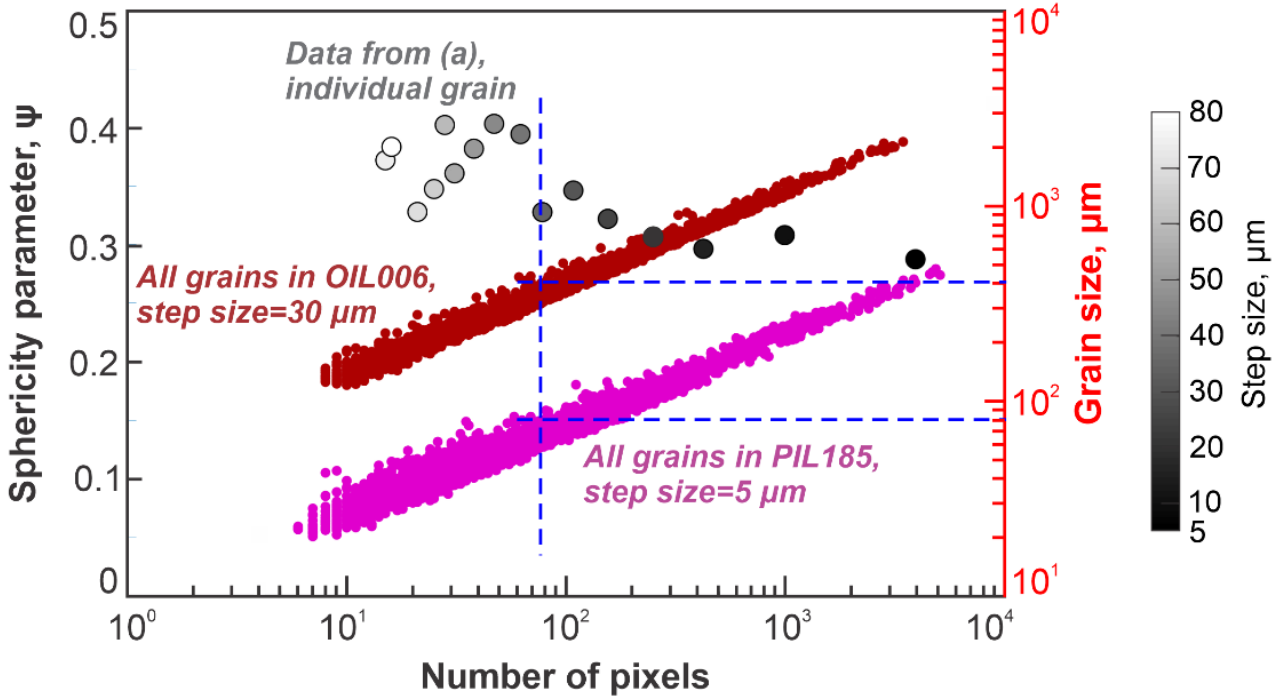


Test the sensitivity of EBSD step size

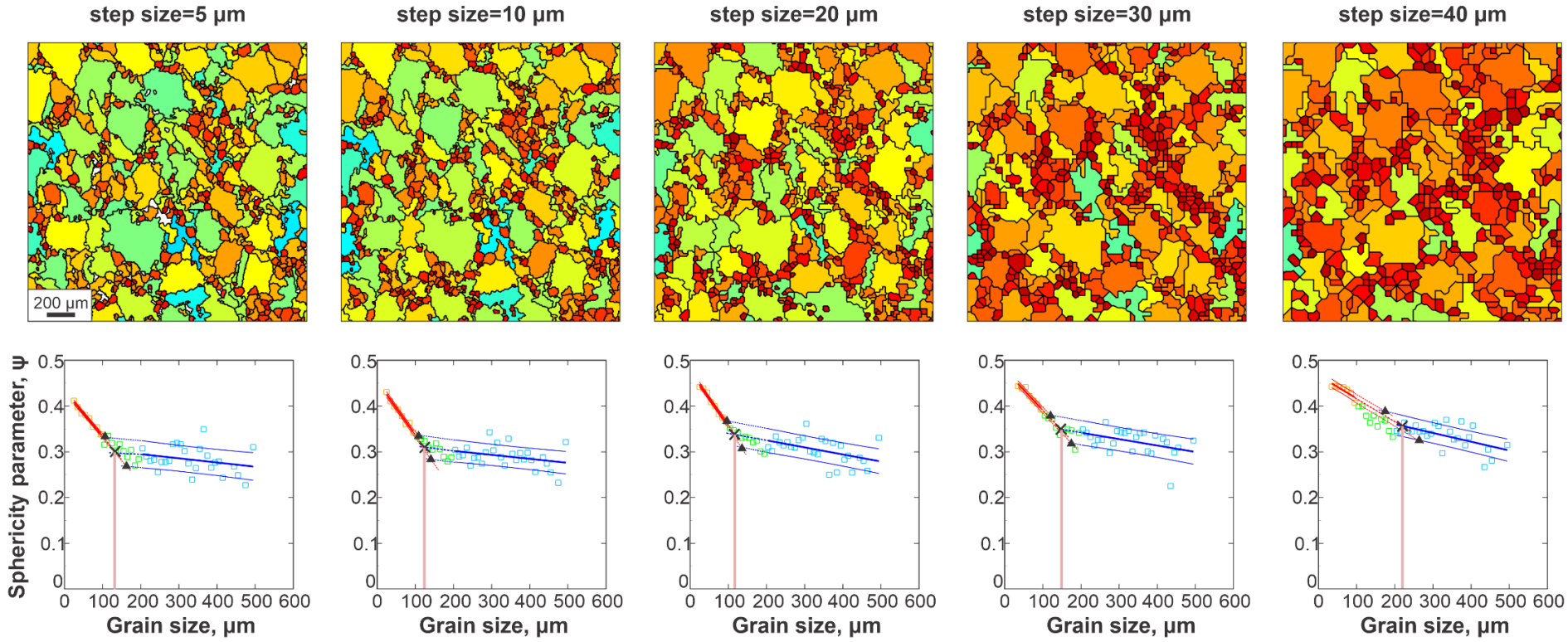
(a) Using an individual grain to visualize the evolution of sphericity as EBSD step size increases



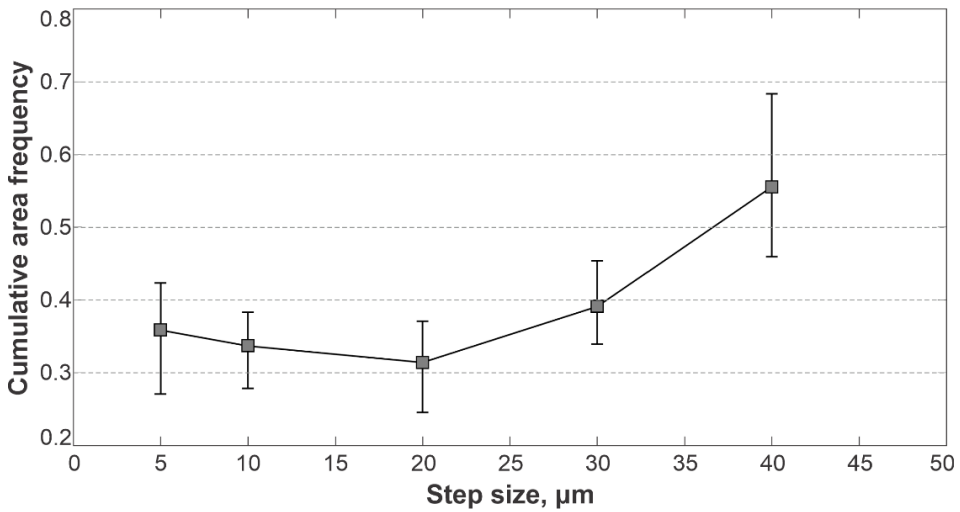
(b) Estimate the minimum grain size required for a relatively accurate measurement of grain sphericity



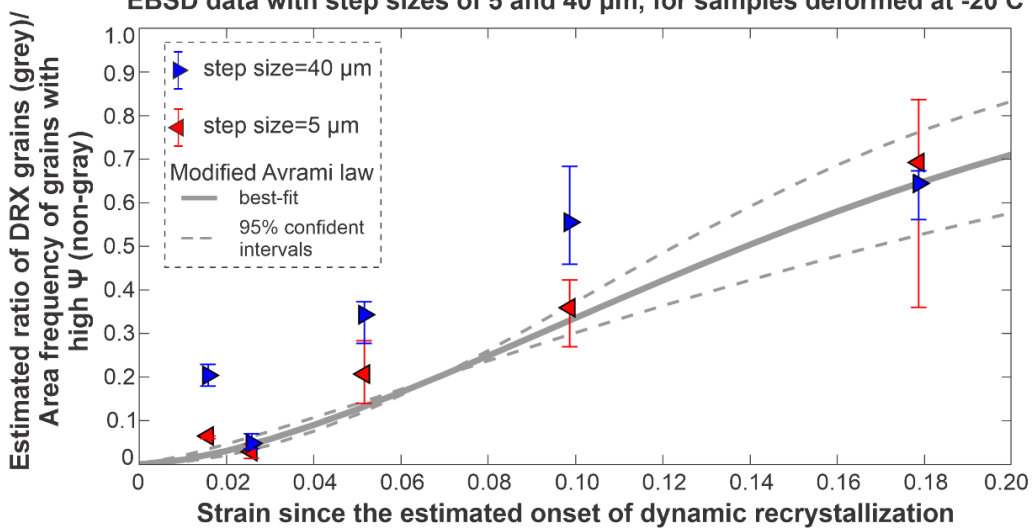
(c) Statistics of grain size and sphericity calculated from EBSD maps with different step sizes



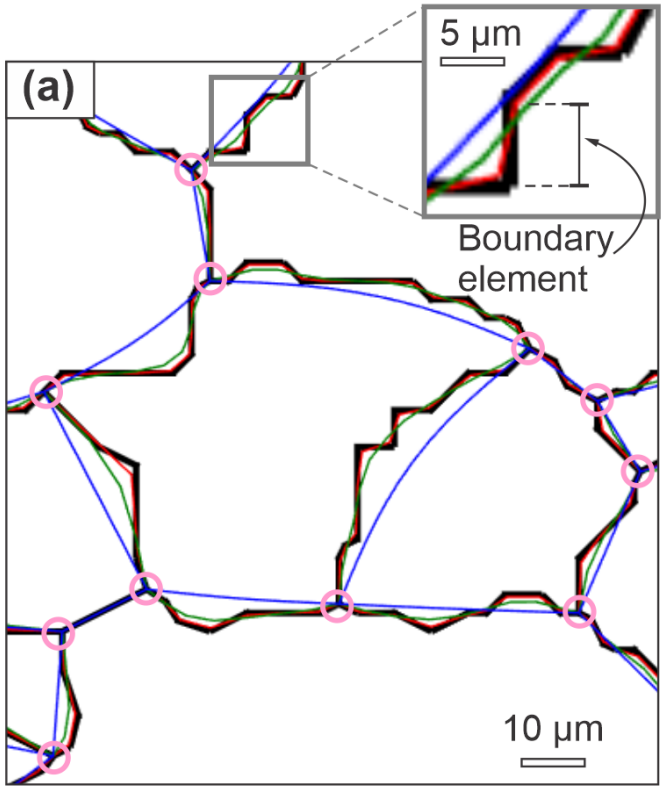
(d) Summary of area frequency of grains with high sphericity calculated from EBSD data with different step sizes (PIL185)



(e) Compare area frequency of grains with high sphericity calculated from EBSD data with step sizes of 5 and 40 μm, for samples deformed at -20℃



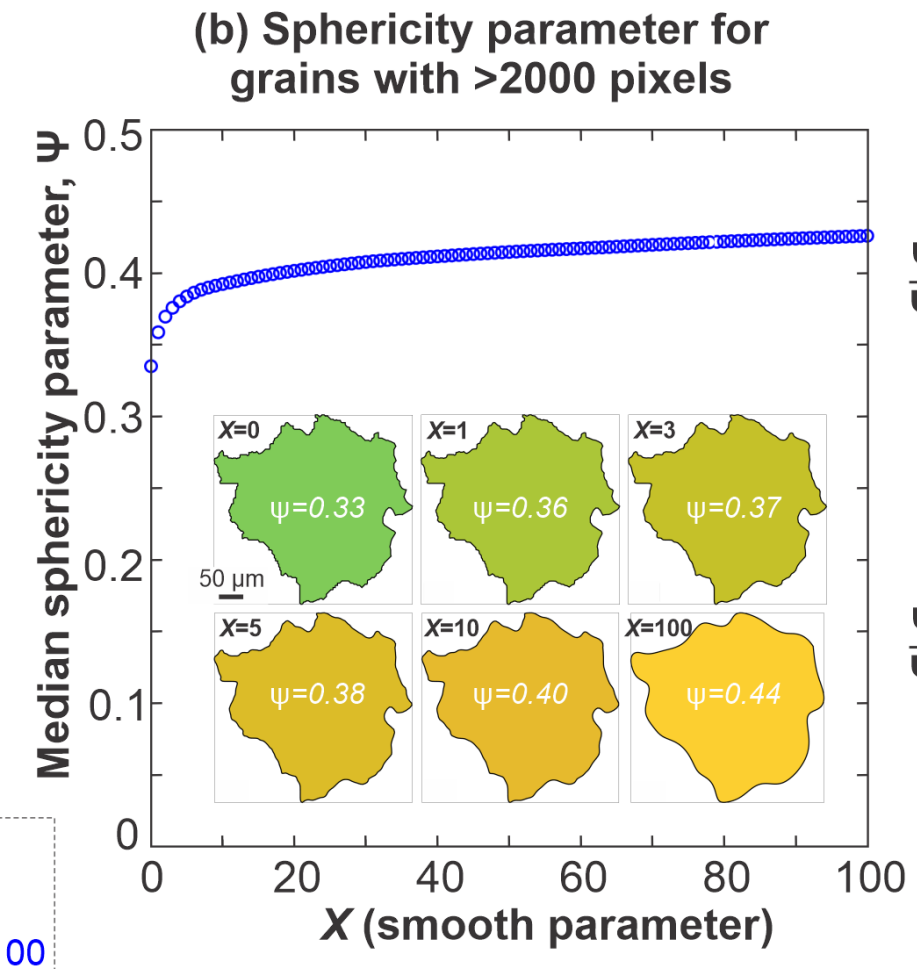
Test the sensitivity of grain boundary smoothness

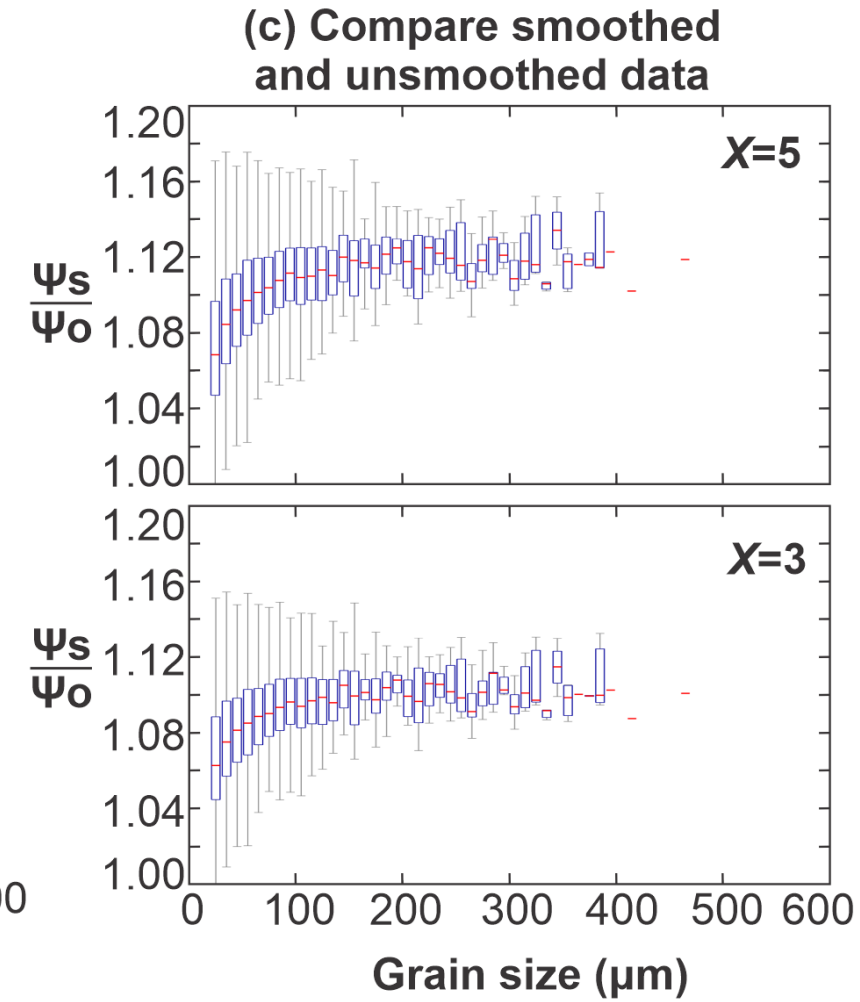


Legend for grain boundaries

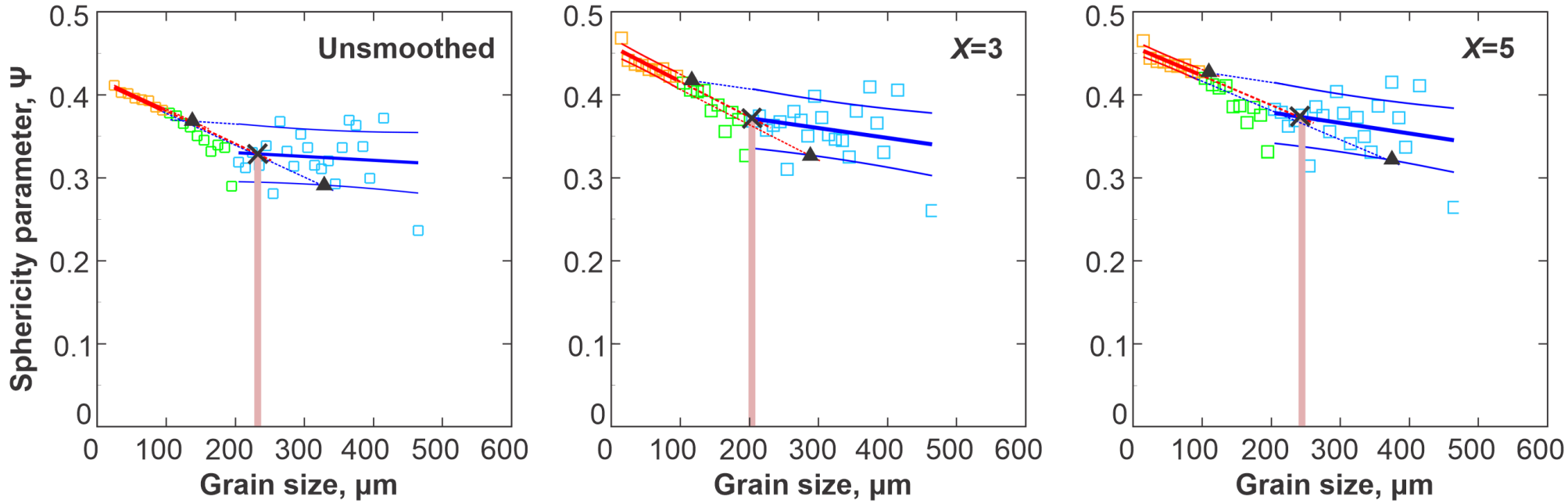
unsmoothed — smoothed, *X*=1

smoothed, *X*=5 — smoothed, *X*=100

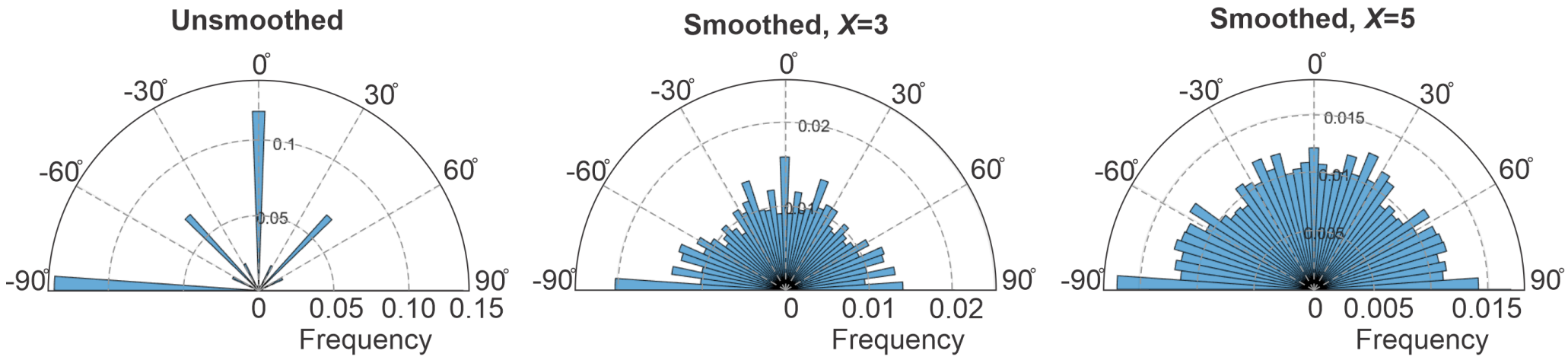




(d) Statistics of grain size and sphericity calculated from smoothed and unsmoothed data



(e) Azimuth of grain boundary segments for undeformed fine-grained ice (~300 μm)



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