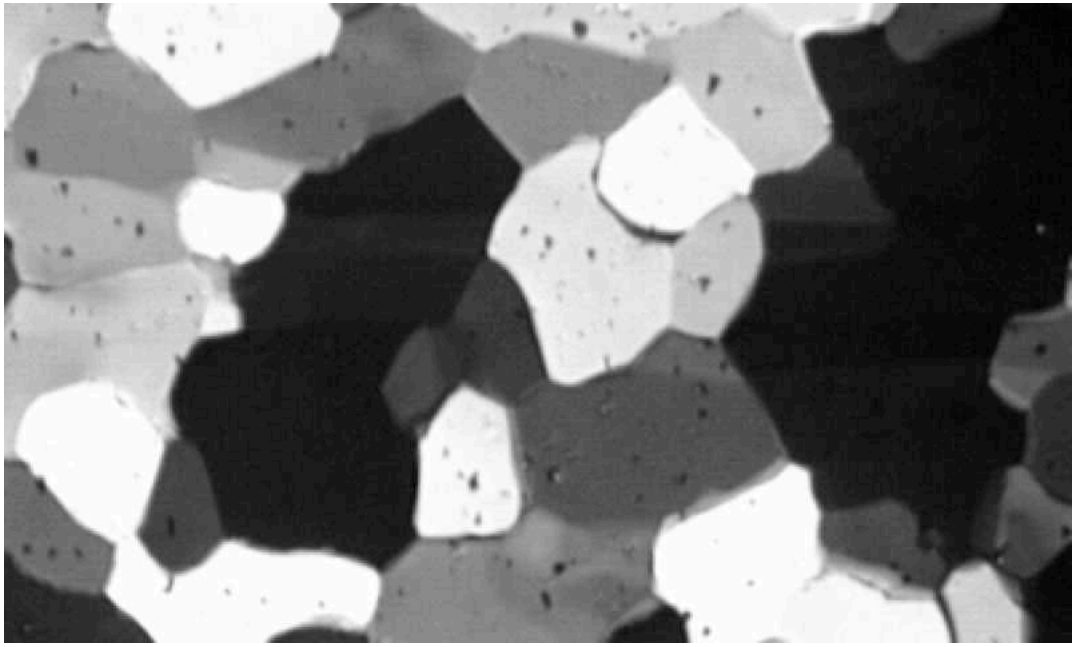
ANNEALING - THE ALZHEIMER OF ROCKS

Renée Heilbronner, Department of Earth Sciences, Basel University
Jan Tullis, Department of Geological Sciences, Brown University

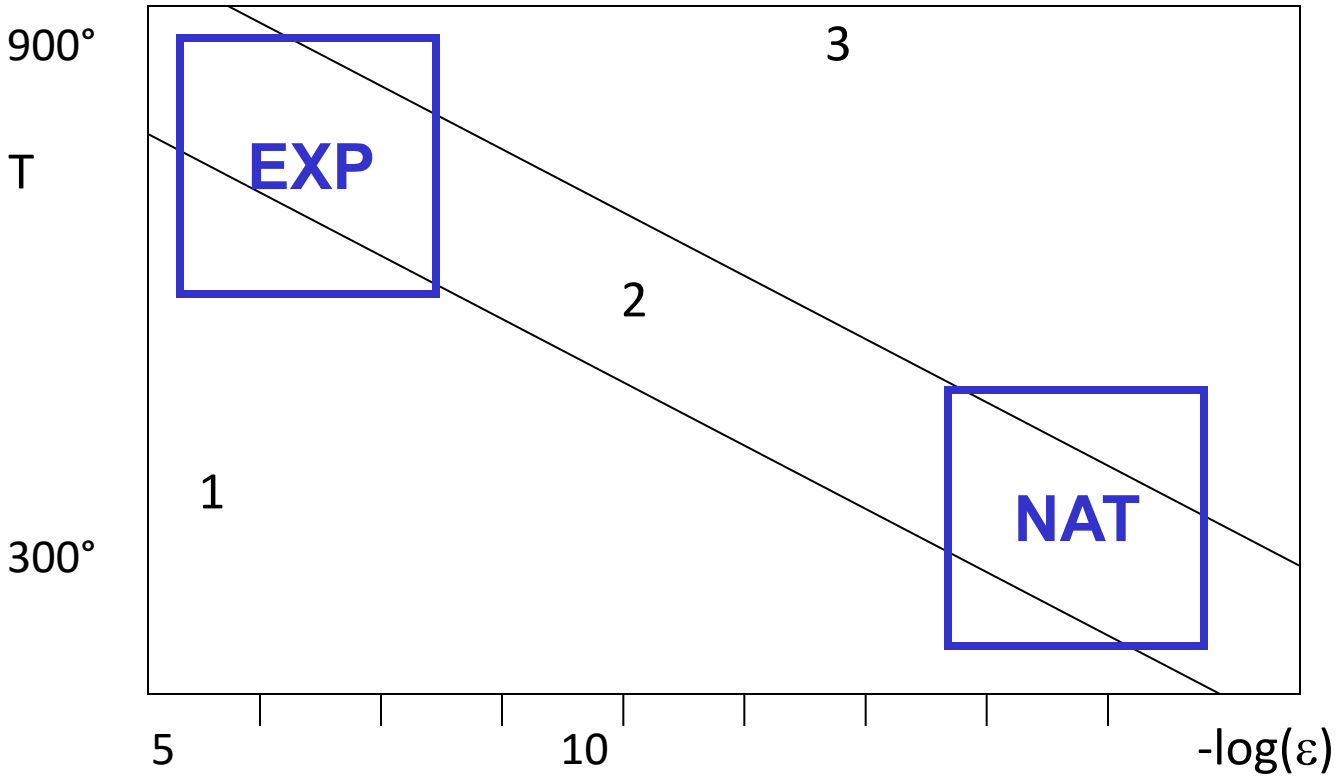


NATURAL AND EXPERIMENTAL DEFORMATION

bulging
~regime 1

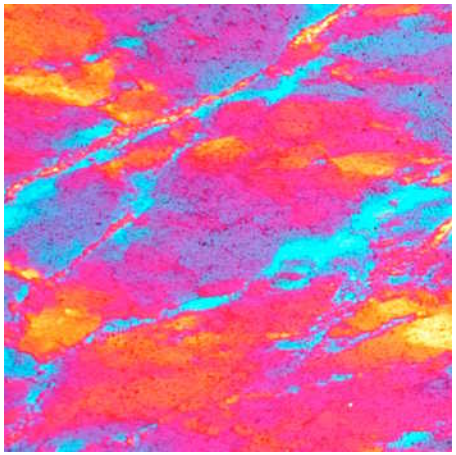
subgrain rotation
~regime 2

g.b.migration
~regime 3

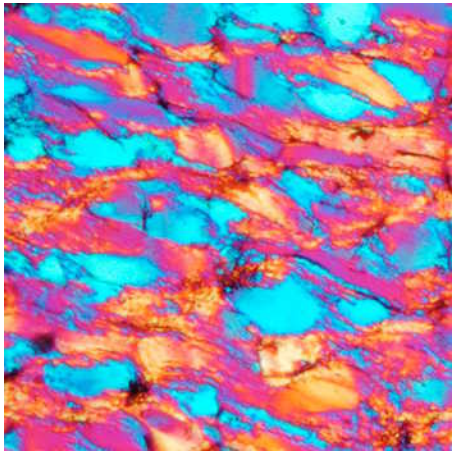


DISLOCATION CREEP IN QUARTZ

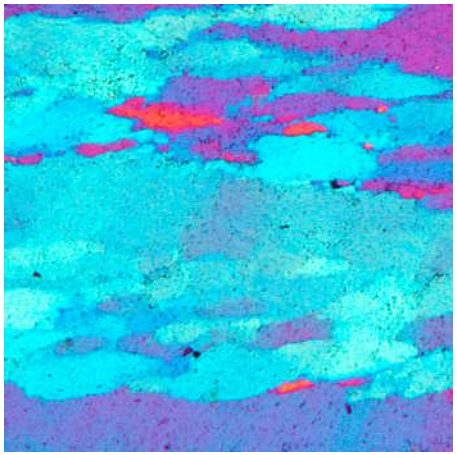
bulging



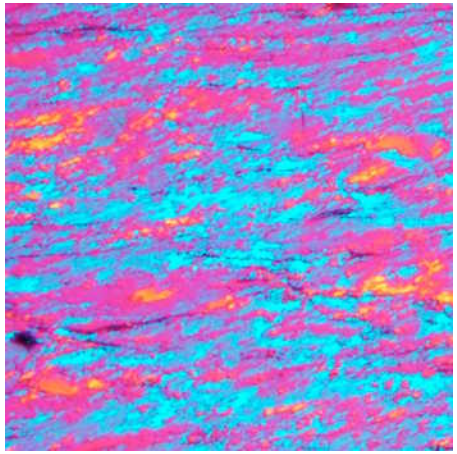
regime 1



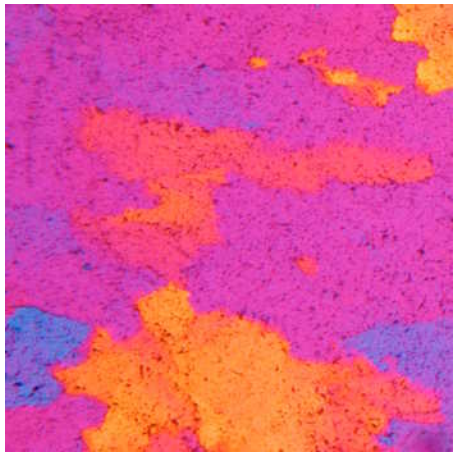
subgrain rotation



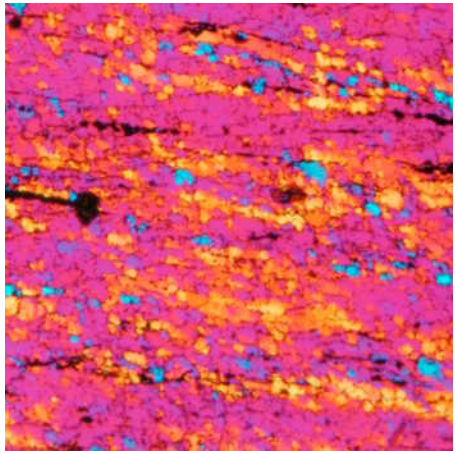
regime 2



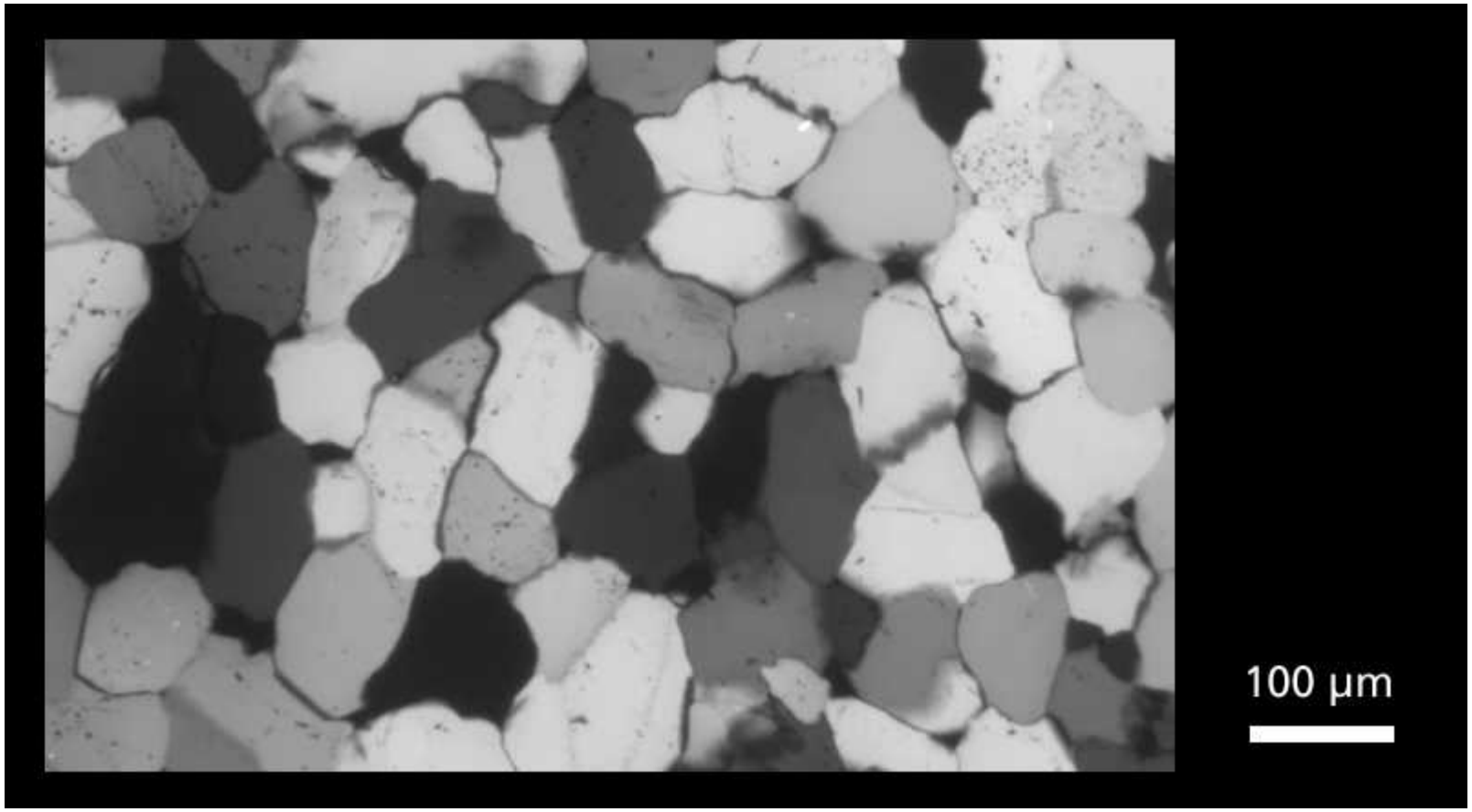
g.b.migration



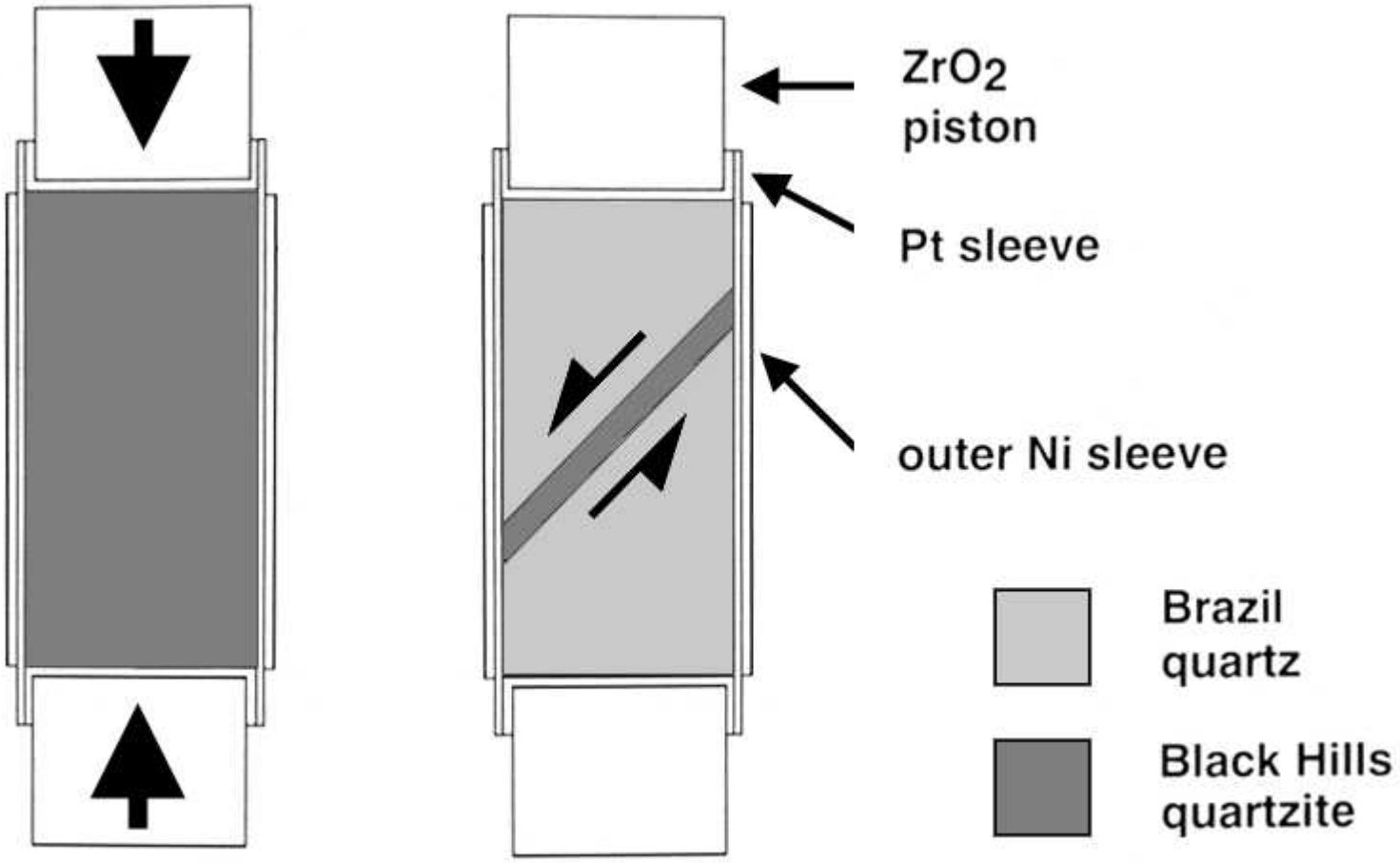
regime 3



STARTING MATERIAL: BLACK HILLS QUARTZITE



ASSEMBLY FOR AXIAL AND SHEARING EXPERIMENTS

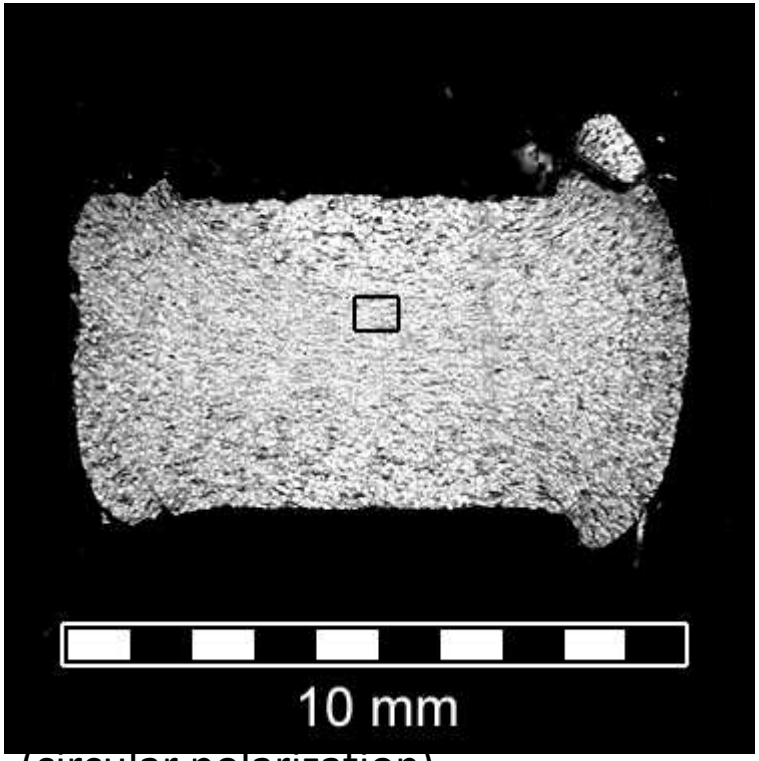


EXPERIMENTAL CONDITIONS

Temperature	850°, 900°C
Confining pressure	1.5 GPa
Strain rate	10^{-6}, 10^{-5} s^{-1}
Water content	0, 0.17wt%
Annealing temperature	850°, 900°C
Annealing time	120 h

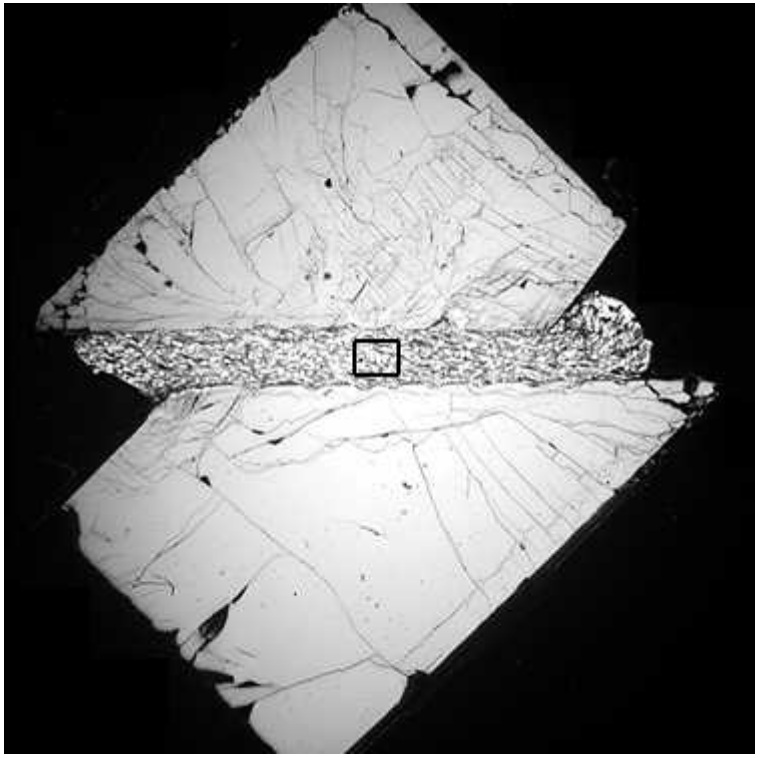
DEFORMED SAMPLES

AXIAL



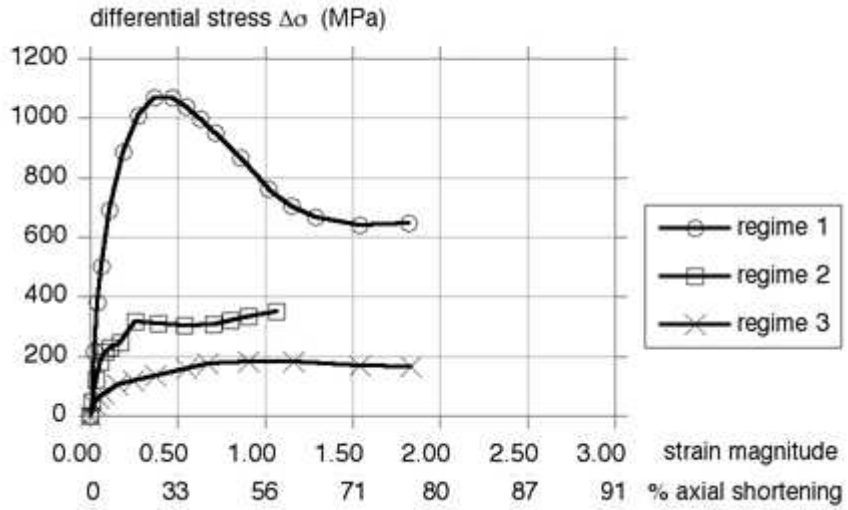
(circular polarization)

SHEARING

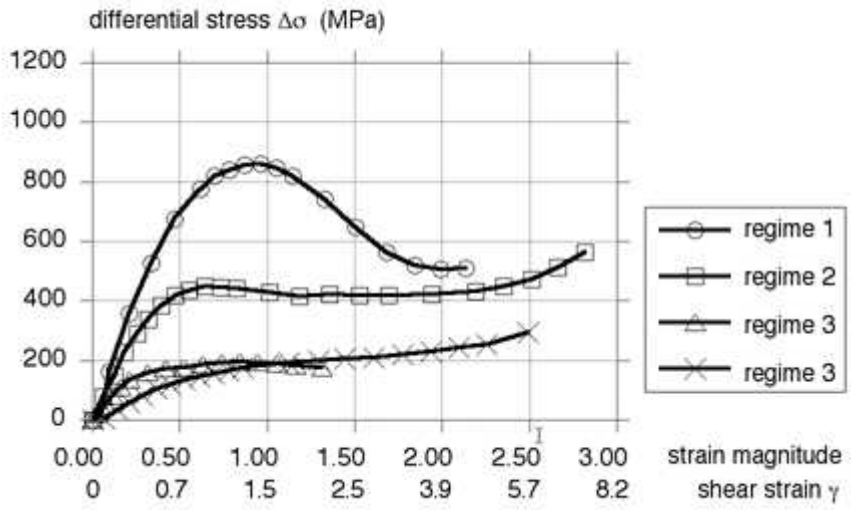


MECHANICAL DATA

AXIAL



SHEARING



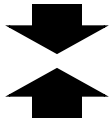
regime 1

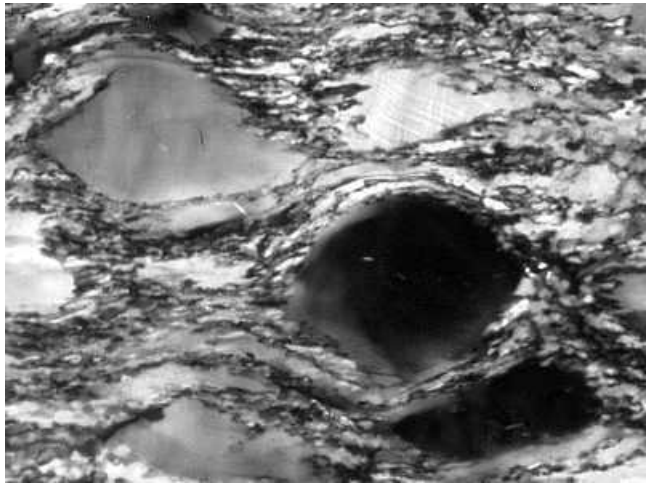
microstructure

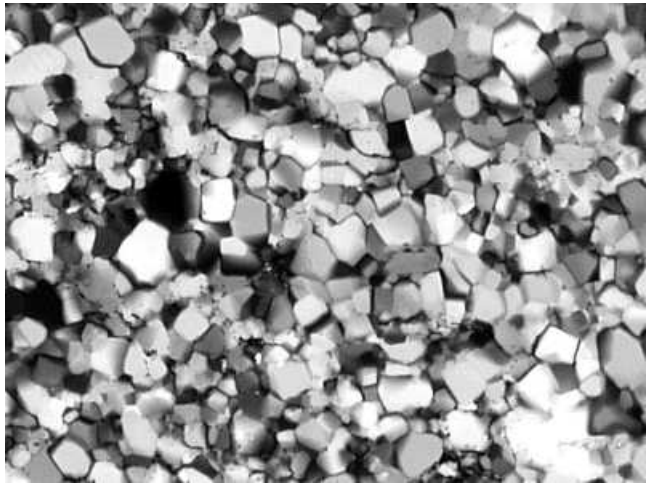
deformed

annealed

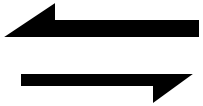
axial

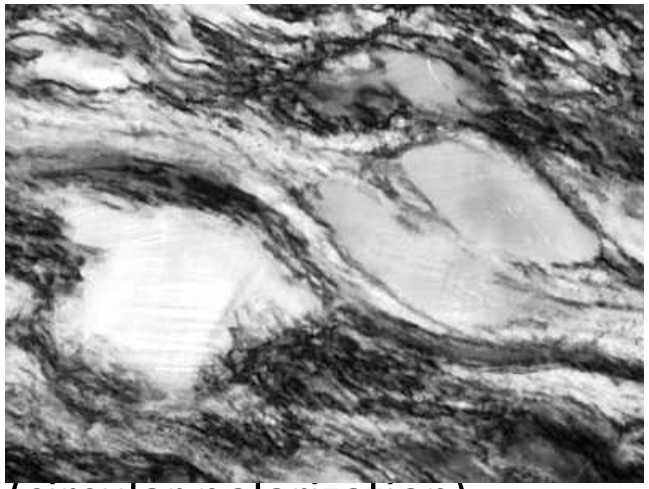


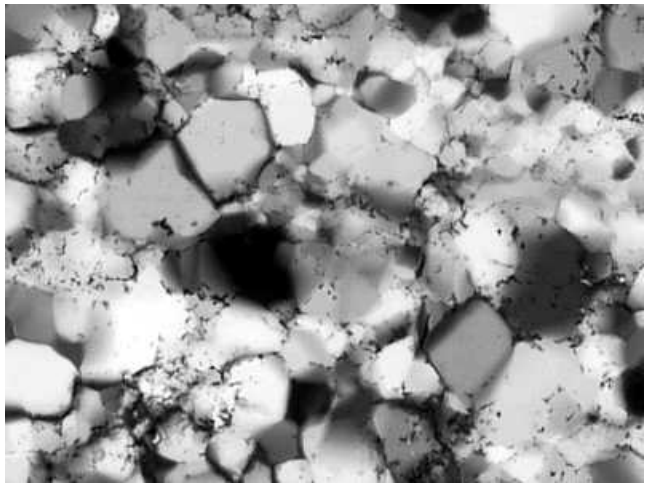




shearing







100 µm

(circular polarization)

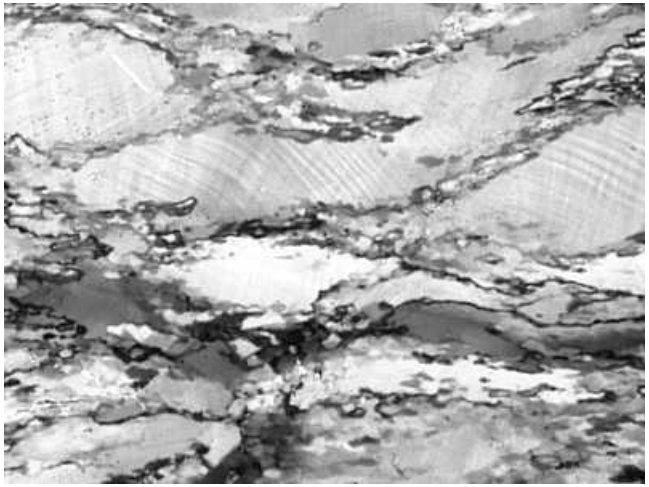
regime 2

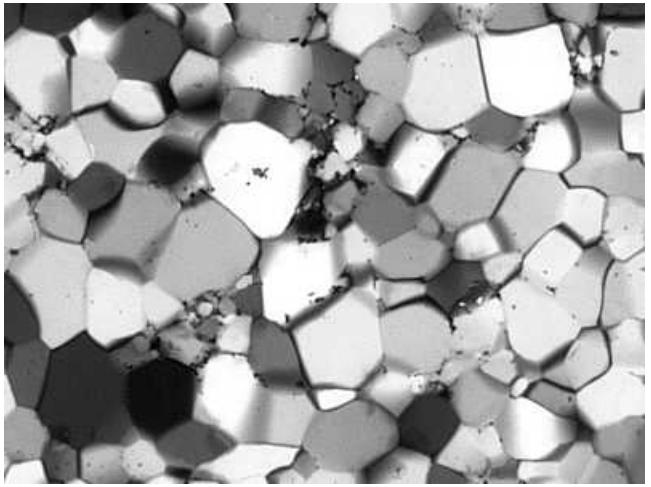
microstructure

deformed

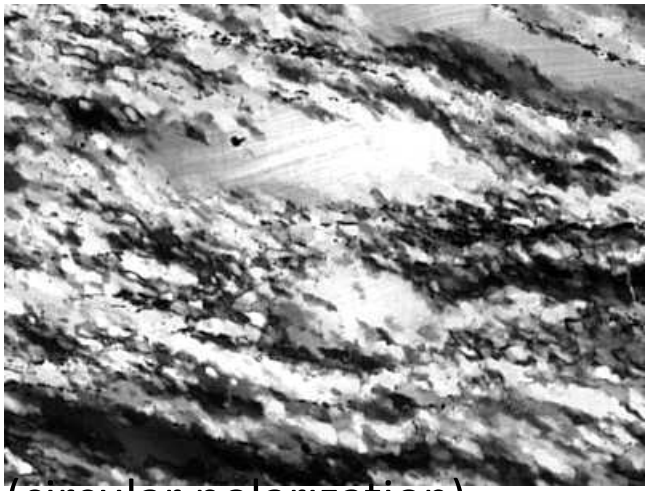
annealed

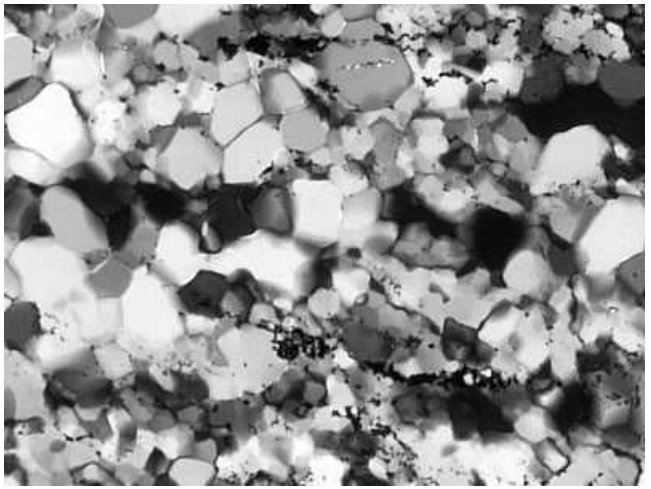
axial





shearing





100 µm

(circular polarization)

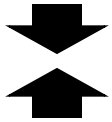
regime 3

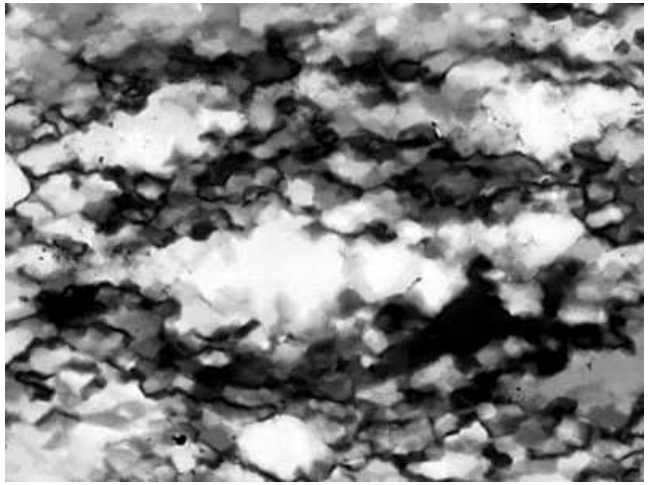
microstructure

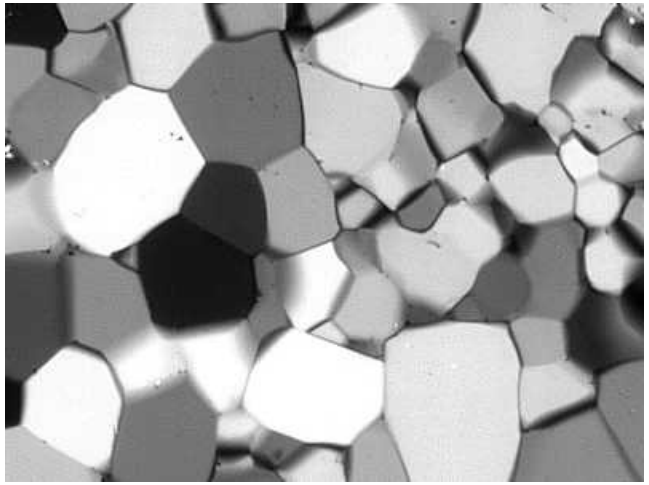
deformed

annealed

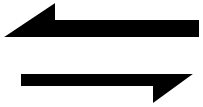
axial

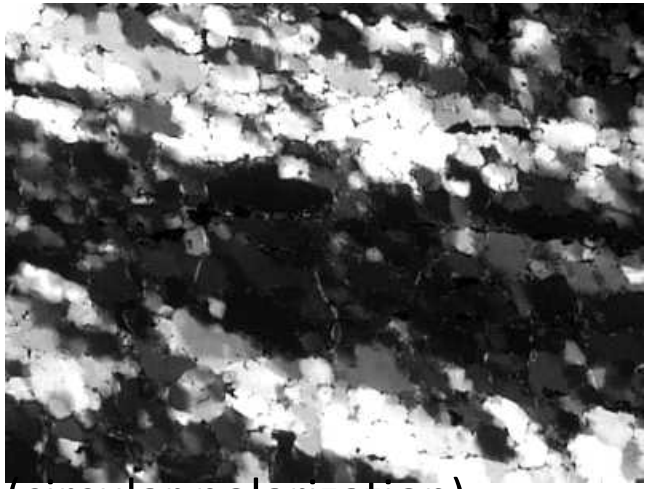


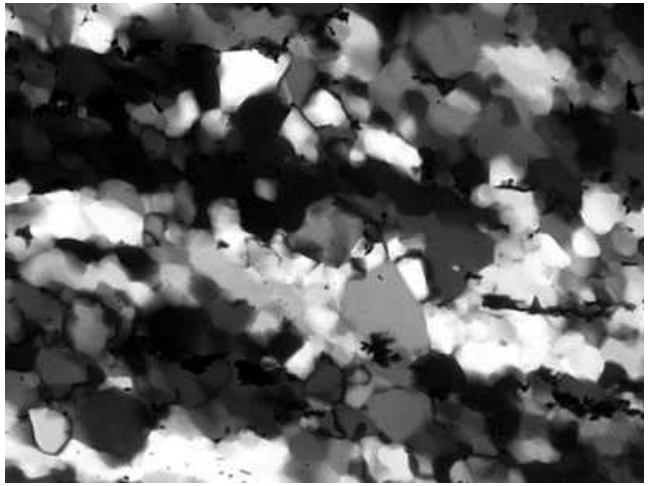




shearing



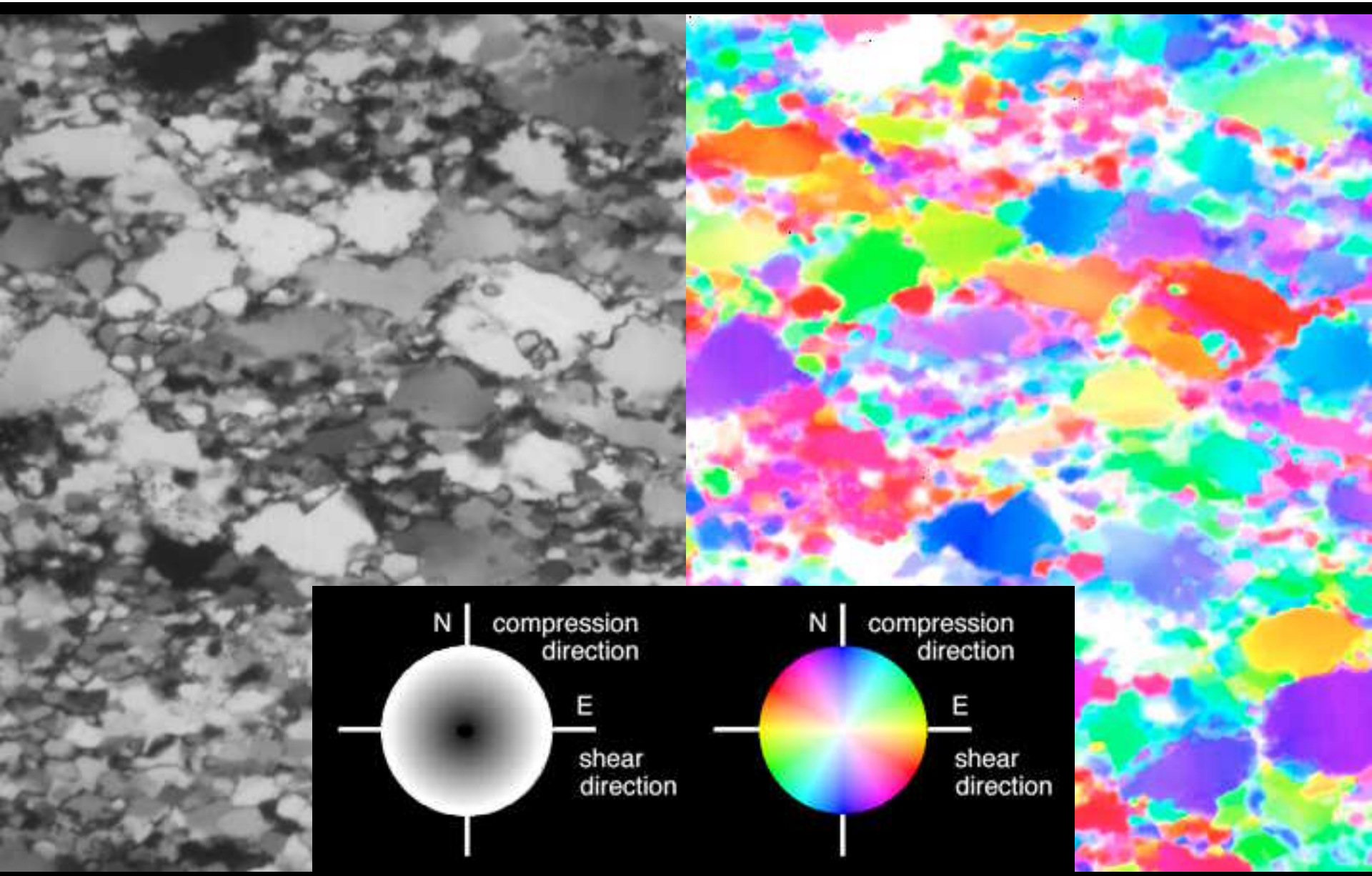




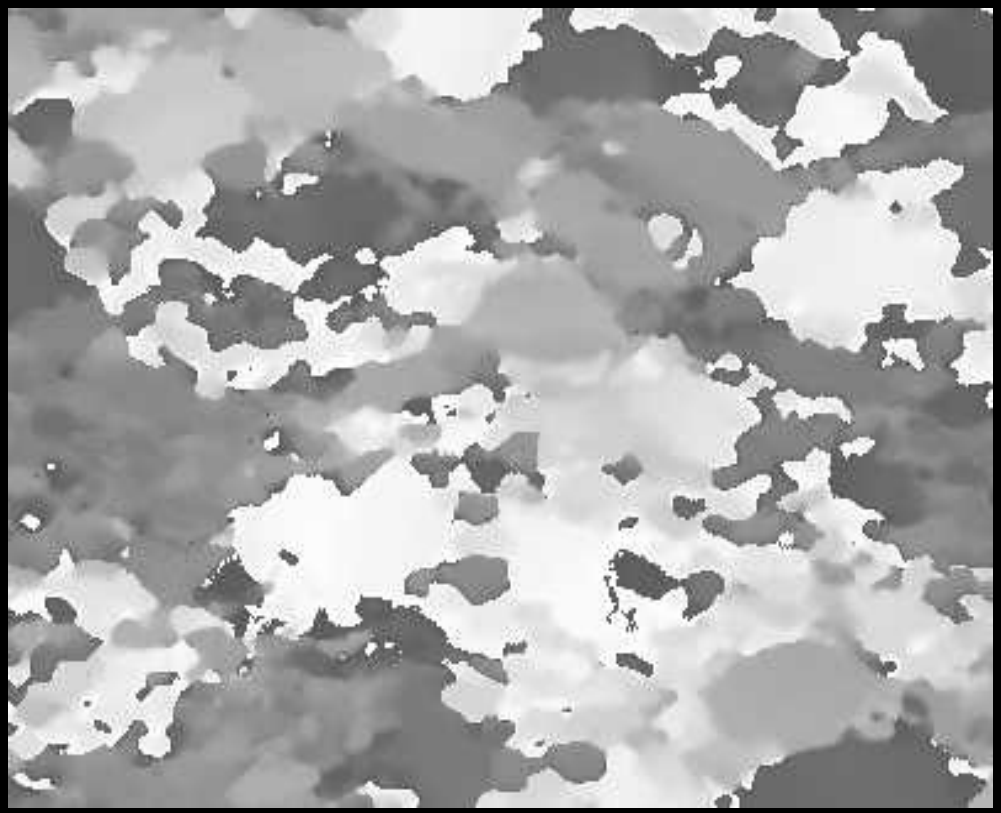
100 µm

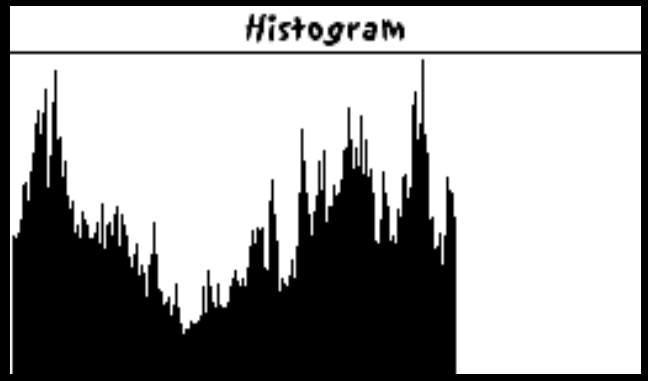
(circular polarization)

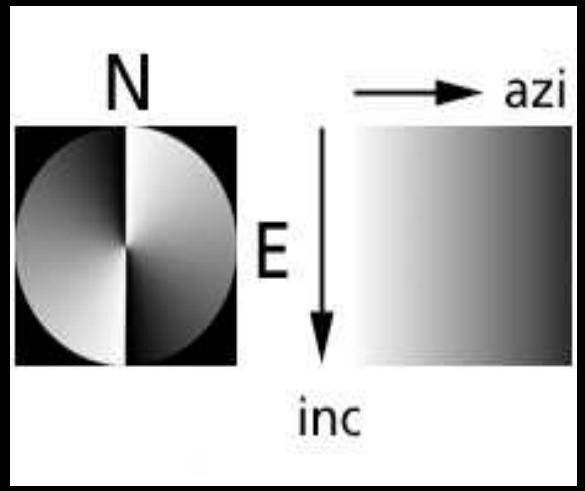
CIP ➡ORIENTATION IMAGING



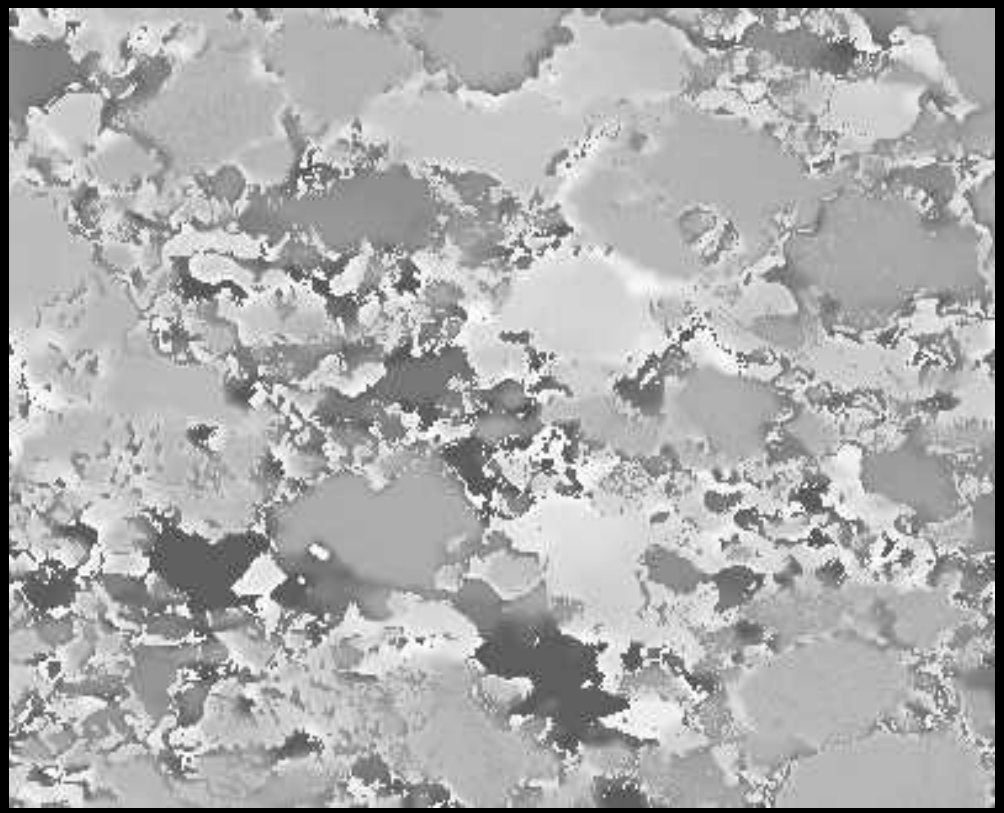
Azimuth image

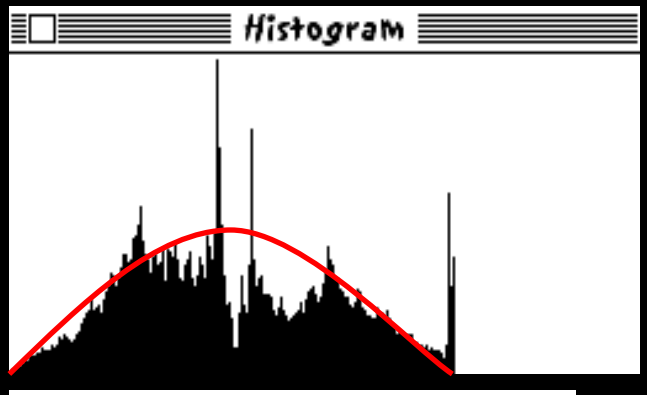


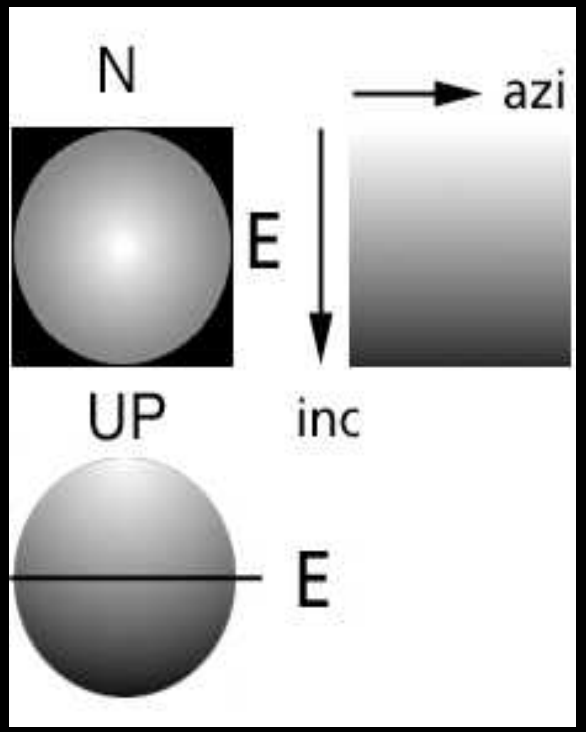




Inclination image

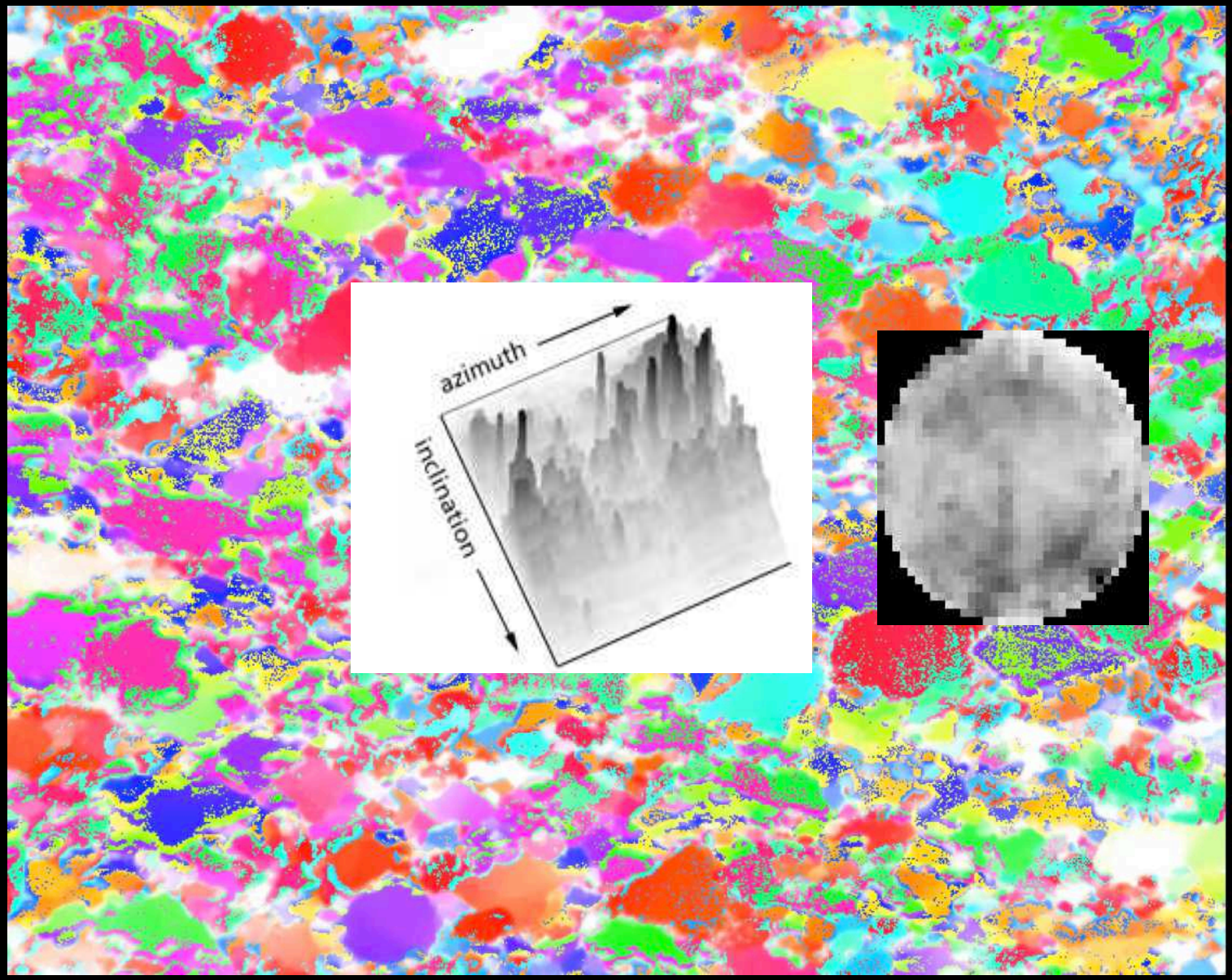






www.unibas.ch/earth/micro/
eucor 131.152.51.10

c-axis orientation image (COI)

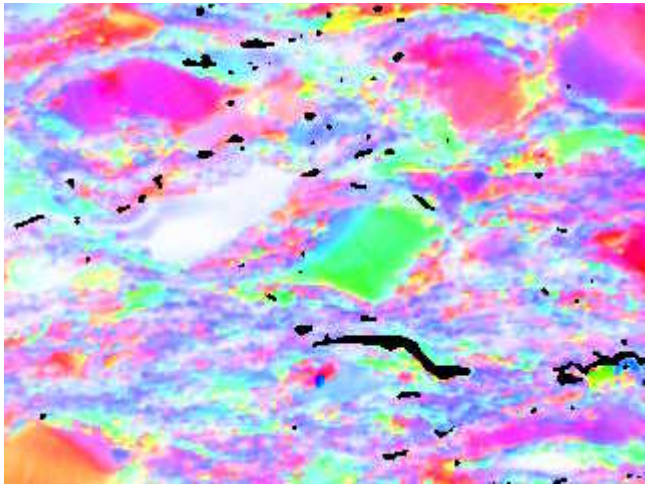


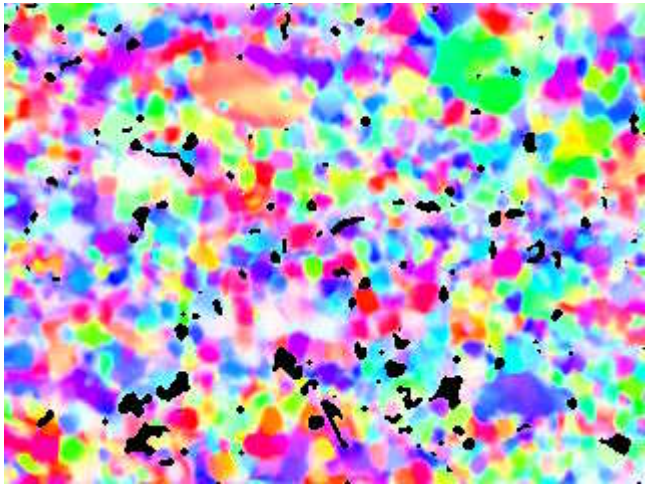
Black Hills
regime 3

100 µm

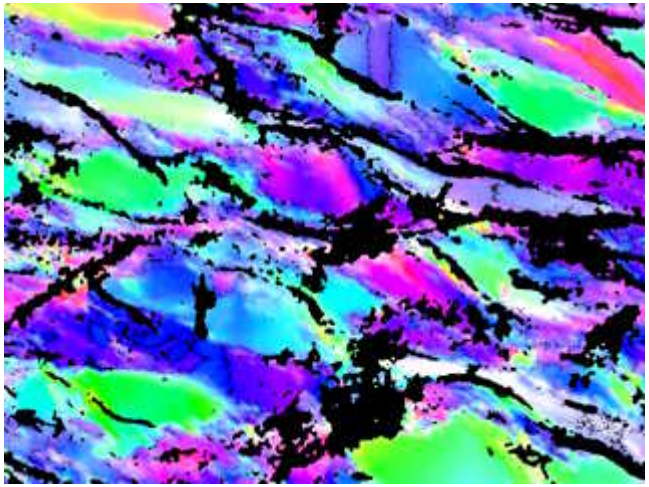
deformed annealed

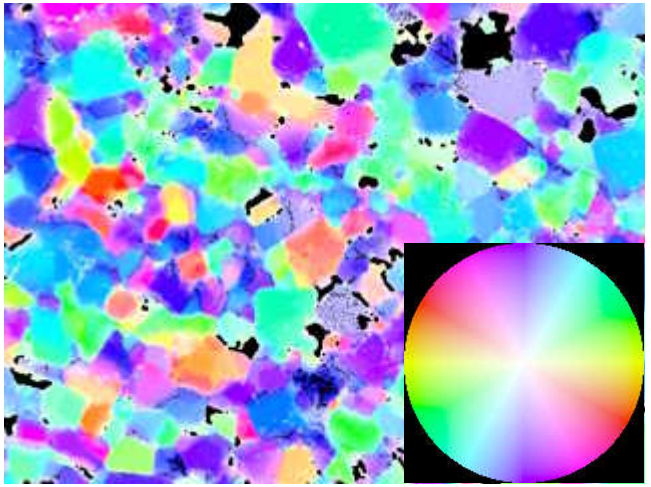
axial





shearing



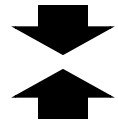


100 µm

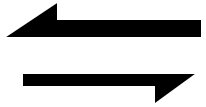
(optical orientation imaging, CIP)

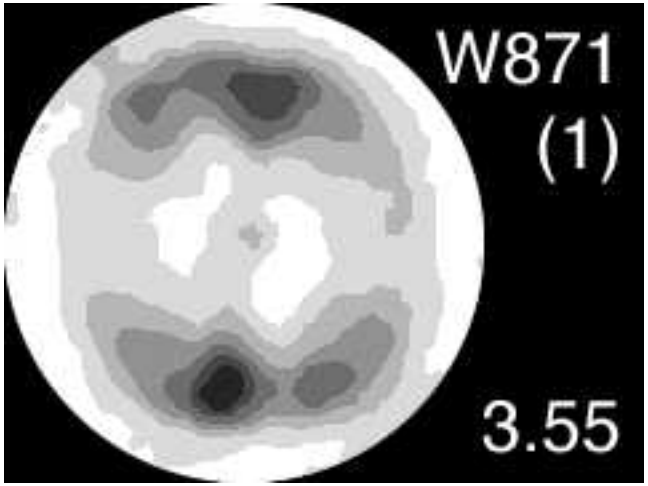
deformed annealed

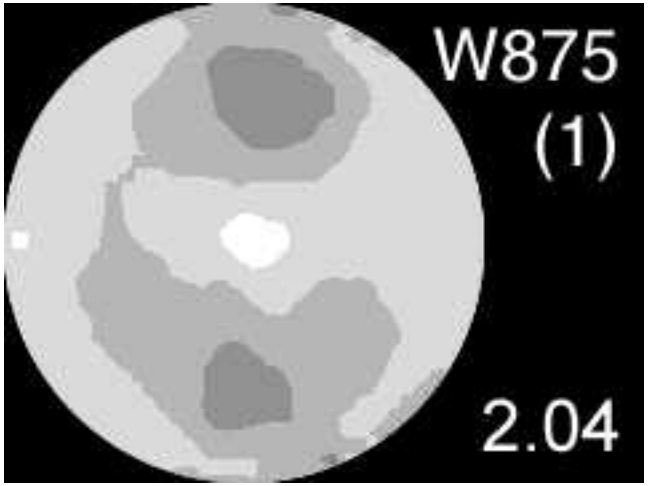
axial

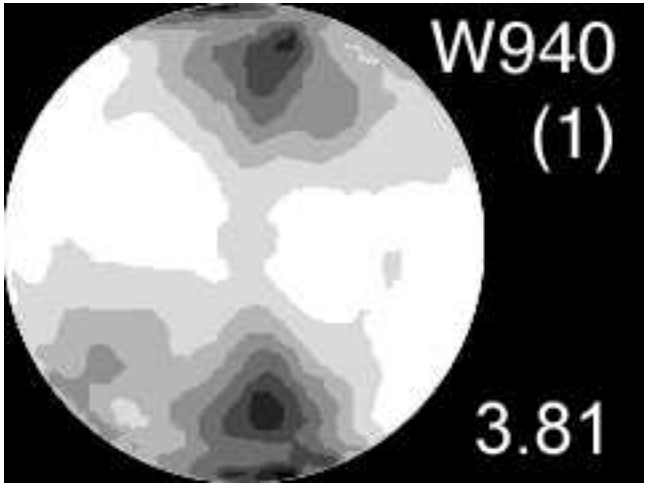


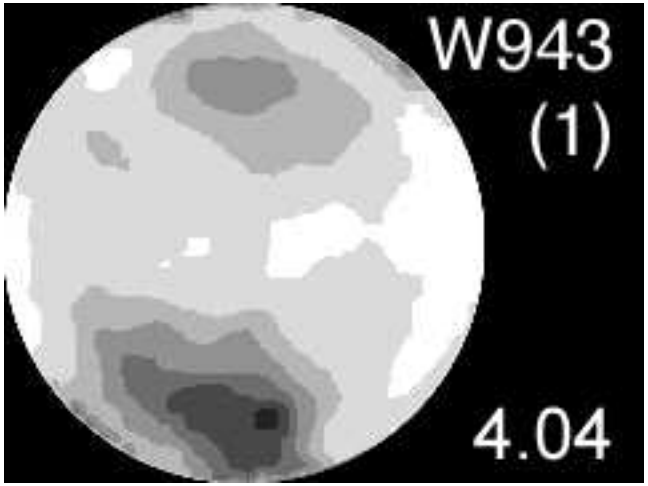
shearing







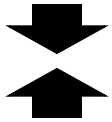


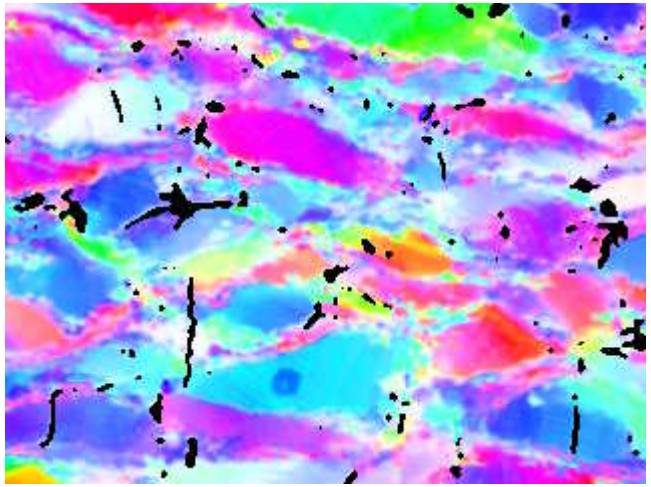


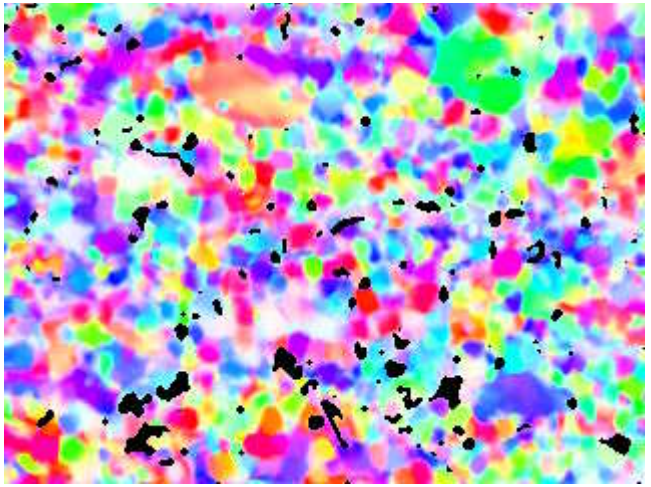
(c-axis pole figures, CIP)

deformed annealed

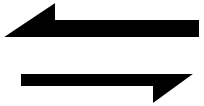
axial

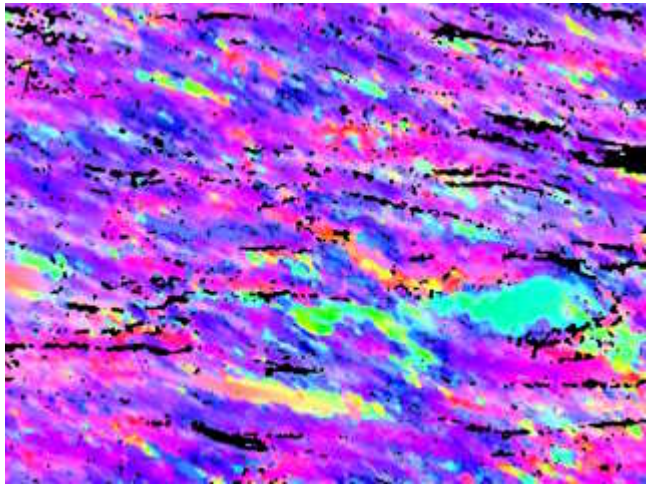


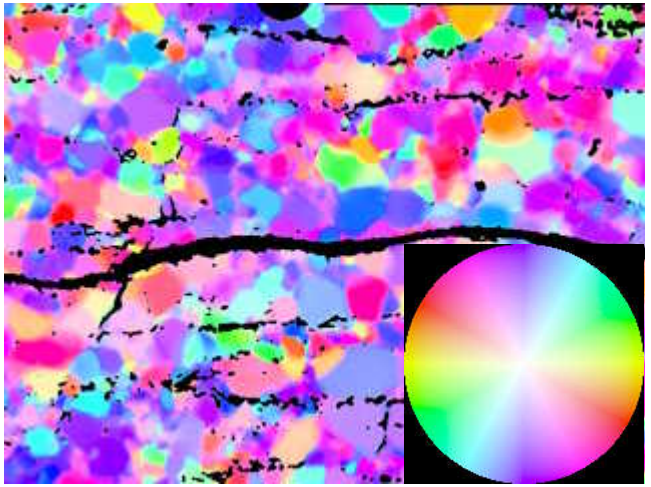




shearing





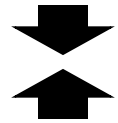


100 µm

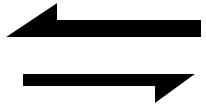
(optical orientation imaging, CIP)

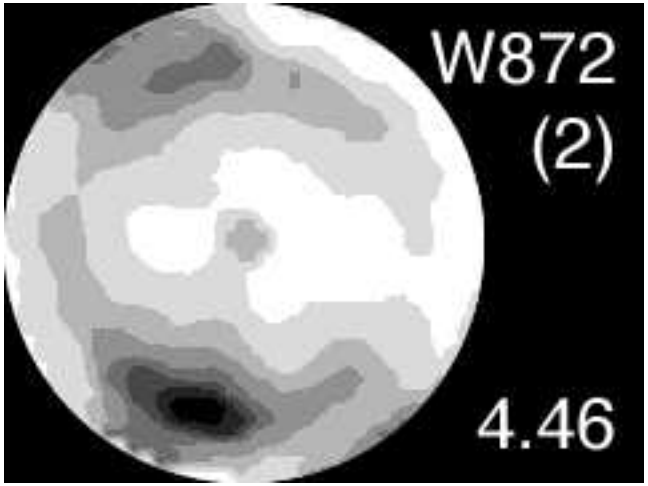
deformed annealed

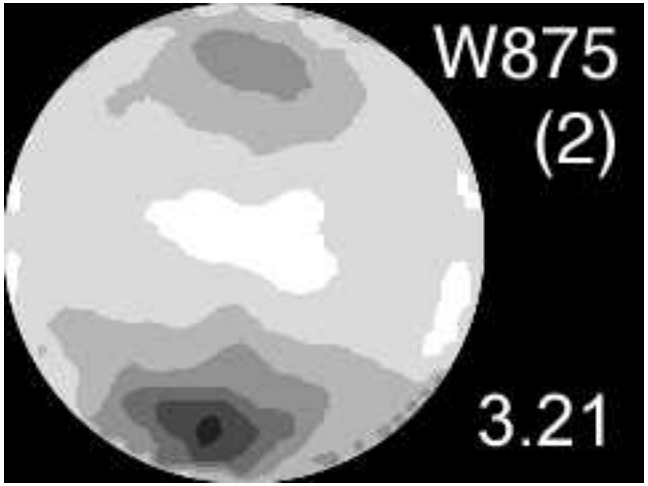
axial

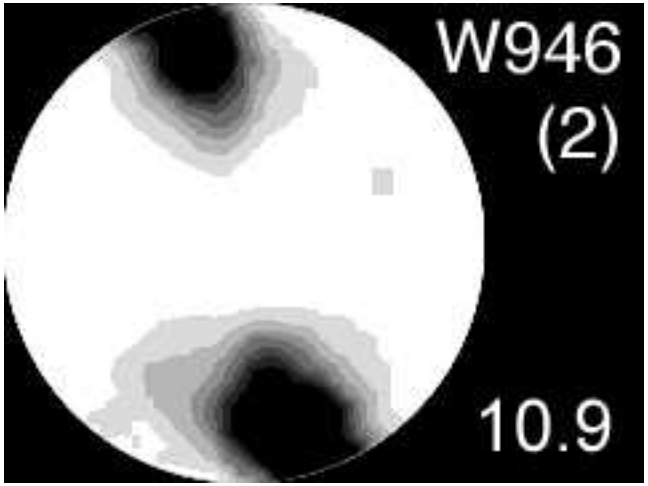


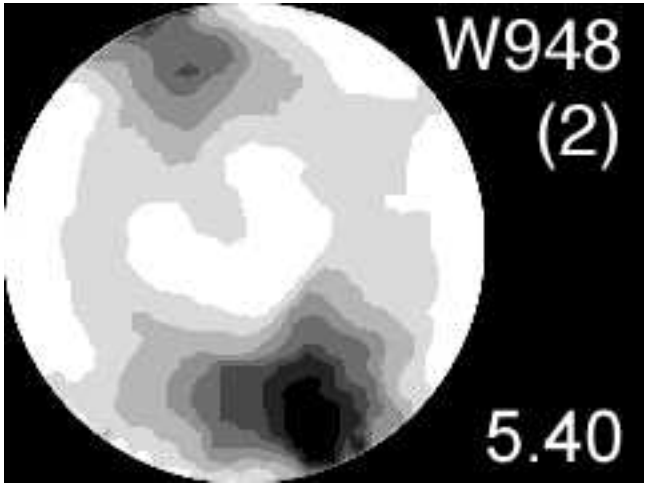
shearing







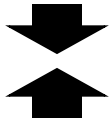


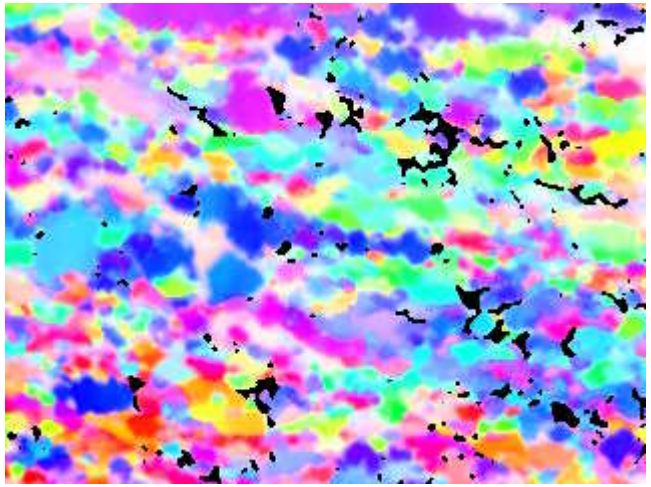


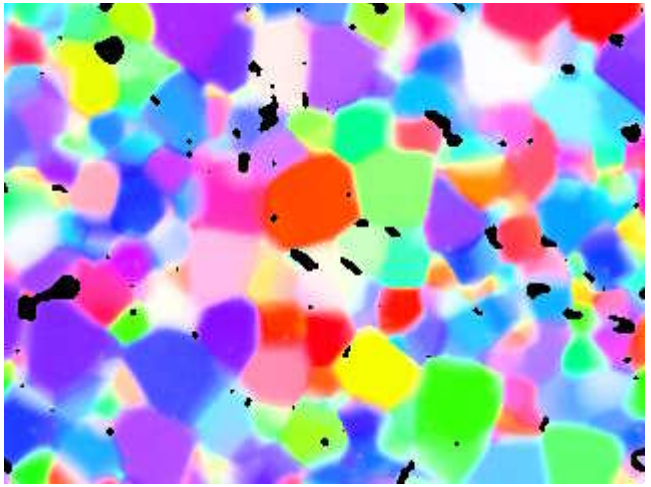
(c-axis pole figures, CIP)

deformed annealed

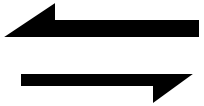
axial

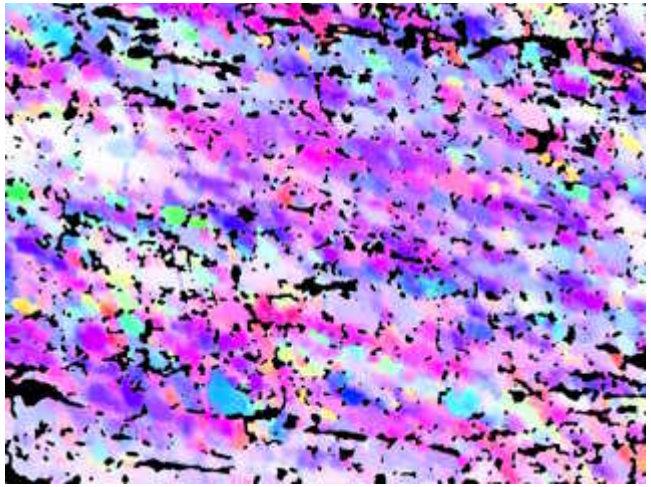


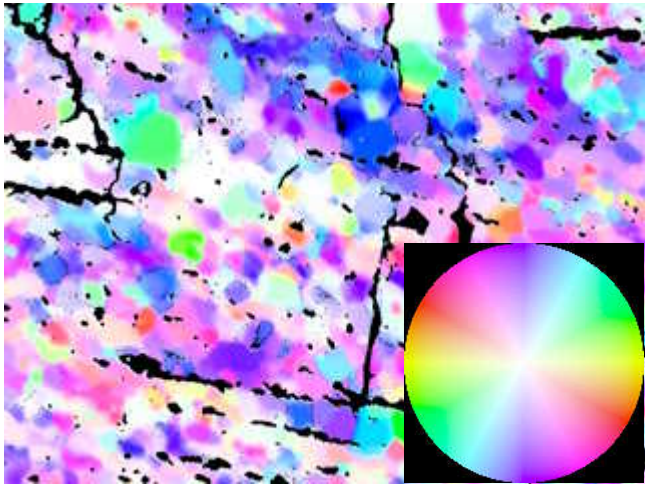




shearing





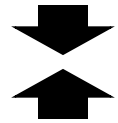


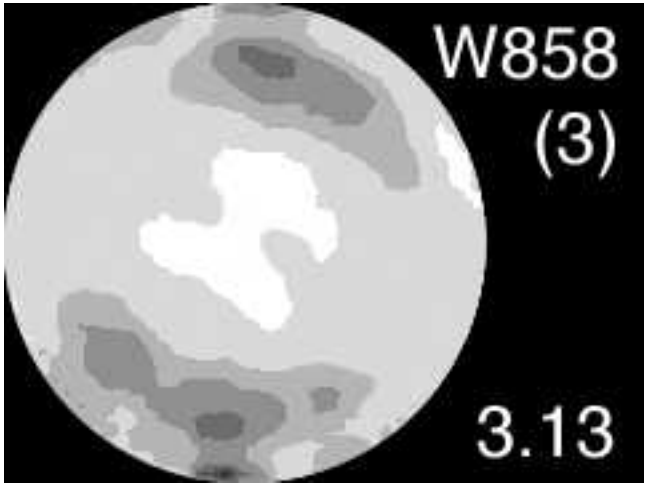
100 µm

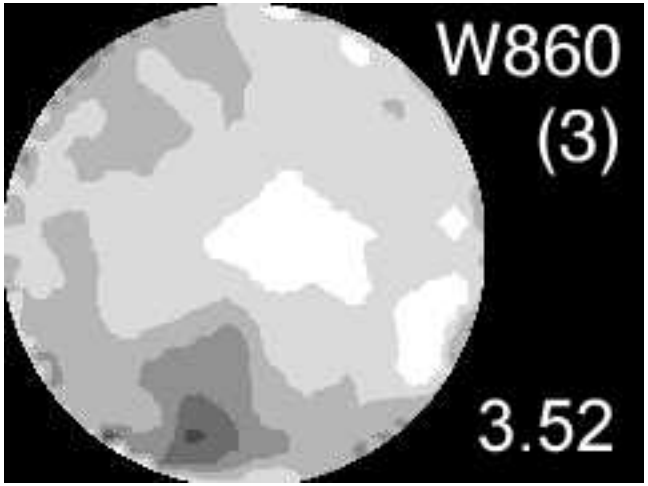
(optical orientation imaging, CIP)

deformed annealed

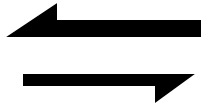
axial

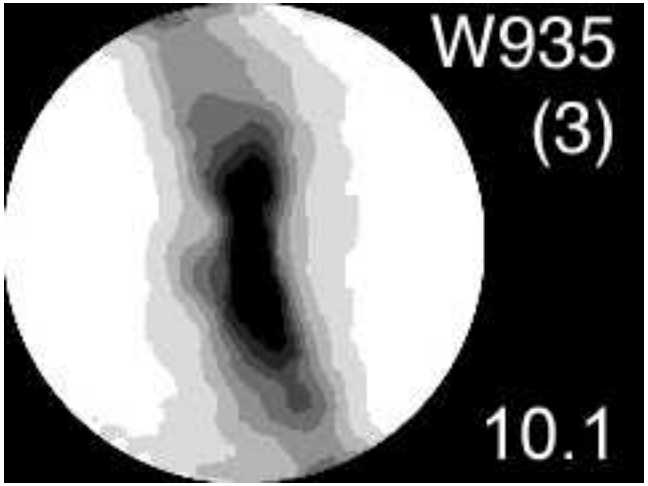


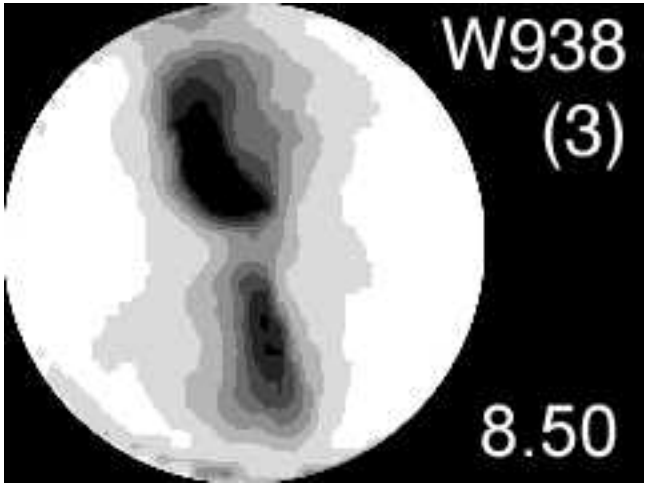




shearing







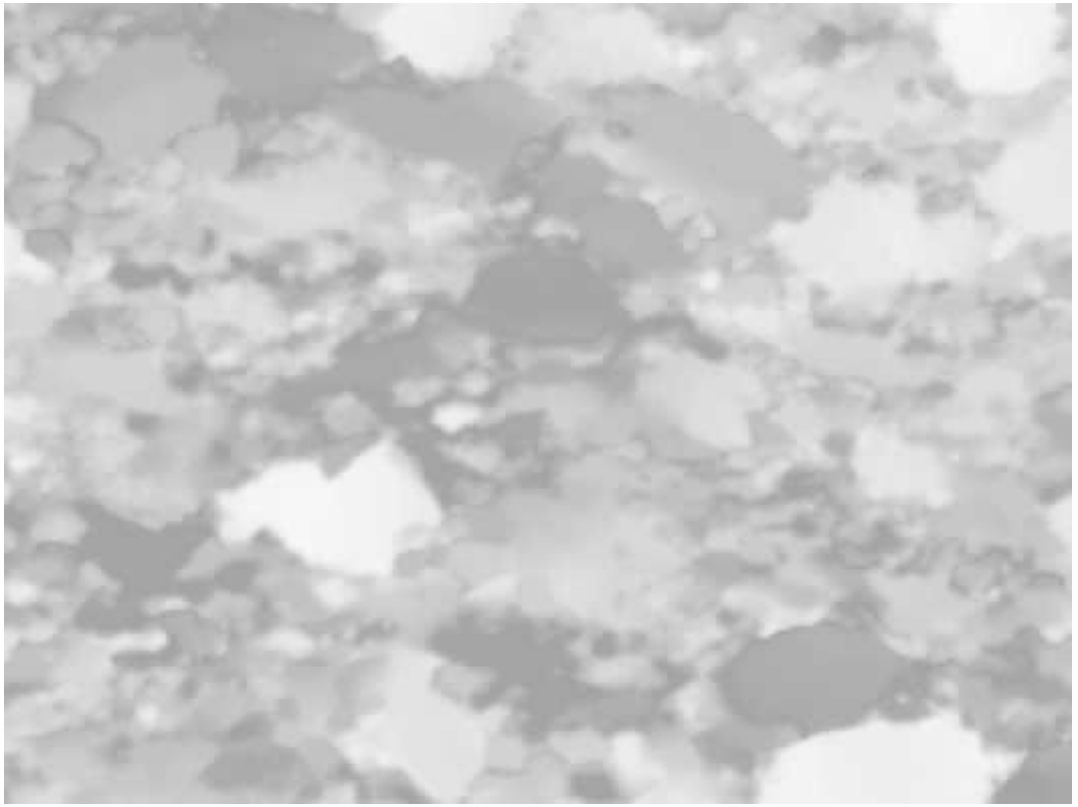
(c-axis pole figures, CIP)

SUMMARY

sample (regime)	Δvol recryst.	Δvol annealed	CPO max. density (bulk texture)	CPO max. density of recryst. fraction
w871 (1)	50		3.55	4.29
w872 (2)	40		4.46	5.16
w858 (3)	85		3.13	2.59
w875 (1 ann.)		100	2.04	= *
w874 (2 ann.)		100	3.21	=
w860 (3 ann.)		100	3.52	=
w940 (1)	50		3.81	4.22
w946 (2)	90		10.9	11.1
w920 (3)	45		3.06	2.69
w935 (3)	100		10.1	=
w943 (1 ann.)		100	4.04	=
w948 (2 ann.)		100	5.40	=
w921 (3 ann.)		100	2.50	=
w938 (3 ann.)		100	8.50	=

* same as bulk because 100 % recrystallized

GRAIN BOUNDARY MAPPING ➔ EXTRAPOLATION



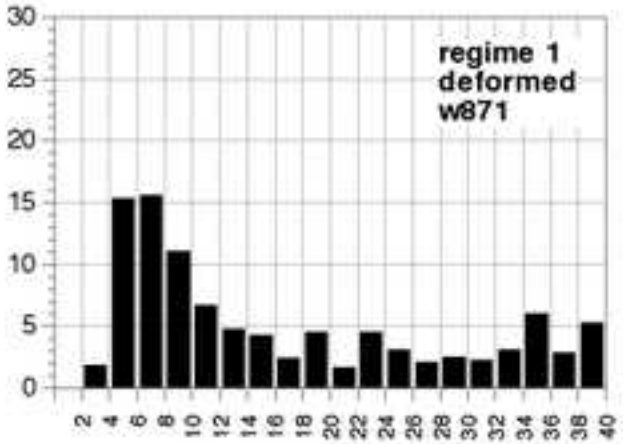
regime 1

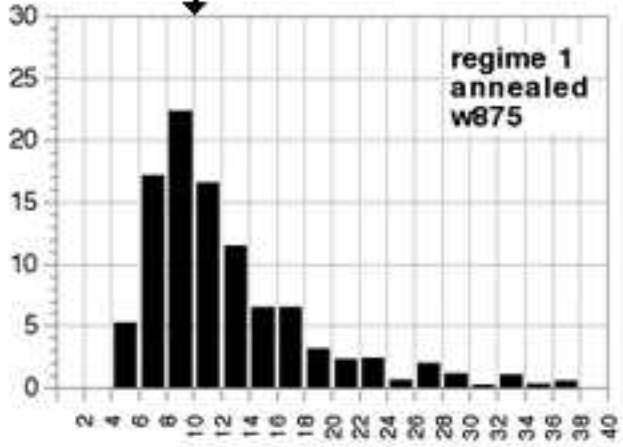
3-D grain size

deformed

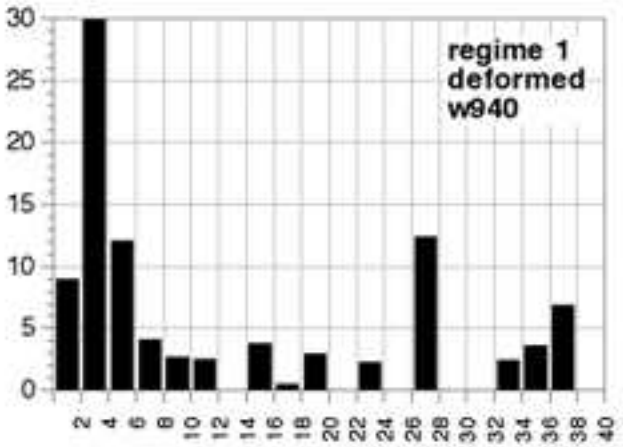
annealed

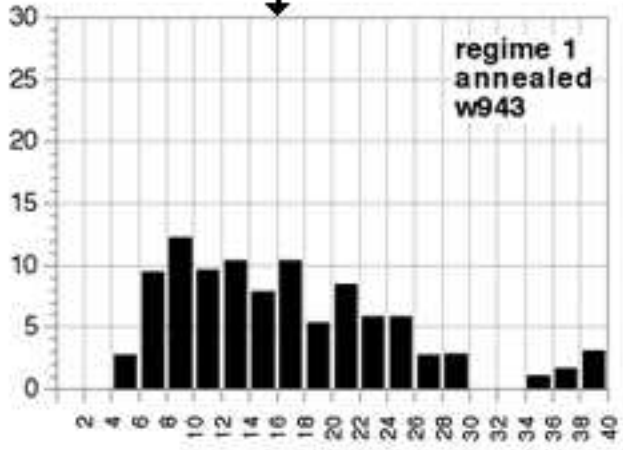
axial





shearing





(Lazy grainboundaries, StripStar)

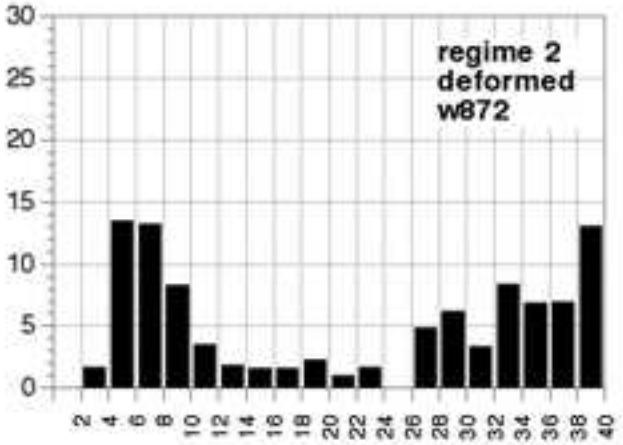
regime 2

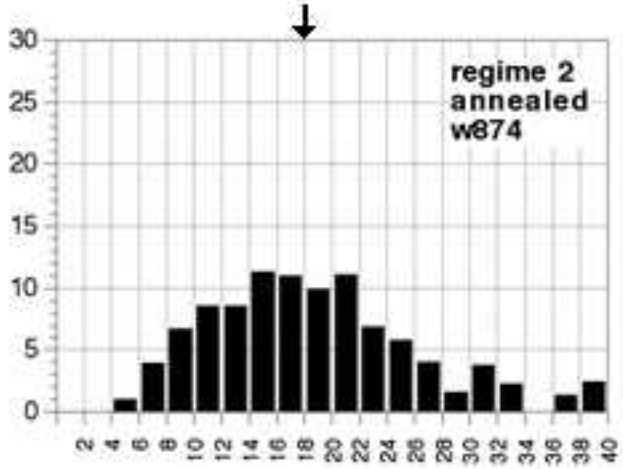
3-D grain size

deformed

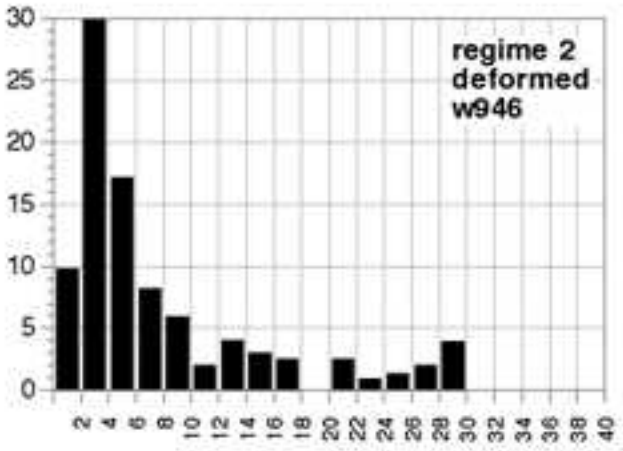
annealed

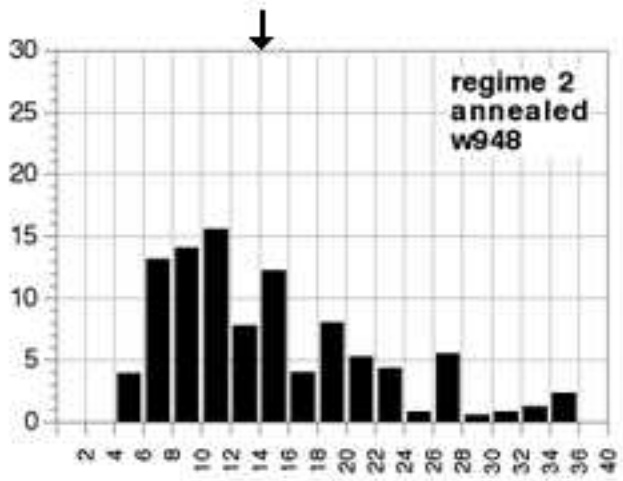
axial





shearing





(Lazy grainboundaries, StripStar)

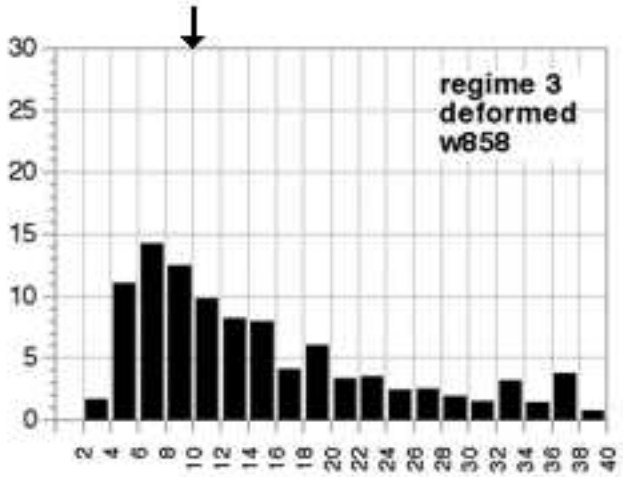
regime 3

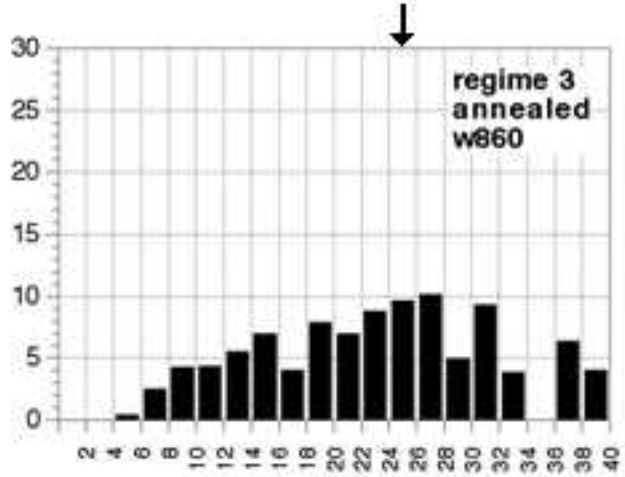
3-D grain size

deformed

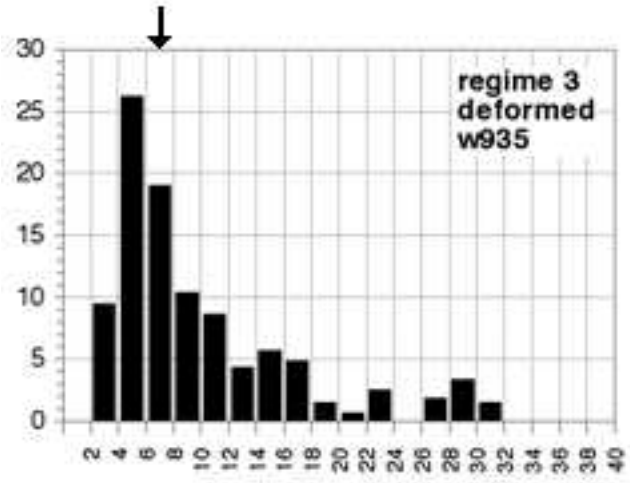
annealed

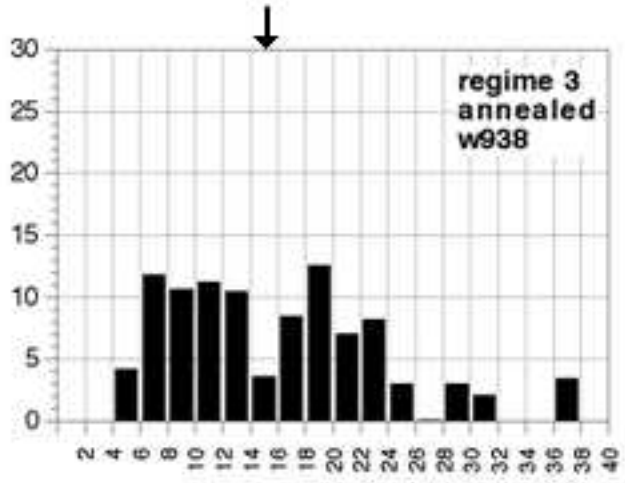
axial





shearing





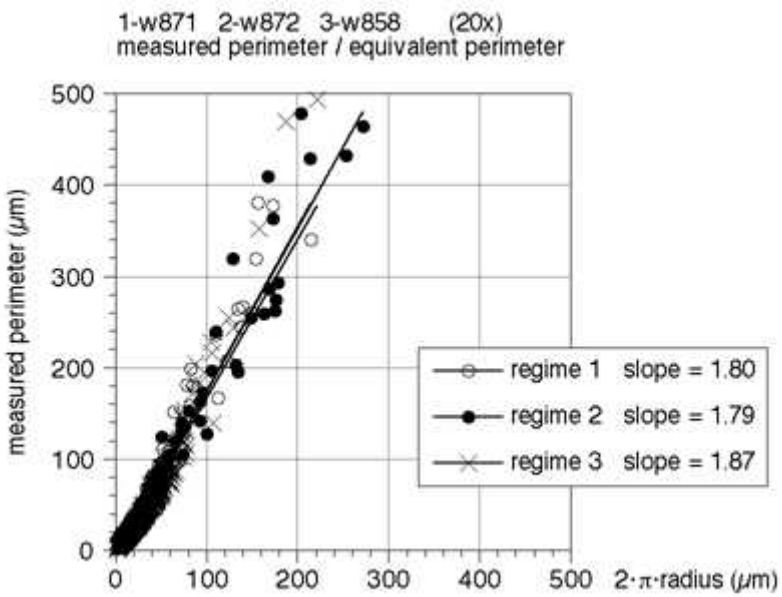
(Lazy grainboundaries, StripStar)

SUMMARY

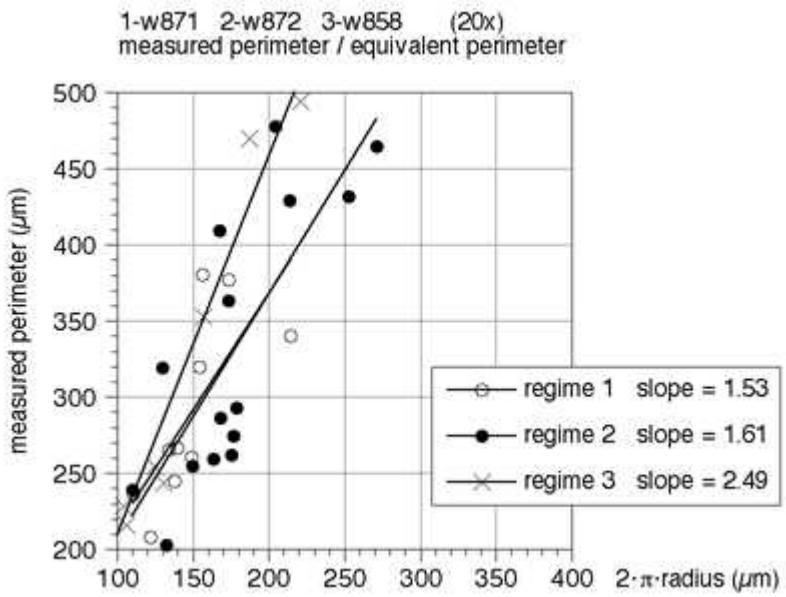
sample (regime)	Δvol recryst.	Δvol annealed	mode grain diameter (μm)
w871 (1)	50		5
w872 (2)	40		7
w858 (3)	85		20
w875 (1 ann.)		100	20
w874 (2 ann.)		100	36
w860 (3 ann.)		100	50
w940 (1)	50		7
w946 (2)	90		8
w920 (3)	45		14
w935 (3)	100		14
w943 (1 ann.)		100	32
w948 (2 ann.)		100	28
w921 (3 ann.)		100	42
w938 (3 ann.)		100	30

SHAPE FACTORS

deformed: all grains

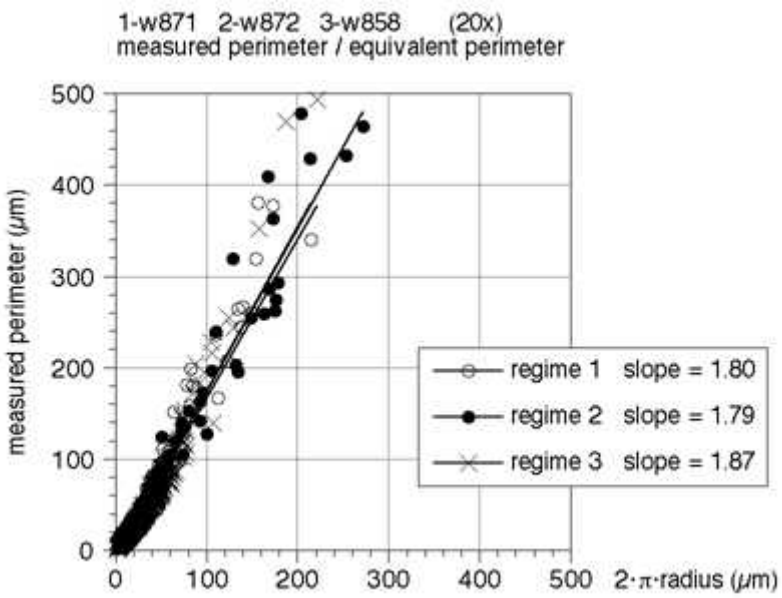


large grains only

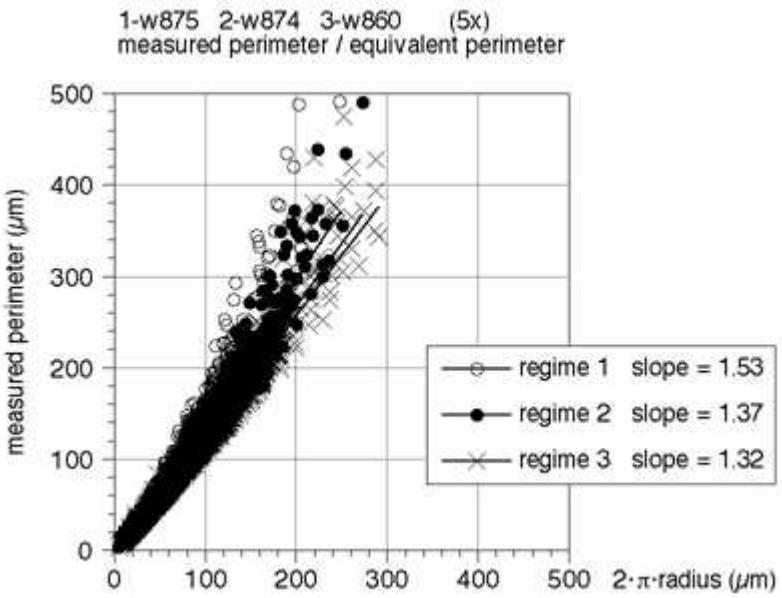


SHAPE FACTORS

deformed



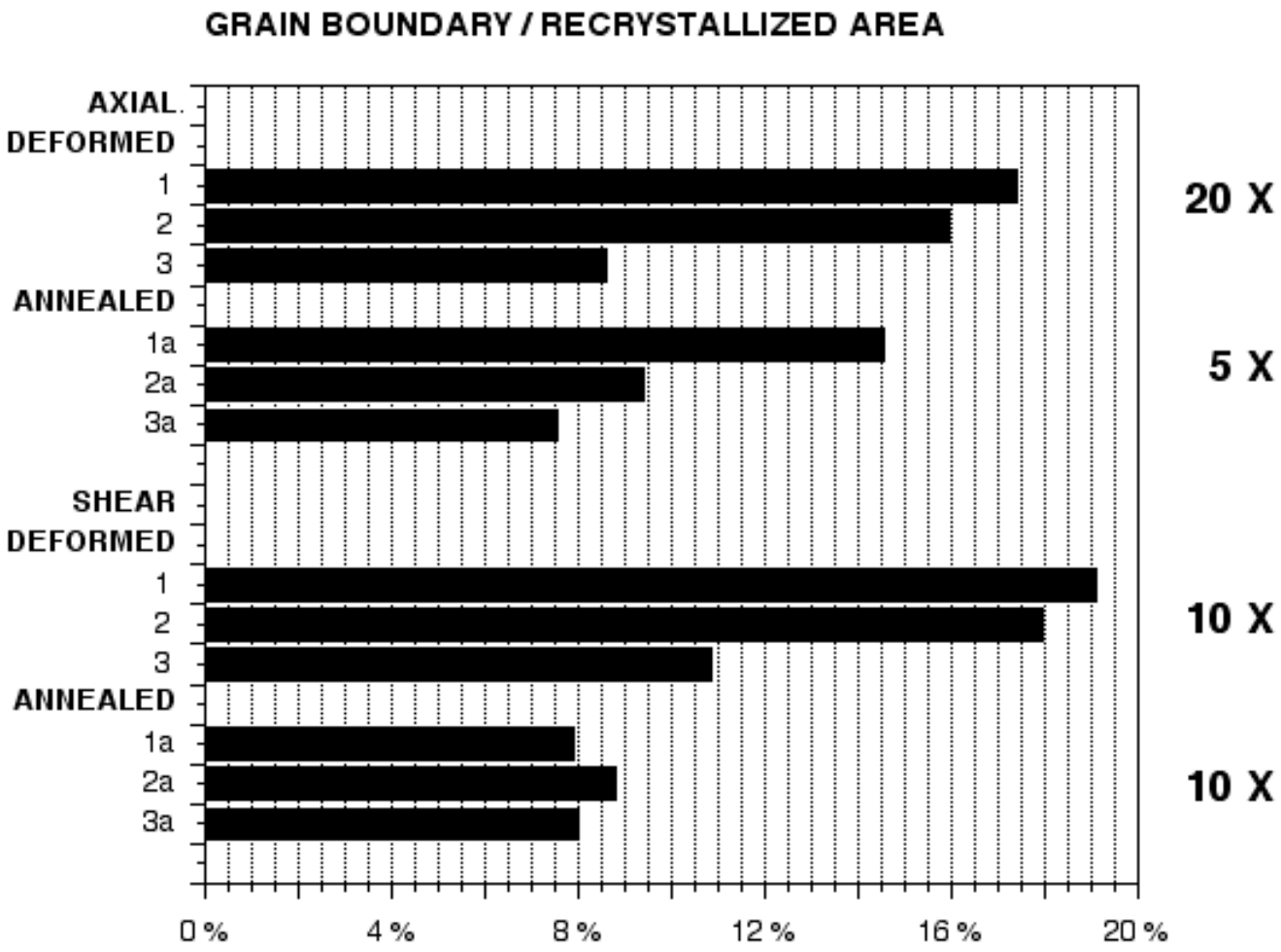
annealed



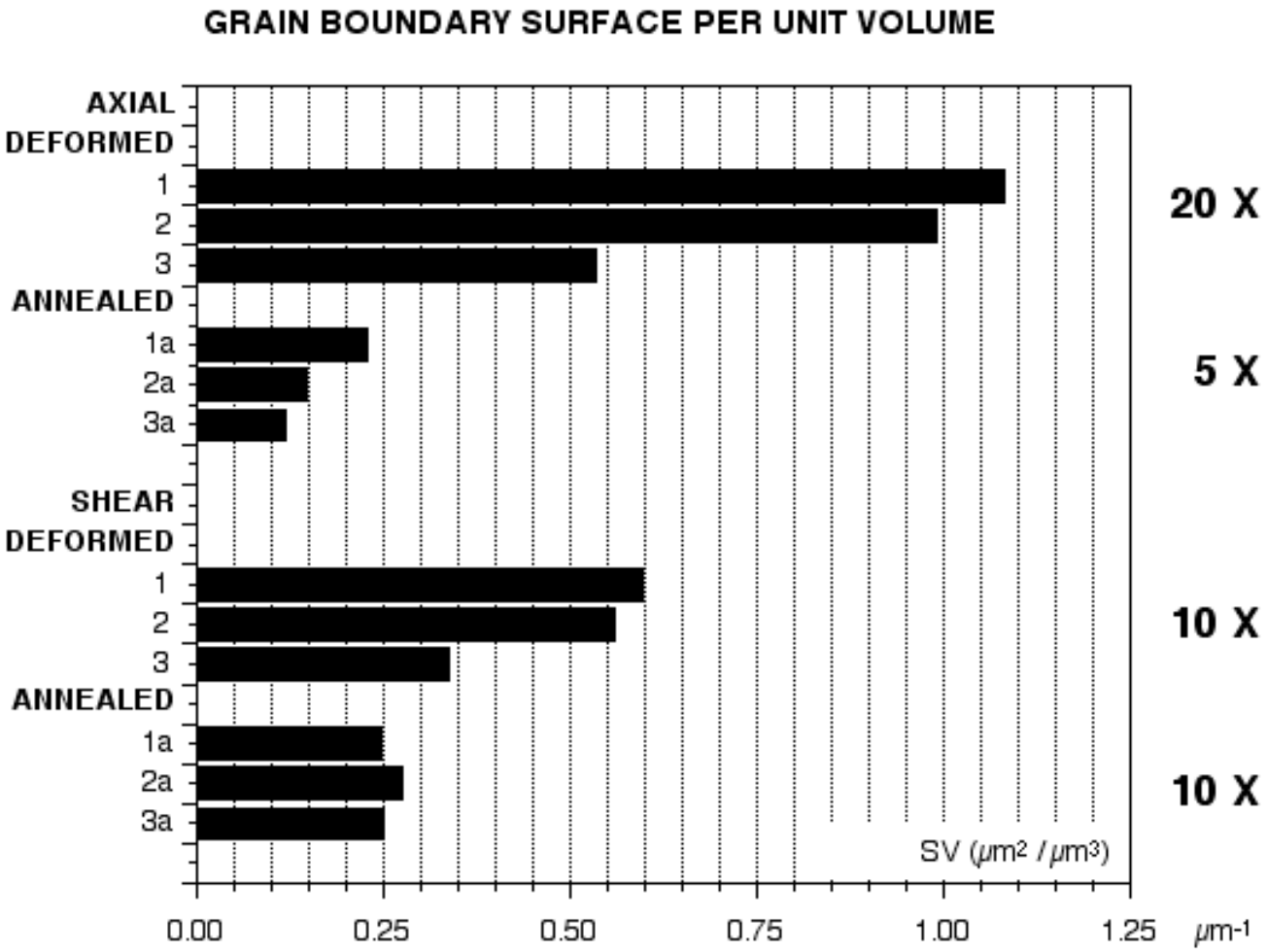
SUMMARY

sample (regime)	Δvol recryst.	Δvol annealed	meas. perimeter / equ. perimeter	PARIS factor (%)
w871 (1)	50		1.80	33.3
w872 (2)	40		1.79	35.6
w858 (3)	85		1.87	14.4
w875 (1 ann.)		100	1.53	0.2
w874 (2 ann.)		100	1.37	0.8
w860 (3 ann.)		100	1.32	0.9
w940 (1)	50			
w946 (2)	90			
w920 (3)	45			
w935 (3)	100			
w943 (1 ann.)		100		
w948 (2 ann.)		100		
w921 (3 ann.)		100		
w938 (3 ann.)		100		

GRAIN BOUNDARY DENSITY



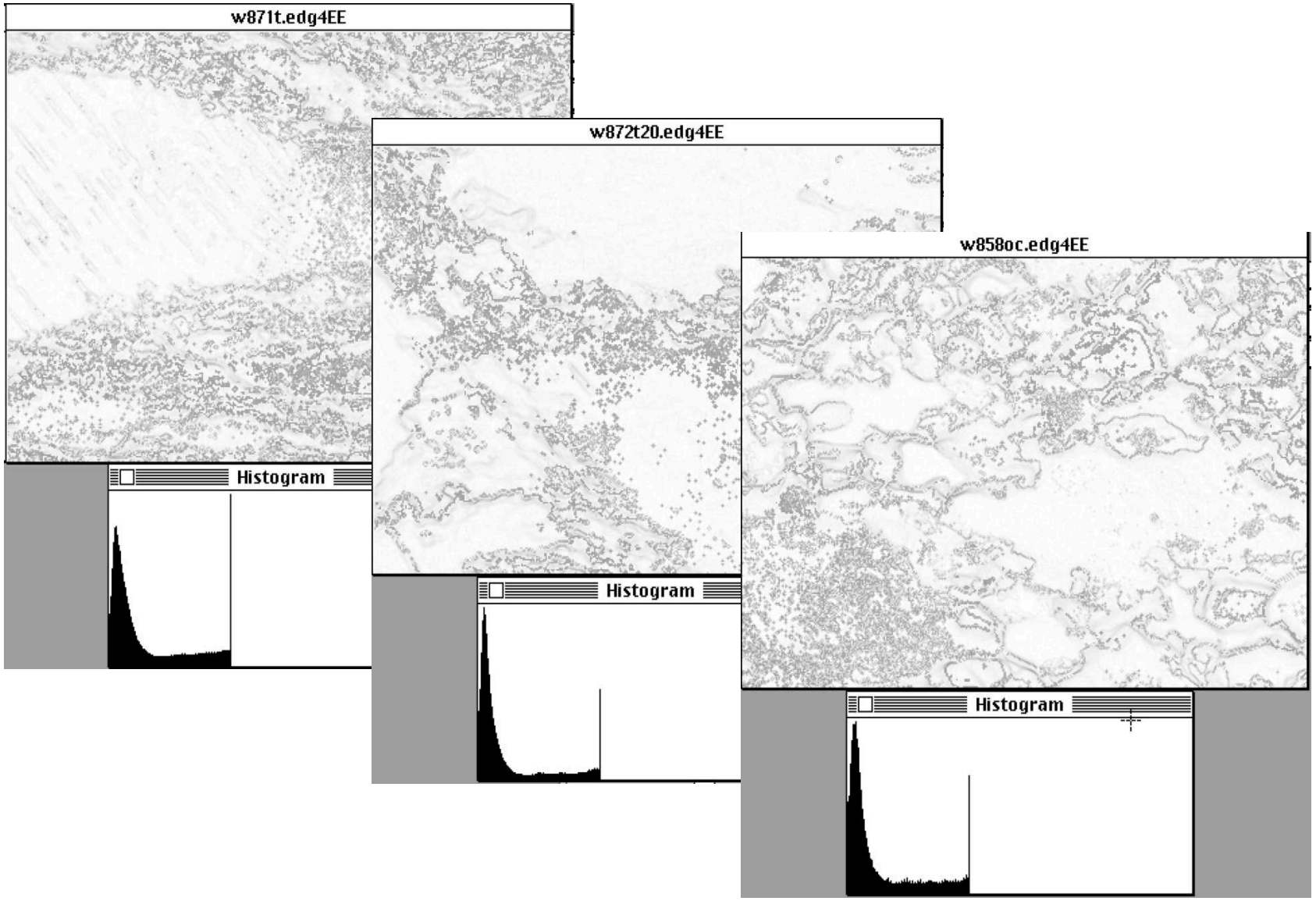
GRAIN BOUNDARY DENSITY



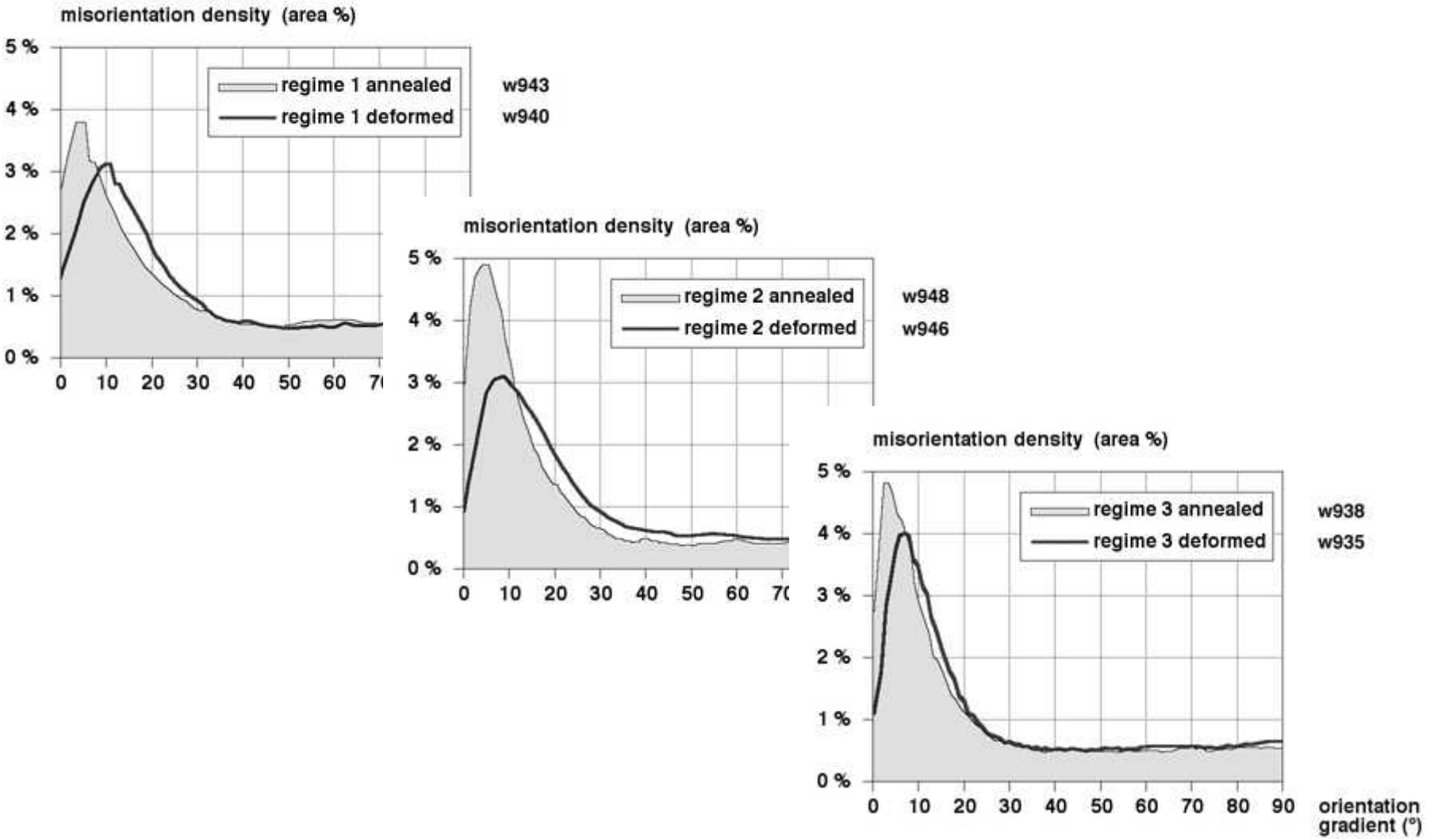
SUMMARY

sample (regime)	Δvol recryst.	Δvol annealed	gb surface per volume (μm-1)
w871 (1)	50		1.08
w872 (2)	40		0.99
w858 (3)	85		0.53
w875 (1 ann.)		100	0.23
w874 (2 ann.)		100	0.15
w860 (3 ann.)		100	0.12
w940 (1)	50		0.60
w946 (2)	90		0.56
w920 (3)	45		
w935 (3)	100		0.34
w943 (1 ann.)		100	0.25
w948 (2 ann.)		100	0.27
w921 (3 ann.)		100	
w938 (3 ann.)		100	0.25

MISORIENTATION DENSITY



ORIENTATION GRADIENTS ⇒ INTERNAL ENERGY



SUMMARY

sample (regime)	Δvol recryst.	Δvol annealed	mode of orient. gradient distrib. (°)
w871 (1)	50		
w872 (2)	40		
w858 (3)	85		
w875 (1 ann.)		100	
w874 (2 ann.)		100	
w860 (3 ann.)		100	
w940 (1)	50		10
w946 (2)	90		9
w920 (3)	45		
w935 (3)	100		7
w943 (1 ann.)		100	4
w948 (2 ann.)		100	4
w921 (3 ann.)		100	
w938 (3 ann.)		100	4

SUMMARY

sample (regime)	Δvol recryst.	Δvol annealed	mode grain diameter (µm)	CPO max. density (bulk texture)	CPO max. density of recryst. fraction	mode of orient. gradient distrib. (°)	meas. perimeter / equ. perimeter	PARIS factor (%)	gb surface per volume (µm-1)
w871 (1)	50		5	3.55	4.29		1.80	33.3	1.08
w872 (2)	40		7	4.46	5.16		1.79	35.6	0.99
w858 (3)	85		20	3.13	2.59		1.87	14.4	0.53
w875 (1 ann.)		100	20	2.04	= *		1.53	0.2	0.23
w874 (2 ann.)		100	36	3.21	=		1.37	0.8	0.15
w860 (3 ann.)		100	50	3.52	=		1.32	0.9	0.12
w940 (1)	50		7	3.81	4.22	10			0.60
w946 (2)	90		8	10.9	11.1	9			0.56
w920 (3)	45		14	3.06	2.69				
w935 (3)	100		14	10.1	=	7			0.34
w943 (1 ann.)		100	32	4.04	=	4			0.25
w948 (2 ann.)		100	28	5.40	=	4			0.27
w921 (3 ann.)		100	42	2.50	=				
w938 (3 ann.)		100	30	8.50	=	4			0.25

* same as bulk because 100 % recrystallized

CONCLUSIONS

after annealing:

- CPOs unchanged (asymmetry retained), strength decreased
- grain size increase greatest for lowest T, least for highest T
- largest annealed grain size for samples deformed at highest T, smallest for lowest T
- reduced grain boundary lobateness to a common value
- smoothing of grain boundary surface greatest for samples at highest T
- reduced misorientation density (lower modal value)

CONCLUSIONS