CRYSTAL2PLATE

How does plate tectonics work:
From crystal-scale processes to mantle convection with self-consistent plates

Introduction to crystal plasticity: deformation mechanisms, microstructures, and crystal preferred orientations

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Short course on "Microstructures, textures & anisotropy"
Geosciences Montpellier (F) - 28 June - 2 July, 2010

Macroscopic and microscopic observations & deformation regimes

Dislocation creep:

- *Grain elongation (may be erased by recrystallization)*
- *Undulose extinction, deformation bands & subgrains*
  (microstructures directely related to dislocations = may be erased by annealing)
- *Dynamic recryistallization may produce a bimodal grain size distribution at high stress (porphyroclasts vs. Neoblasts)*
- *HT: sinuous or polygonal grain boundaries : migration*
  synkinematic grain growth hinder grain size reduction
- ***Crystallographic preferred orientation (CPO) = preserved even in annealed (statically recrystallized) rocks***

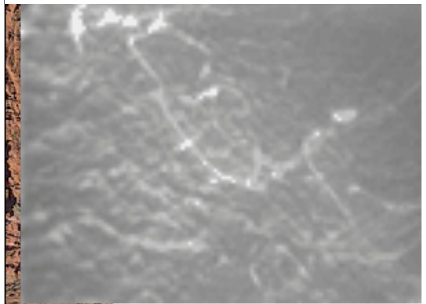
Diffusion creep or diffusion-assisted GBS:

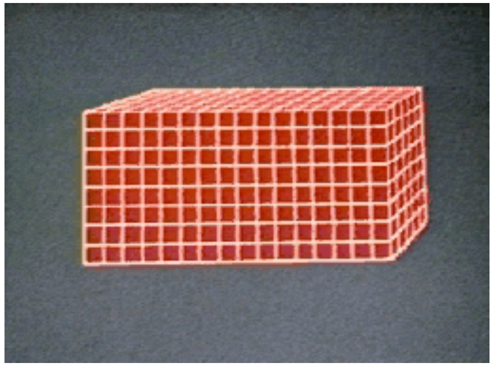
- *Fine-grained material (µm)*
- *Weak elongation may exist, but generaly absent*
- *Absence of intracrystalline deformation features (Undulose extinction, deformation bands & subgrains)*
- ***Absence of CPO***

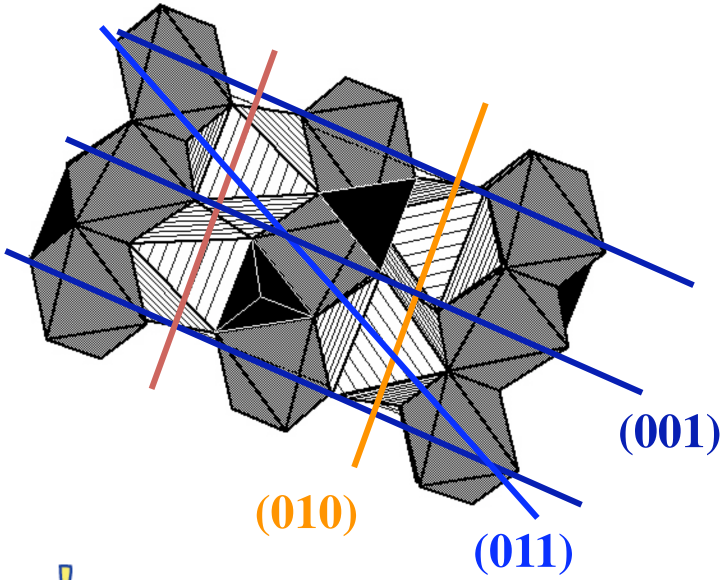
Dislocation creep : crystal orientation evolution

within a grain (crystal):

dislocation glide in Ti alloy

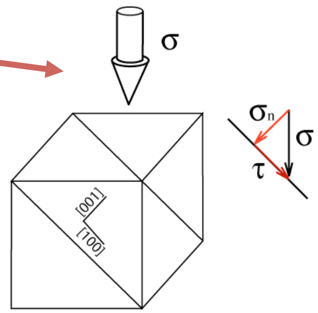


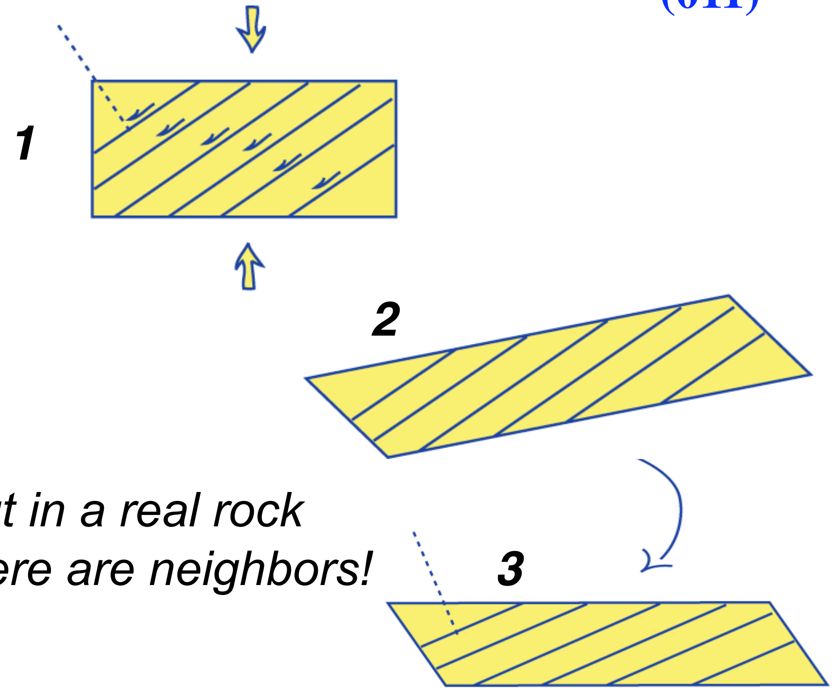




strain = motion of dislocations on well-defined crystal planes & directions

$$\dot{\gamma}^s = \left(\frac{\tau_r^s}{\tau_0^s} \right)^n$$

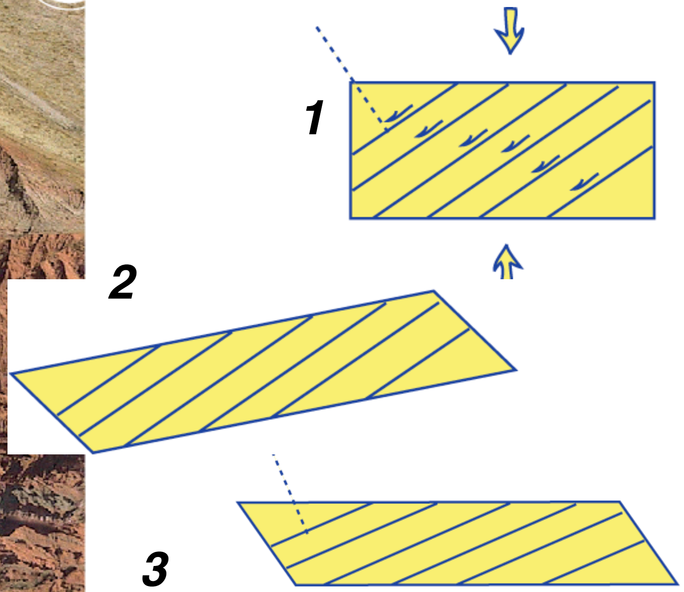


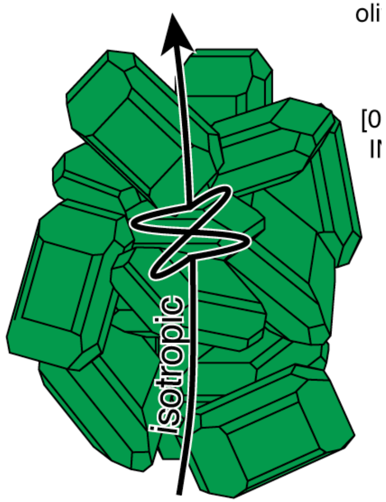


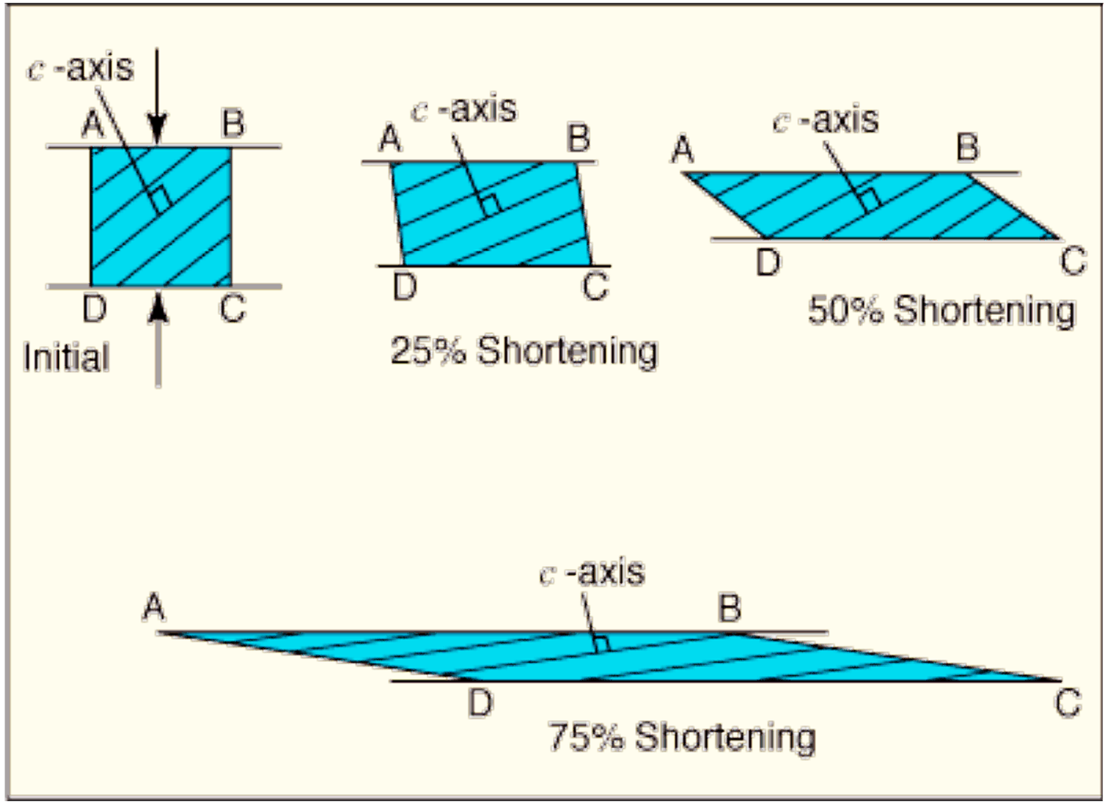
But in a real rock there are neighbors!

Dislocations move on well-defined crystal planes & directions
= crystal deformation has a limited degree of freedom

- *strain compatibility = rotation of the crystal*
- *development of a crystal preferred orientation*

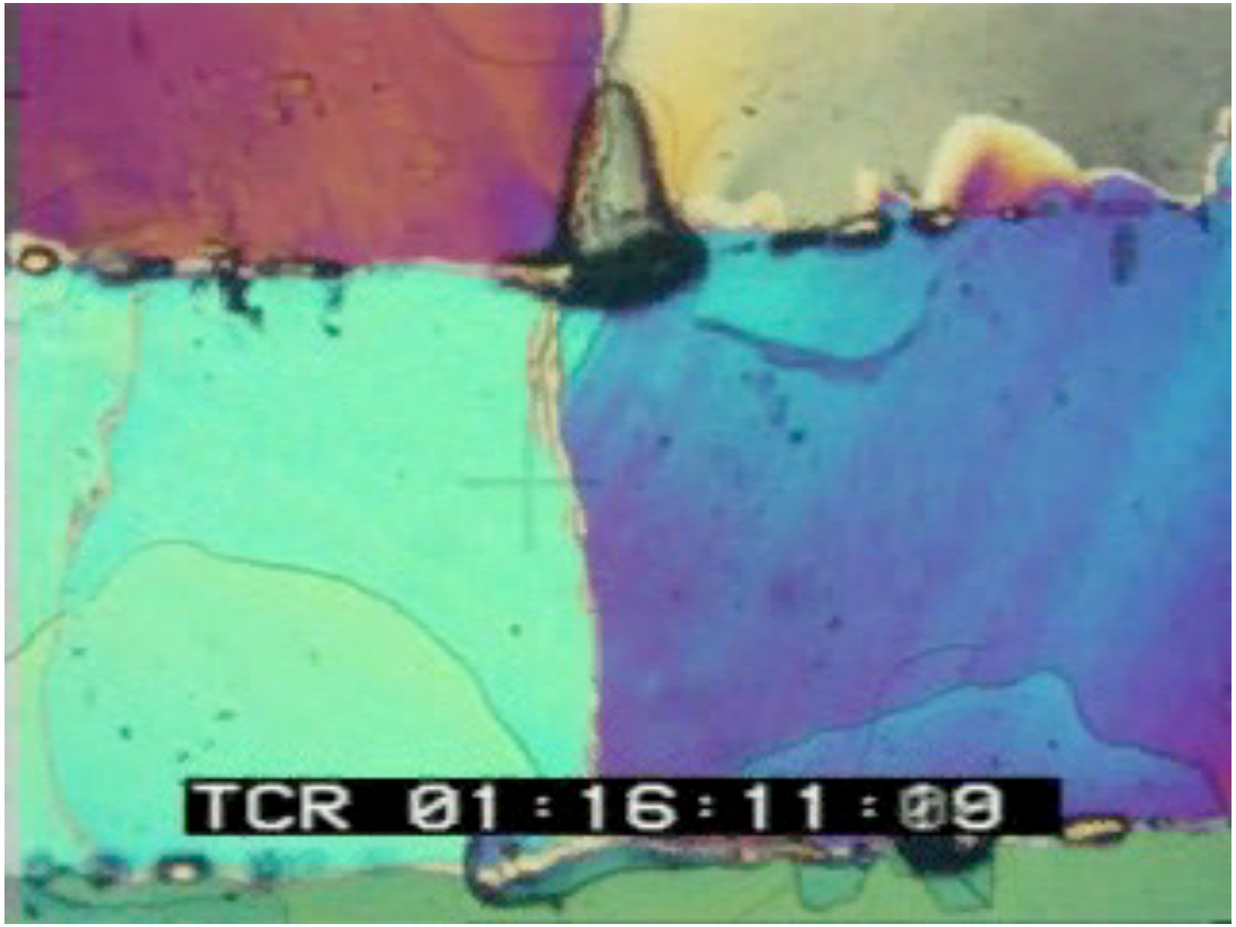






Viscoplastic deformation of ice

dislocation creep = dislocation glide
+ dynamic recrystallization



polycrystalline ice - HT
in-situ deformation: pure shear
C. Wilson - Univ. Melbourne, Australia

• *parameters controlling CPO evolution during deformation*

✓ *deformation geometry*

✓ *active slip systems, which depend on:*

crystal structure
temperature
deviatoric stress
water
pressure
melt

✓ *dynamic recrystallisation*

• *preservation / destruction of CPO & anisotropy?*

✓ *dynamic recrystallisation*

✓ *thermal and chemical processes*

quartz

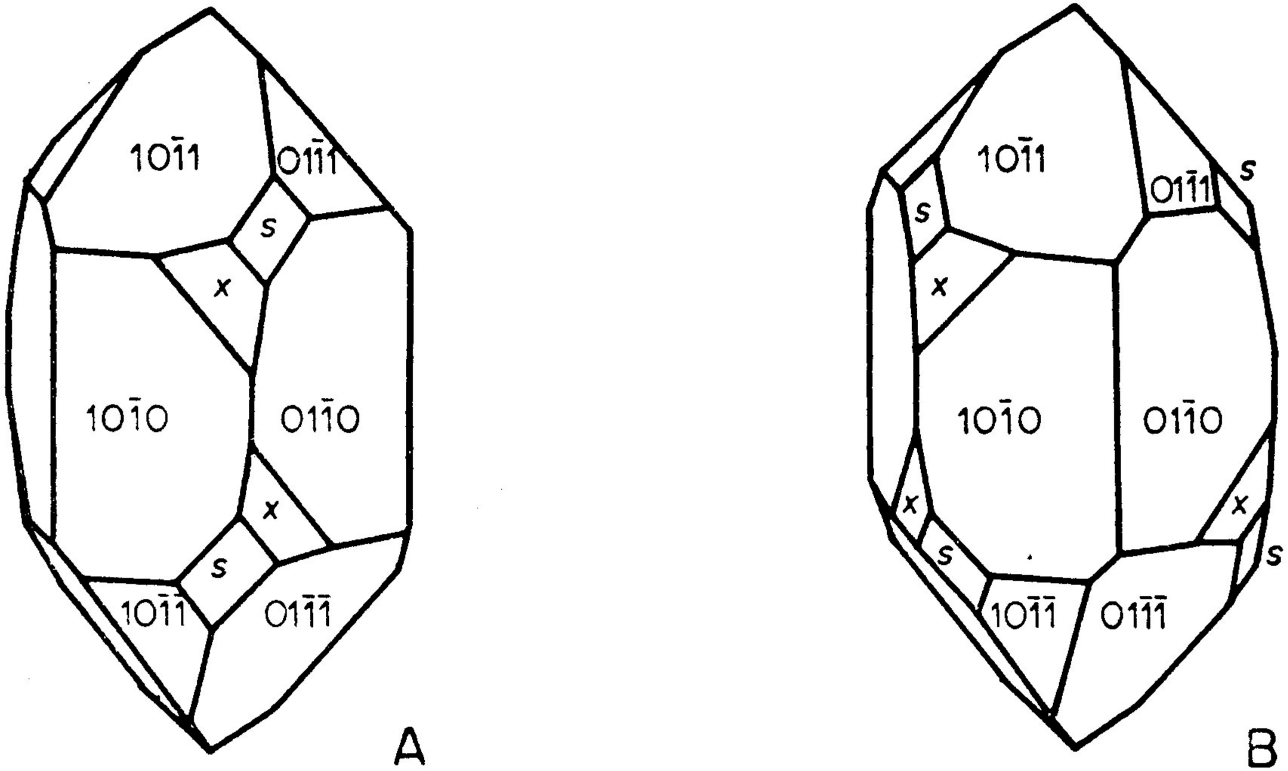
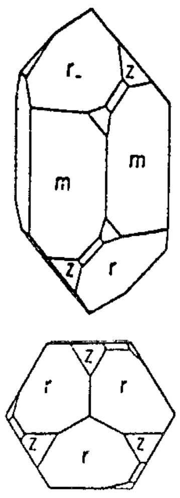
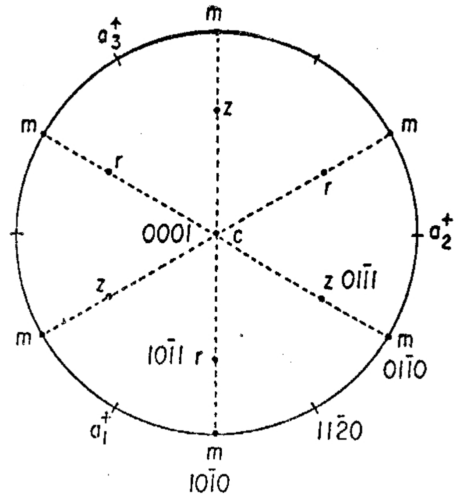


Fig. 175 Right (A) and left handed (B) crystals of quartz. Forms present are hexagonal prism {$10\bar{1}0$}; rhombohedra {$10\bar{1}1$} and {$01\bar{1}1$}; trigonal bipyramid (s) {$11\bar{2}1$} (A) and {$2\bar{1}\bar{1}1$} (B) and the trigonal trapezohedra (*x*) {$51\bar{6}1$} (A) and {$6\bar{1}\bar{5}1$} (B).

quartz





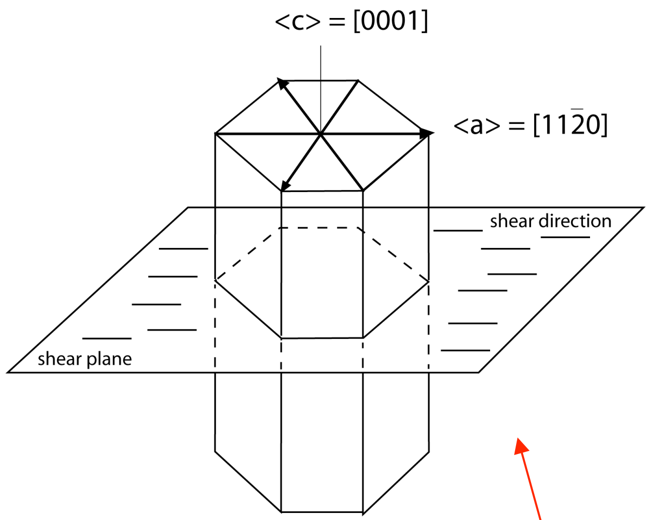


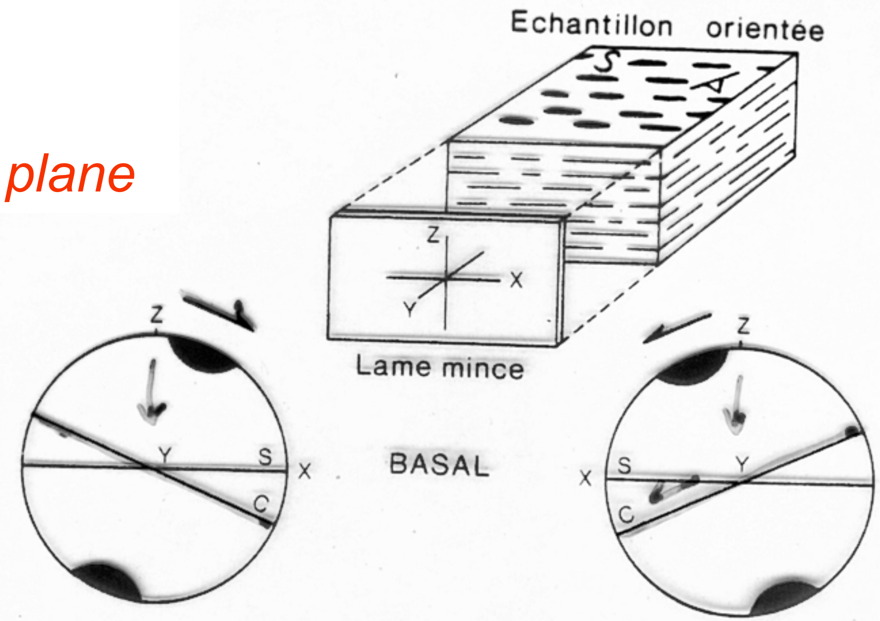
Table 5.5. Principal slip systems in α and β quartz (+: common, −: uncommon)

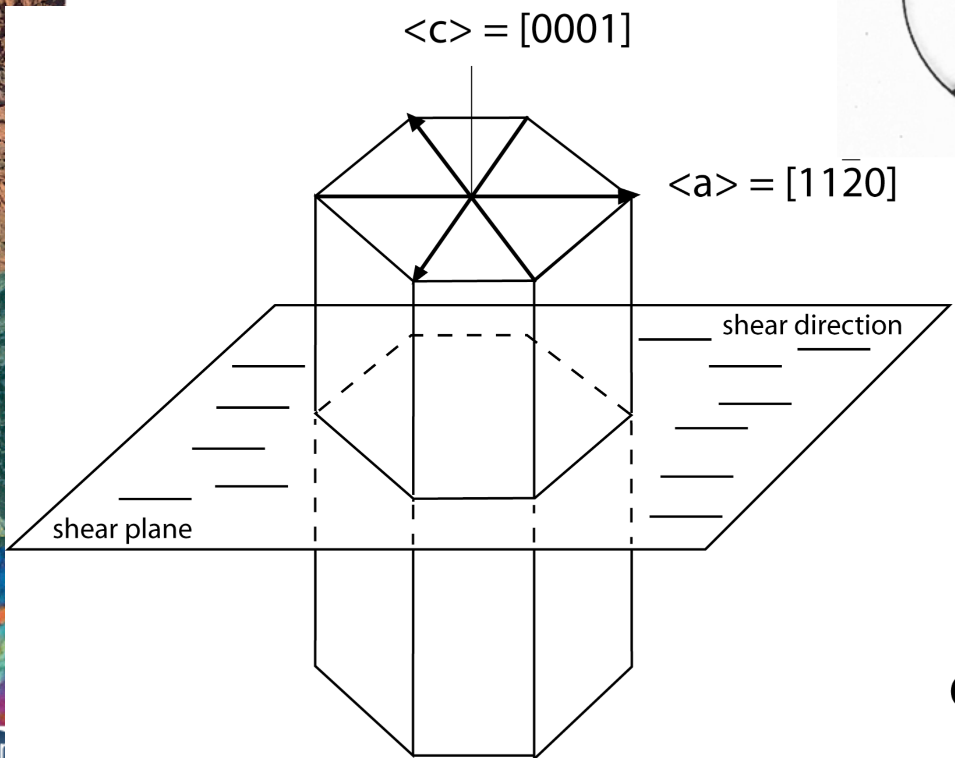
Basal	$(0001)\langle 11\bar{2}0\rangle^{+}$	Low T, high $\dot{\varepsilon}$
1st ord. prismatic	$\{10\bar{1}0\}[0001]^{+}$	very High T, low $\dot{\varepsilon}$
	$\{10\bar{1}0\}\langle 1\bar{2}10\rangle^{+}$	High T, low $\dot{\varepsilon}$
	$\{10\bar{1}0\}\langle 1\bar{2}13\rangle^{-}$	High T, low $\dot{\varepsilon}$
2nd ord. prismatic	$\{11\bar{2}0\}[0001]^{-}$	very High T, low $\dot{\varepsilon}$
2nd ord. pyramidal	$\{11\bar{2}2\}\langle 11\bar{2}3\rangle^{-}$	High T, low $\dot{\varepsilon}$

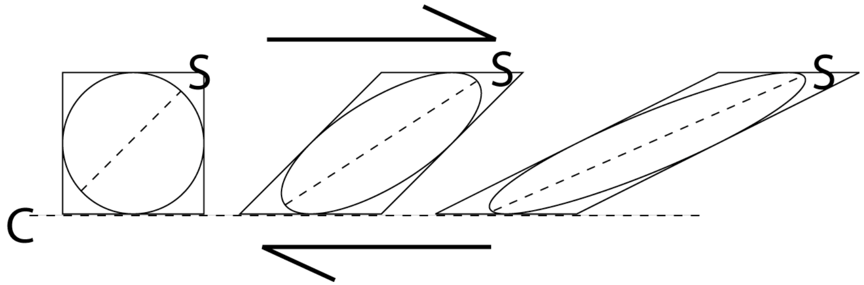
Quartz

@ LT = basal glide

<a> dislocations move on the (0001) plane



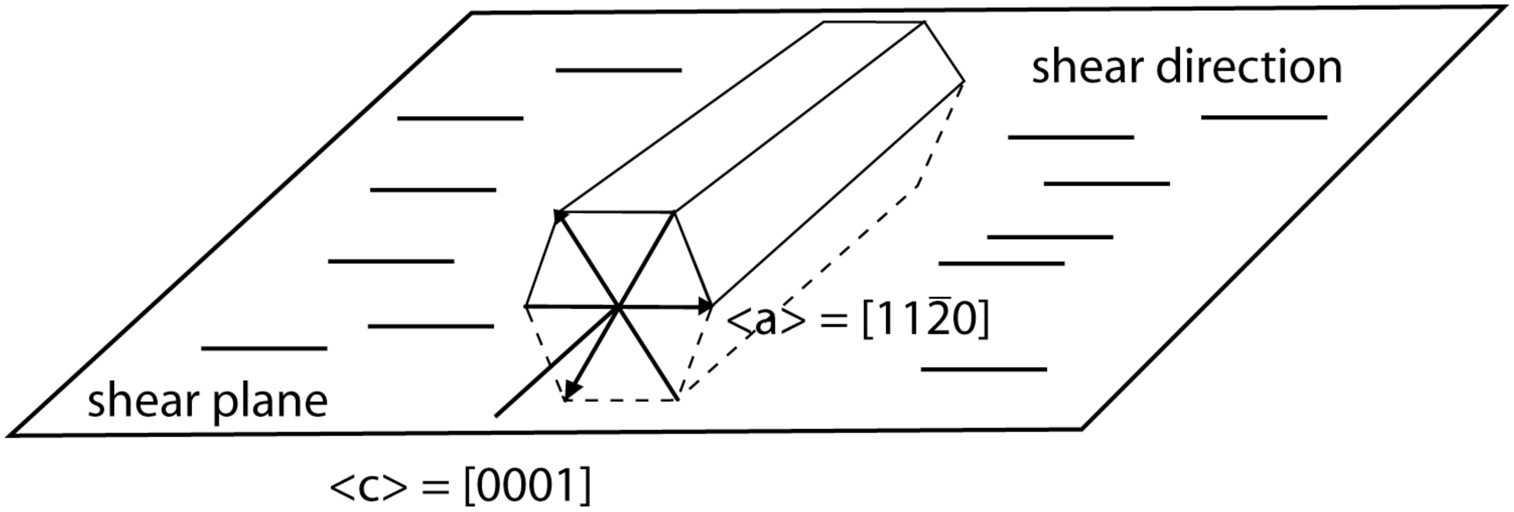


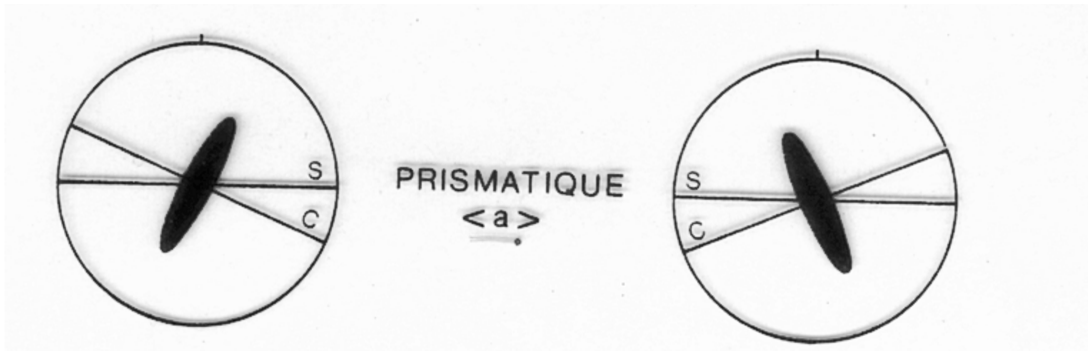


Quartz

@ MT = prismatic glide

<a> dislocations move on the prism planes

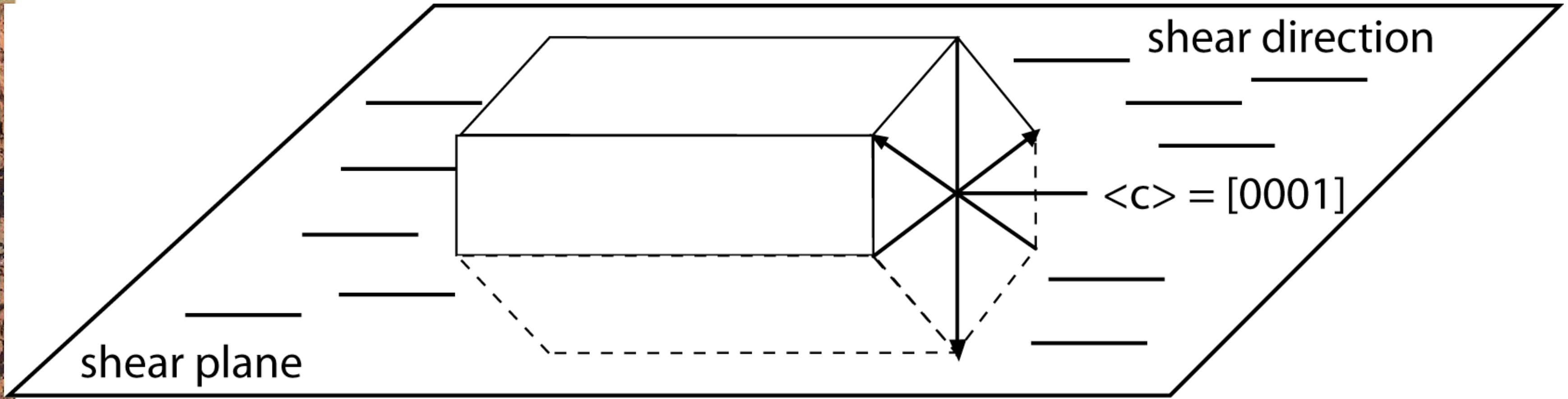


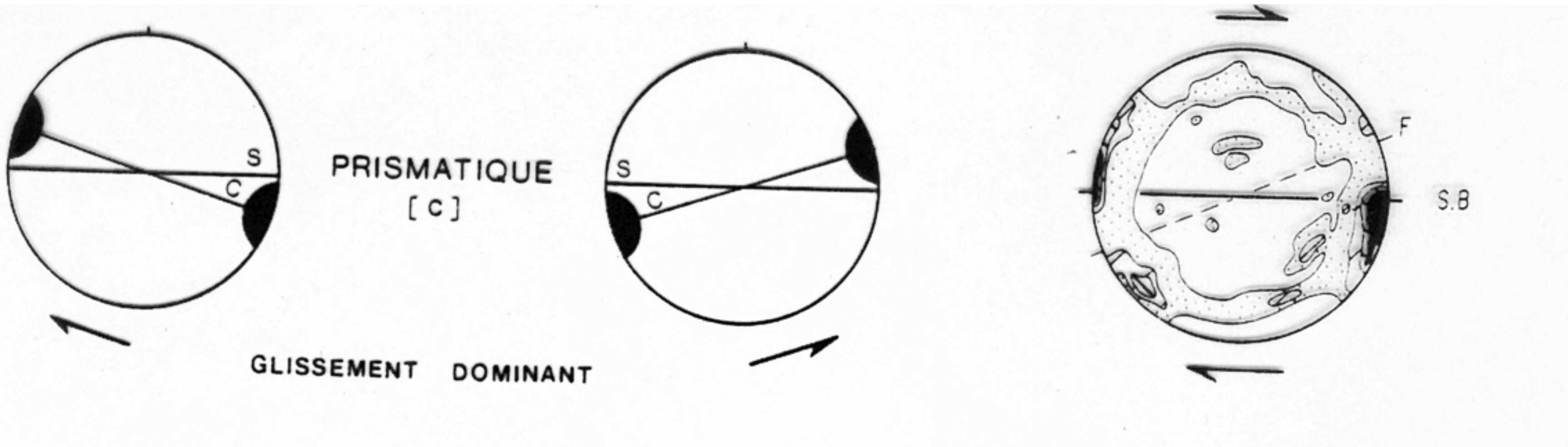


Quartz

@ HT = prismatic glide

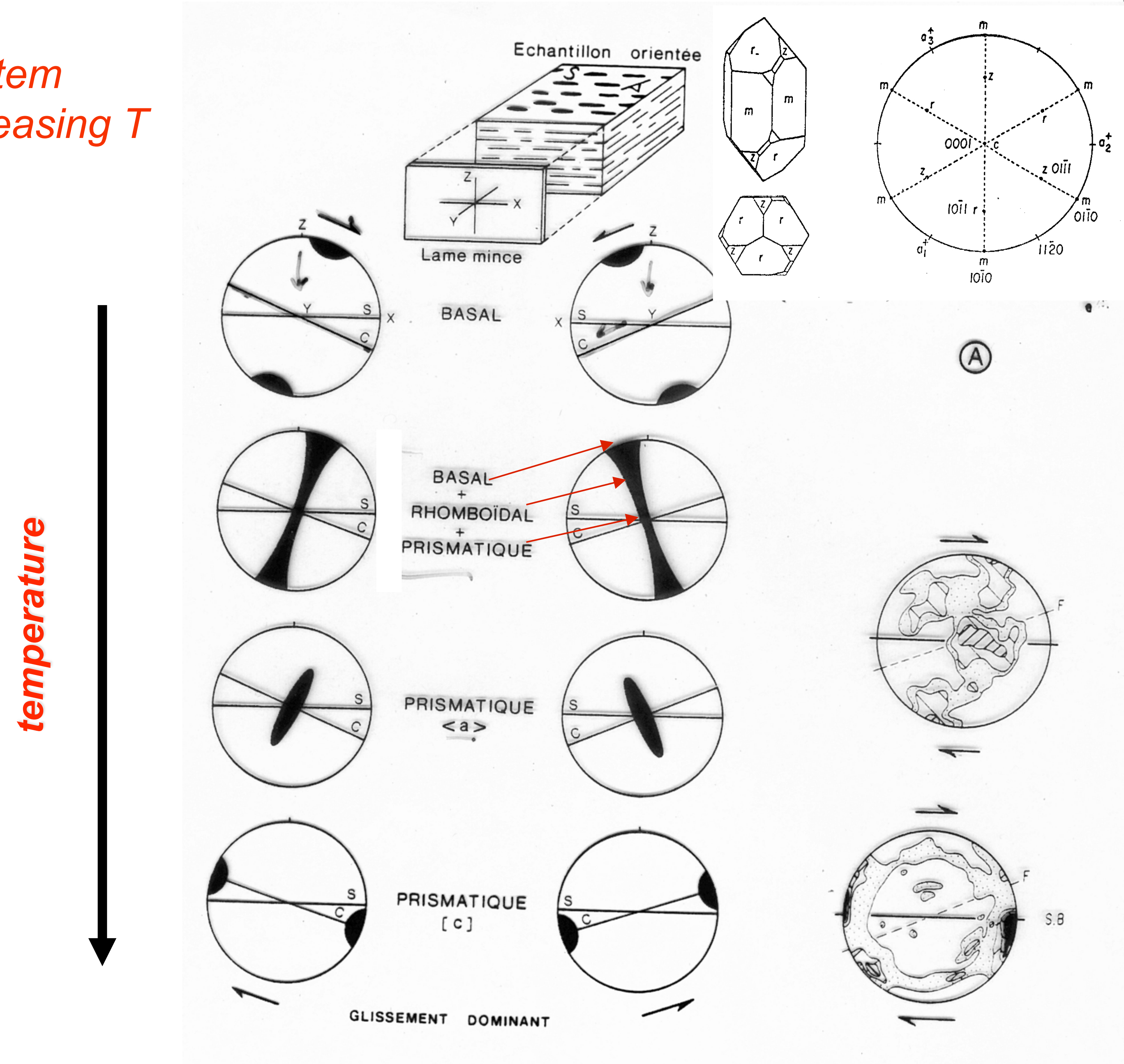
[0001] or <c> dislocations move on the prism planes





Quartz

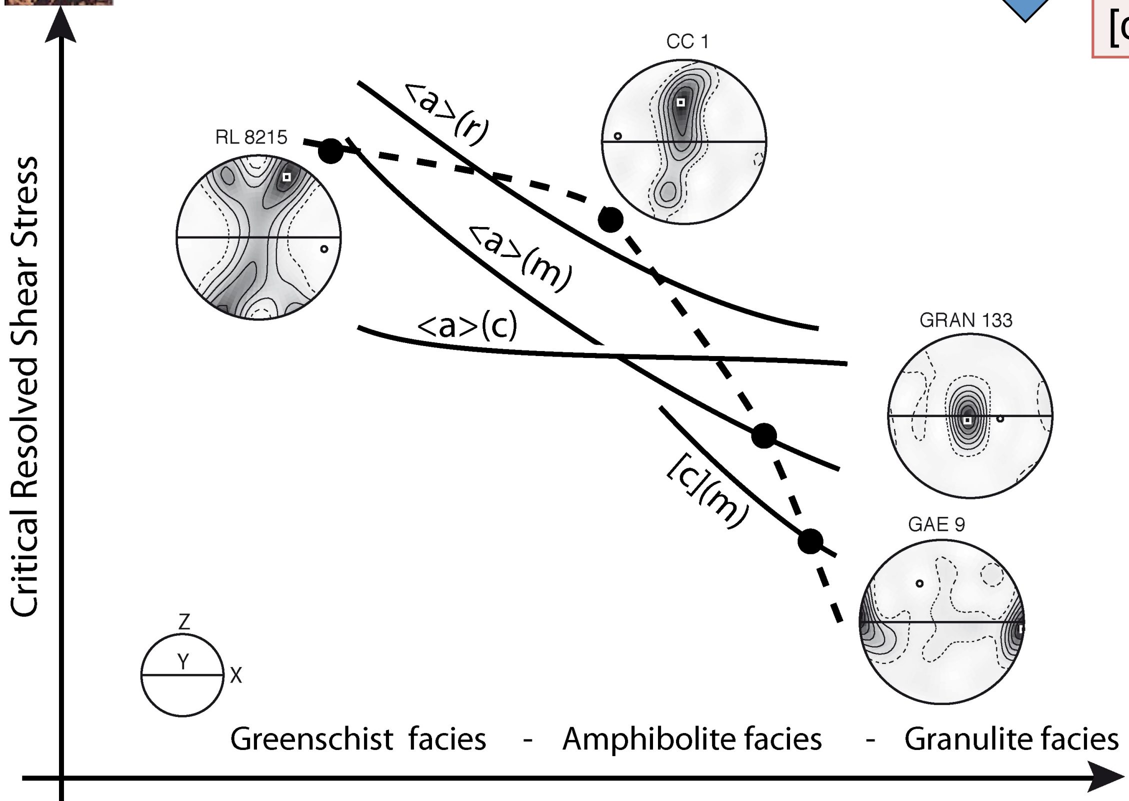
Dominant slip system changes with increasing T



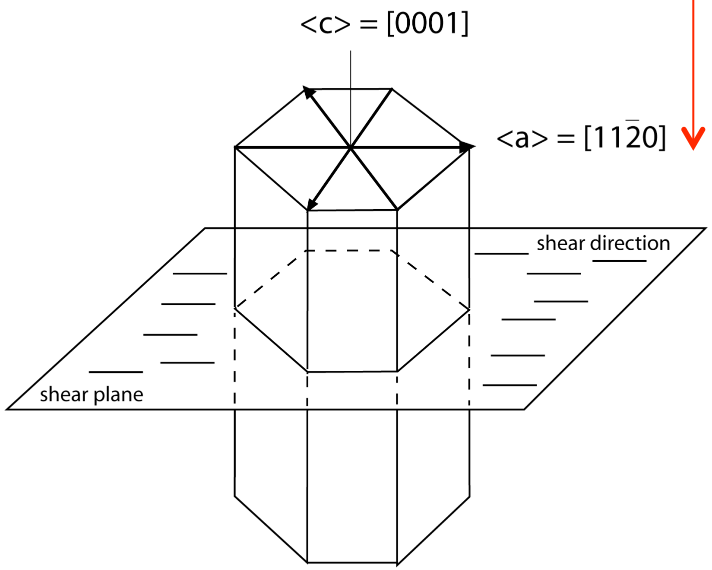
Quartz slip systems

Increasing T(°C)

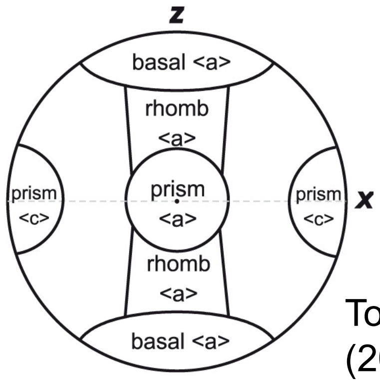
Family	Slip system
<a> (c)	[2-1-10](0001)
<a> {r}	[2-1-10](0-111)
<a> {z}	[-1-120](1-101)
<a>{π}	[2-1-10](0-112)
<a>{π'}	[-1-120](1-102)
<a>{m}	[2-1-10](0-110)
[c]{m}	[0001](0-110)
[c]{a}	[0001](2-1-10)



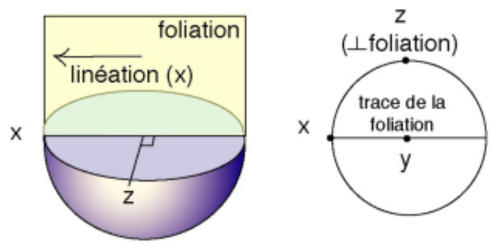
Gibert & Mainprice, 2008



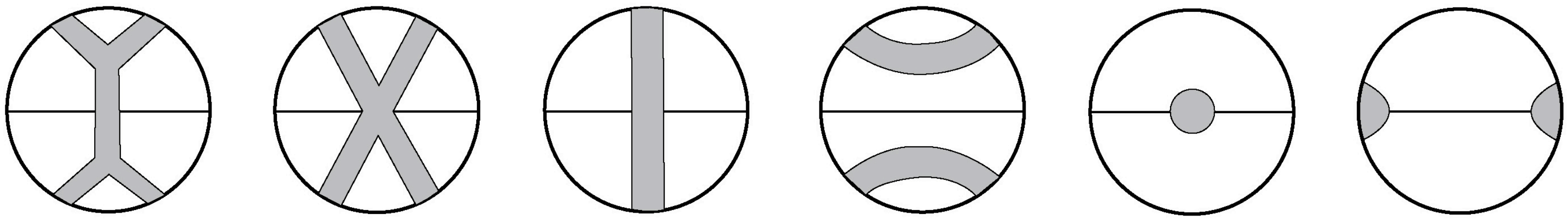
Quartz CPO
Common patterns



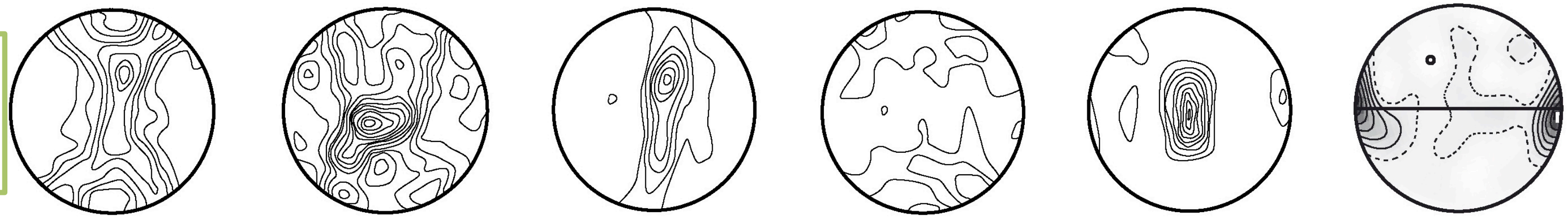
Toy et al. (2008)



	Type I crossed girdles	Type II crossed girdles	Single girdle	Small circle girdles (conical girdles)	Point maxima in Y	Point maxima in X
Quartz CPO fabric skeletons						



CPOs of Schmid & Casey (1986) and Gibert & Mainprice (2008)

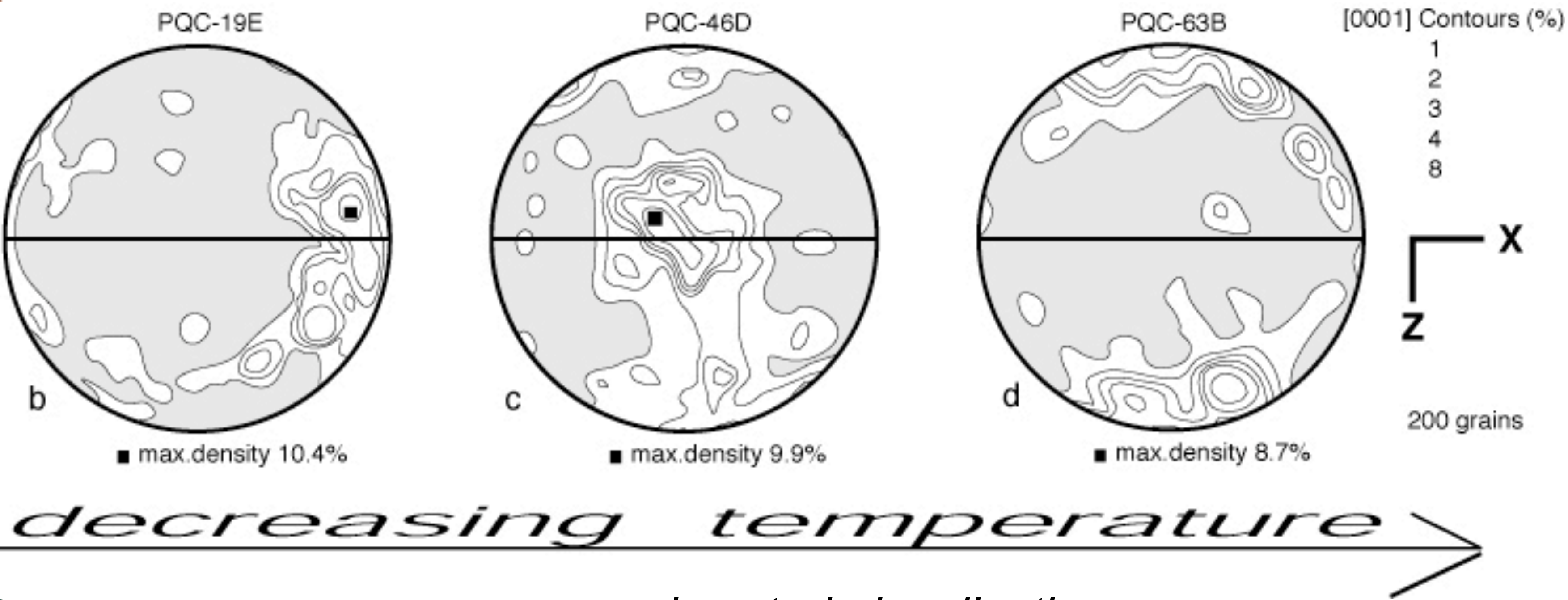


metamorphic facies conditions for CPO development	greenshist	greenshist	greenshist	amphibolite/granulite	amphibolite/granulite	granulite/subsolidus
rock-type	quartz tectonite	qtz-feldspar rocks	quartz vein	thin quartz ribbons in granulite	quartz ribbons	quartz-rich granulite
microestruturas	"core-and-mantle" microstructure	"core-and-mantle" microstructure with very flattened crystals	variation between elongated and recrystallized quartz	syntectonically recrystallized quartz with thin ribbons, only one grain broad	syntectonically recrystallized quartz with thin ribbons, only one grain broad	

Quartz

Dominant slip system changes with deformation T

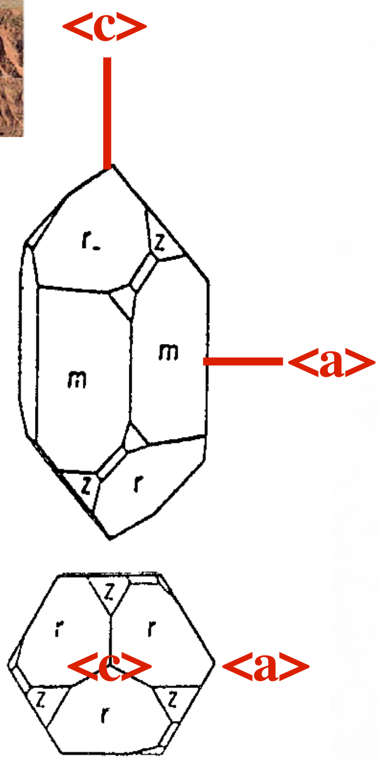
CPO measured in a synkinematic granite emplaced in the middle crust

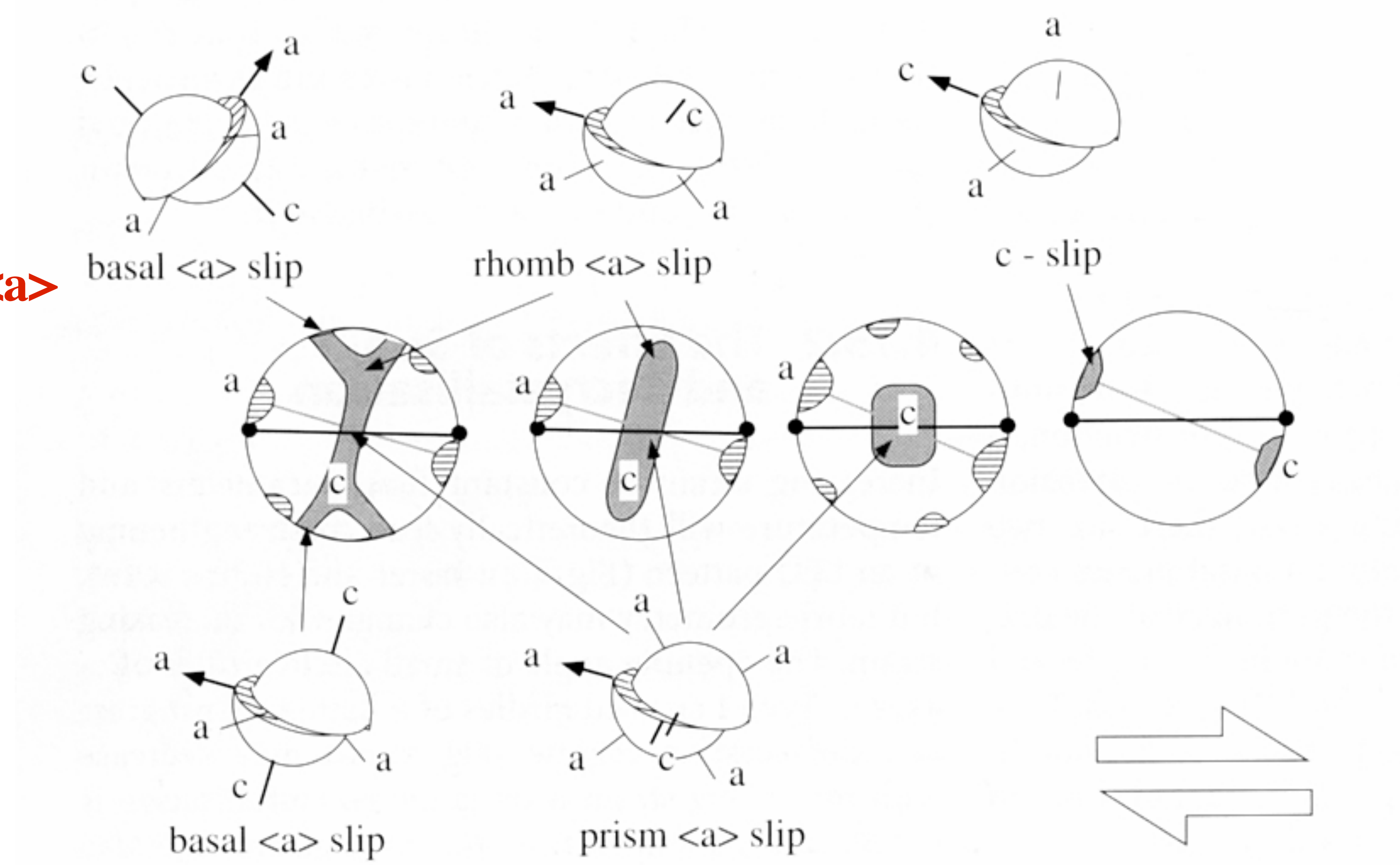


progressive strain localization

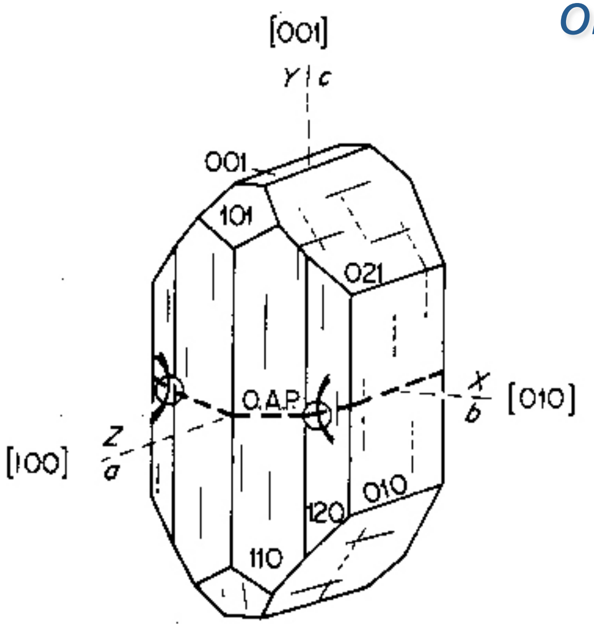
Quartz

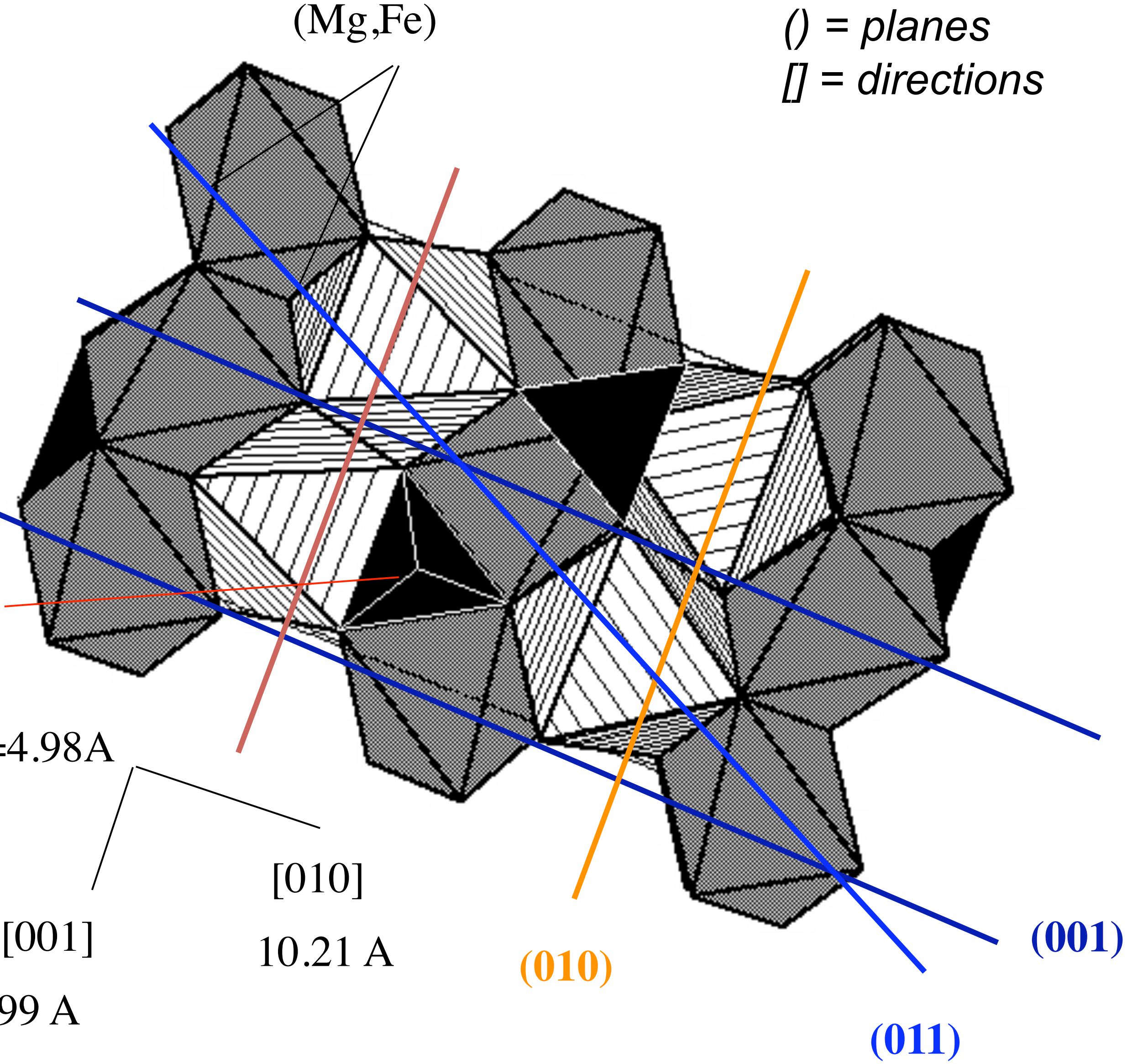
Correlation between the orientation of <c> & <c> axes





olivine crystal seen along the [100] direction

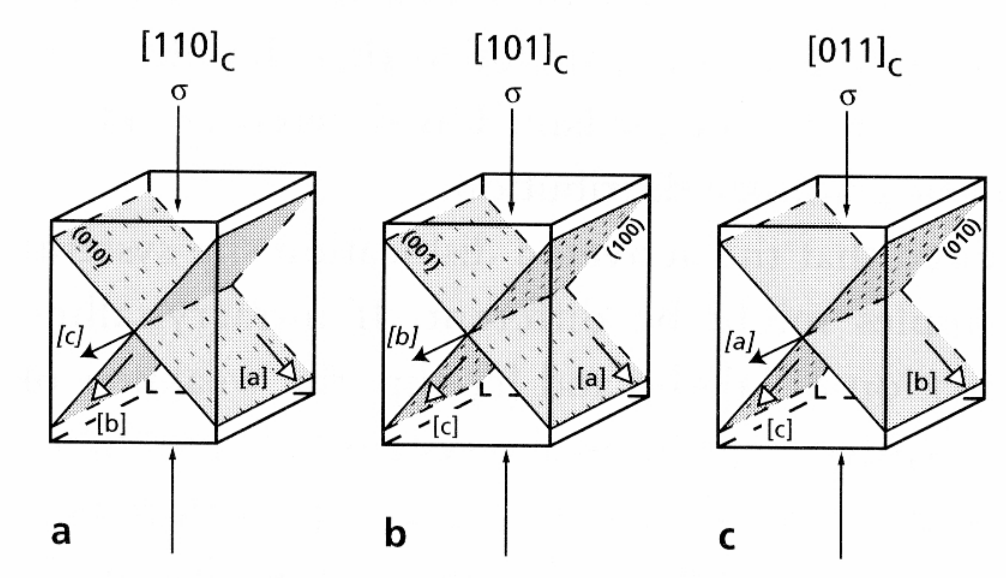


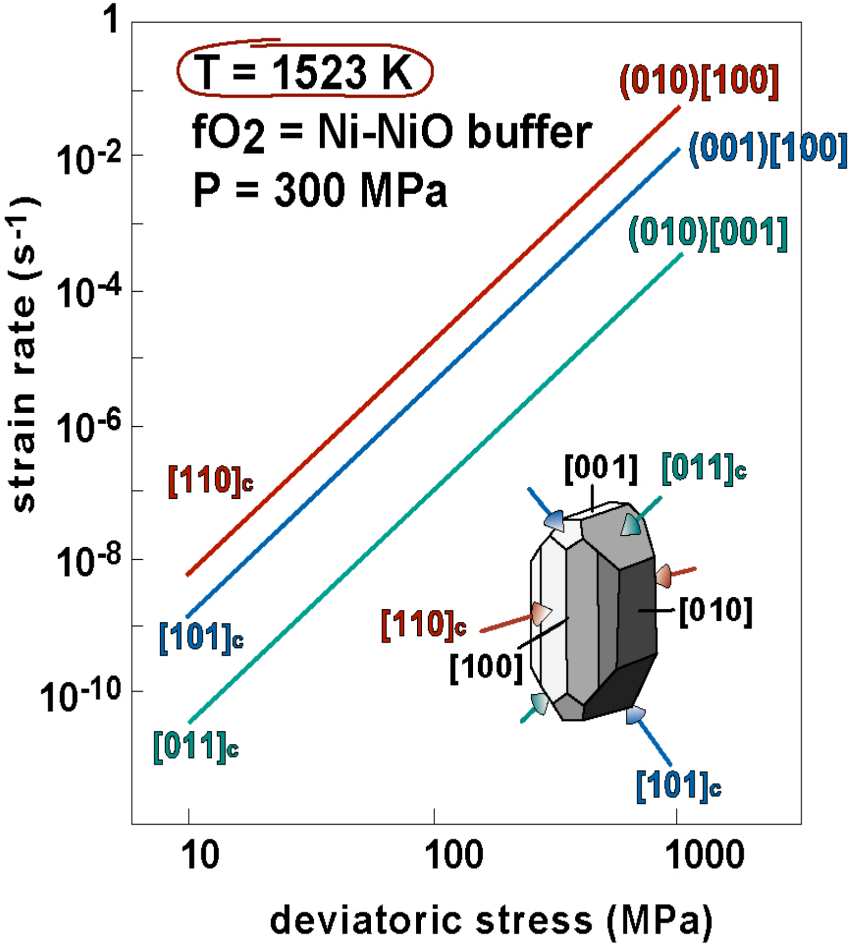


How can we determine the active slip systems and their relative strength?

Experimental deformation of single crystals in ≠ orientations:

olivine

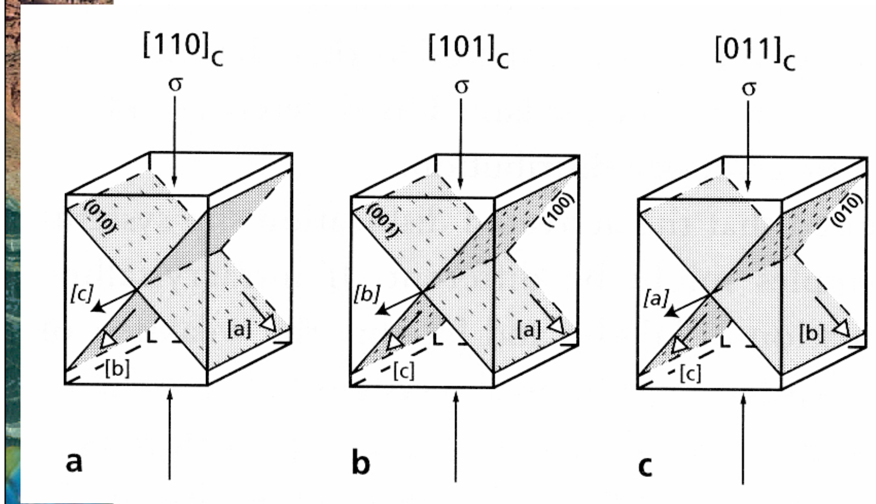




Bai et al. 1990 - JGR

Olivine CPO = f(active slip systems)= f(T, stress)

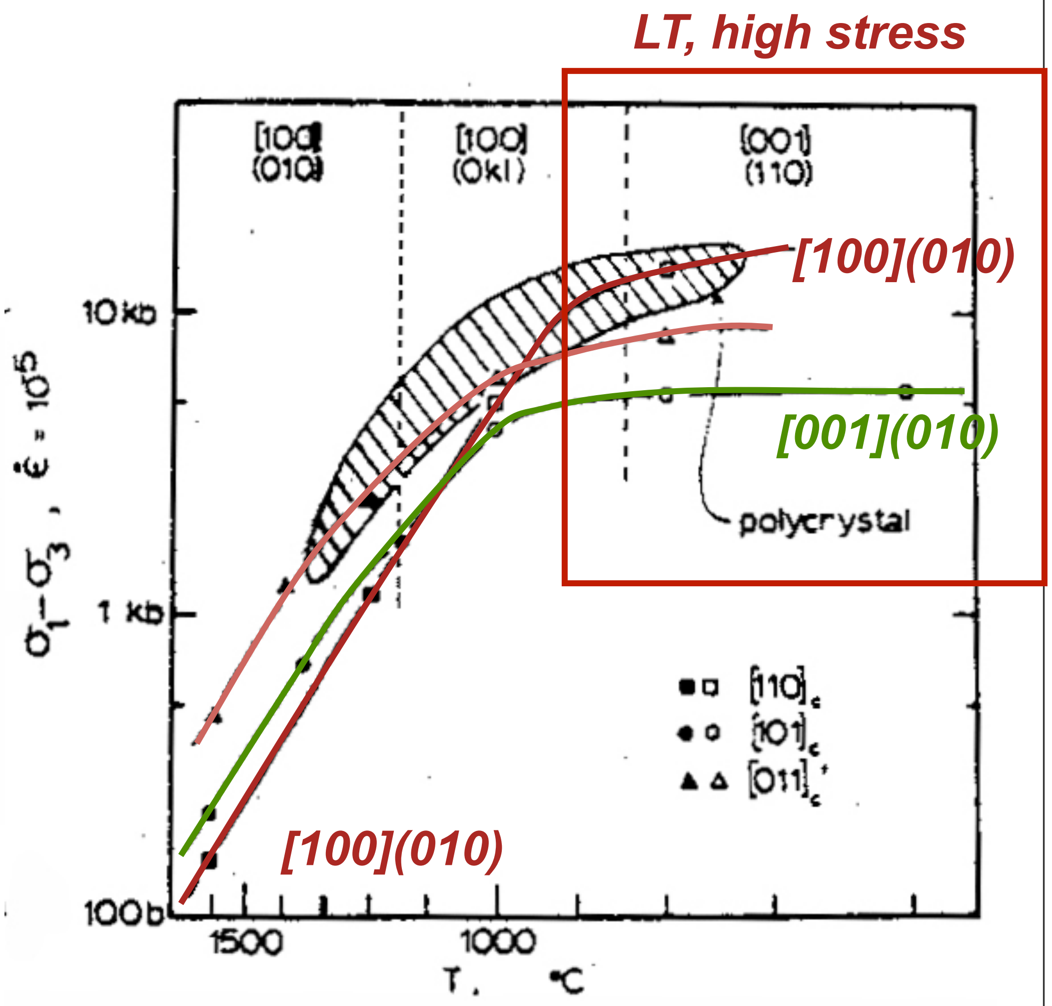
deformation experiments
olivine single crystal
in different orientations



[100](010)

[100](001)
[001](100)

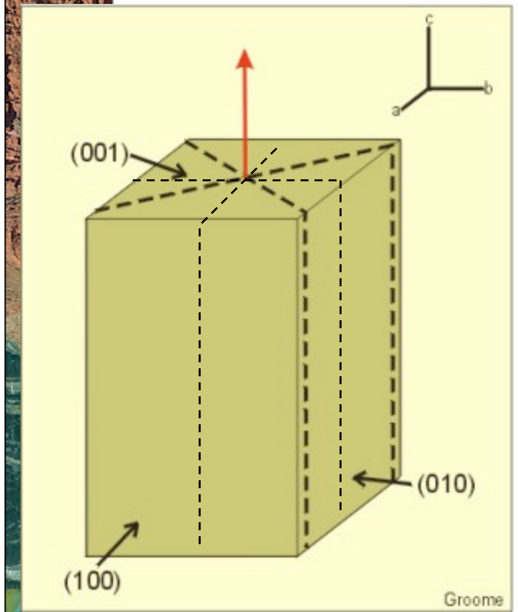
[001](010)



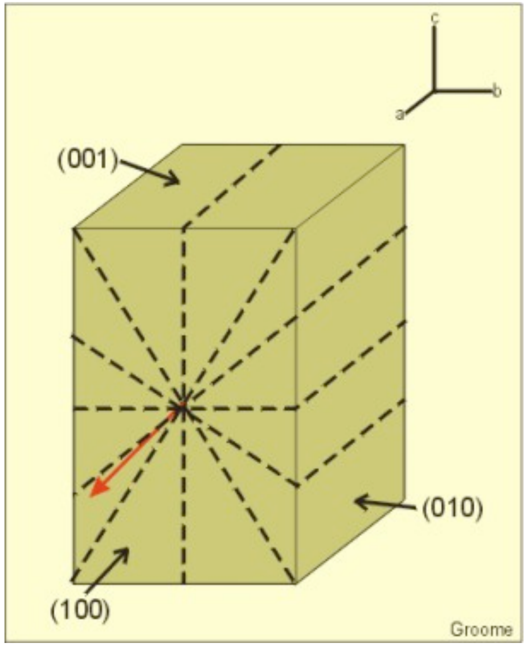
Durham & Goetze JGR 1977

Dominant slip system changes with deformation temperature

Olivine - LT

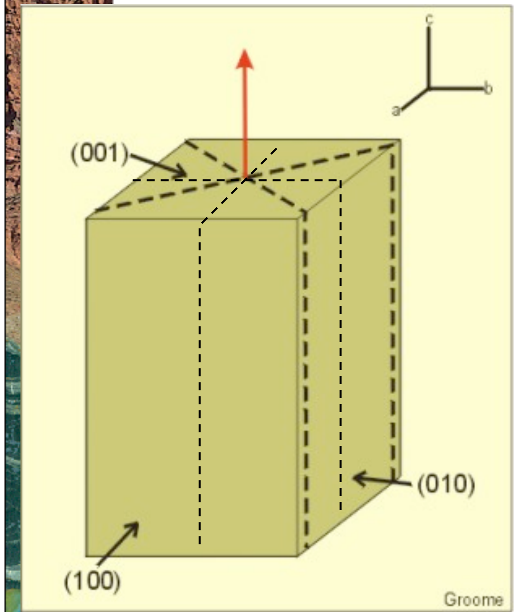


BT (<1000°C)	HT
(010)[100]	**(010)[100]**
(001)[100]	**(001)[100]**
{011}[100]	**{011}[100]**
{031}[100]	**{031}[100]**
(010)[001]	(010)[001]
(100)[001]	(100)[001]
{110}[001]	{110}[001]

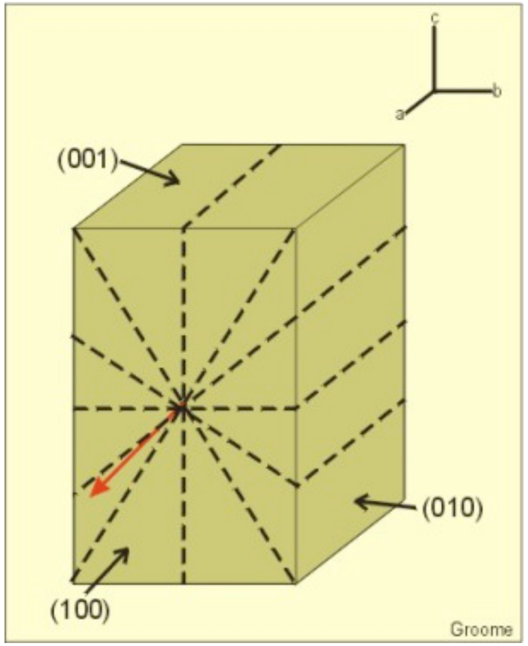


Dominant slip system changes with deformation temperature

Olivine - HT

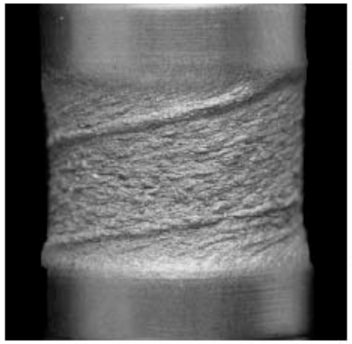


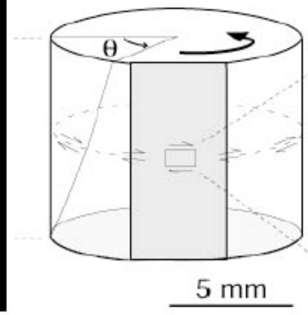
BT (<1000°C)	HT
(010)[100]	**(010)[100]**
(001)[100]	**(001)[100]**
{011}[100]	**{011}[100]**
{031}[100]	**{031}[100]**
(010)[001]	(010)[001]
(100)[001]	(100)[001]
{110}[001]	{110}[001]

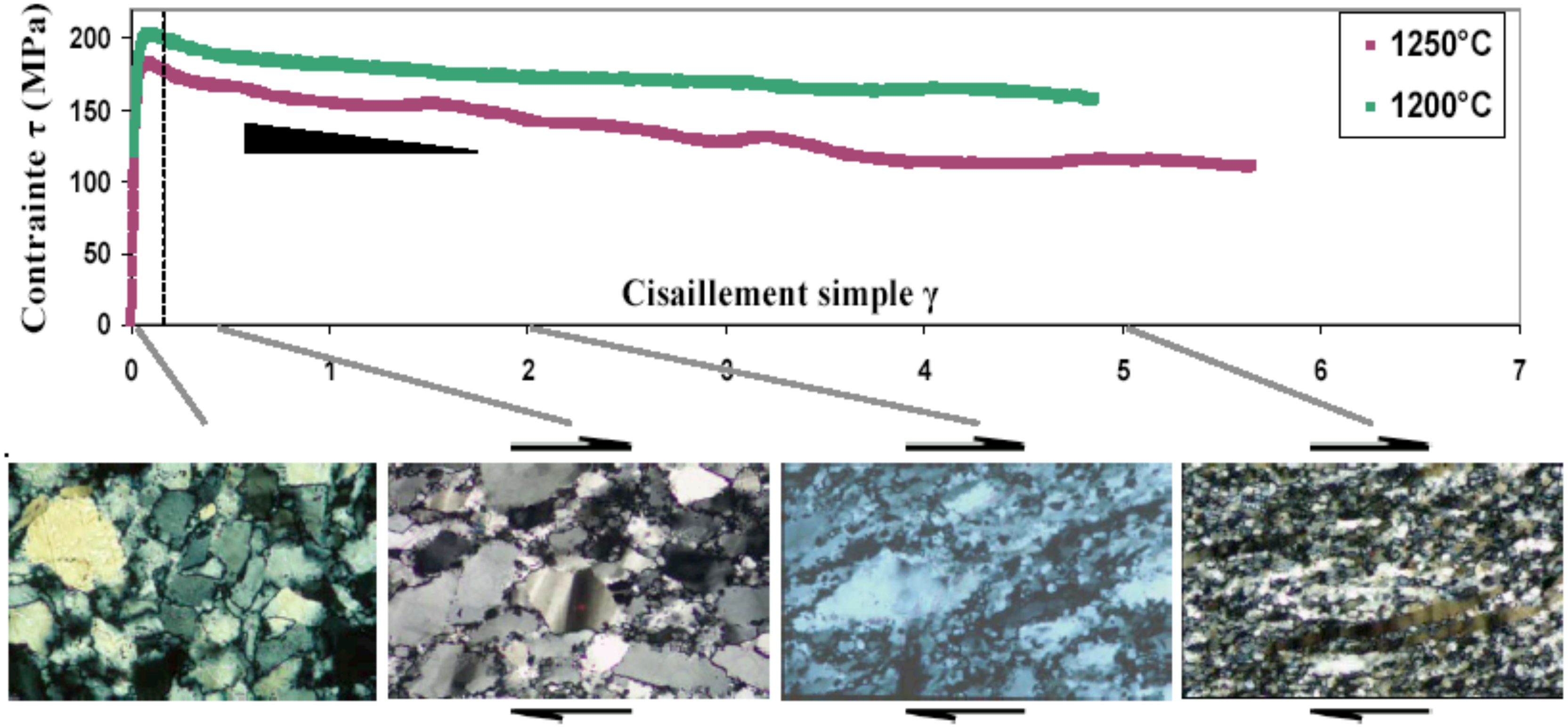


Torsion experiments:

- ***high shear strains***
- ***CPO evolution = F(strain)***



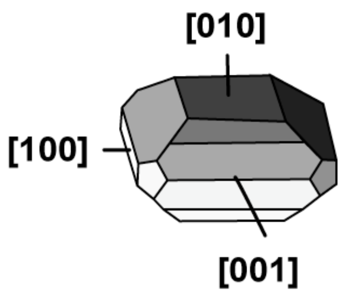




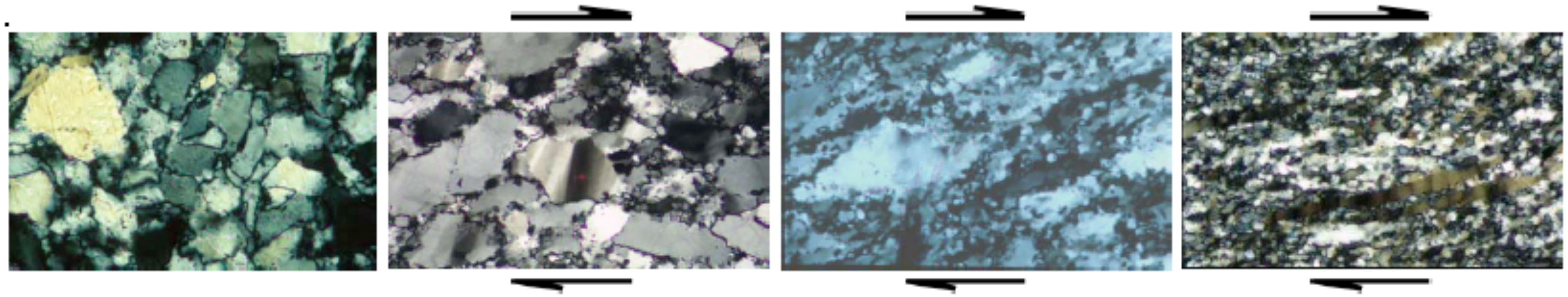
$\gamma = 0$ $\gamma = 0.5$ $\gamma = 2$ $\gamma = 5$

Bystricky et al. Science 2000

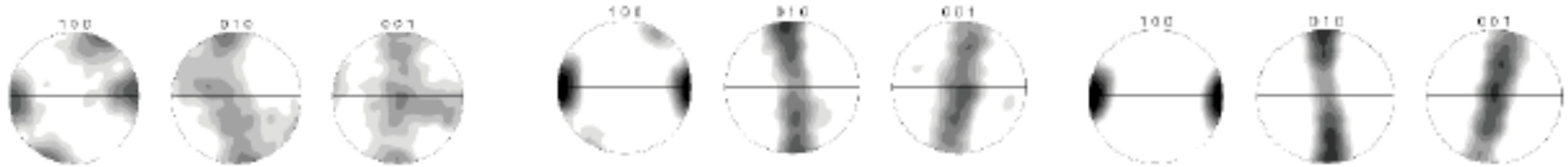
Torsion experiments - high shear strains
CPO evolution as a function of strain



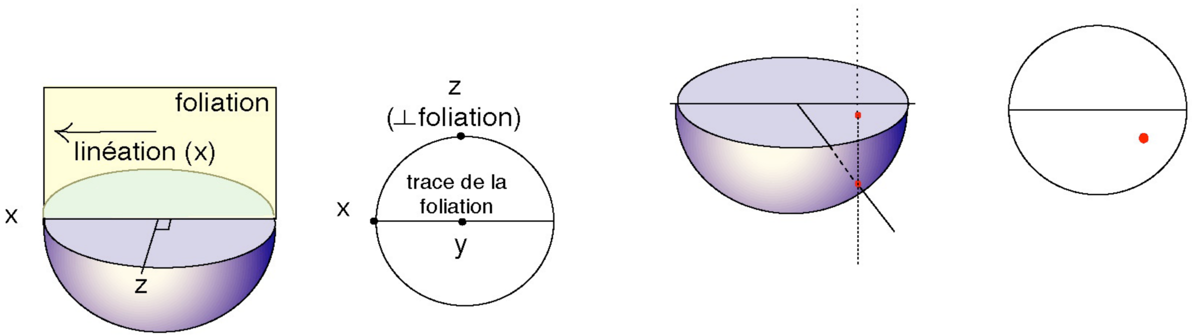
***[100] // shear direction** & [010] normal to shear plane*



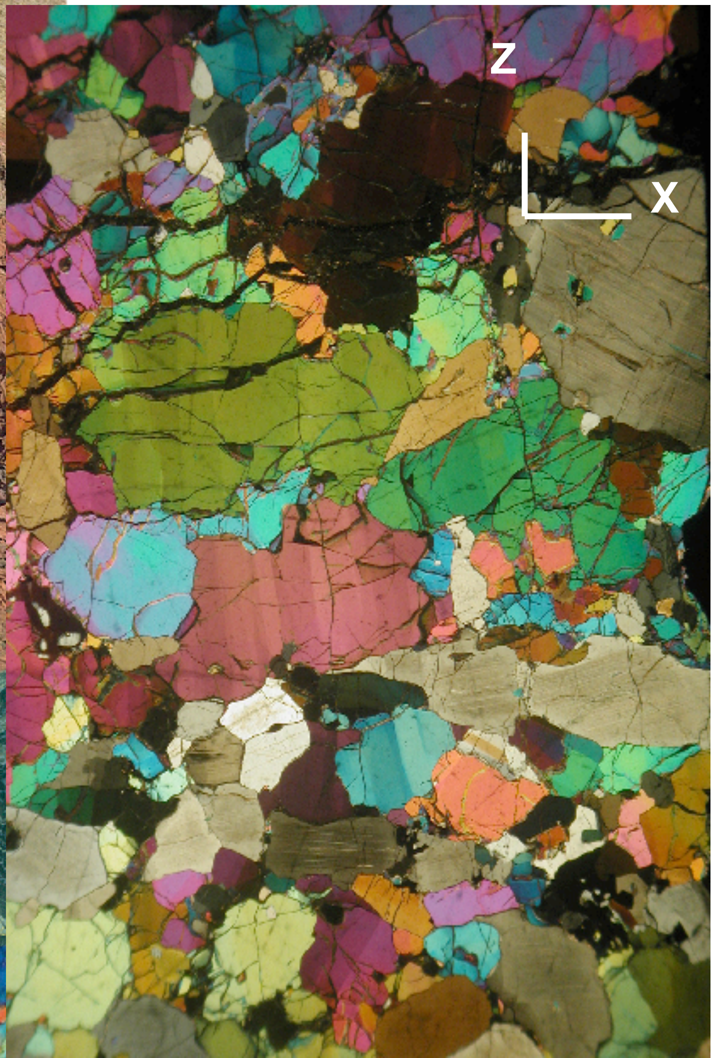
γ = 0 γ = 0.5 γ = 2 γ =5

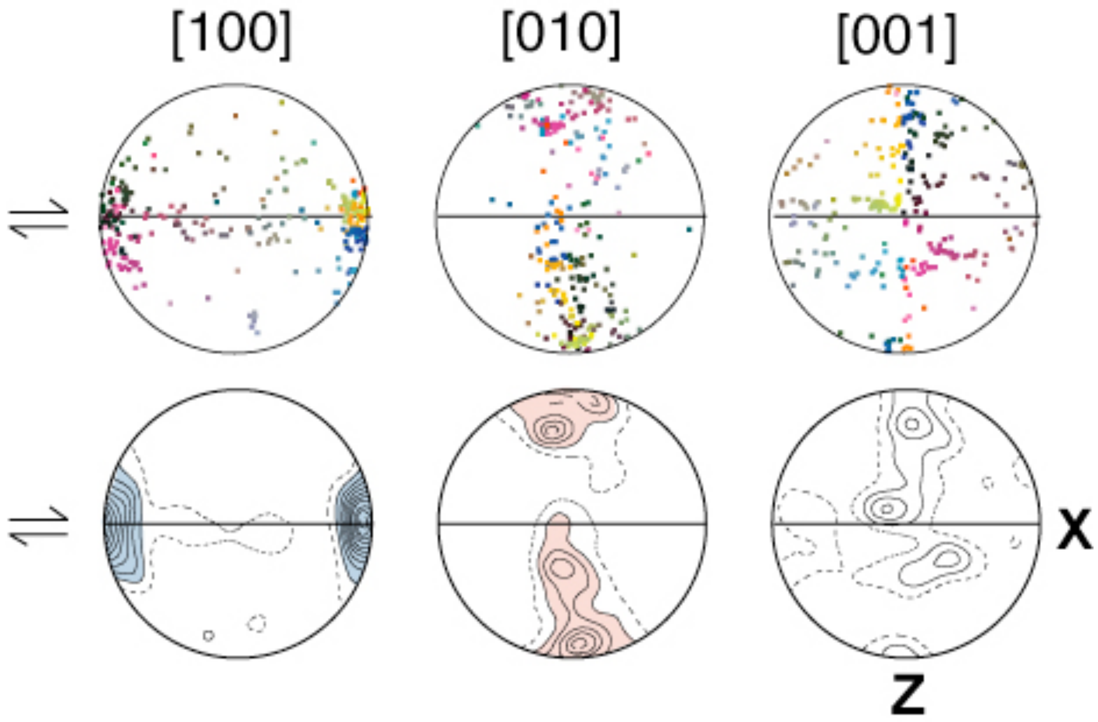


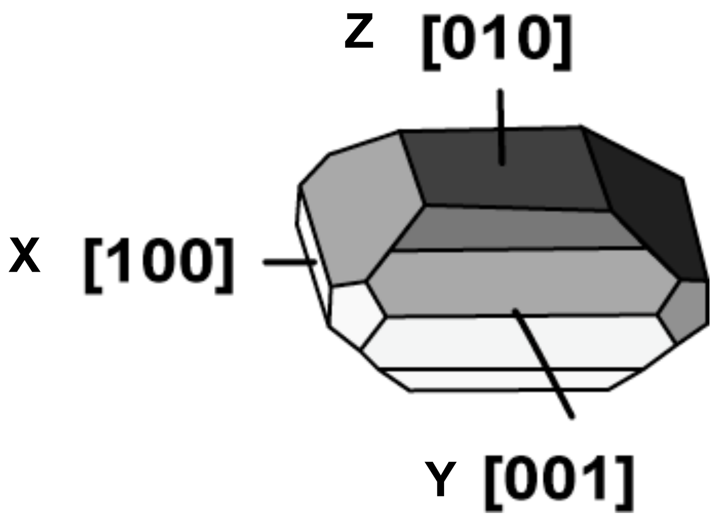
γ = 1 - 2 γ = 3 - 4 γ = 6 - 7



Bystricky et al. Science 2000

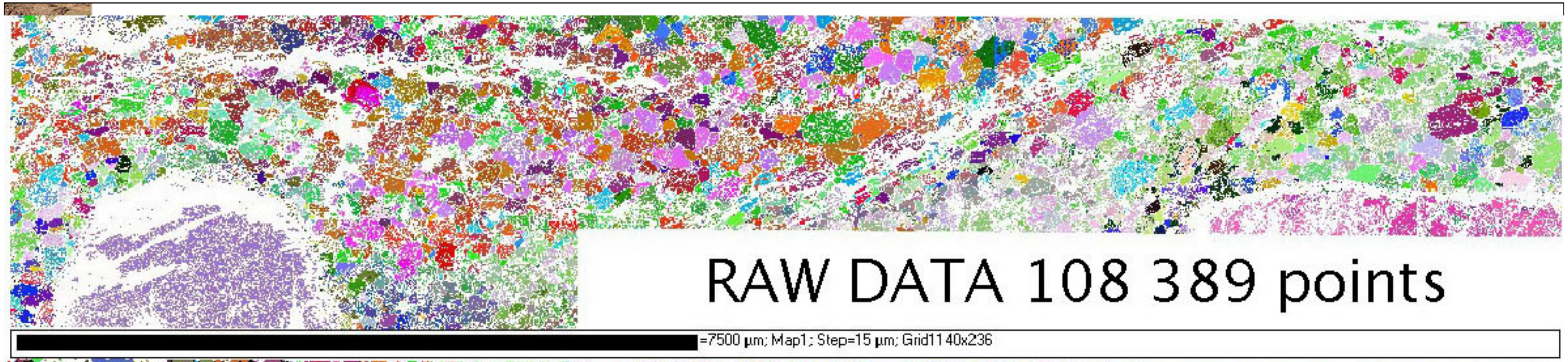


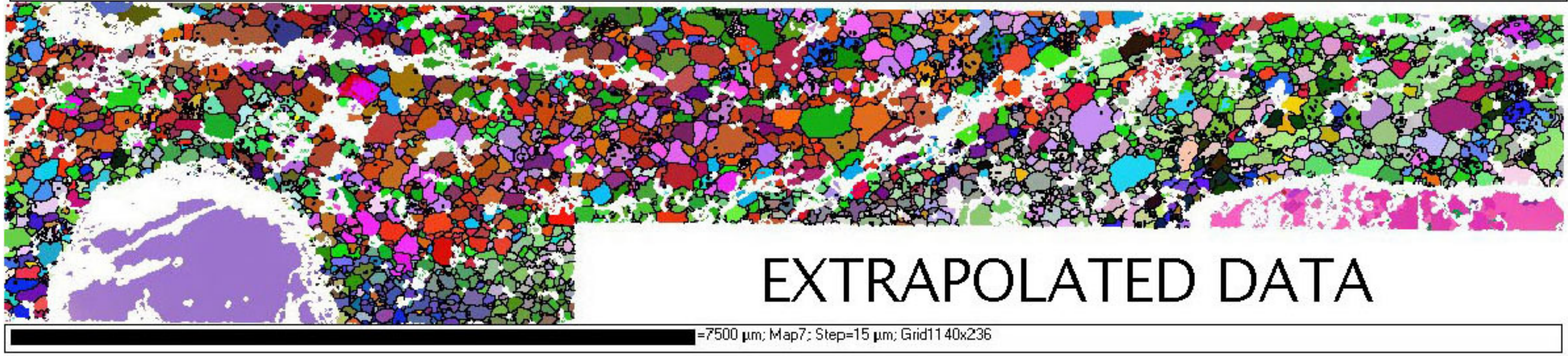




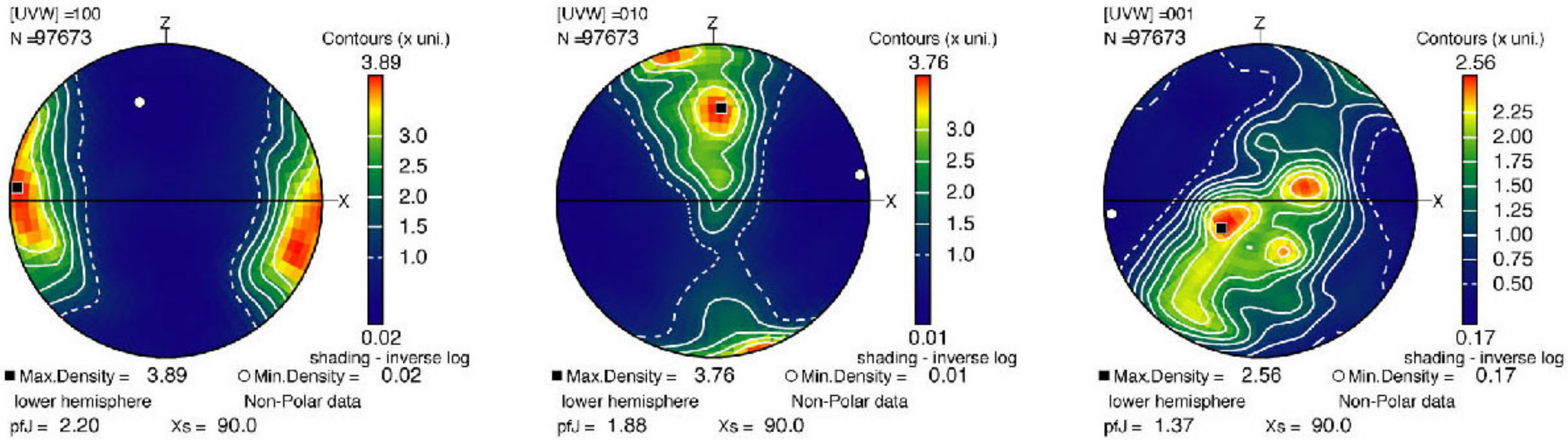
lherzolite, Tahiti

T & σ conditions?



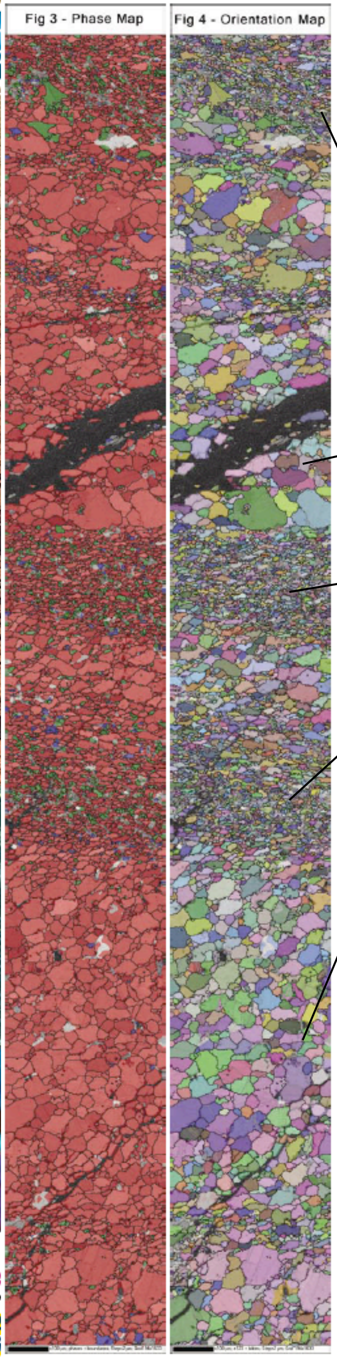


[100],[010] & [001] Olivine pole figures



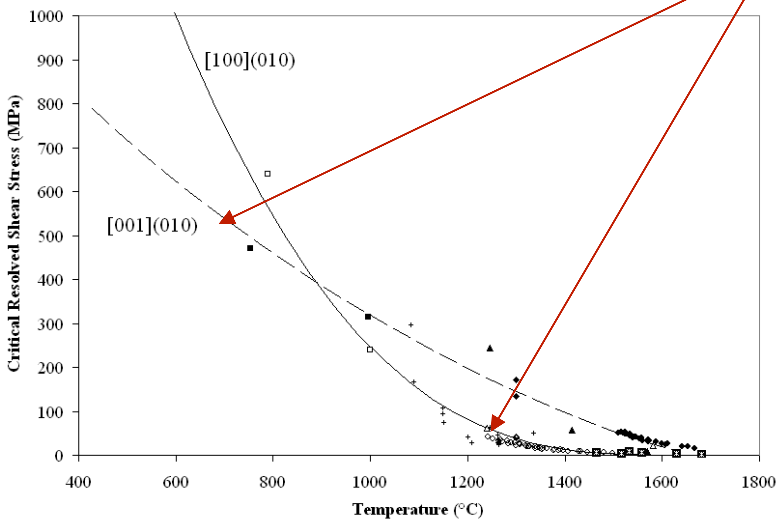
Olivine CPO in a low temperature, high-stress mylonite

Oman

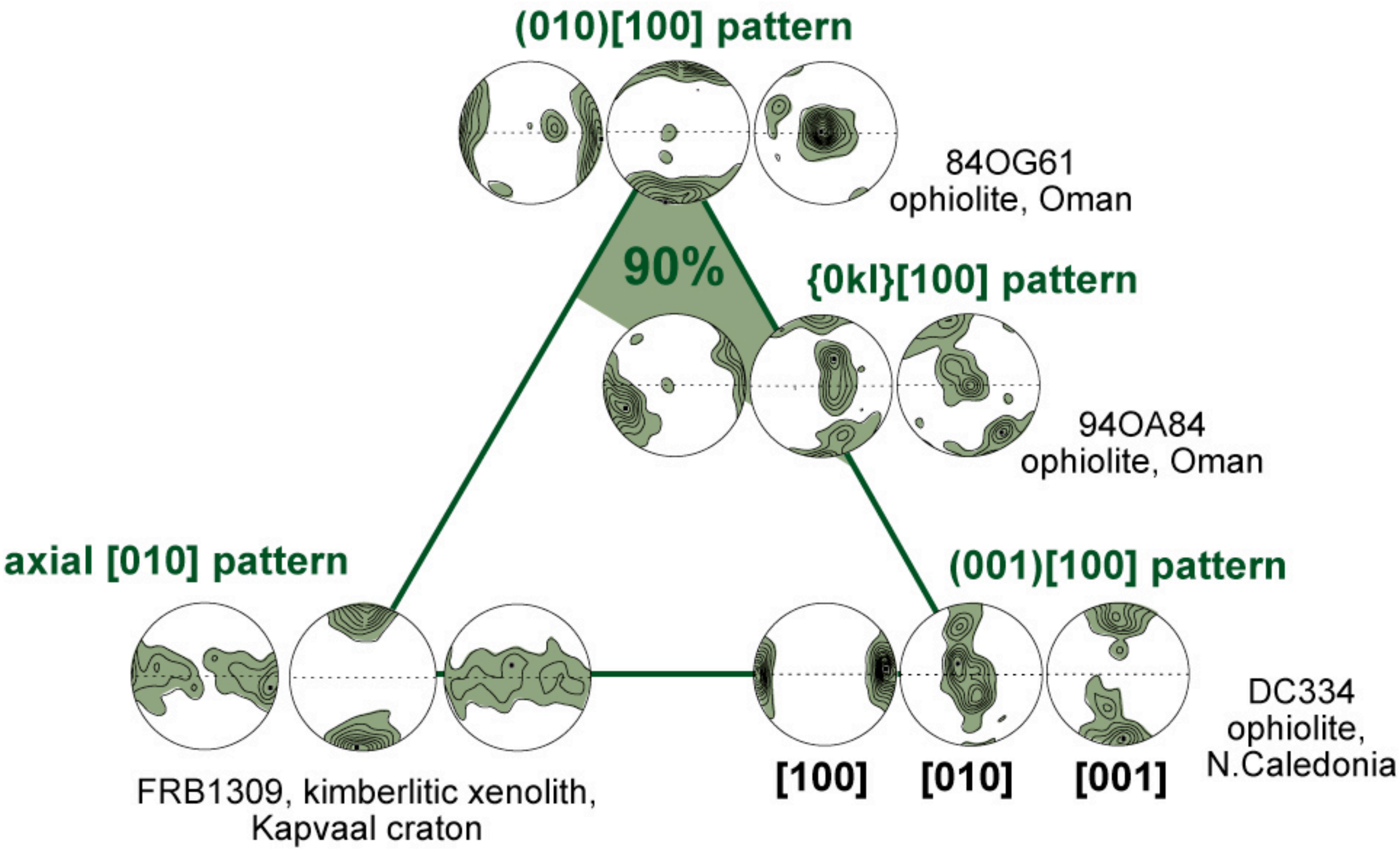


P.Trimby, HKL Technology

[100](010)



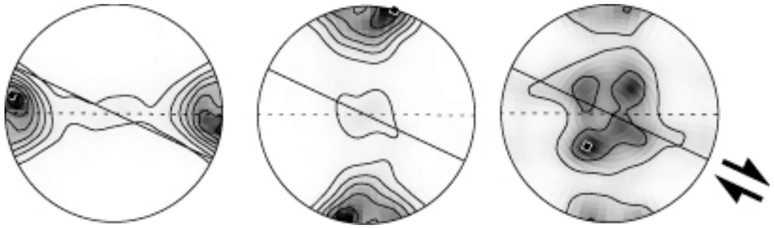
olivine database: >200 samples — 3 textural end-members



✓**dominant [100] slip**

Olivine CPO:

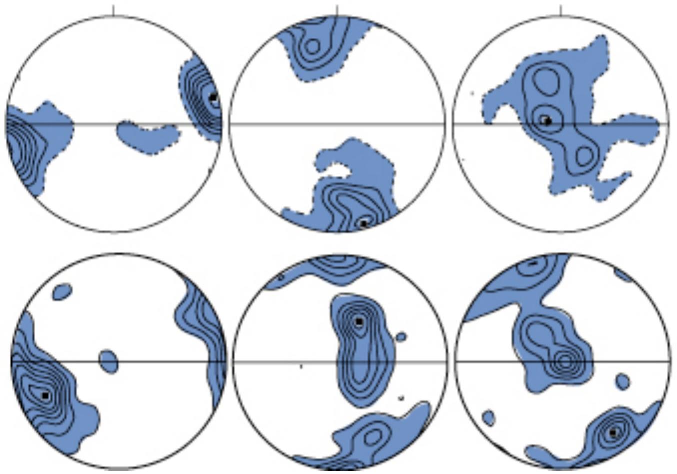
Polycrystal plasticity models:



Naturally deformed peridotites:

olivine CPO database (Montpellier): >300 samples

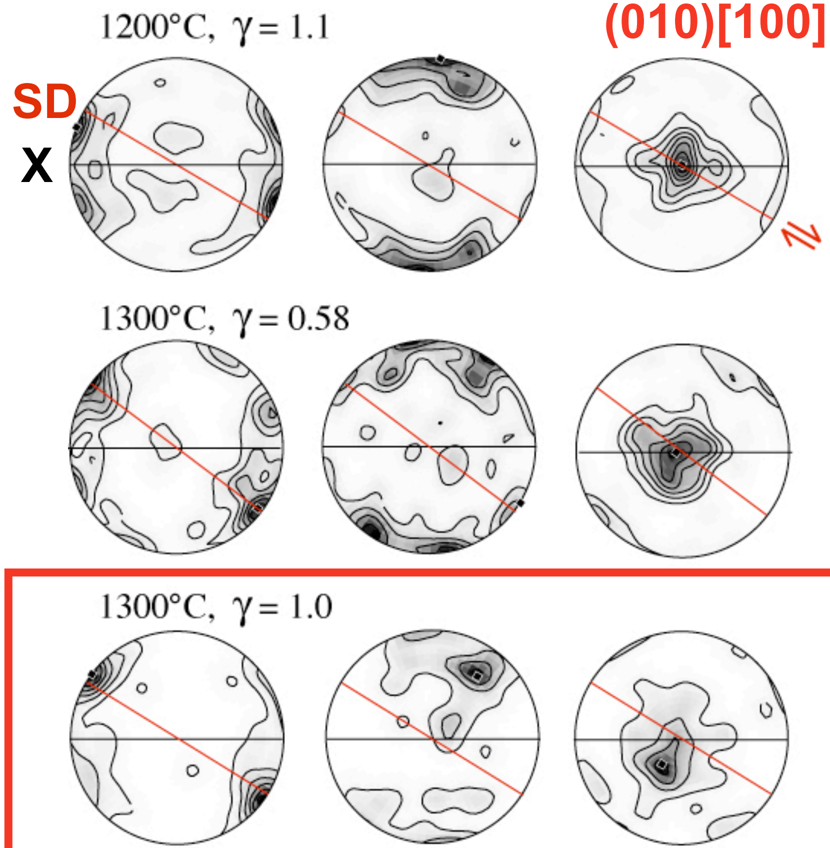
~ 80% of the samples



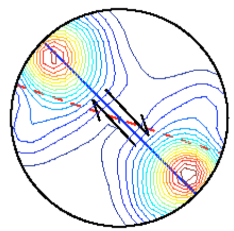
CPO/SPO asymmetry: simple shear

Experimental deformation: simple shear

Zhang & Karato (1995) Nature



dynamic recrystallization: faster reorientation of [100] // SD

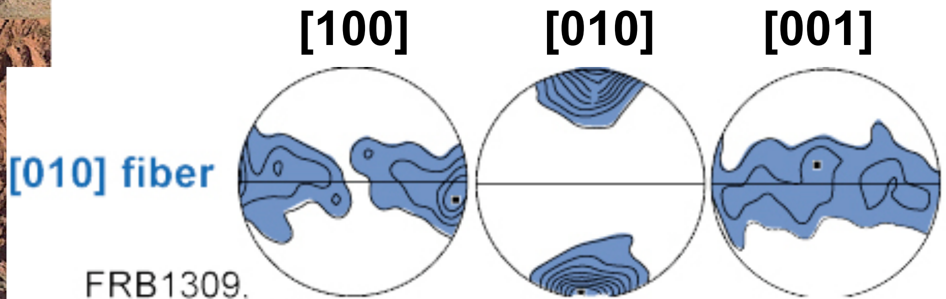


Kaminski & Ribe 2001 EPSL

Naturally deformed peridotites

olivine LPO database (Montpellier): >300 samples

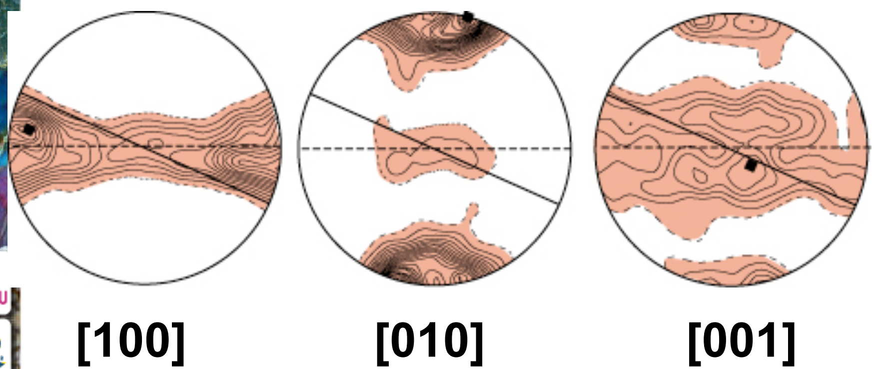
20-30% of the samples (continental)



FRB1309,
kimberlitic xenolith,
Kapvaal craton

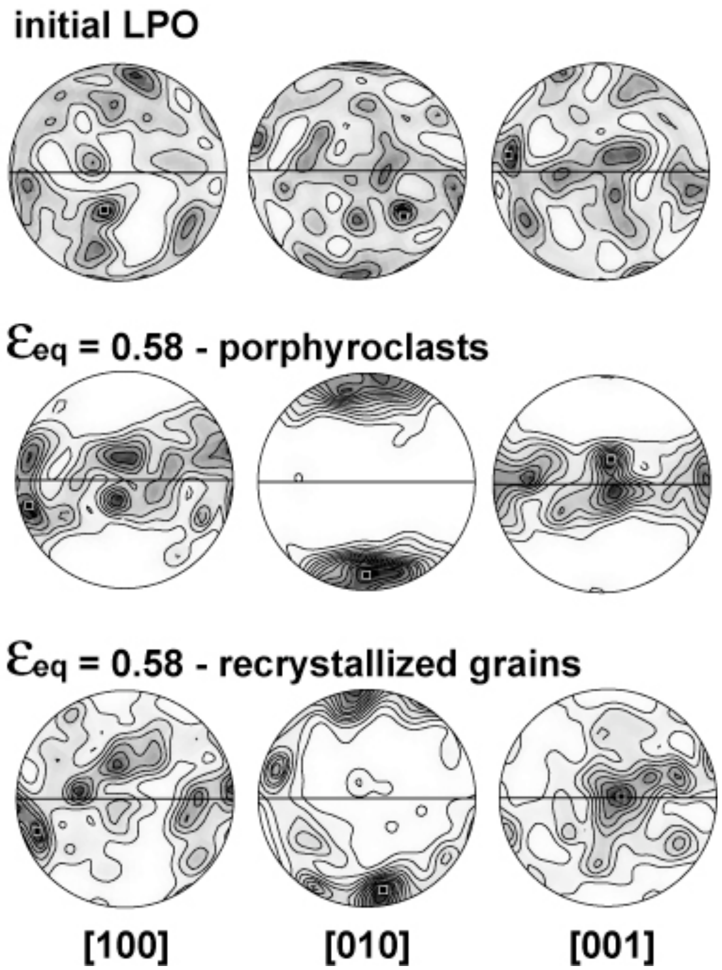
axial compression or transpression

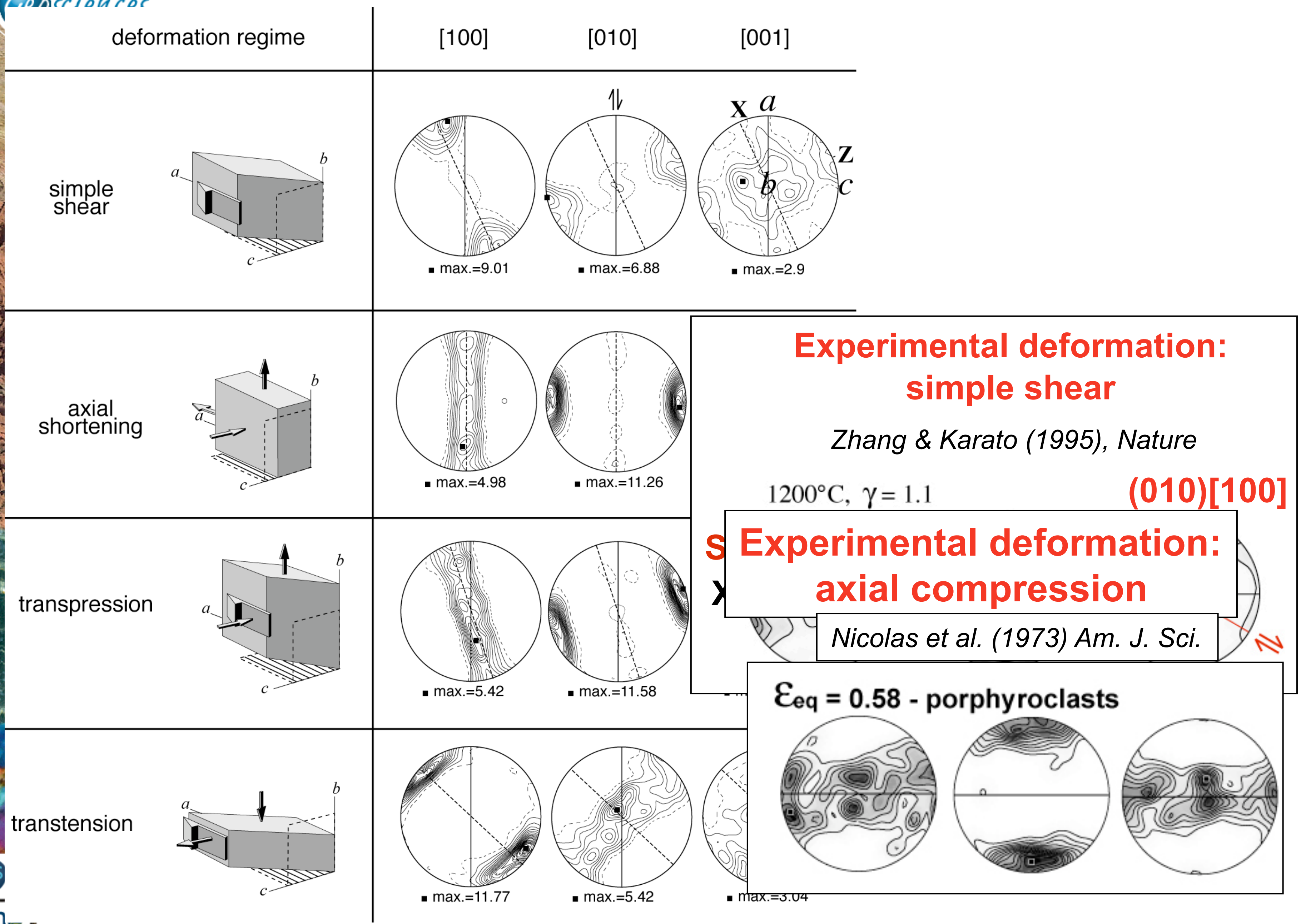
Polycrystal plasticity models: transpression



Experimental deformation: axial compression

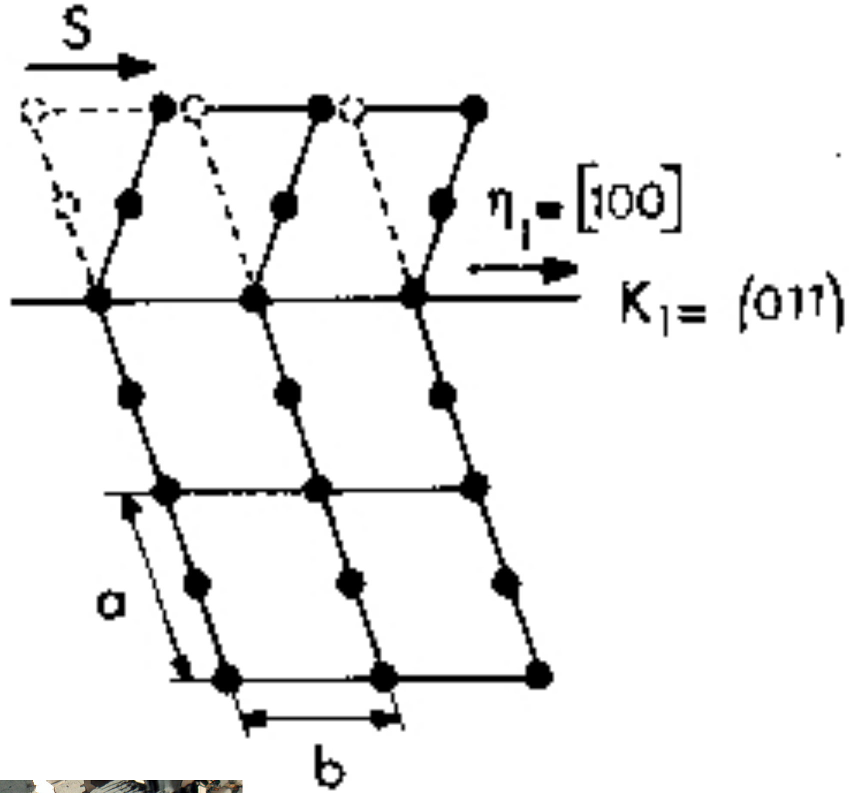
Nicolas et al. (1973) Am. J. Sci.




deformation regime
[100]
[010]
[001]
simple shear
a
b
c
max.=9.01
max.=6.88
X a
Z
b
c
max.=2.9
axial shortening
max.=4.98
max.=11.26
transpression
max.=5.42
max.=11.58
transtension
max.=11.77
max.=5.42
max.=3.04
Experimental deformation: simple shear
Zhang & Karato (1995), Nature
1200°C, γ = 1.1
(010)[100]
Experimental deformation: axial compression
Nicolas et al. (1973) Am. J. Sci.
εeq = 0.58 - porphyroclasts

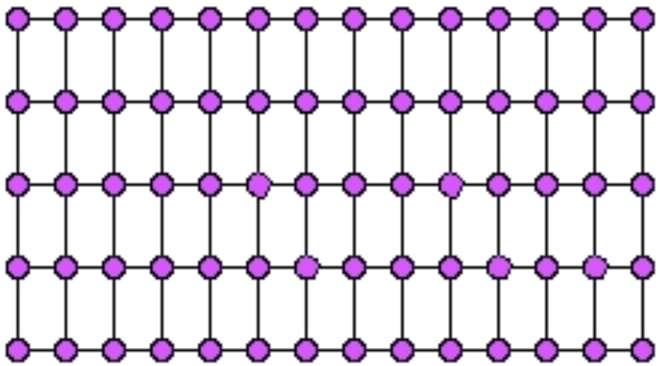
Processes other than dislocation creep may also form or modify a CPO?

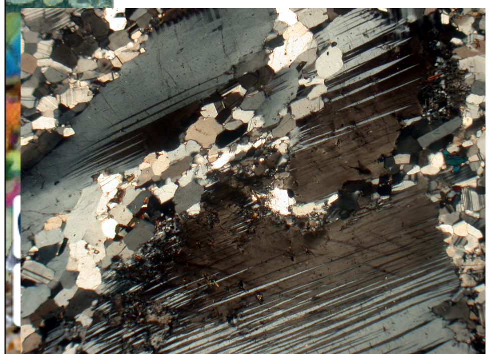
Mechanical twinning



Twinning = shear along a pre-defined crystallographic plane

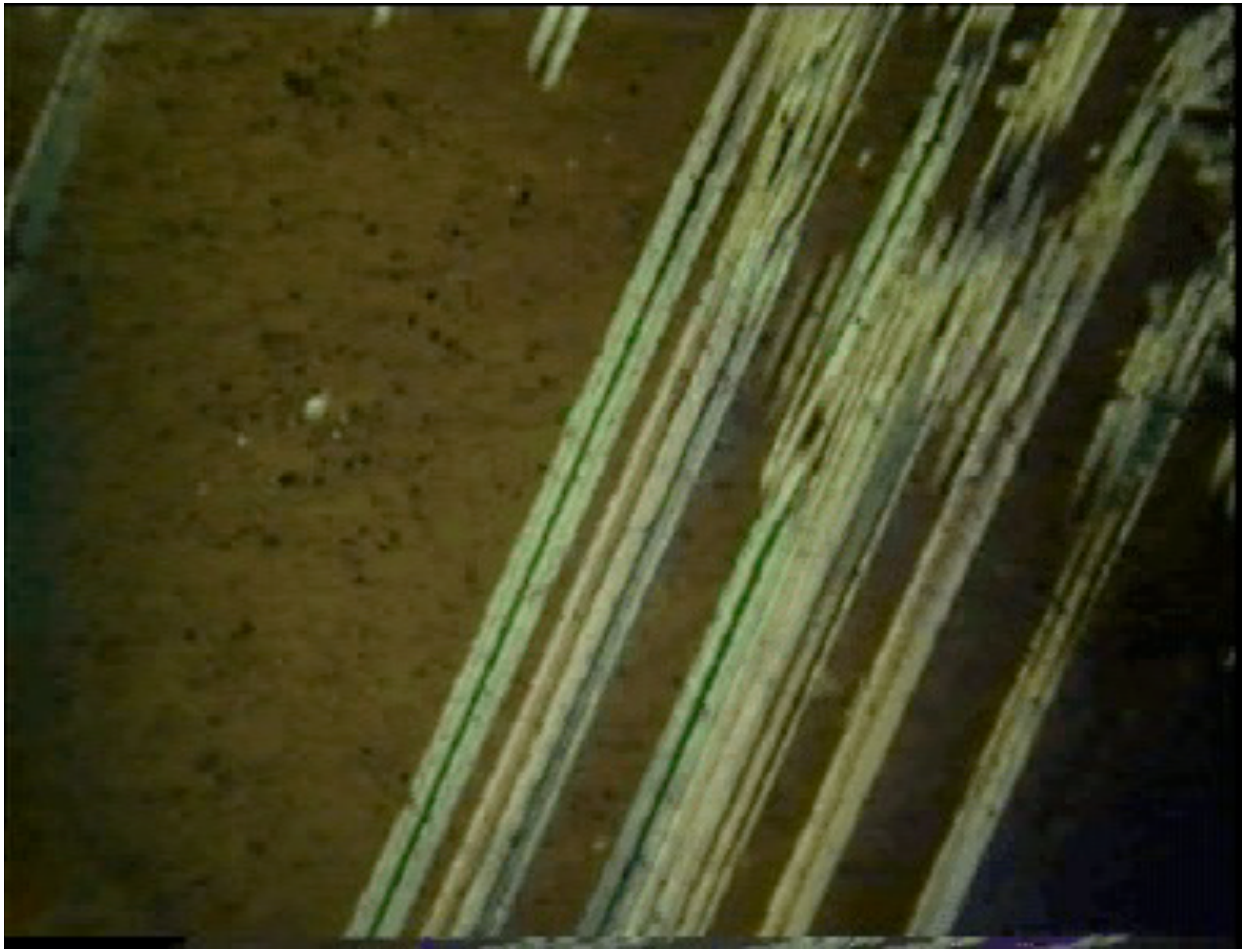
- ✓ *may be activated @ LT*
- ✓ *limited strain*



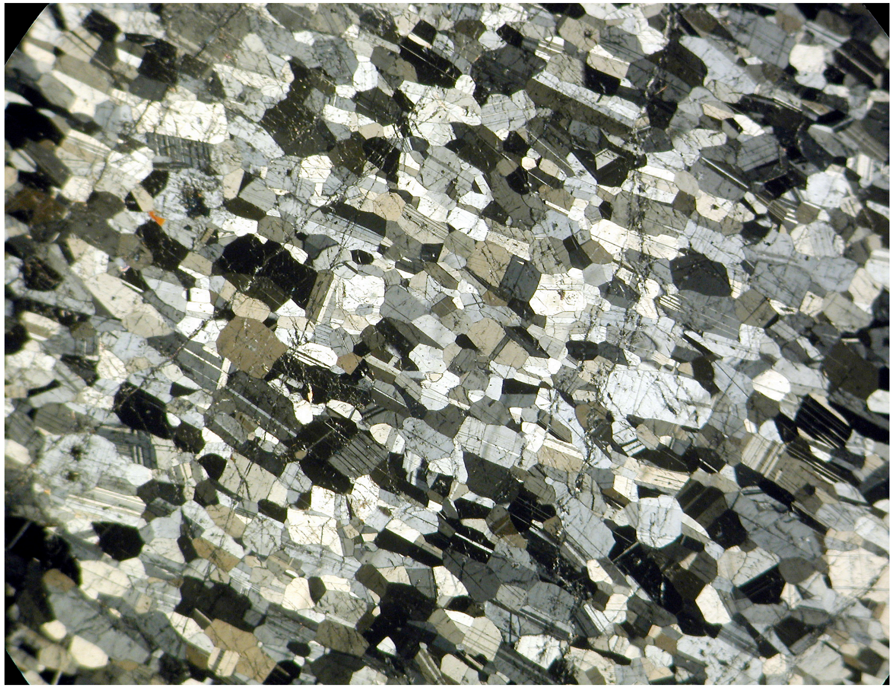


- *Feldspars*
- *Calcite*
- *Diopside…*

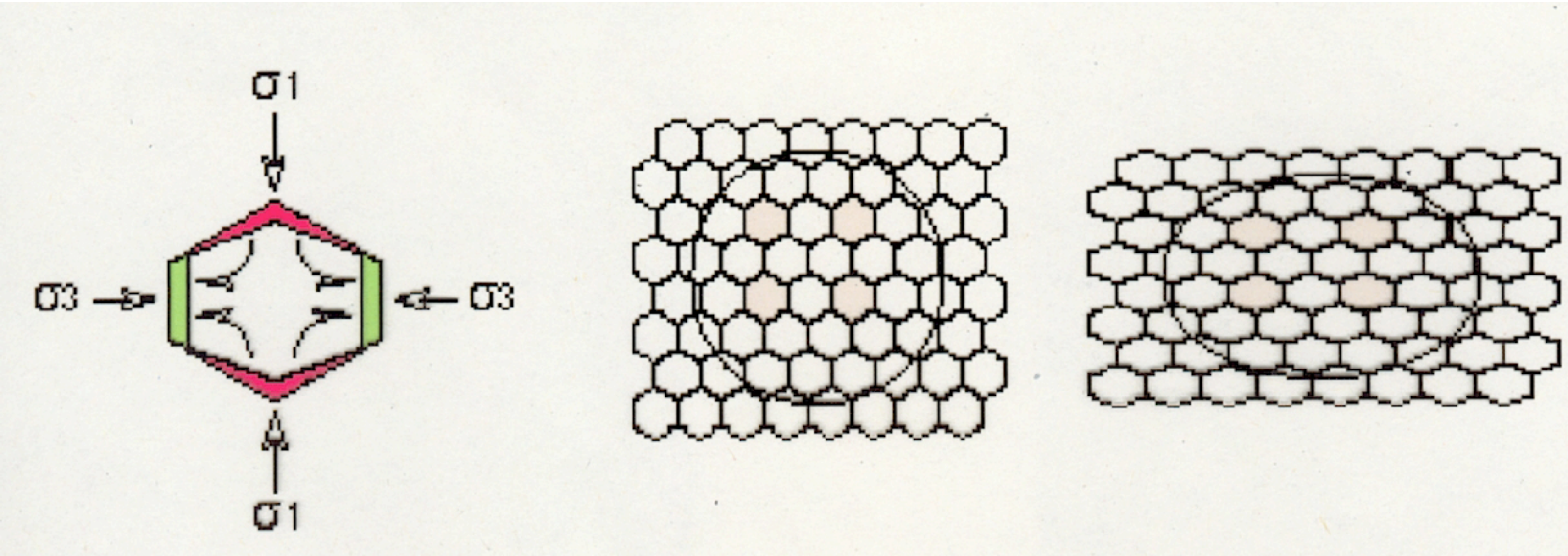
Mechanical twinning & CPO: switch between 2 crystal orientations



Magmatic flow: Deformation of a partially crystallized magma



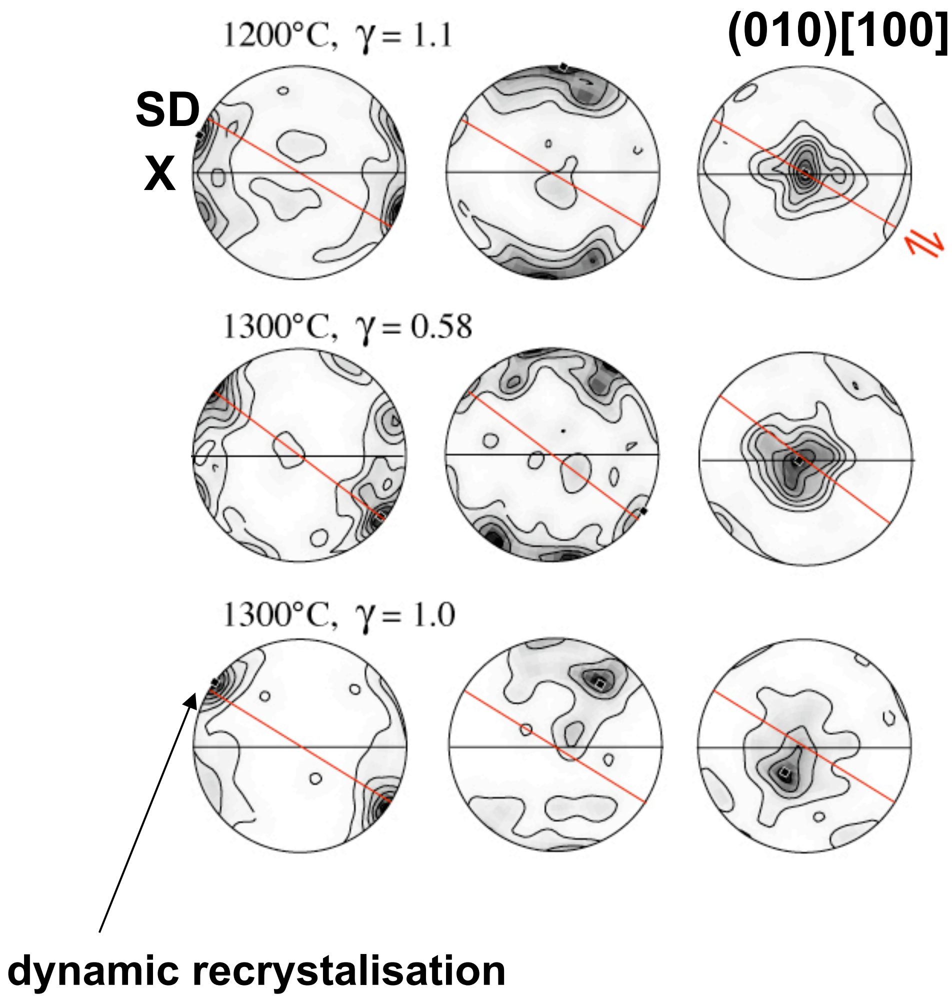
difusion: changes the shape, not the CPO



Recrystallization?

Experimental deformation: simple shear

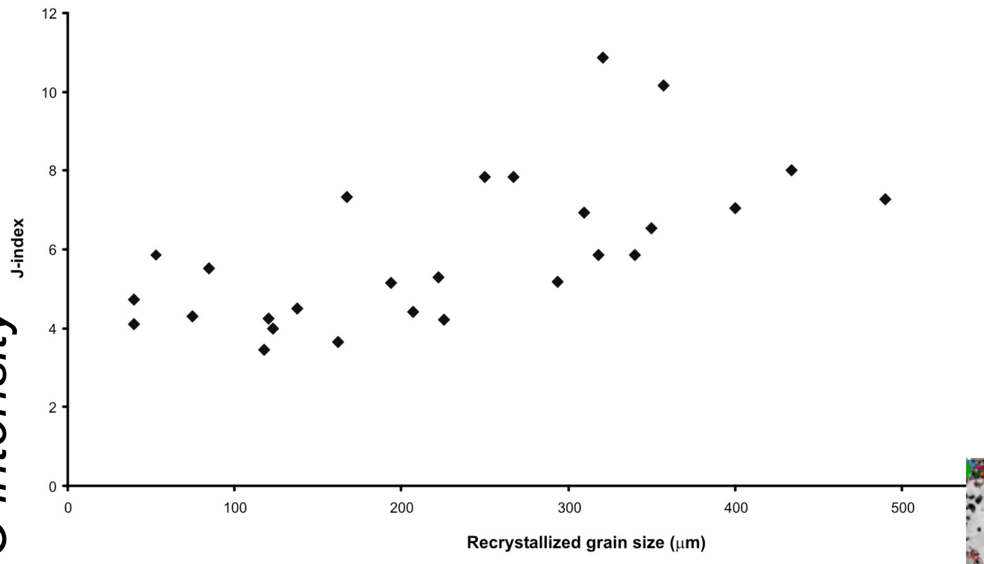
Zhang & Karato (1995), Nature

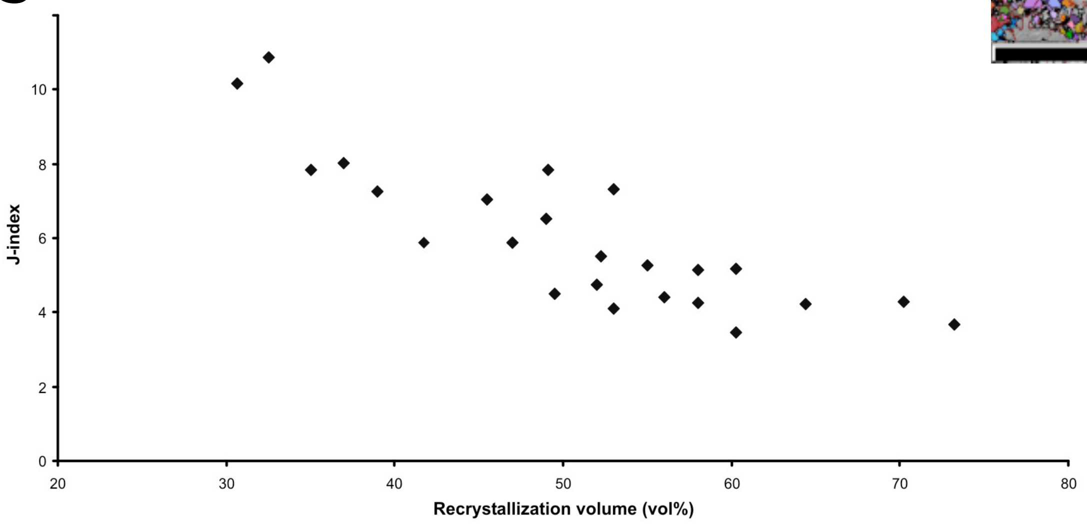


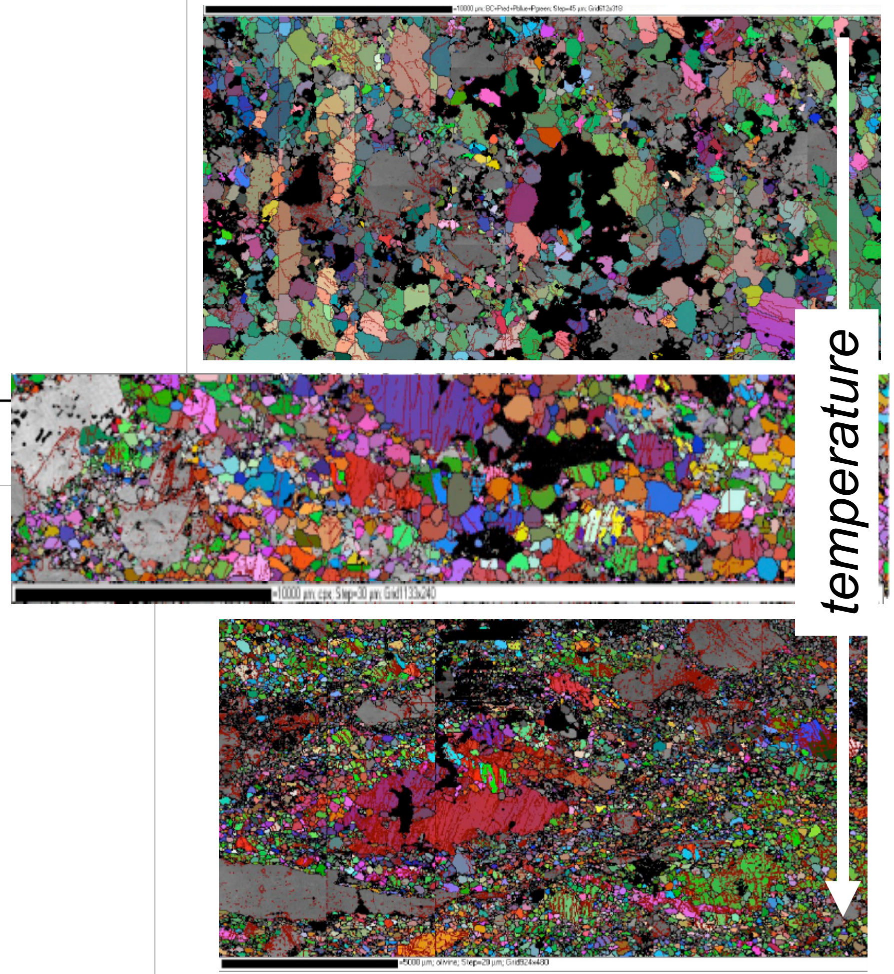
Dynamic recrystallisation @ lithospheric conditions

shallow lithospheric mantle xenoliths :
East Carpathians

CPO intensity



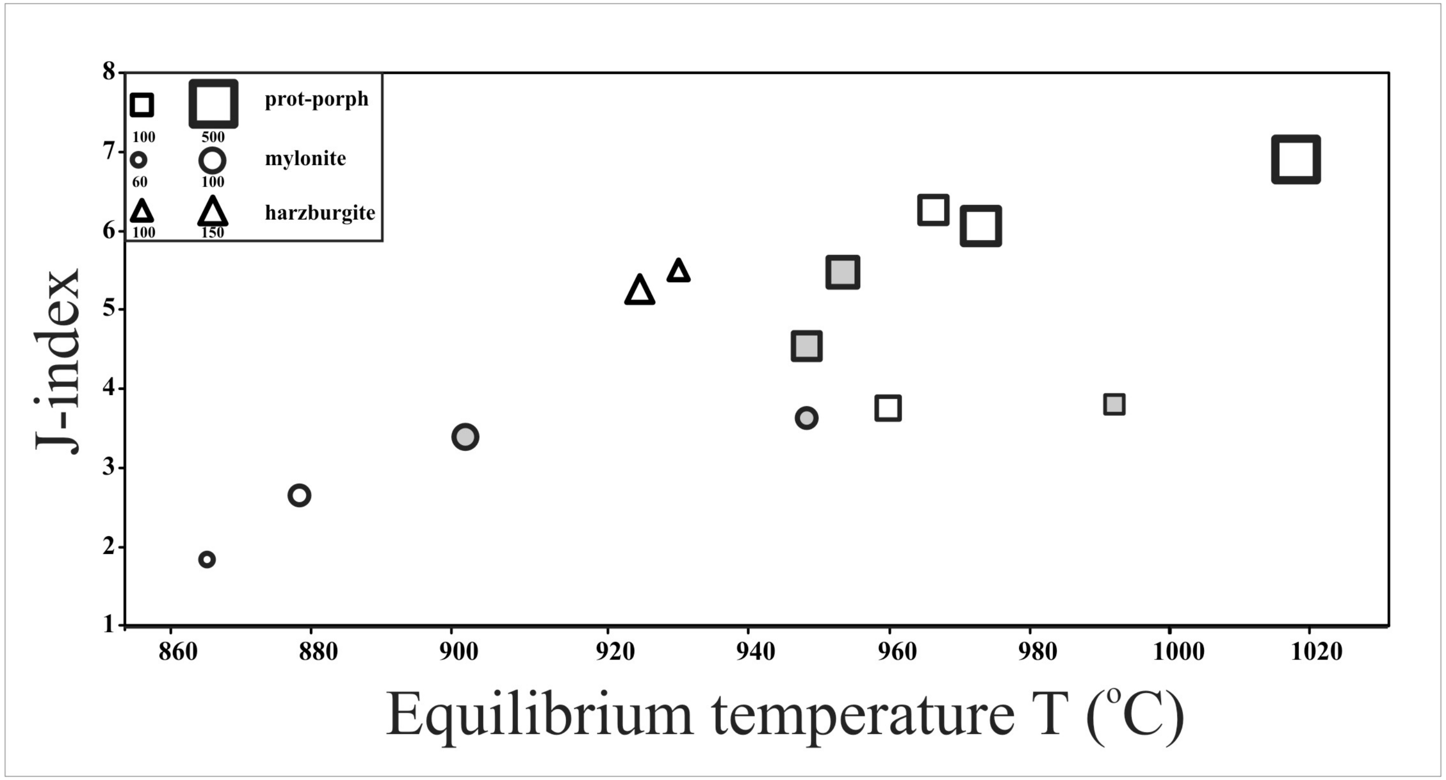




T↗, σ↘ : *grain growth*

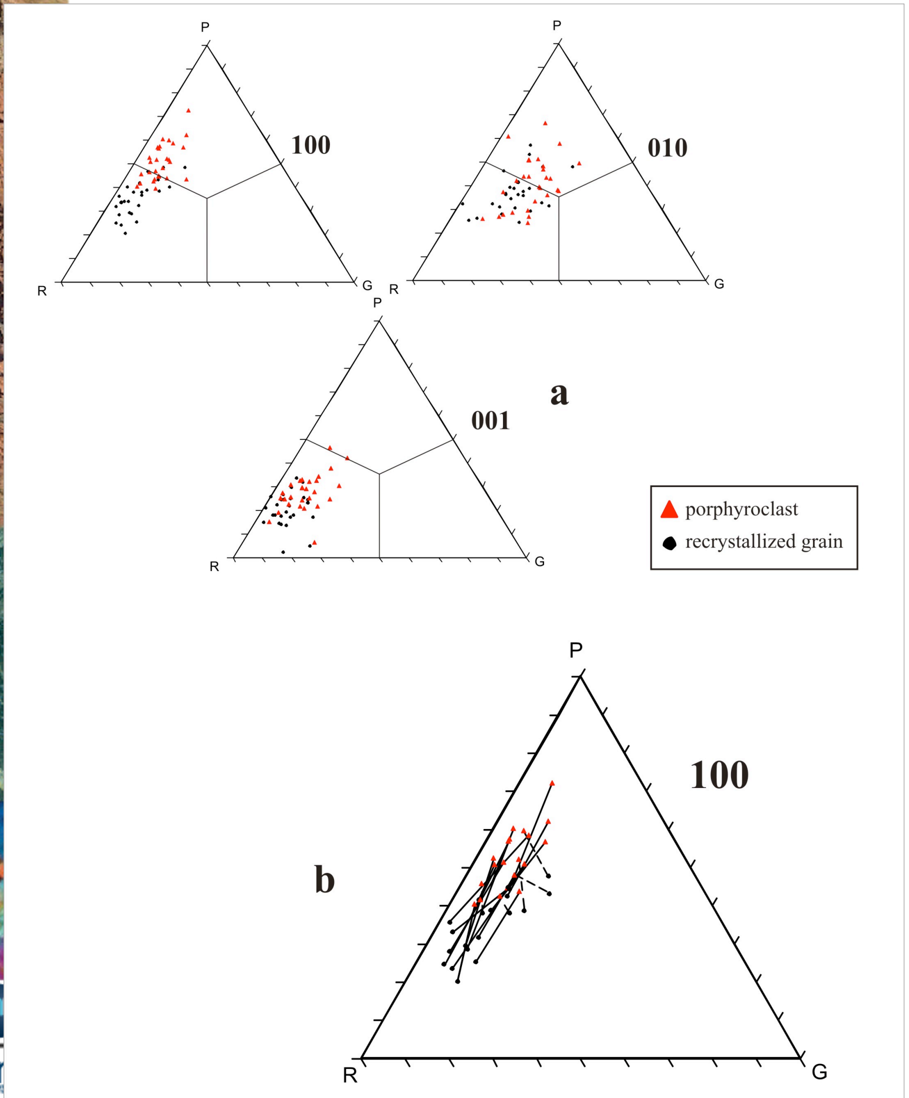
Falus & Tommasi, in prep.

Recrystallization & CPO strength

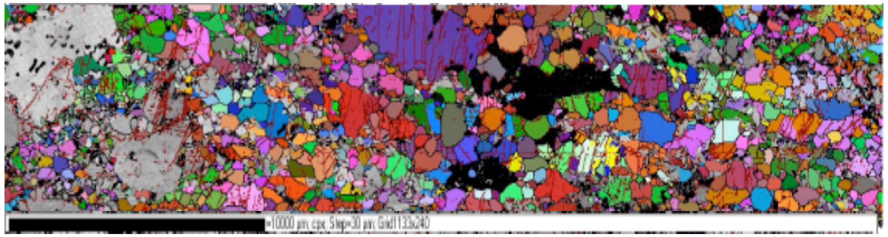


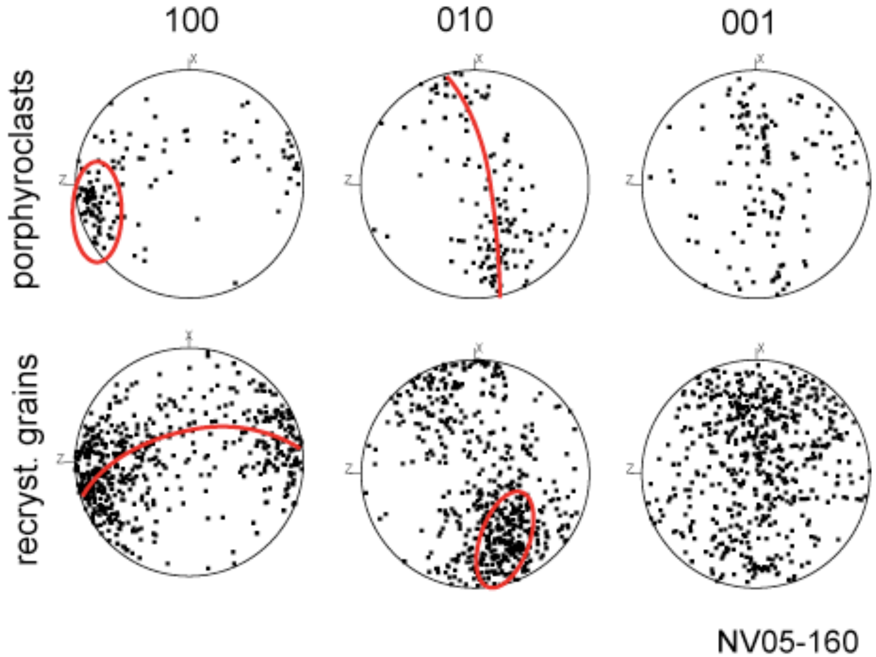
Falus et al EPSL 2008

Recrystallisation by subgrain rotation

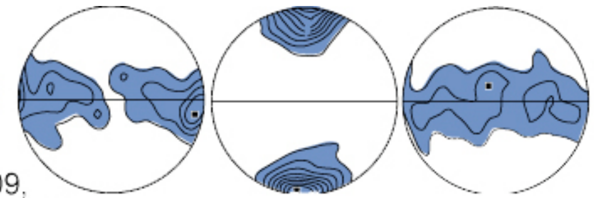


Falus & Tommasi, in prep.





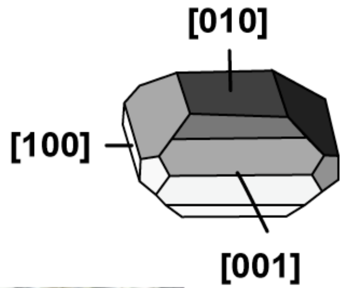
dispersion of [100]
development of axial [010] CPO



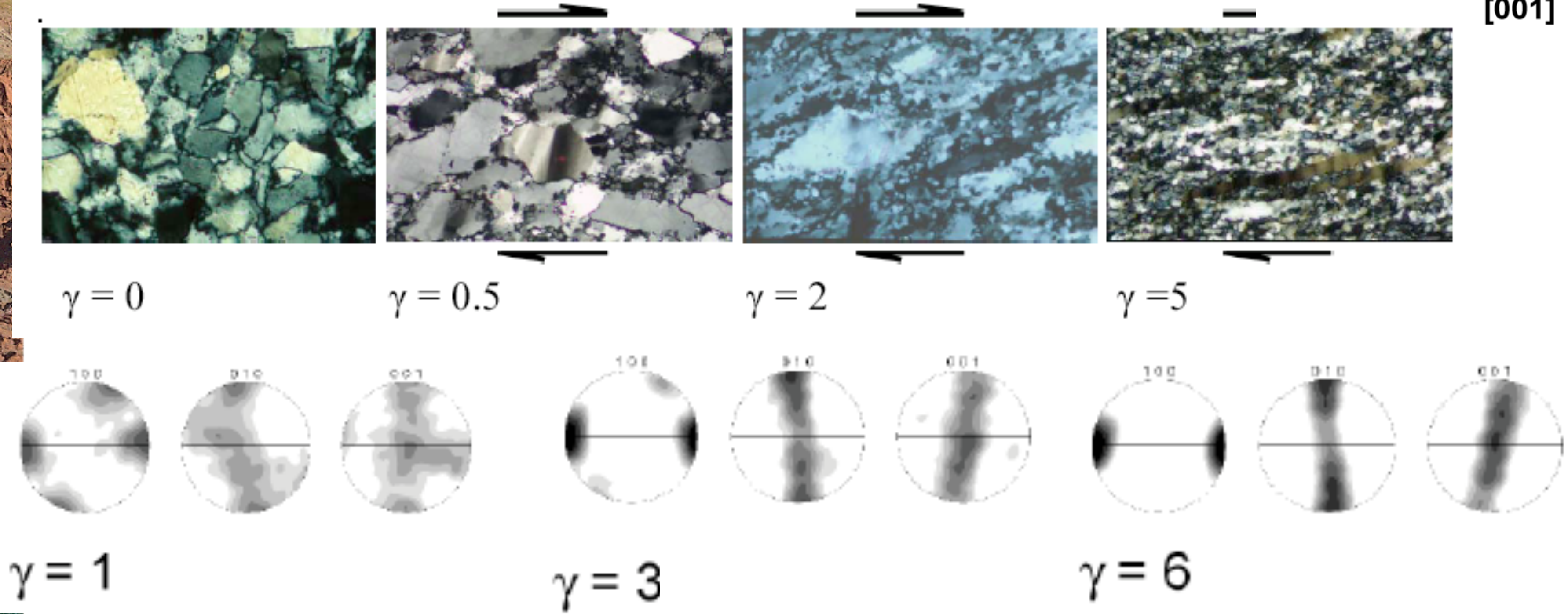
[010] fiber

FRB1309,
kimberlitic xenolith,
Kapvaal craton

Torsion experiments - high shear strains
CPO evolution as a function of strain

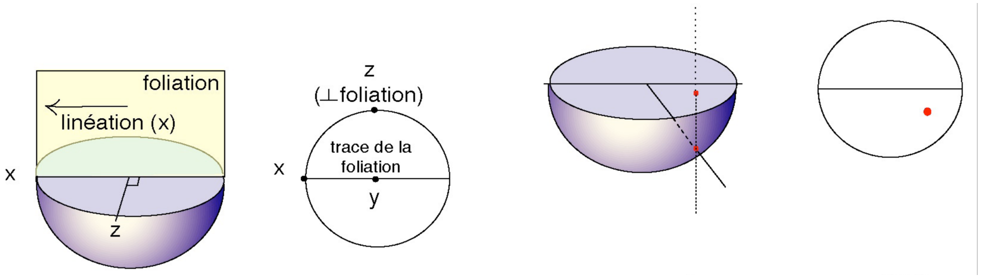


***[100] // shear direction** & [010] normal to shear plane*



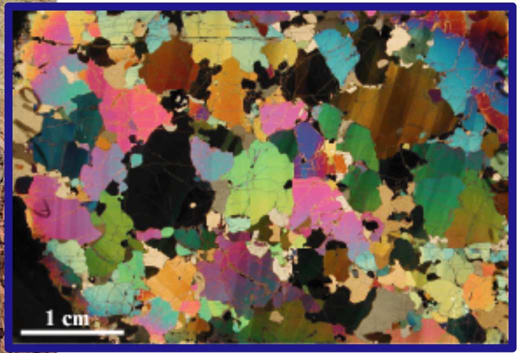
low strain:
fast CPO evolution

high strain:
very slow CPO evolution

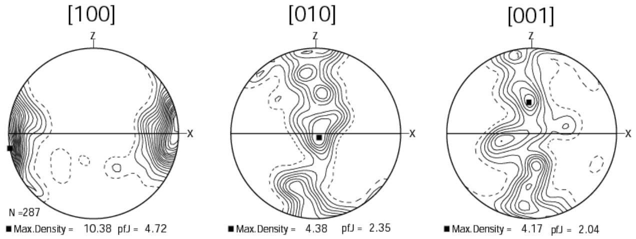


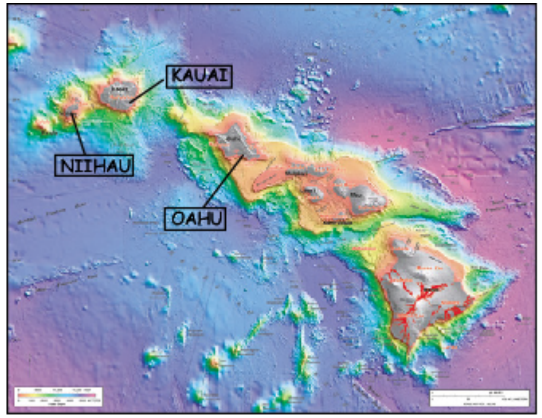
Bystricky et al. Science 2000

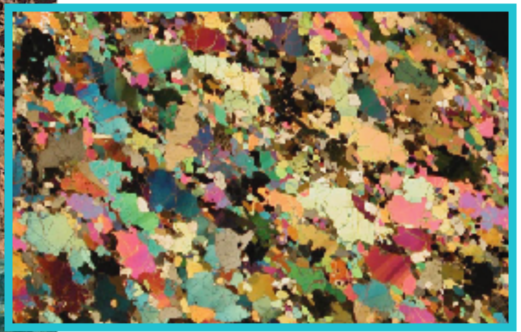
Hawaii



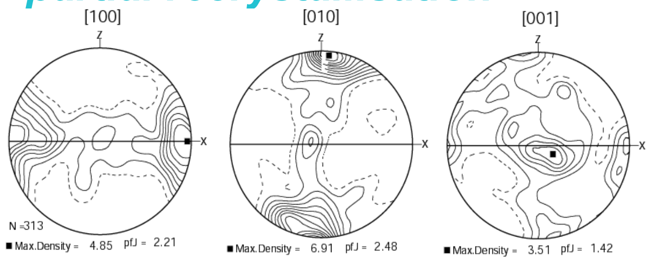
HT coarse-grained porphyroclastic

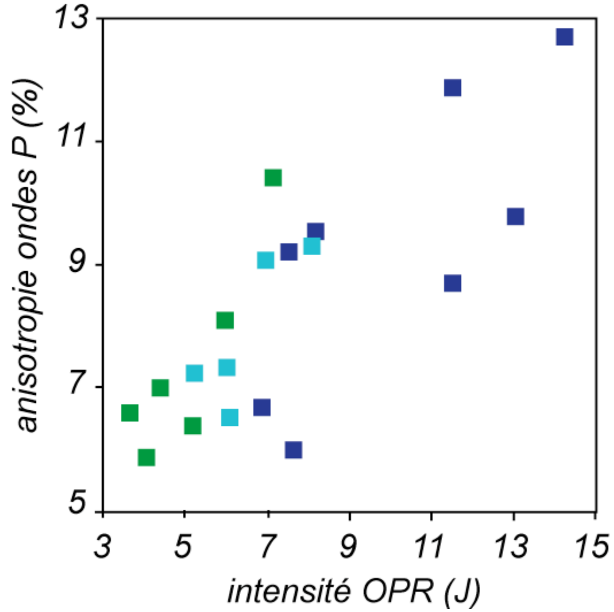




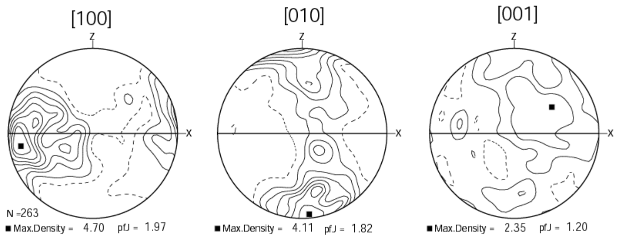


partial recrystallisation



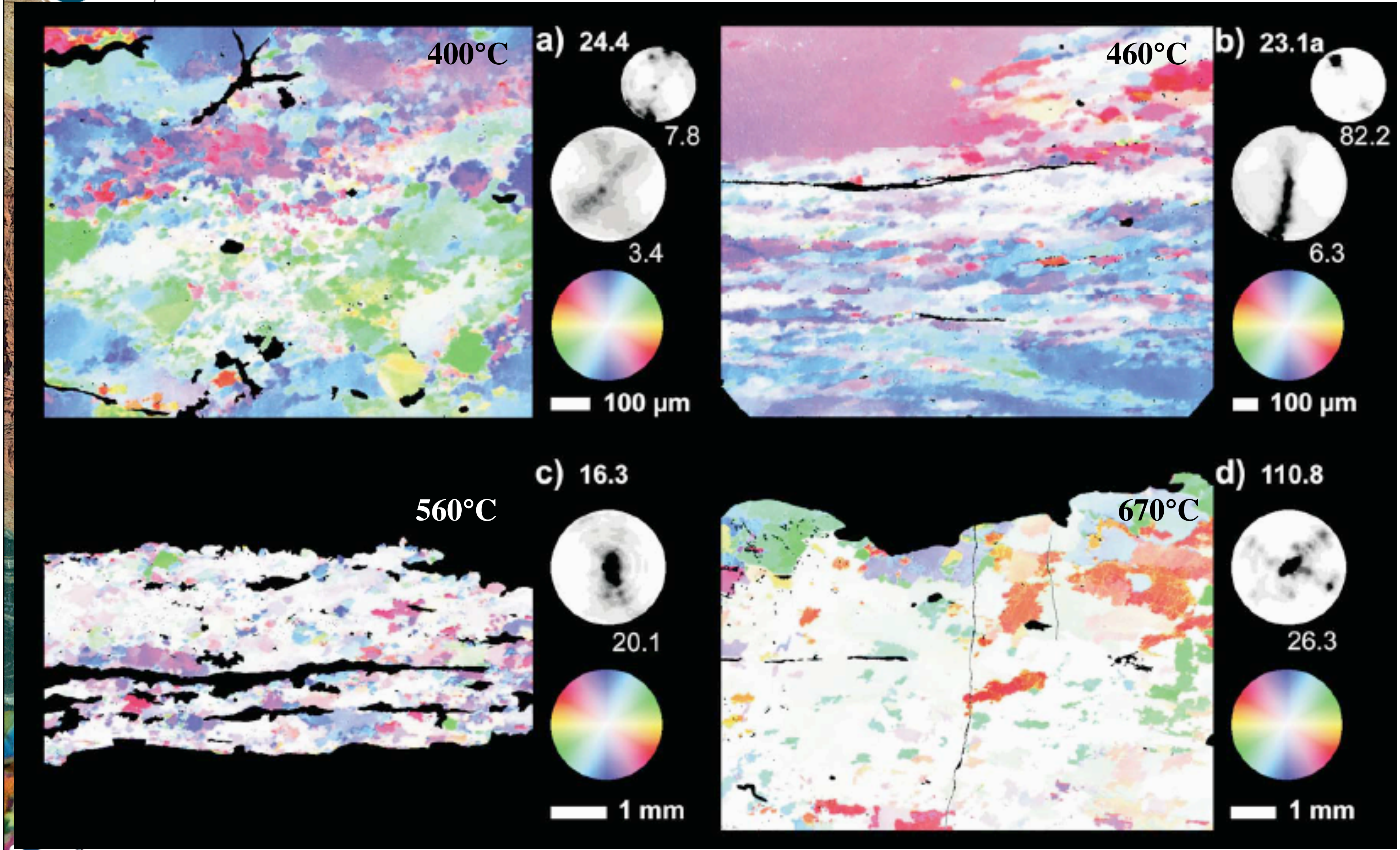


equigranular: 100% recrist.



recrystallisation : dispersion CPO = decrease in anisotropy
related to the Hawaii plume?
opx-cpx thermometers record no heating!

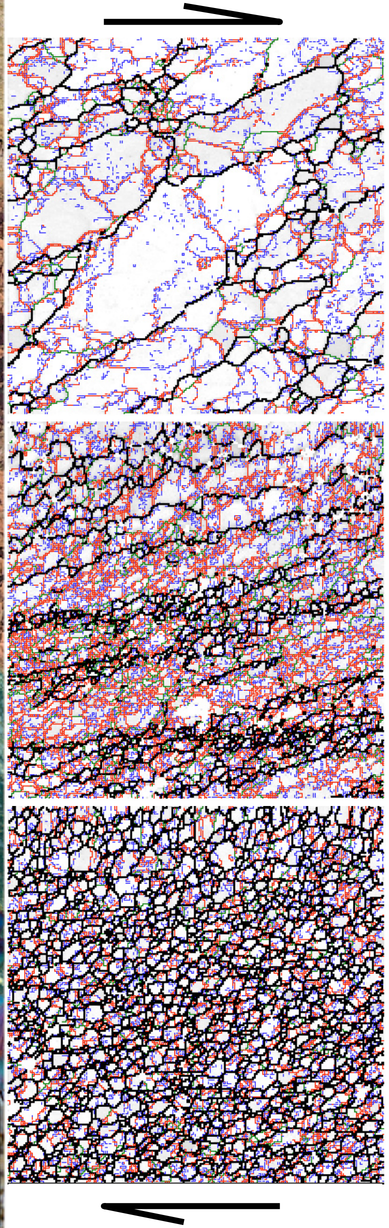
deformation of quartz over a temperature range from 250 to 700 °C



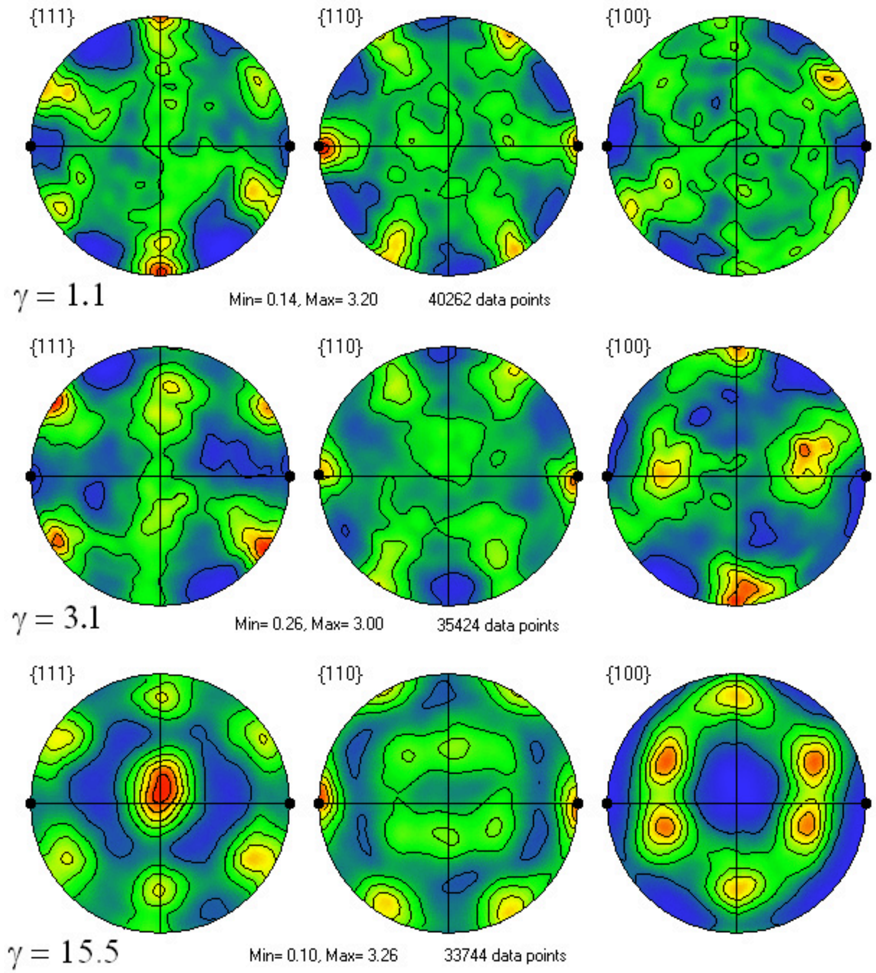
M. Stipp et al. / Journal of Structural Geology 24 (2002) 1861–1884

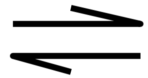
Torsion test – texture evolution with increasing strain

MgO : ~ 10-30% lower mantle (700-2700 km)



<1°
1-5°
>5°





Heidelbach et al. JGR, 2006

Change in CPO due to dynamic recrystallization?

Dynamic recrystallization:

- faster reorientation of the CPO // imposed shear

- stabilization of the CPO

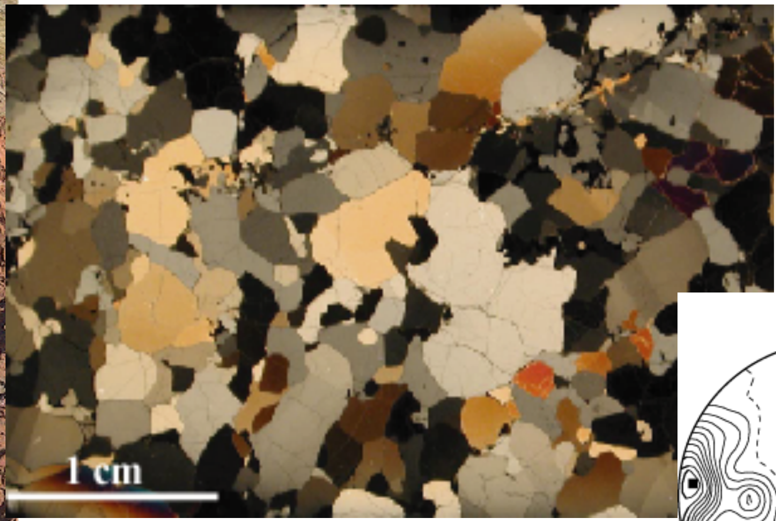
subgrain rotation, nucleation = dispersion CPO

migration = concentration CPO

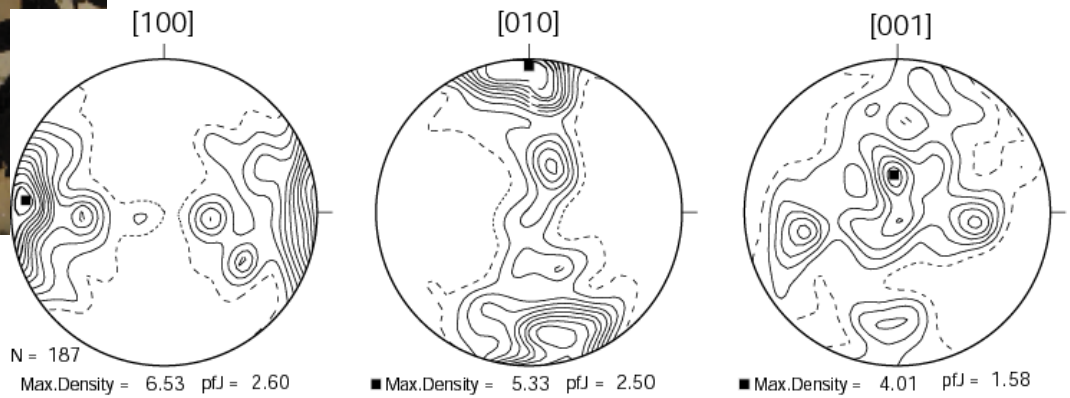
- MgO??

Static recrystallization (annealing)

REMARK: Peridotite "protogranular" microstructures & olivine crystal preferred orientations



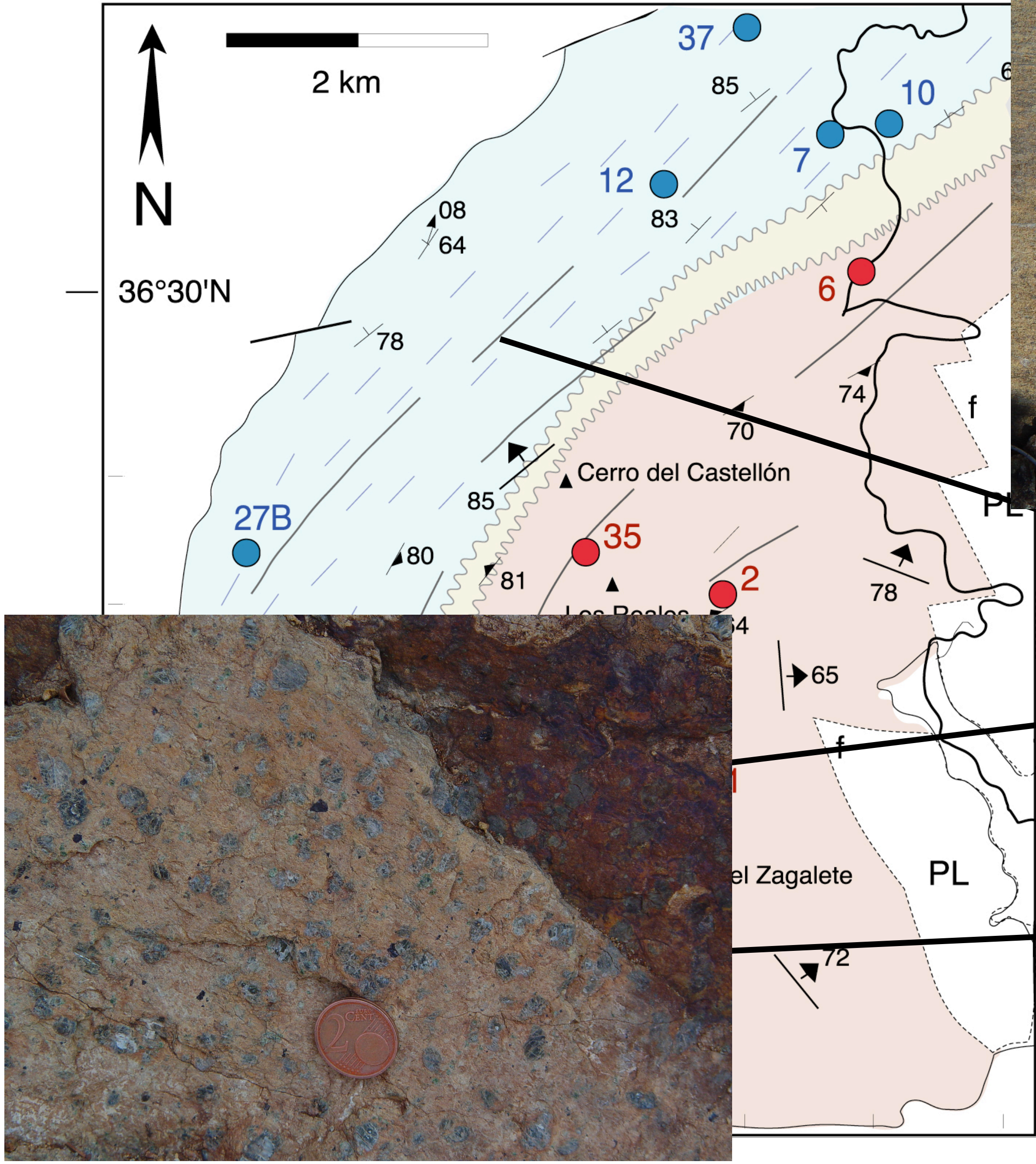
harzburgite Hawaii



strong CPO = deformation by dislocation creep
microstructure = static recrystallization & grain growth

except for very fine grained mylonites, CPO is always present
➢ ***undeformed mantle probably does not exist anymore on Earth...***

Does partial melting and melt infiltration affect crystal preferred orientation ?

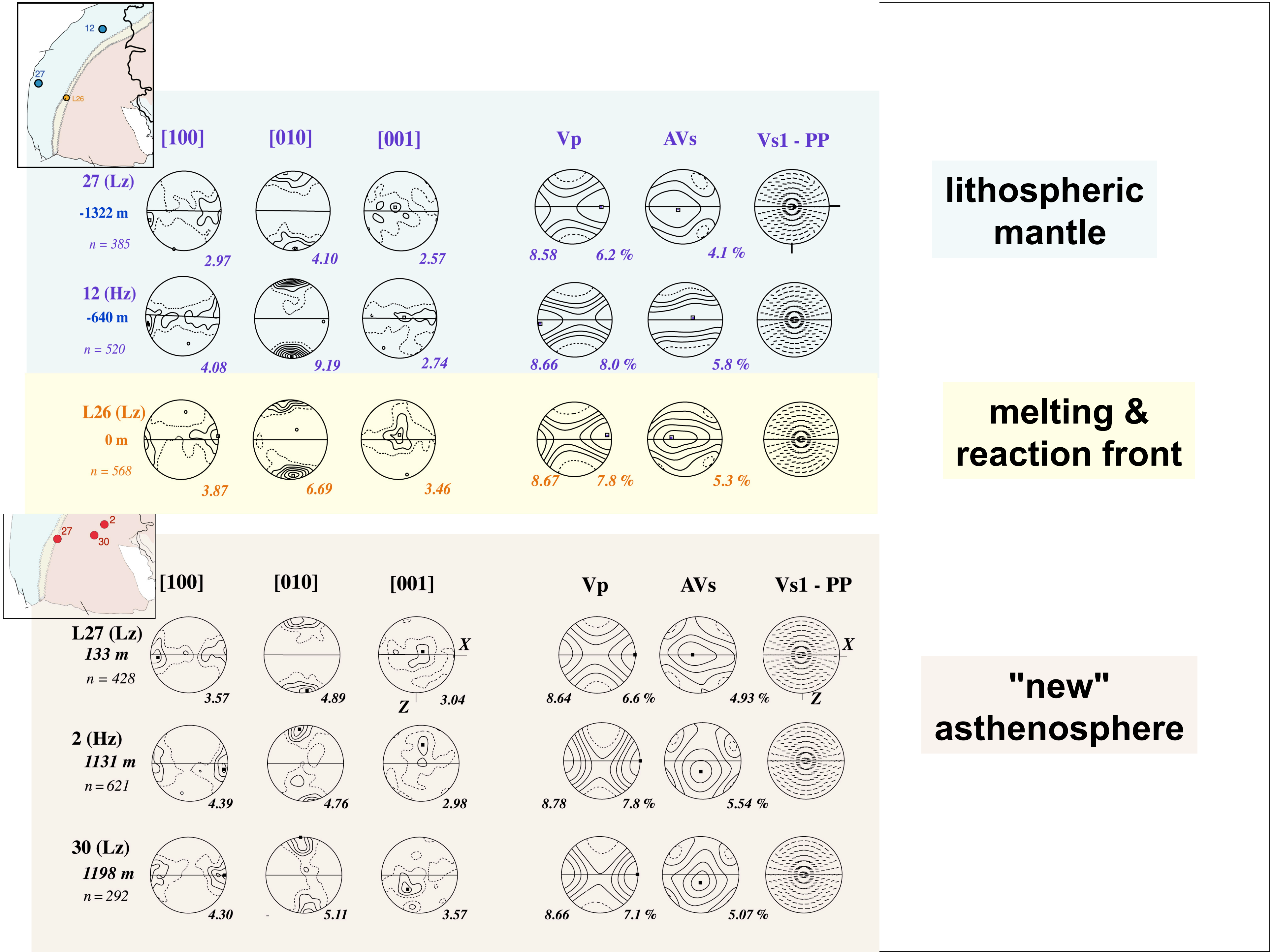


lithospheric mantle

melting & reaction front
- Δ microstructure
- Δ chemical composition

"new" asthenosphere:
➢ **2-6% partial melting + melt-rock interaction**

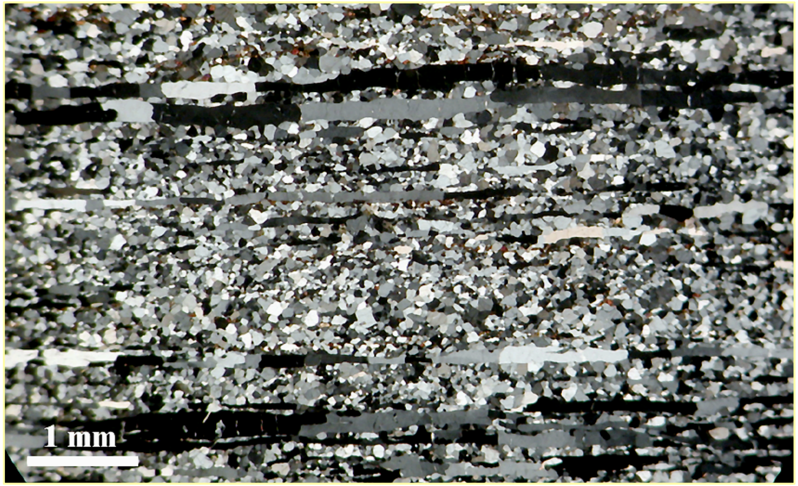
Vauchez & Garrido 2002 EPSL

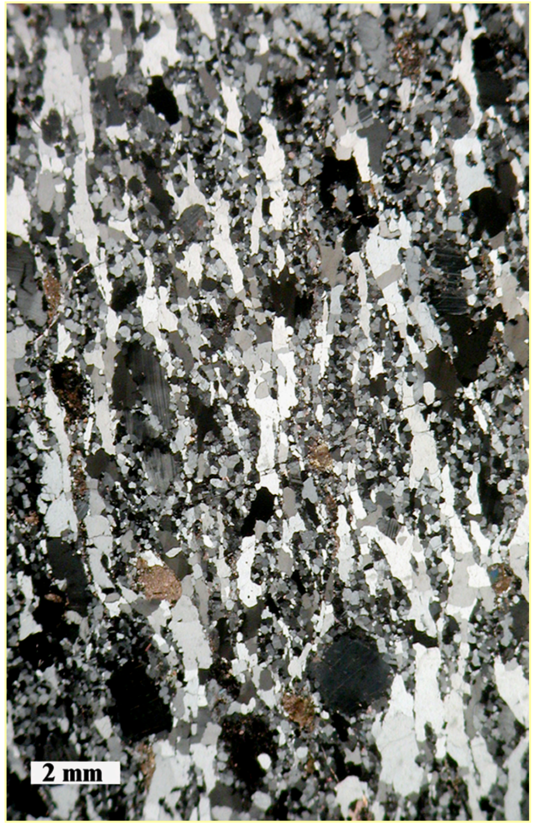

12
27
L26
[100]
[010]
[001]
Vp
AVs
Vs1 - PP
27 (Lz)
-1322 m
n = 385
2.97
4.10
2.57
8.58
6.2 %
4.1 %
12 (Hz)
-640 m
n = 520
4.08
9.19
2.74
8.66
8.0 %
5.8 %
L26 (Lz)
0 m
n = 568
3.87
6.69
3.46
8.67
7.8 %
5.3 %
2
27
30
[100]
[010]
[001]
Vp
AVs
Vs1 - PP
L27 (Lz)
133 m
n = 428
3.57
4.89
3.04
X
Z
8.64
6.6 %
4.93 %
X
Z
2 (Hz)
1131 m
n = 621
4.39
4.76
2.98
8.78
7.8 %
5.54 %
30 (Lz)
1198 m
n = 292
4.30
5.11
3.57
8.66
7.1 %
5.07 %
lithospheric mantle
melting & reaction front
"new" asthenosphere

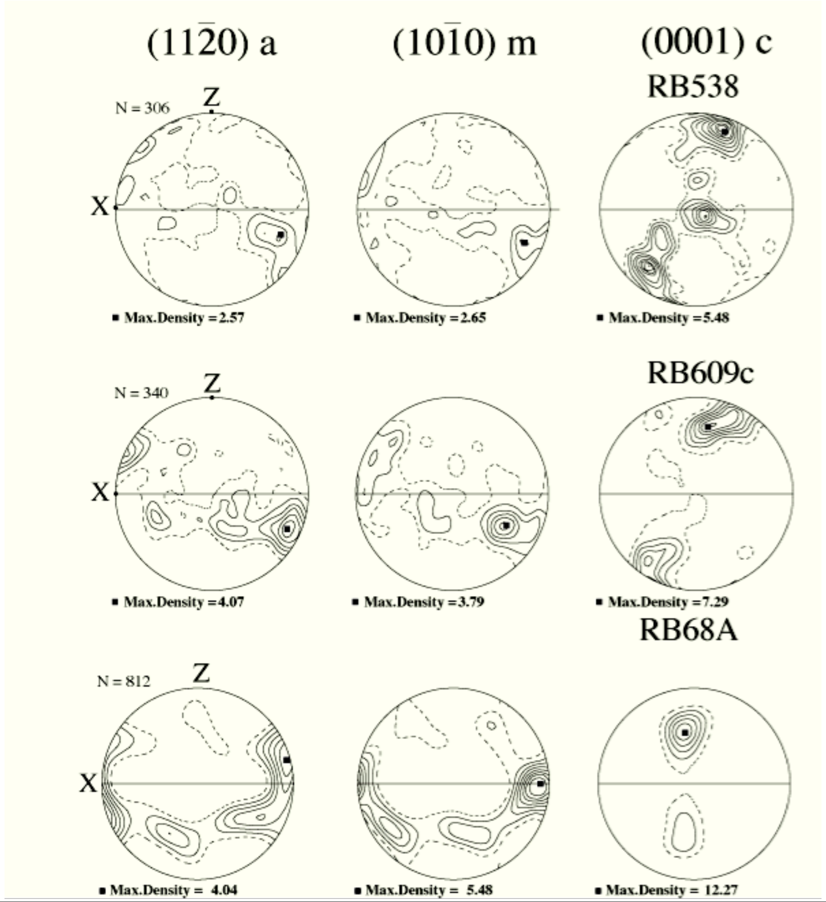
Static recrystallization:

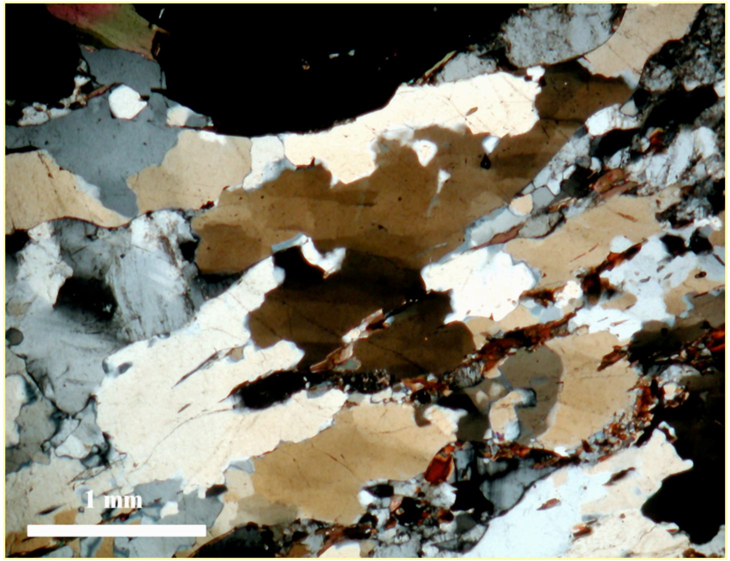
- poorly-known effect
- olivine : no effect if not accompanied by neo-crystallization of olivine (reaction – open system)
- quartz?

Géosciences Montpellier





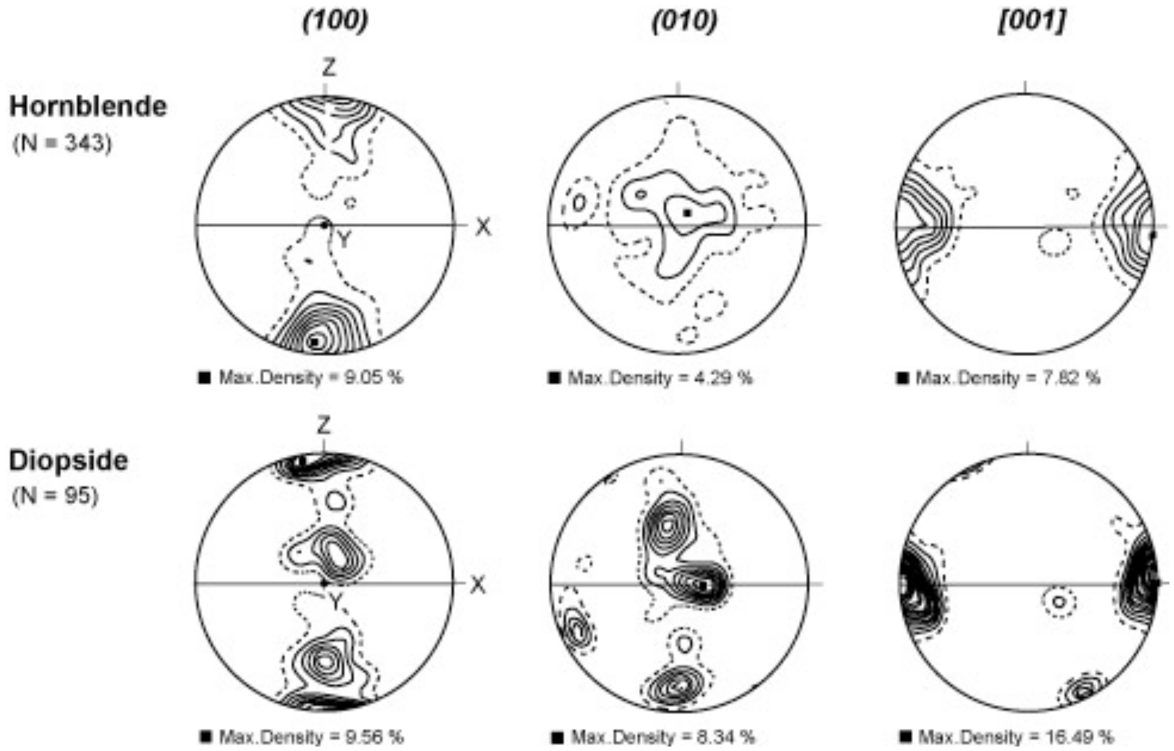




Oriented crystallization (reactions & phase transformations)

Partial melting experiments

hornblende + plg = magma + diopside
(amphibolite 80% hb)

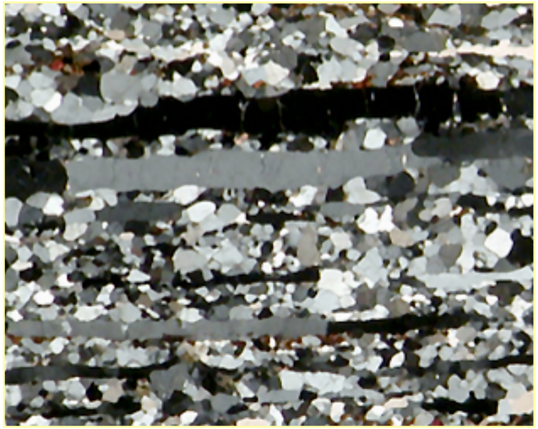


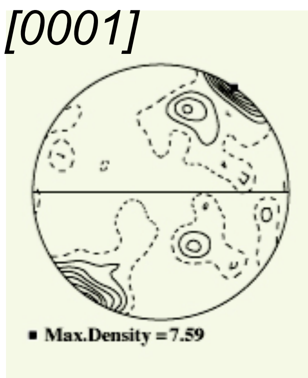
J. Ramelow, GFZ Potsdam

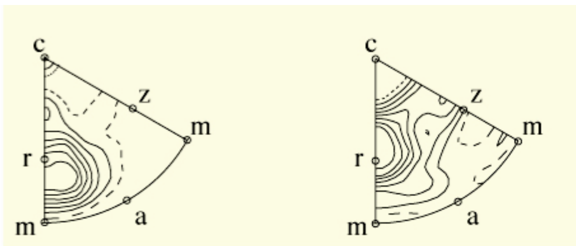
- ***CPO evolution during deformation depends on :***
  - ✓***deformation geometry***
  - ✓***slip systems activity, which depends on:***
    - ***temperature***
    - ***deviatoric stress***
    - ***water***
    - ***pressure***
    - ***melt***
  - ✓***finite strain, but:***
    - *dynamic recrystallisation : dispersion of CPO*
    - *dynamic grain growth : enhancement (preferential growth of crystals in easy glide orientations)*
    - ✓***CPO stable for shear strains >4-5***

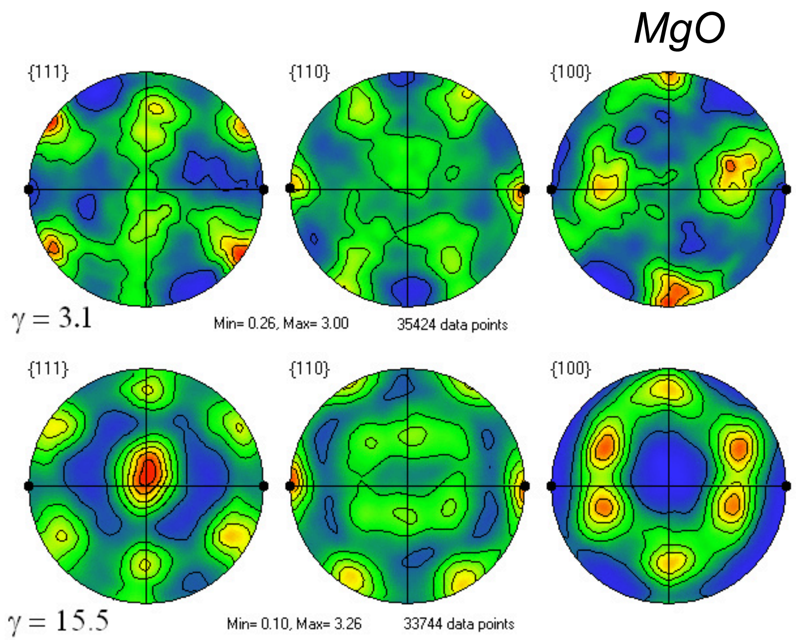
- ***Thermal and chemical processes do not destroy CPO, but a new deformation may reorient it***

- ***Open questions:***
  - ✓***Deformation mechanisms & slip systems' strength:***
    Temperature, pressure, water….
  - ✓***Recrystallization ?***







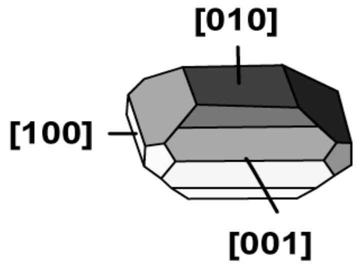


  - ✓***Development of CPO during diffusion creep?***

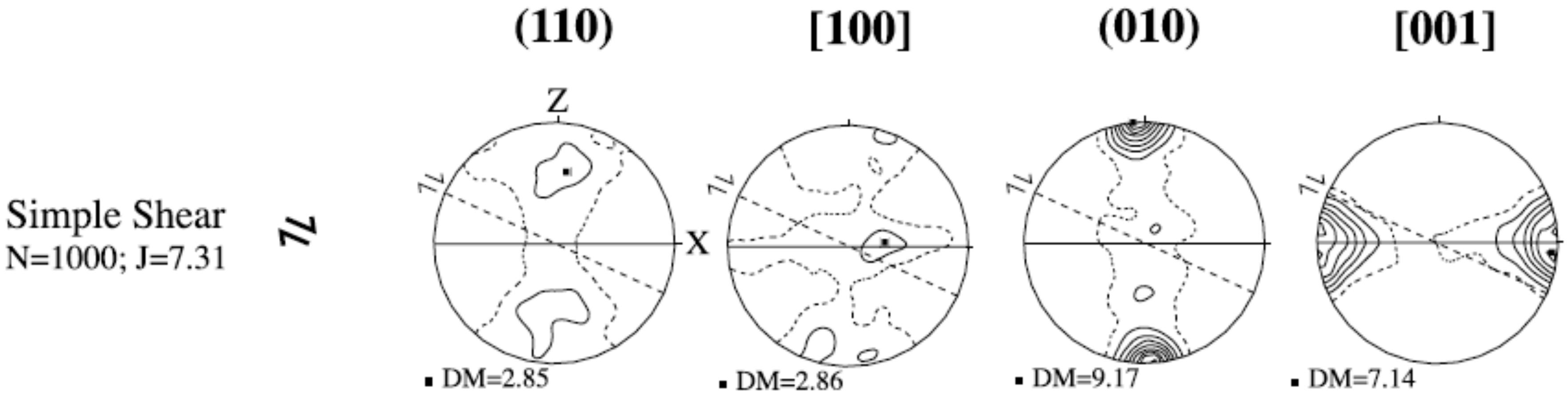
• *Final remark:*

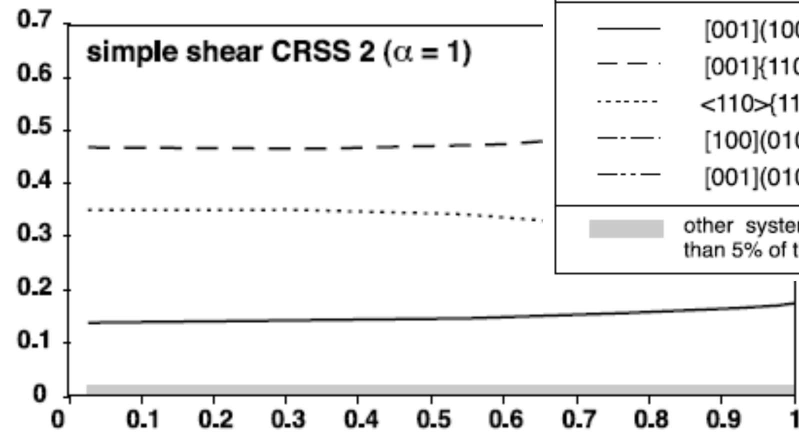
• ***dominant slip system // macroscopic shear***

✓ ***only valid for basal slip = olivine***

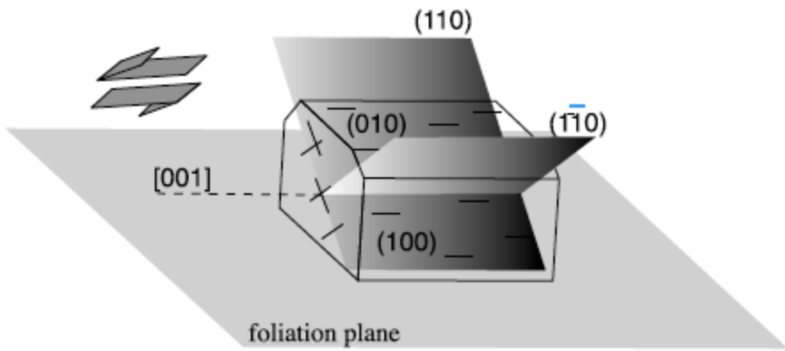


clinopyroxene: dominant slip system {110}[001]





slip system		CRSS 1	CRSS 2
———	[001](100)	1	1
— —	[001]{110}	10	1
-------	<110>{110}	3	1
—·—	[100](010)	3	8
—··—	[001](010)	8	8
(grey)	other systems that accomodate less than 5% of the imposed deformation		



Bascou et al. JSG 2002