

Rheology of the Lower Crust: Concepts, Methods & Observations from the rock record

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UNIVERSITY OF LEEDS

Thanks :



team

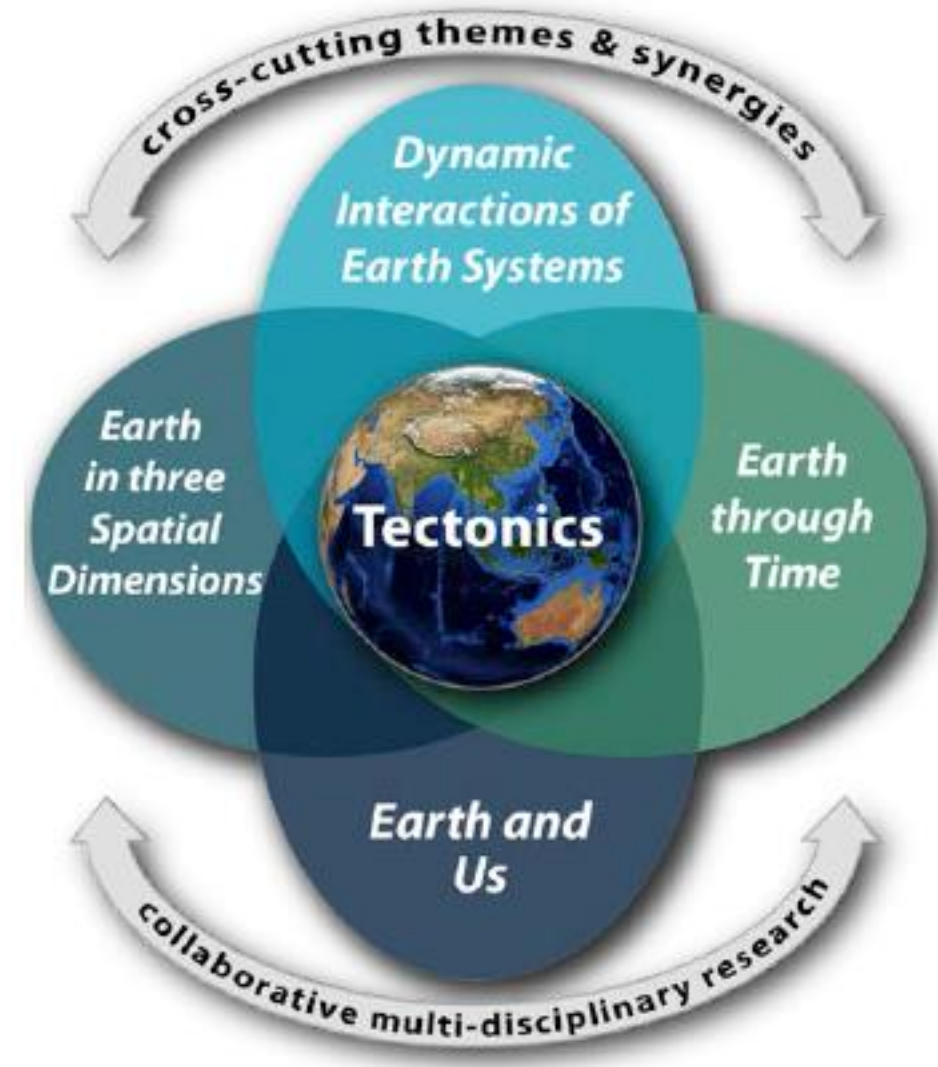
N. Daczko, P. Trimby, R. Gardner, L. Spruzeniece, D. Cyprych, & many more

Rheology of the Lower Crust: Concepts, Methods, Observations

- 1) Rheology of the Lower Crust: General importance & Recap of Solid state deformation mechanism and flow laws
- 2) Quantitative Orientation Analysis: How does it work? How can it help me to understand the Lower Crust – rheology
- 3) Quantitative Orientation Analysis: Examples and Opportunities - Rheology and evolution of the Lower Crust
- 4) Rheology of the Lower Crust: Other measurements and considerations

*ASK – we are all
here to learn*

*Note: Link to György HETÉNYI,
Rock view <-> Geophysical view
-> same/similar problems
-> across scales*



Modified after Huntington & Klepeis et al. 2017

Strength of the Continental Lithosphere?

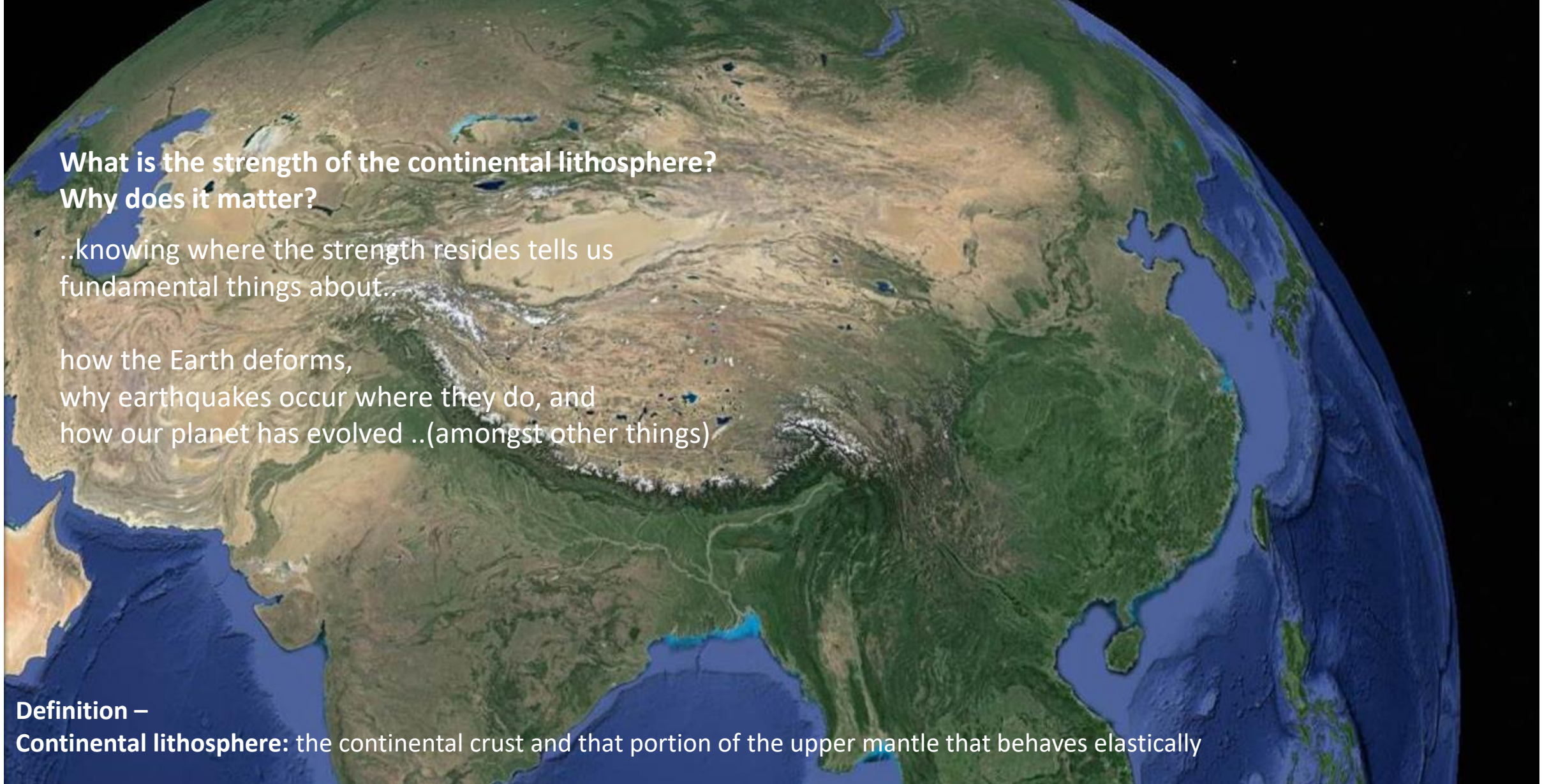
**What is the strength of the continental lithosphere?
Why does it matter?**

..knowing where the strength resides tells us
fundamental things about..

how the Earth deforms,
why earthquakes occur where they do, and
how our planet has evolved ..(amongst other things)

Definition –

Continental lithosphere: the continental crust and that portion of the upper mantle that behaves elastically



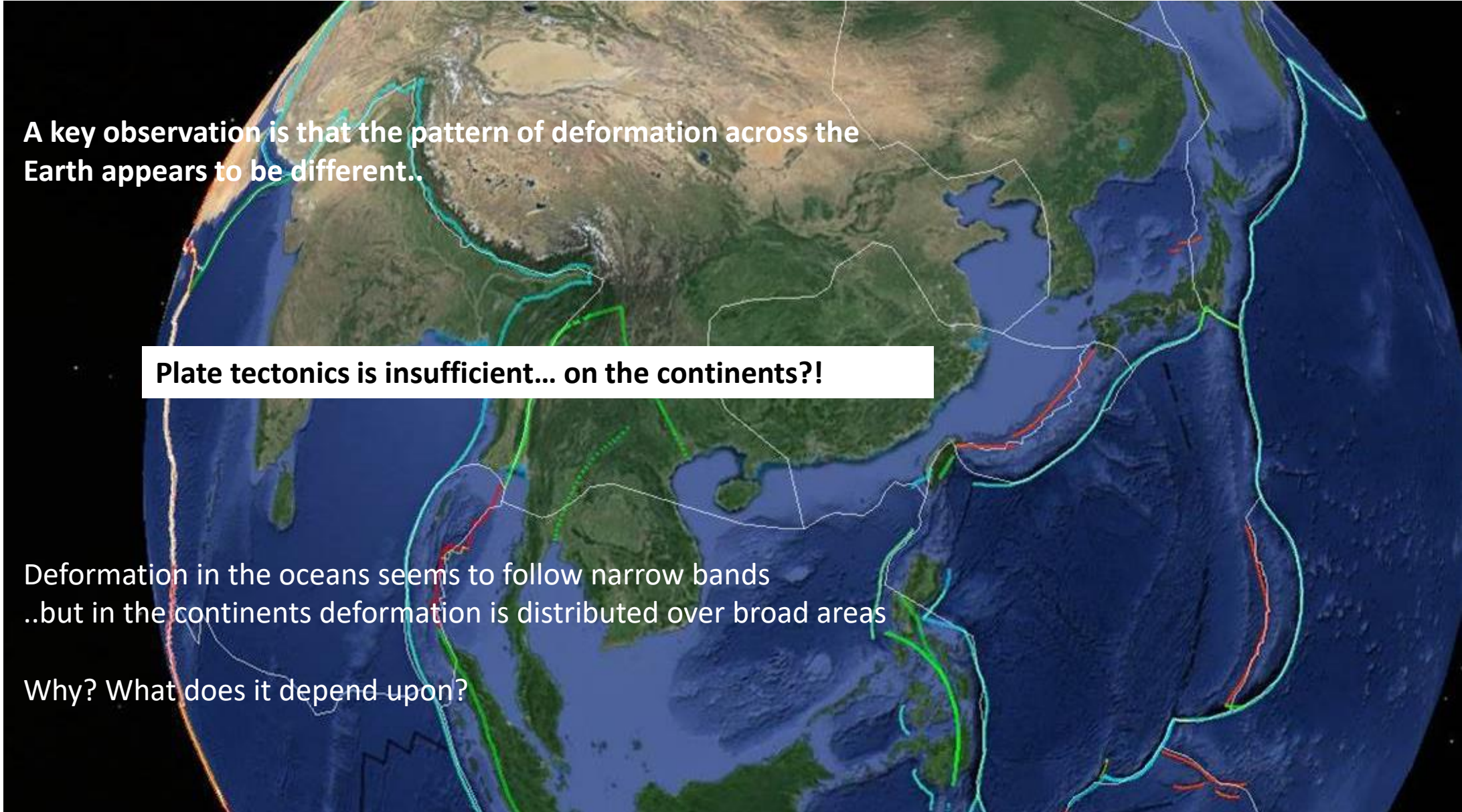
Deformation Behaviour of the Continental Lithosphere?

A key observation is that the pattern of deformation across the Earth appears to be different..

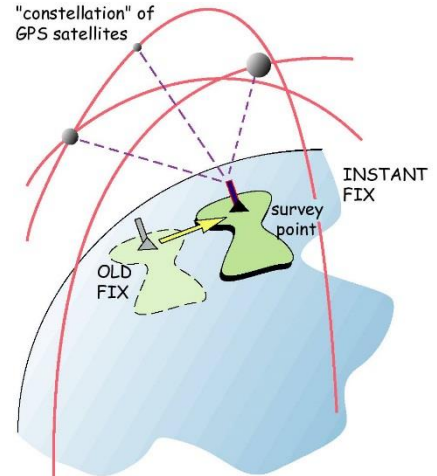
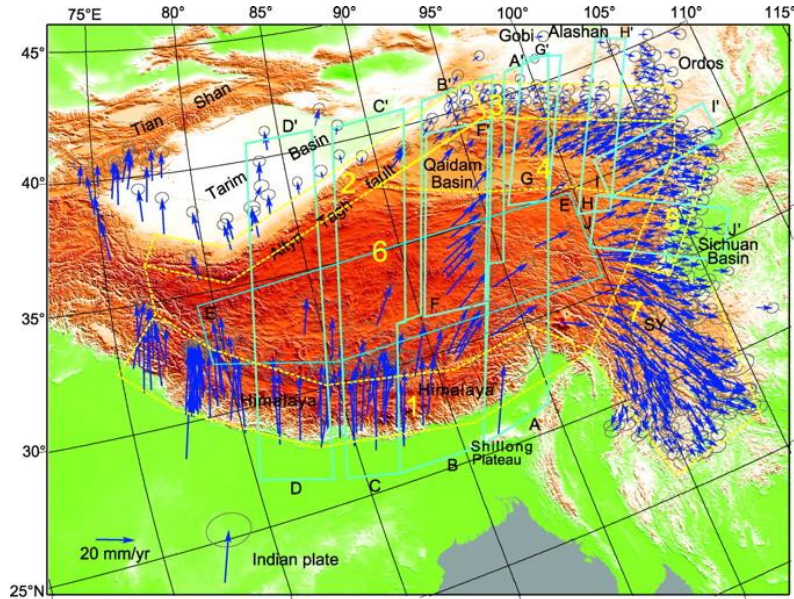
Plate tectonics is insufficient... on the continents?!

Deformation in the oceans seems to follow narrow bands
..but in the continents deformation is distributed over broad areas

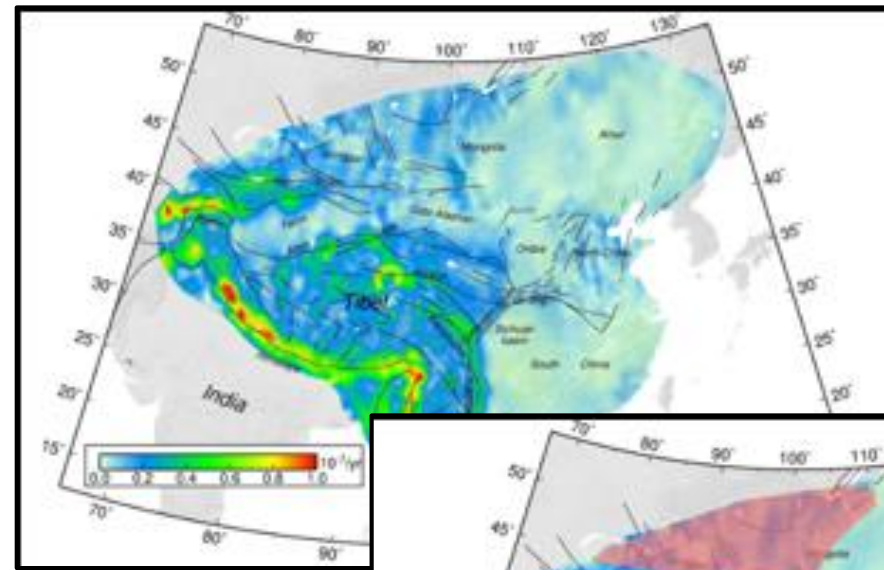
Why? What does it depend upon?



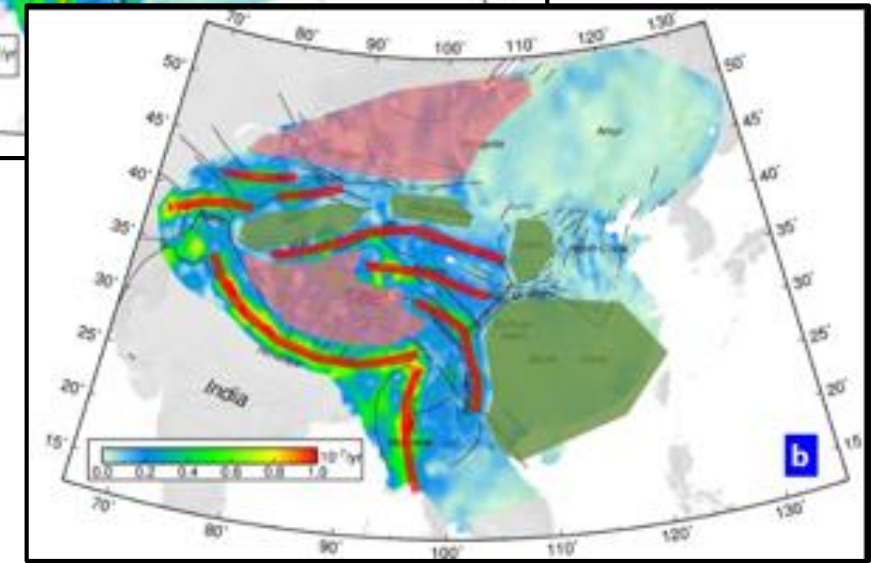
Continuous – discontinuous deformation?



Global Positioning & INSAR System



Zheng et al., 2017



Smooth N-ward decrease in convergence
No steps across faults? continuous deformation

Extrusion along ESE axis
 Increases towards ESE
 -> **Lower (?) Crustal flow**

Some clear high strain zones
Some distributed strain
Some no strain

Crustal flow – in some parts -> What does that mean?

Back to basics: Three main types of rheological behaviour

- **Elastic** deformation
 - Strain disappears when force taken away
 - Rubber band, bouncing ball
- **Brittle** deformation (discrete)
 - Discontinuous deformation
 - Faults, earthquake
 - glass
- **Ductile** deformation
 - Flowing movement (continuous)
 - Folds
 - Toothpaste

Rheology is the study of the **flow** of any material under the influence of applied stress



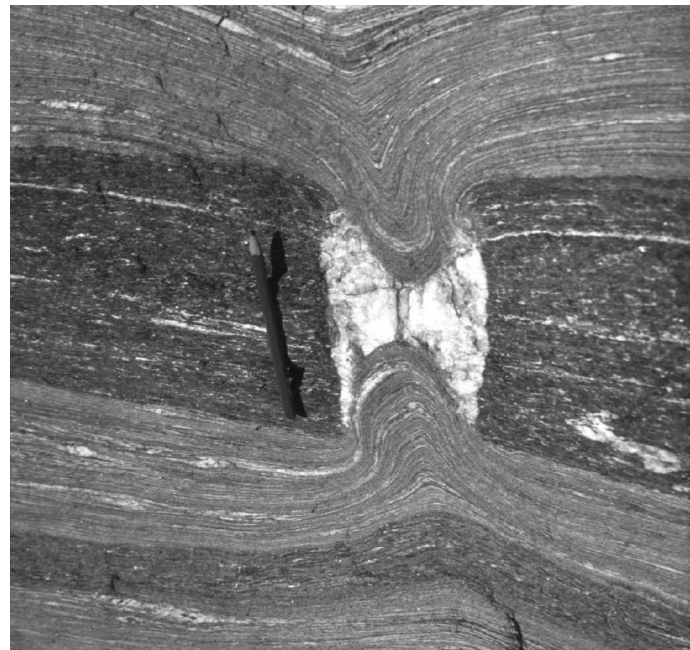
How a rock deforms is a function of:

- Temperature
- Composition
- Deformation rate
- Pressure

Mars bar experiment

Silly putty experiment

Contrast in
Rheology

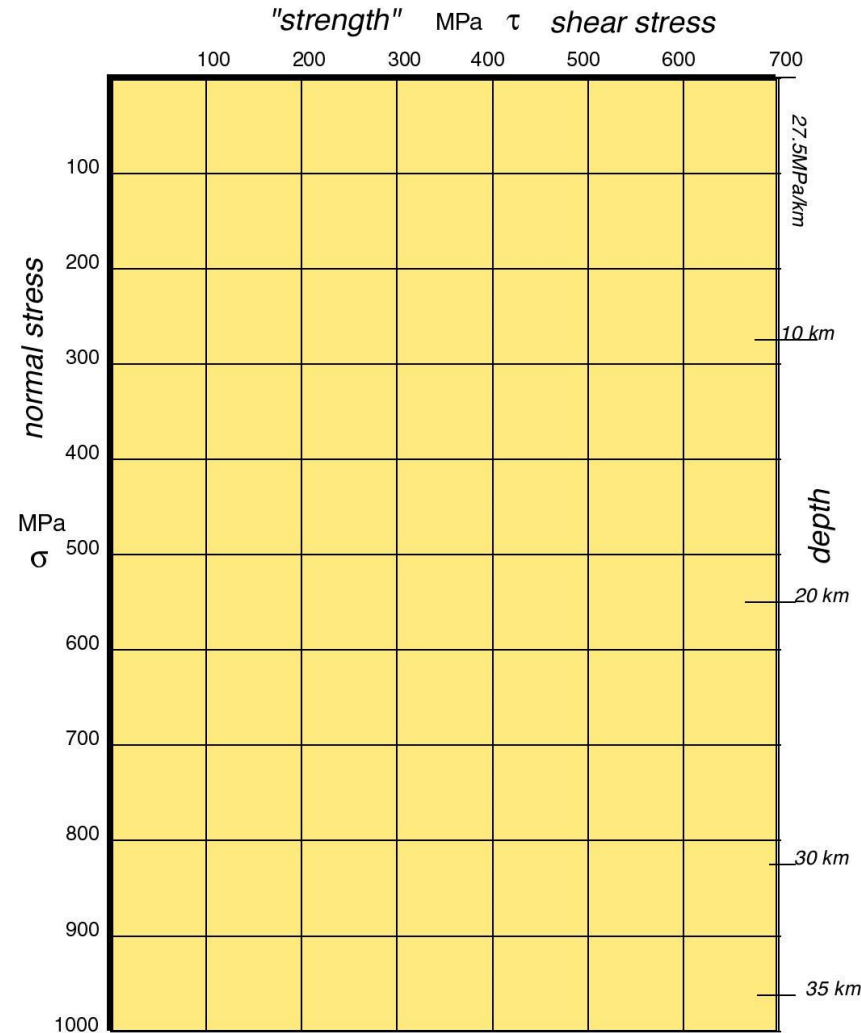


Pure shear

How does the Continental Lithosphere deform – Strength profile

Strength vs Depth Profiles:

The strength of the continental lithosphere (shear stress) can be plotted with respect to depth (normal stress)



Definitions –

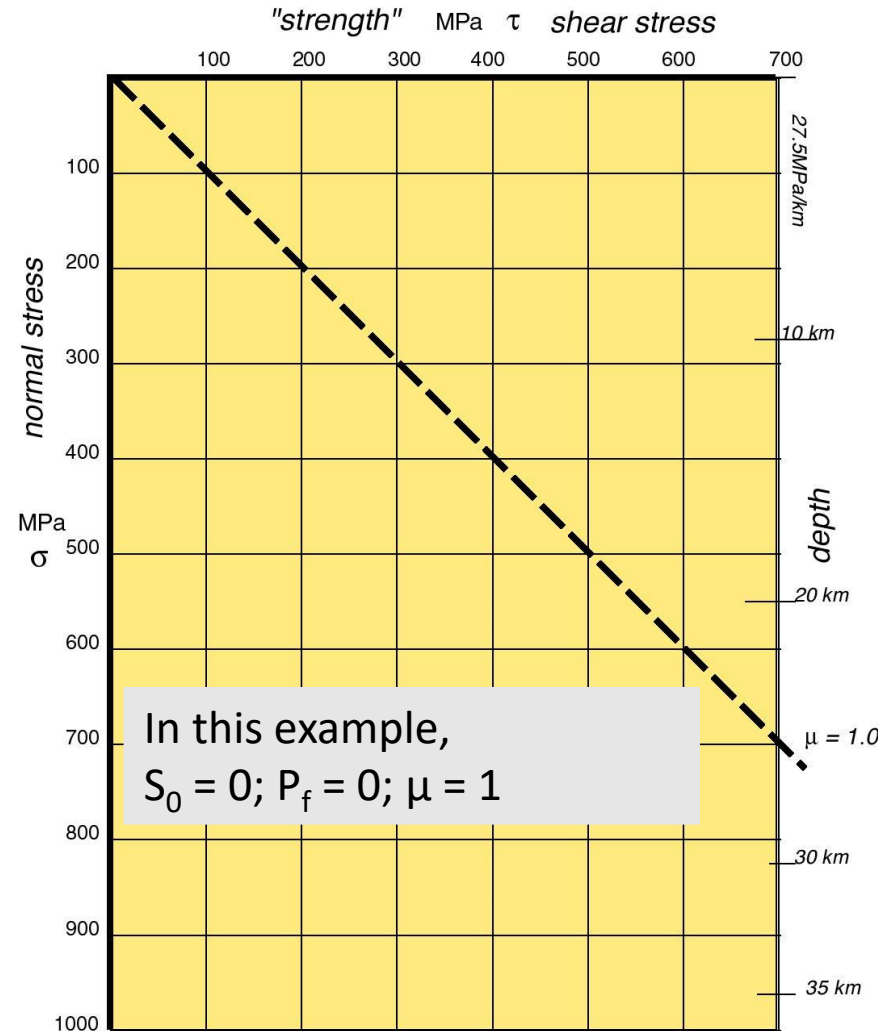
Strength: The total force per unit width necessary to deform a lithospheric section (at a given strain rate)

Shear stress: stress acting parallel to plane of reference

Normal stress: stress acting perpendicular to plane of reference

How does the Continental Lithosphere deform – Strength profile

Strength-depth relationships are very similar regardless of rock type – **for intact materials!**
IDEAL CRUSTAL STRENGTH –
Byerlee's Law:
 $\tau = S_0 + \mu(\sigma_n - P_f)$



Definitions –

Byerlee's Law: relationship between critical shear stress and normal stress

τ = shear stress

S_0 = cohesion (internal strength)

μ = coefficient of friction

σ_n = normal stress

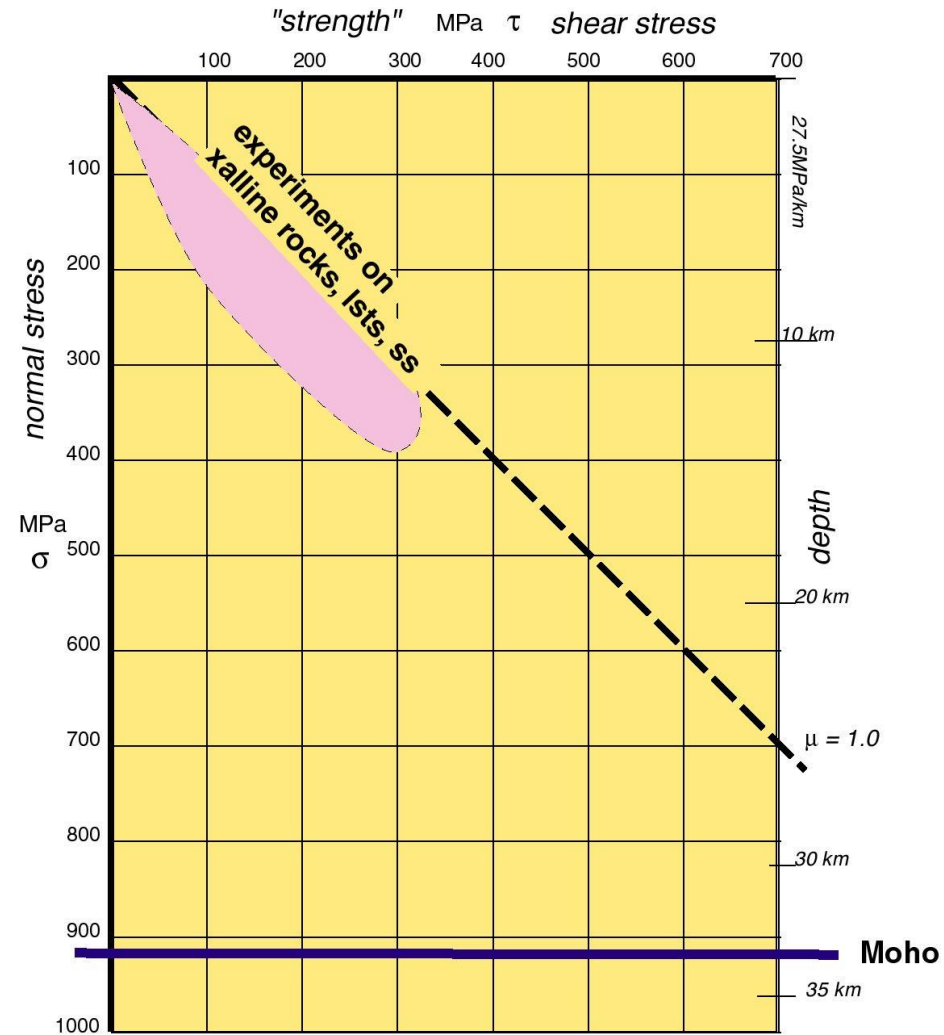
P_f = pore fluid pressure

Strength and Byerlee:

Use this law to define the brittle limit of failure in intact rock (e.g. 'strength')

How does the Continental Lithosphere deform – Strength profile

Strength-depth relationships are very similar regardless of rock type – **for intact materials!**
 IDEAL CRUSTAL STRENGTH –
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 $\tau = S_0 + \mu(\sigma_n - Pf)$

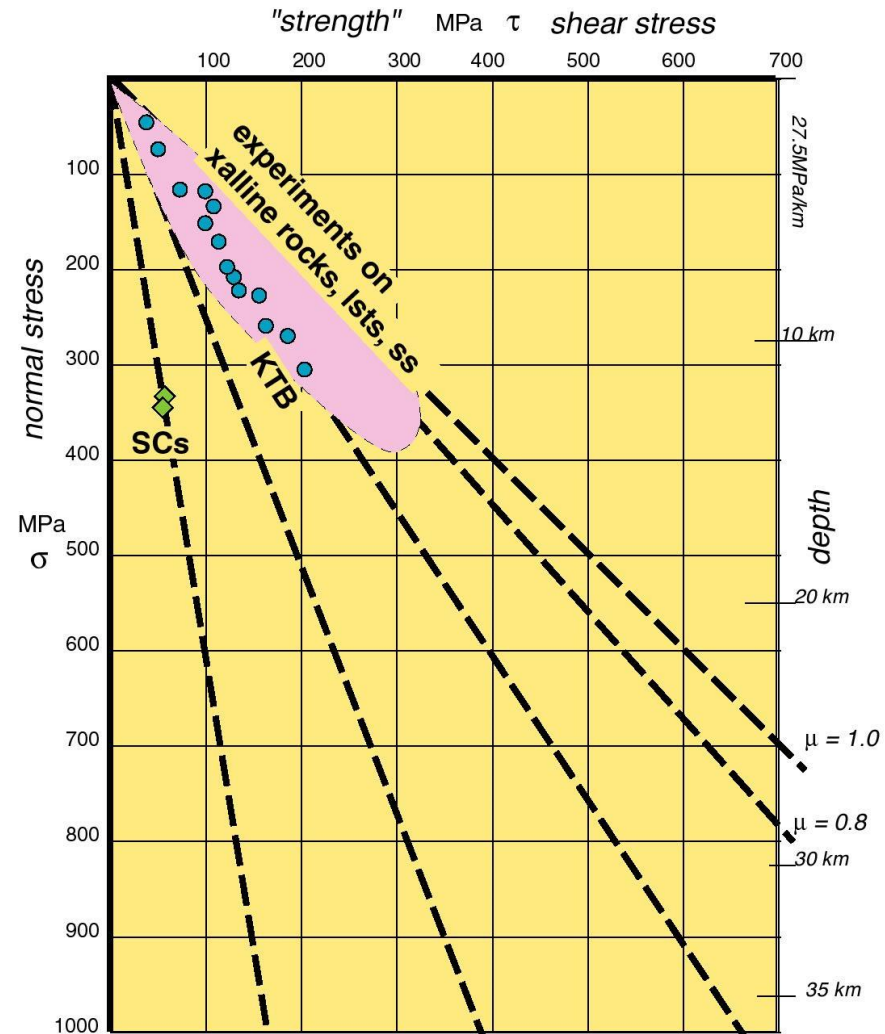


How does the Continental Lithosphere deform – Strength profile

Strength-depth relationships are very similar regardless of rock type – **for intact materials!**
 IDEAL CRUSTAL STRENGTH –
Byerlee's Law:
 $\tau = S_0 + \mu(\sigma_n - Pf)$

KTB = German Continental Deep Drilling Program

SCS = Single Channel Seismic



How does the Continental Lithosphere deform – Strength profile

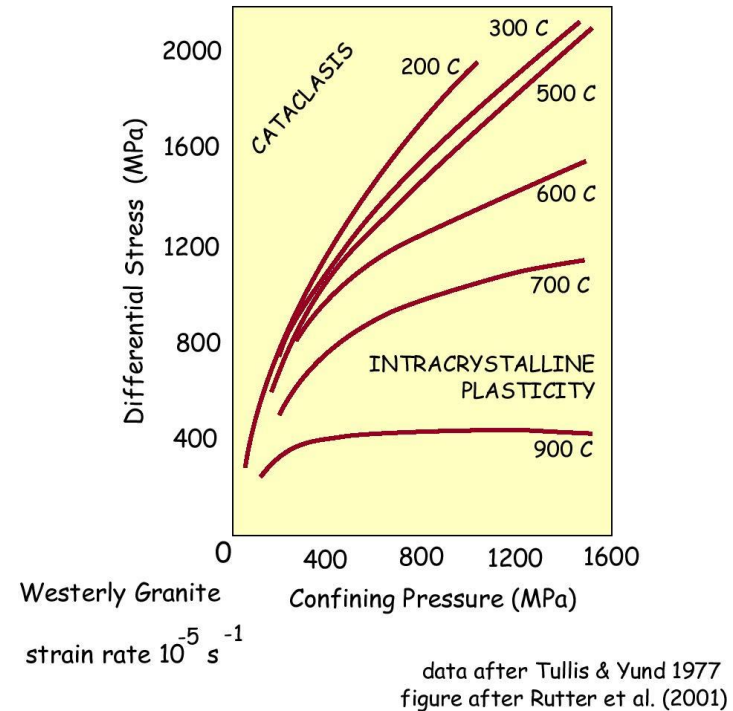
BUT...

at higher temperatures
(i.e. greater depths)
rocks deform in different ways.

With increasing T the strain
rate increases and rocks
deform by a plastic flow law

Temperature
increases with Depth:
GEOTHERM IMPORTANT

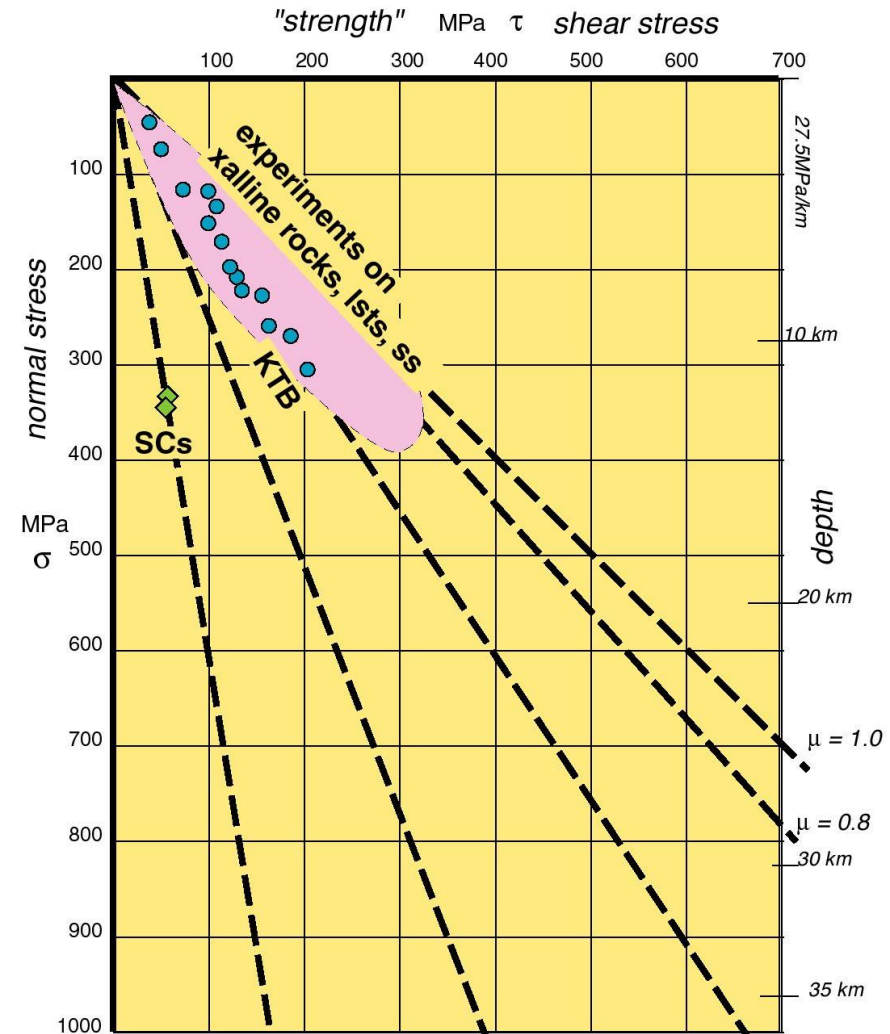
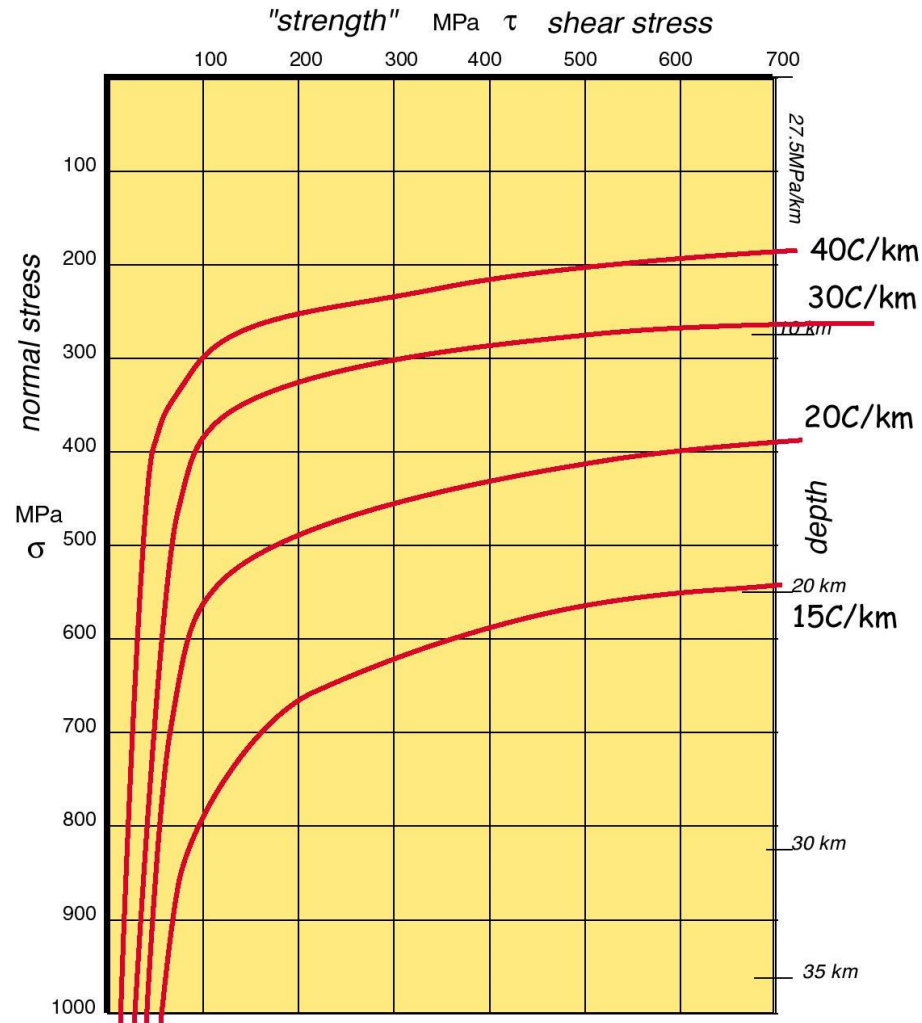
The basis for strength-depth profiles ?



	PRESSURE SENSITIVE	TEMPERATURE SENSITIVE
CATA	✓	✗
ICP	✗	✓

300 C

How does the Continental Lithosphere deform – Strength profile

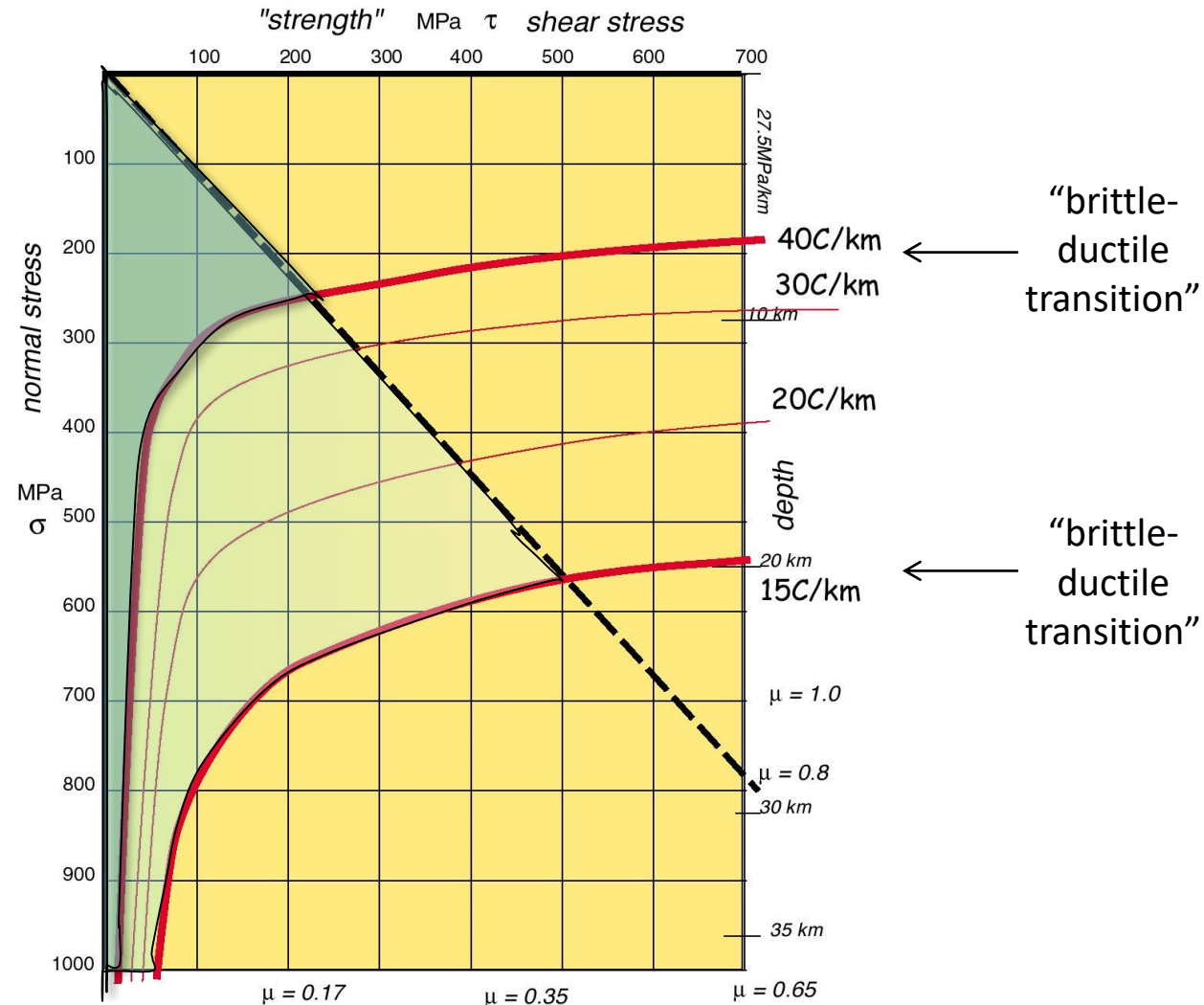


temperature-dependent rheology

$$\dot{\epsilon} = 10^{-12} \tau^{3.0}; \text{ fds } 70\% \quad \text{Handy et al. 1999}$$

How does the Continental Lithosphere deform – Strength profile

INTEGRATED STRENGTH PROFILE

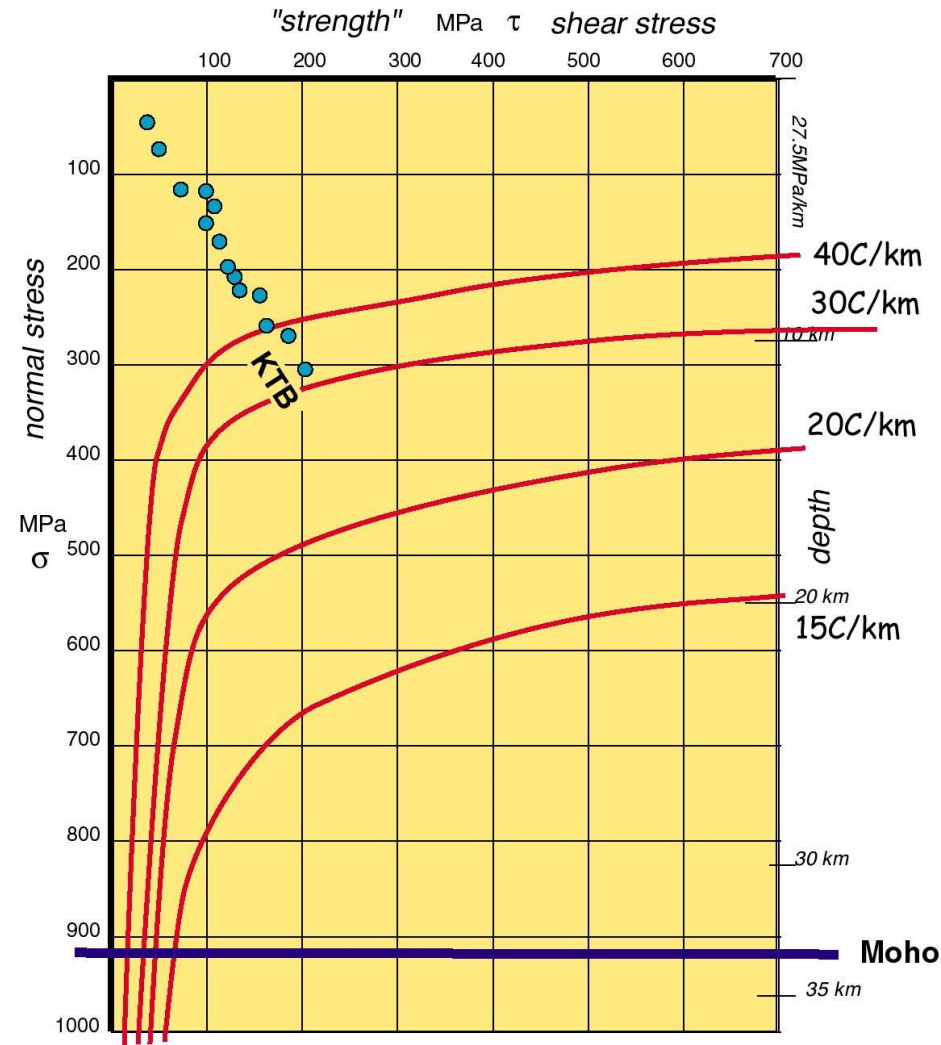


temperature-dependent rheology

$\dot{\epsilon} = 10^{-12}$ qz 30%; fds 70% Handy et al. 1999

How does the Continental Lithosphere deform – Strength profile

Strength profile at KTB



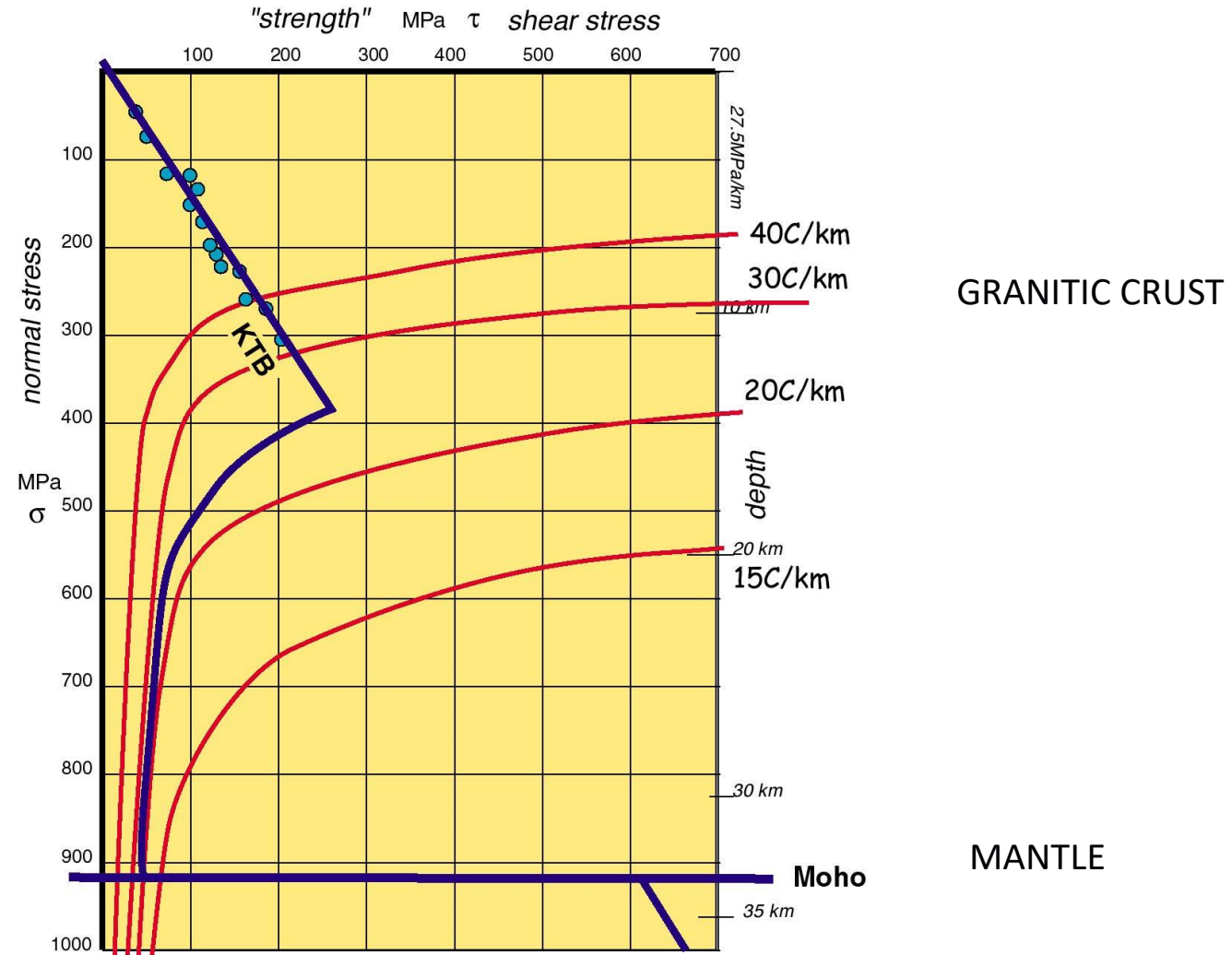
temperature-dependent rheology

$\dot{\epsilon} = 10^{-12}$ at 30%; $\dot{\epsilon} = 70\%$ Handy et al. 1999

How does the Continental Lithosphere deform – Strength profile

Strength profile at KTB

25°C/km



temperature-dependent rheology

$n = 10$

-12

-20

-30

-40

-50

-60

-70

-80

-90

-100

-110

-120

-130

-140

-150

-160

-170

-180

-190

-200

-210

-220

-230

-240

-250

-260

-270

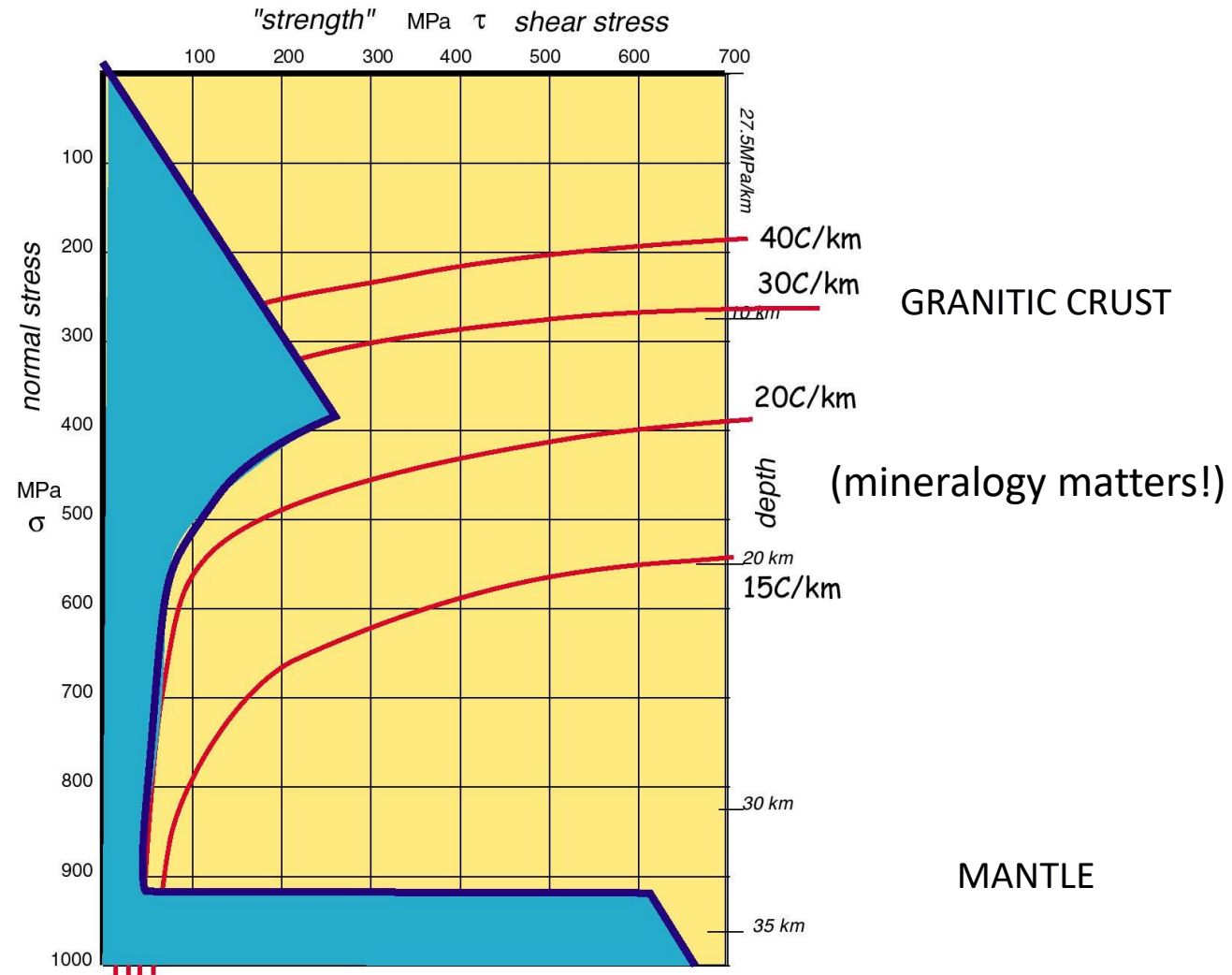
-280

-290

How does the Continental Lithosphere deform – Strength profile

Strength profile at KTB

25°C/km



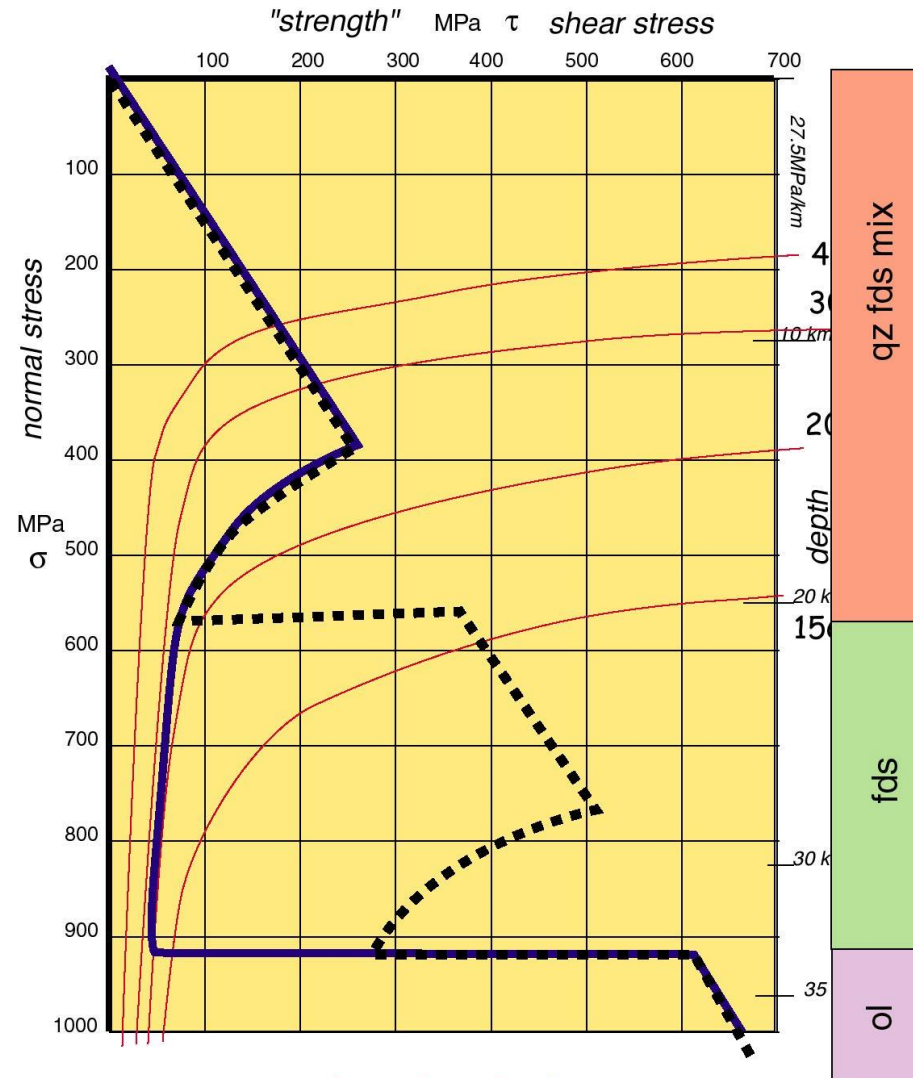
temperature-dependent rheology

$\dot{\epsilon} = 10^{-12}$ at 30% f_d 70% Handy et al. 1999

How does the Continental Lithosphere deform – Strength profile

Layered
rheology:

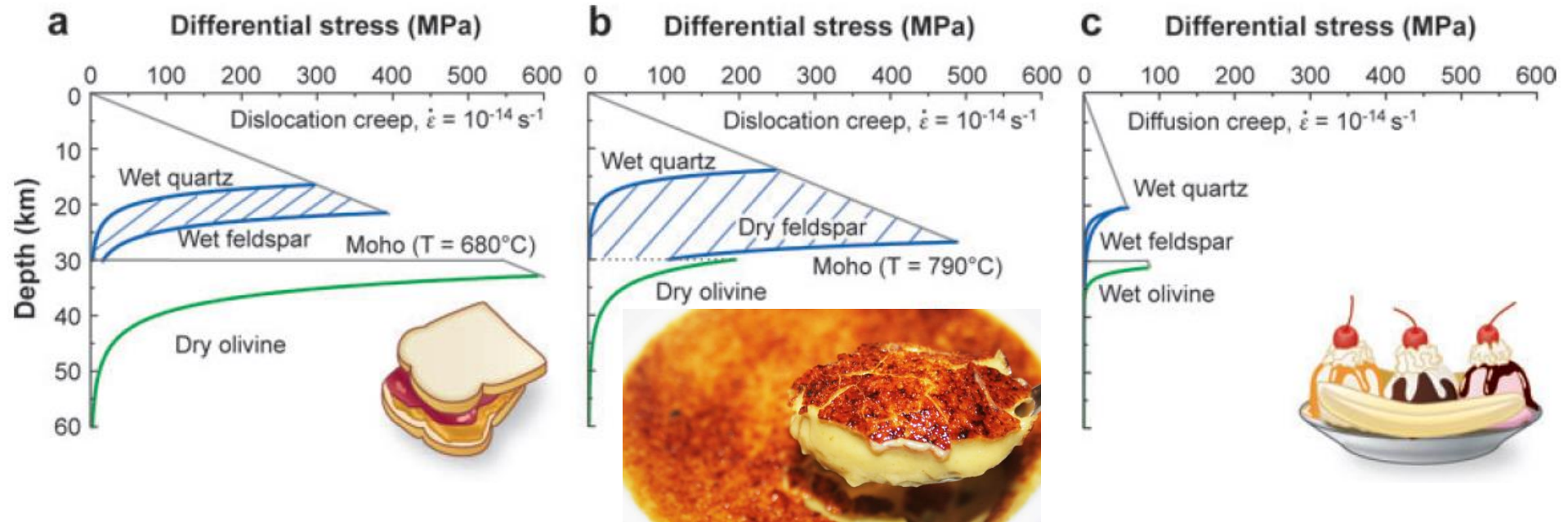
CHRISTMAS
TREE STRUCTURE!



temperature-dependent rheology

$\dot{\epsilon} = 10^{-12}$ at 30%: fds 70% Handy et al. 1999

How does the Continental Lithosphere deform – Strength profile



- “Rheology of the Lower Crust & Upper Mantle: Evidence from Rock Mechanics, Geodesy & Field Observations”

Bürgmann and Dresen, Annual Reviews (2008)

“How weak are the continents?” Rob Butler, Geoscientist (2006)

Recap deformation mechanisms and their relationship to T , stress, strain rate?

Principles of Deformation Mechanisms
Flow laws

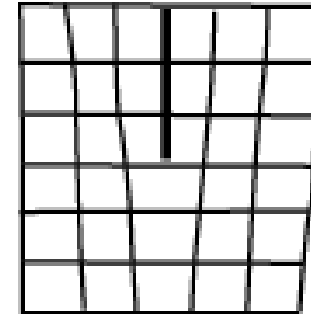
Many diagrams from Passchier & Trouw 2005 & deformation microstructure course (www.microstructure.info)

Ductile Deformation – Crystal plasticity - Basics

What is needed for intracrystalline deformation?

Defects - imperfections in the structure of a crystal

0-dimensional (point),
1-dimensional (dislocations)
2-dimensional (boundaries)



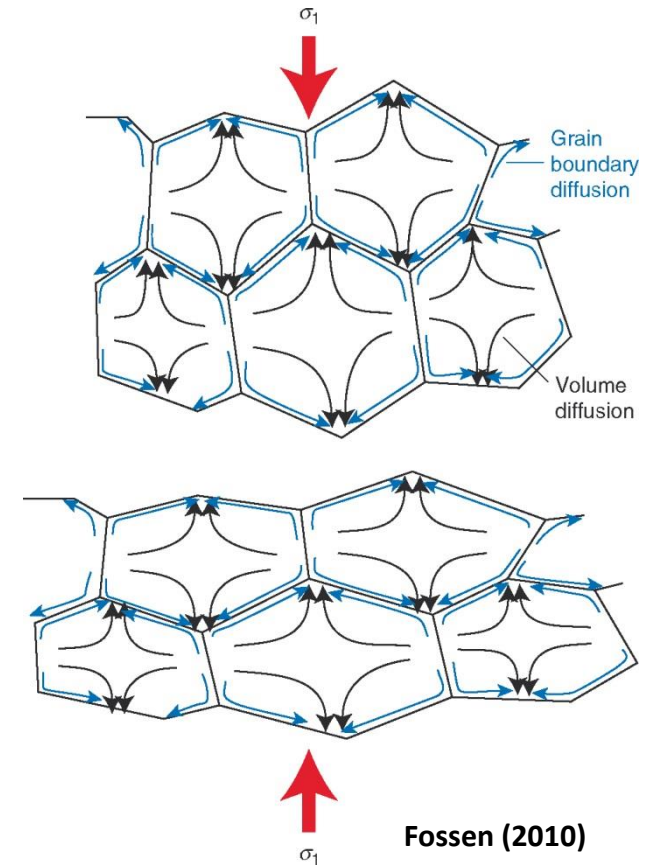
Why are defects so important?

Intimate involvement in several grain scale processes

 Provide driving force

Deformation by movement of lattice defects

- Point defects / Vacancies
 - Diffusion creep***
 - **Nabarro-Herring creep** - through
 - **Coble creep** – around
 - **Pressure Solution**
/ Dissolution-precipitation
- Line defects
 - **Dislocation glide/creep**



Flow Laws

Diffusional creep:

$$\text{Nabarro Herring creep: } \dot{\varepsilon} = \frac{\alpha D_{sd} \Omega}{kT} \frac{\sigma_n}{d^2}$$

$$\text{Coble creep flow law: } \dot{\varepsilon} = \frac{\alpha u D_{sd(gb)} \Omega}{kT} \frac{\sigma_n}{d^3}$$

Linear relationship
Stress Strain rate

Grain size dependence:
Dependent on exact
mechanism

Dissolution precipitation creep:

$$\text{diffusion control: } \dot{\varepsilon} = \frac{AC_E^* D_{fl} \Omega u (1-a)}{kT} \frac{\sigma}{d^3}$$

$$\text{reaction control: } \dot{\varepsilon} = \frac{I \Omega}{kT} \frac{\sigma}{d}$$

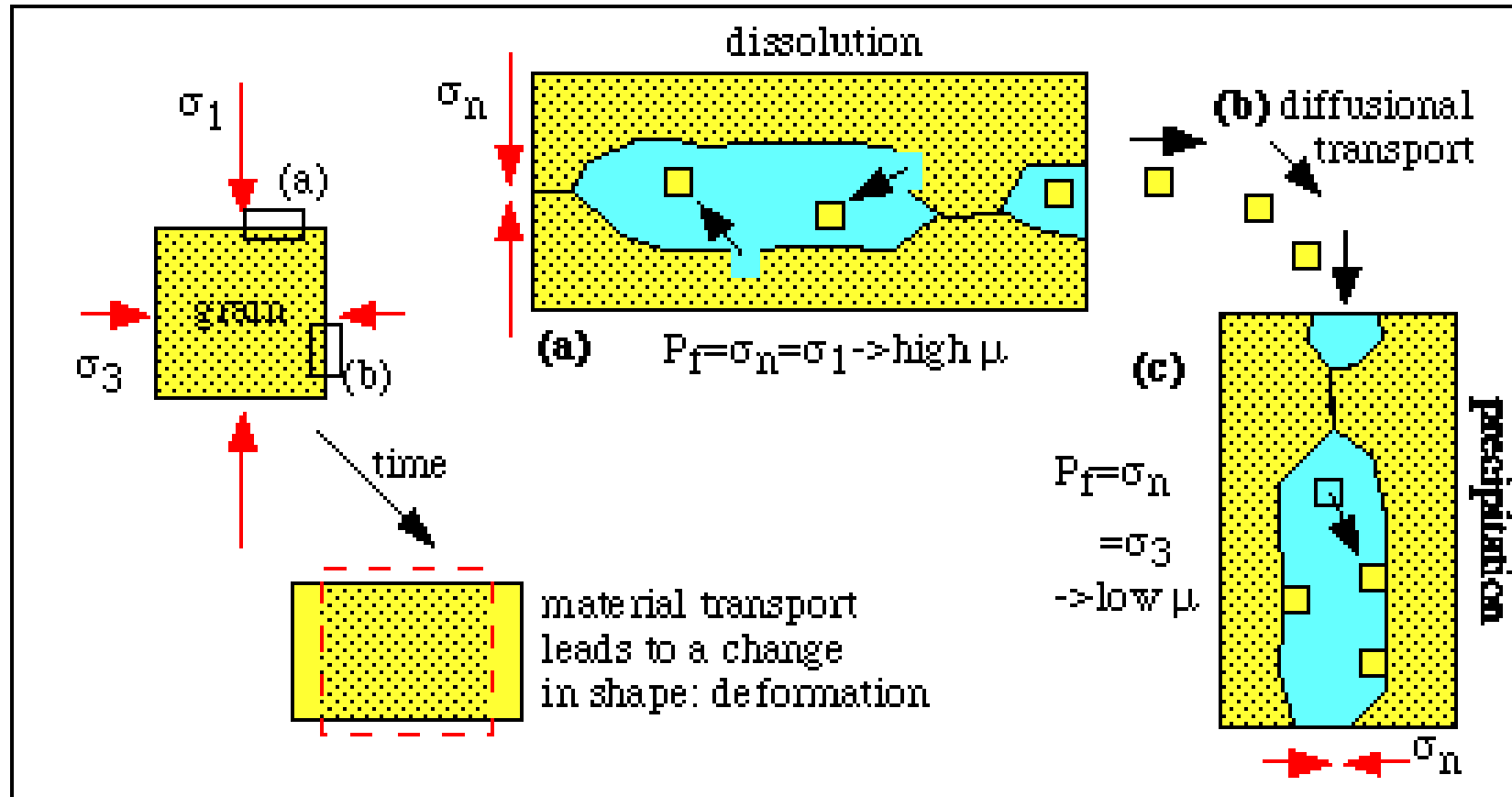
Linear relationship
Stress Strain rate

Grain size dependence:
Dependent on exact
mechanism

Dissolution precipitation creep – RATE CONTROL in a serial process

Dissolution-precipitation creep is a deformation mechanism that involves three serial steps.

Ions dissolve -> Diffusional transport in GB-fluid -> Ions precipitate

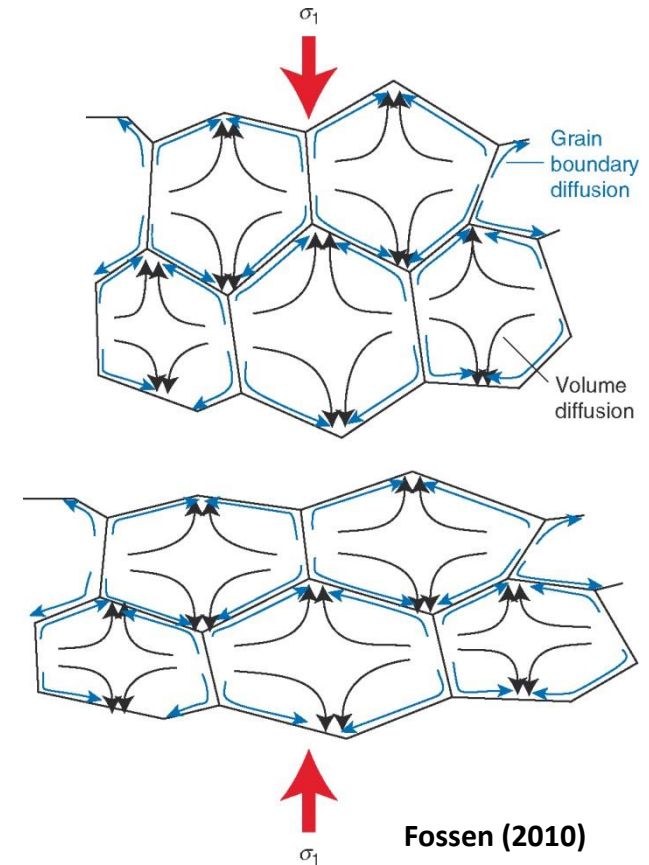


Therefore: Rate is controlled by the rate of one of these serial steps

Deformation by movement of lattice defects

- Point defects / Vacancies
 - Diffusion creep***
 - **Nabarro-Herring creep** - through
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 - **Pressure Solution**
 - / Dissolution-precipitation**

- Line defects
 - **Dislocation glide/creep**



Intracrystalline plasticity – 2 main types

1. dislocation glide; & 2. dislocation climb (dislocation creep).

Exponential relationship
between strain-rate &
stress (i.e. Dorn Law):

$$\dot{\epsilon} = \dot{\epsilon}_0 \exp \left\{ -F(1 - \sigma / \sigma_p) / RT \right\}$$

strain-rate & stress
subscript terms values at
0°K; F, constant.

*Not considered important
in most minerals due to
high stresses needed at
geological conditions (n.b.
crystal slip not same as
dislocation glide as climb
also involves slip).*

Power law relationship: $\dot{\epsilon} = A \exp(-Q_c / RT) \sigma^n$

A, pre-exponential constant; Q_c , activation enthalpy for
dislocation creep; n, stress exponent.

Does not include H₂O – ‘dry’ quartz 10x stronger than
‘wet’ (Si-O-Si bonds replaced by weaker Si-OH-OH-Si
hydroxyl bonds – hydraulic or water weakening effect).

Constant n also depends on H₂O content.

Mean stress also omitted – increases water diffusion
rates, water solubility & activation enthalpies.

Impurities may be important (e.g. in quartz) – cause
considerable weakening through control of dislocation
glide velocities.

General flow law for rocks:

$$\dot{\epsilon} = A \cdot \exp\left(-\frac{Q}{kT}\right) \cdot \frac{\sigma^n}{d^m}$$

How to determine A, Q, n, m ?

In logarithmic space: $\ln(\dot{\epsilon}) = \ln\left(A \cdot \exp\left(-\frac{Q}{kT}\right) \cdot \frac{\sigma^n}{d^m}\right)$

Experimentally

$$\Leftrightarrow \ln(\dot{\epsilon}) = \ln(A) - \frac{Q}{kT} + n \ln(\sigma) - m \ln(d)$$

A, Q, n, m can all be determined by from

- plots in log-log space

- linear fits

stress exponent: $\left(\frac{d \ln(\dot{\epsilon})}{d \ln(\sigma)}\right)_{T,d} = n$

grain size exponent: $\left(\frac{d \ln(\dot{\epsilon})}{d \ln(d)}\right)_{T,\sigma} = -m$

activation energy: $\left(\frac{d \ln(\dot{\epsilon})}{d(1/T)}\right)_{d,\sigma} = -\frac{Q}{k}$

Experimental empirical laws

$$\dot{\epsilon} = A \exp \left\{ \left(-Q + PV \right) / RT \right\} d^{-m} \sigma^n$$

A : pre-exponential constant; Q , activation energy; P , mean stress; V , activation volume (often ignored); d , grain size; σ , stress; m & n : dimensionless grain size & stress exponents.

$m = 0, n \geq 3$ - dislocation creep;

$m = 2, n = 1$ - DPC1/ Cobble creep;

$m = 3, n = 1$ - DPC1 /Nabarro-Herring creep;

$m = 2-3, n = 1-3$

– superplasticity/ grain boundary sliding accommodated by different mechanisms (dislocation climb ($n=2$)/ diffusion ($n=1$))

Table 9.2. Parameters for grain-size sensitive flow laws. V is molar volume, GBM is grain boundary migration.

Mineral	$A, m^m \text{MPa}^{-n} \text{s}^{-1}$	Q, Jmol^{-1}	n	m	Wet/Dry	Deformation mechanism, notes	References
Synthetic Calcite	8.511 e 4	1.90 e 5	1.7	1.87	Dry	$\sigma < 25 \text{ MPa}$, $2 < d < 40 \mu\text{m}$, grain boundary sliding	Walker et al. 1990
Synthetic Calcite	100	1.90 e 5	3.3	1.34	Dry	$25 < \sigma < 200 \text{ MPa}$, $2 < d < 40 \text{ mm}$, dislocation creep	Walker et al. 1990
Olivine	6.079 e -13	3.00 e 5	1	2.5	Dry	Diffusion creep: $V = 6 \text{ e}^{-6} \text{ m}^3 \text{mol}^{-1}$	Karato & Wu 1993
Olivine	3.703 e -13	2.40 e 5	1	2.5	Wet	Diffusion creep: $V = 5 \text{ e}^{-6} \text{ m}^3 \text{mol}^{-1}$	Karato & Wu 1993

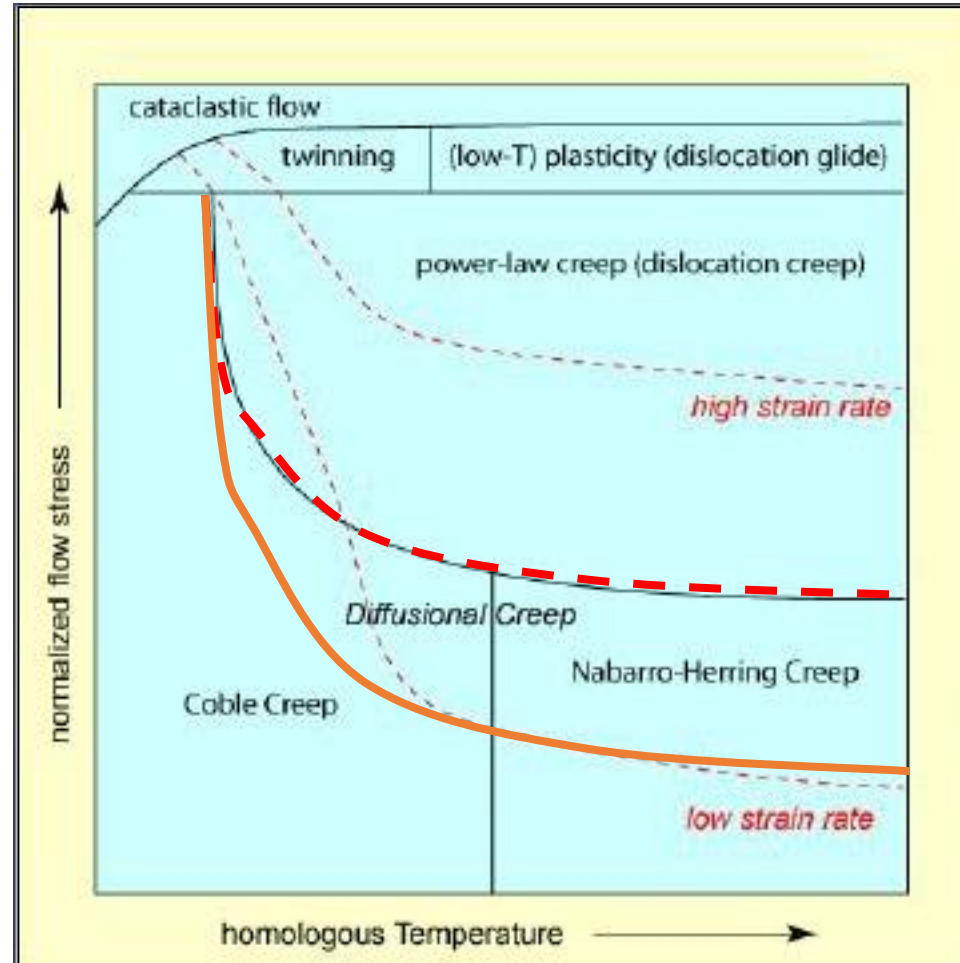
Table 9.3. Parameters for grain-size insensitive flow laws for minerals.

Mineral	$A, m^m \text{MPa}^{-n} \text{s}^{-1}$	Q, Jmol^{-1}	n	Wet/Dry	Deformation mechanism, notes	References
Calcite	1.549 e -4	3.62 e 5	11.5	Dry	σ_1 parallel to [4041], single crystal	De Bresser & Spiers 1990
Quartz	1.2 e -6	9.33 e 4	3.0		O+ orientation, single crystal, $< c >$ slip	Linker & Kirby 1986
Quartz	6.3 e -5	2.13 e 5	5.3		$\perp m$ orientation single crystal, $< a >$ slip	Linker & Kirby 1986
Olivine	2.422 e 5	5.4 e 5	3.5	Dry	Dislocation creep	Karato & Wu 1993
Olivine	3.906	4.3 e 5	3.0	Wet	Dislocation creep	Karato & Wu 1993
Diopside	7.94 e -5	2.84 e 5	4.3	Dry	$\sigma < 700 \text{ MPa}$	Avé Lallement 1978
Diopside	1.58 e -8	4.42 e 5	6.5		Orientation 1	Raterron & Jaoul 1991
Diopside	3.16 e 8	7.42 e 5	8.1		Orientation 2	Raterron & Jaoul 1991
Hedenbergite	2.00 e 8	5.26 e 5	3.6	Wet		Kollé & Blacic 1983

Table 9.4. Parameters for grain-size insensitive flow laws for rocks. Asterisk indicates refitting of original data by Carter and Tsenn (1987)

Rock	$A, m^m \text{MPa}^{-n} \text{s}^{-1}$	Q, Jmol^{-1}	n	Wet/Dry	Deformation mechanism, notes	References
Rocksalt	8.1 e -5	51.6 e 3	3.4	Dry	$\sigma < 10 \text{ MPa}$, creep	Carter et al. 1993
Rocksalt	1.6 e -4	68.1 e 3	5.3	Dry	$\sigma > 10 \text{ MPa}$, glide	Carter et al. 1993
Anhydrite	31.6	1.52 e 5	2		Dislocation glide	Muller & Briegel 1978
Marble	1260	4.18 e 5	7.6		Subgrains, GBM	Schmid et al. 1980
Marble	1.995 e 4	2.13 e 5	1.7		grain boundary sliding	Schmid et al. 1977
Quartzite	Choose correctly	1.52 e 5	2.5	Wet	Various; best estimate from average values	Paterson & Luan 1990
Quartzite	6.5 e -8	1.35 e 5	3.1	Wet	Low to moderate grade	Paterson & Luan 1990
Granite	1.995 e -6	1.87 e 5	3.3	Dry	Semibrittle	Hansen & Carter 1983
Granite	1.995 e -4	1.41 e 5	1.9	Wet	Semibrittle	Hansen & Carter 1983
Albitite*	5.012 e -3	2.45 e 5	2.8	Dry	Dislocation glide, creep	Shelton et al. 1981
Diorite	3.162 e -2	2.12 e 5	2.4	Wet	Semibrittle	Hansen and Carter 1982
Diabase	6.310 e -2	2.76 e 5	3.1	Dry	Dislocation glide	Caristan 1982
Websterite*	3.162 e 5	3.23 e 5	4.3	Dry		Avé Lallement 1978
Websterite	1.99 e -5	3.82 e 5	5.3	Wet	High strain	Avé Lallement 1978
Websterite	3.16 e 3	4.63 e 5	3.3	Wet	Low strain	Avé Lallement 1978
Pyroxenite*	1.584 e -8	3.30 e 5	5.8	Dry	High T, clinopyroxenite	Kirby & Kronenburg 1984
Pyroxenite	1.479 e 5	4.90 e 5	3.3	Wet	clinopyroxenite	Boland & Tullis 1986
Lherzolite	4.5 e 5	5.18 e 5	4.0	Dry		Berckhemer et al. 1979

Deformation mechanism map

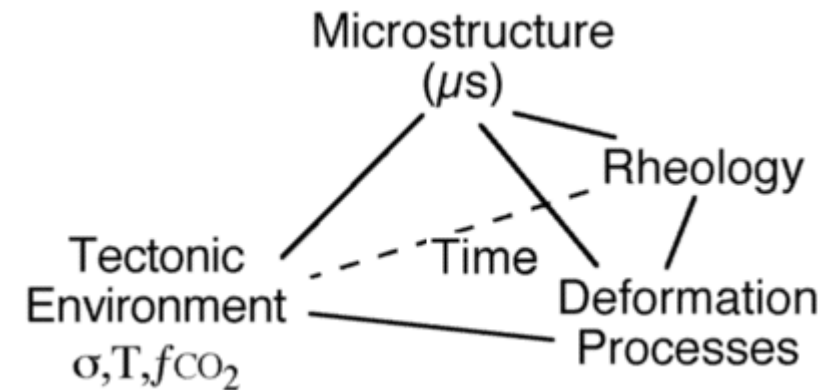


Change of crossovers with grain size?  100 micron
 10 micron

Rheology derived from the outcrop/rock- microstructures. How?

**Know
your
processes**

- 1) By understanding/interpreting how a microstructure forms we can derive the conditions under which it has formed
- 2) As grain scale processes control the macroscopic behaviour of rocks, microstructures can tell us about the processes that led to the microstructures -> flow law/rheology of a rock

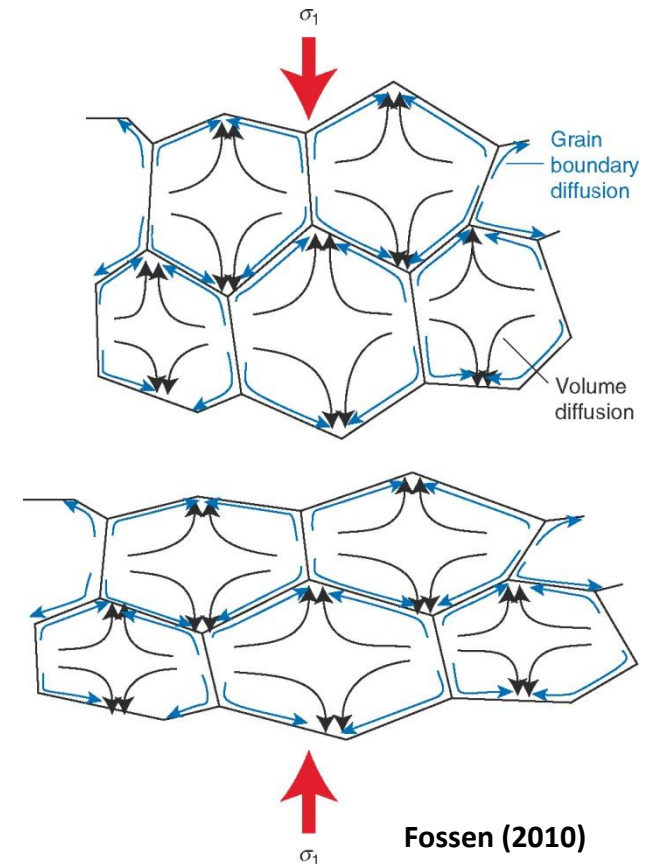


Remember: Deformation by movement of lattice defects

Know
your
processes

- Point defects / Vacancies
 - Diffusion creep***
 - Nabarro-Herring creep - through
 - Cobble creep – around
 - Pressure Solution
 - / Dissolution-precipitation

- Line defects
 - Dislocation glide/creep

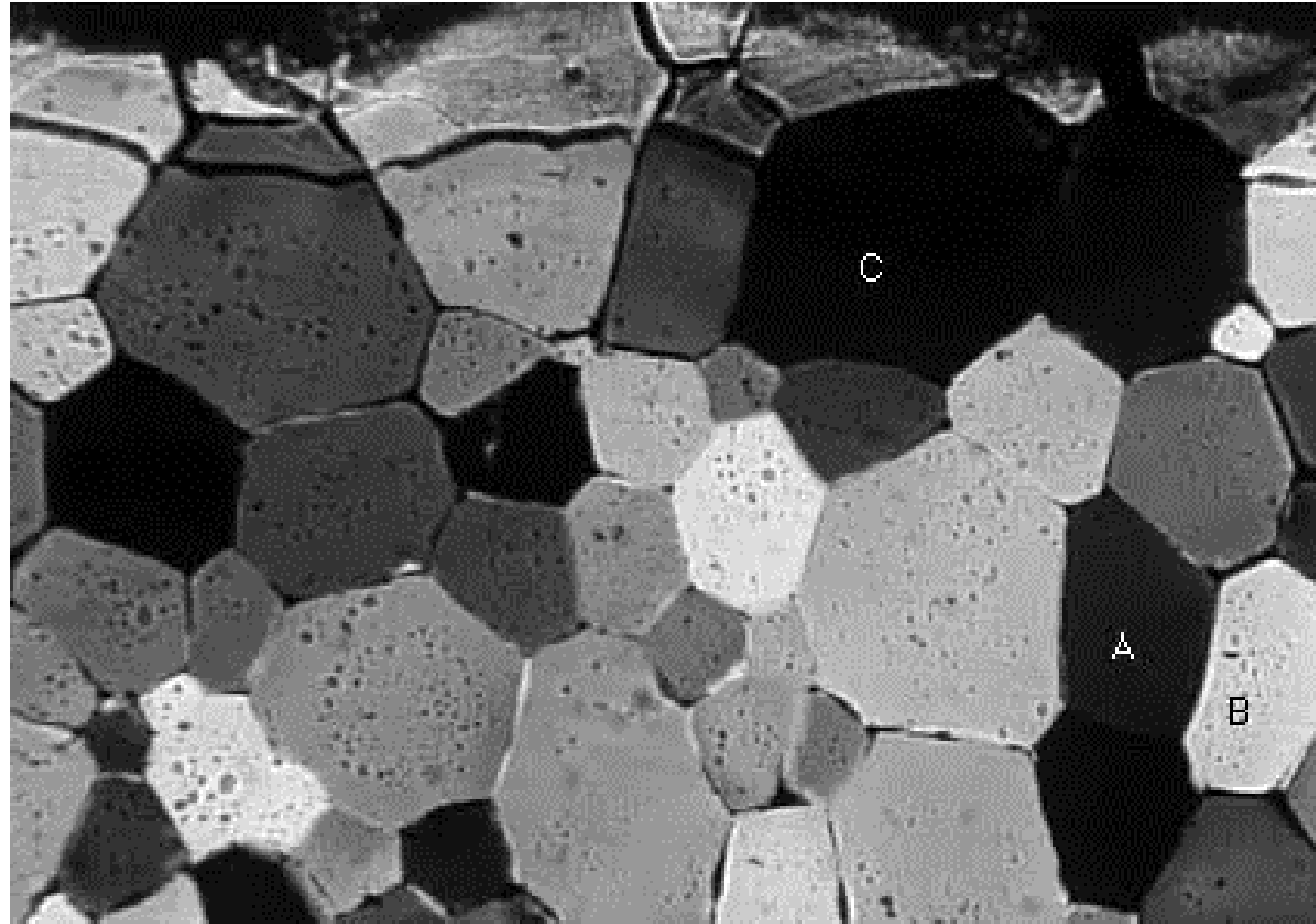


But how does that look in the rock microstructure

Dislocation creep/ Dynamic Recrystallization

**Know
your
processes**

Analog model:
Organic crystalline
material



Means, 1986

Recrystallization: change in microstructure whereby the grain configuration changes; several grain scale processes are involved

Dynamic recrystallization: recrystallization occurring during deformation

Annealing: recrystallization occurring without deformation - often called *Static recrystallization*

Metadynamic recrystallization: recrystallization occurring without deformation but after deformation

Dynamic Recrystallization

General: intra and intercrystalline deformation **during** deformation

**Know
your
processes**

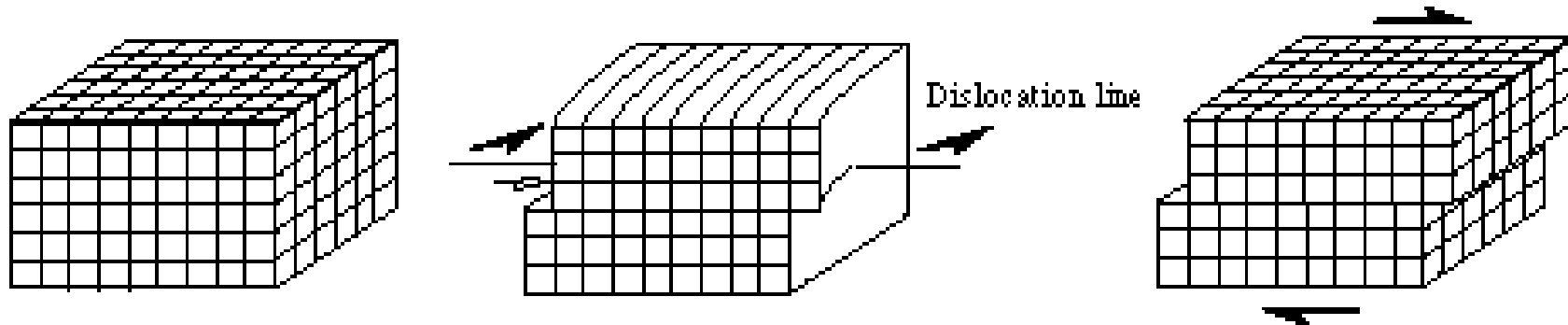
- 1) Shape change of grains
- 2) Subgrain Formation & Recovery
- 3) Small grains -> Rotational Recrystallization
- 4) Small grains -> Recrystallization by nucleation
- 5) Grain Boundary Migration
- 6) Grain Boundary Sliding

1) Shape change by movement of dislocations

Observation: shape change

How?

- 1) Prerequisite: dislocations within the crystal
- 2) dislocation movement



➔ *Result:* shape change and lattice distortion

lattice
distortion/
undulose
extinction



When do we get a lot of defects/dislocations in a crystal?

- High stress
- High strain rate
- low T conditions

2) Subgrain formation & Recovery

Observation: subgrains form in deformed grains

How?

1) dislocations within the crystal

2) free energy in the system is high

 system wants to lower its energy

How can the free energy be lowered?

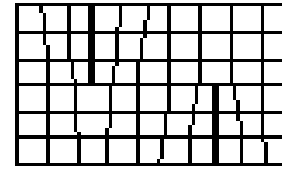
Dislocations must be

A) removed or

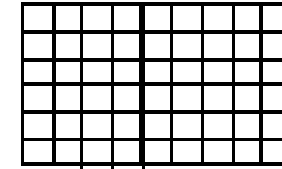
B) organized in low energy configurations

- How is energy decreased?

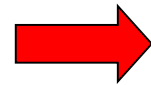
- annihilation of dislocations



Opposite dislocation
edges

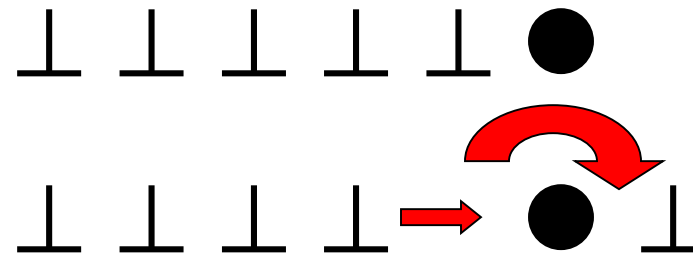


Annihilation

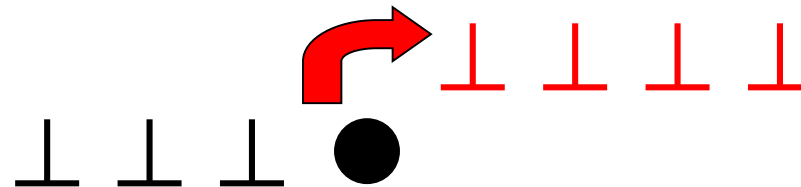


Result: less lattice distortion/
less dislocations

- Overcoming of "pile-ups"

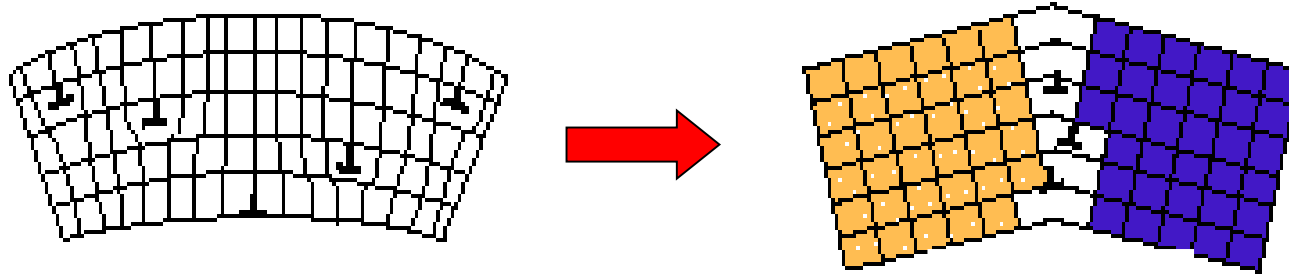


- Dislocation climb



B) Subgrain formation

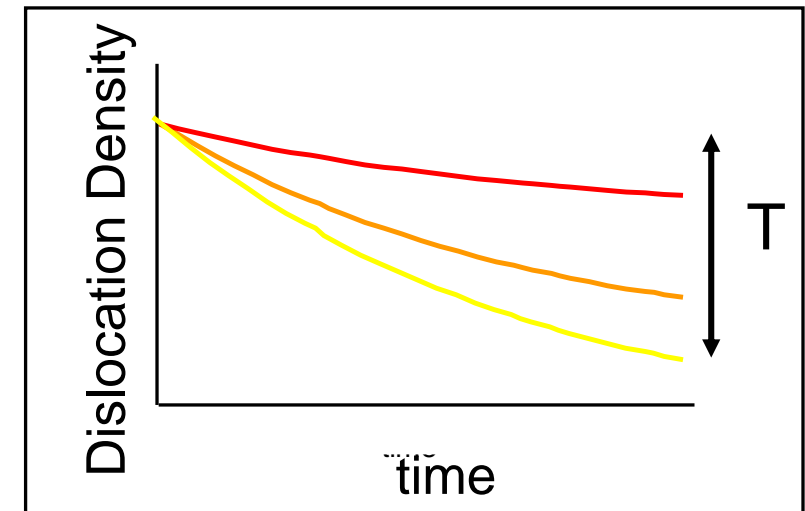
- organization/movement of dislocations into low energy configurations



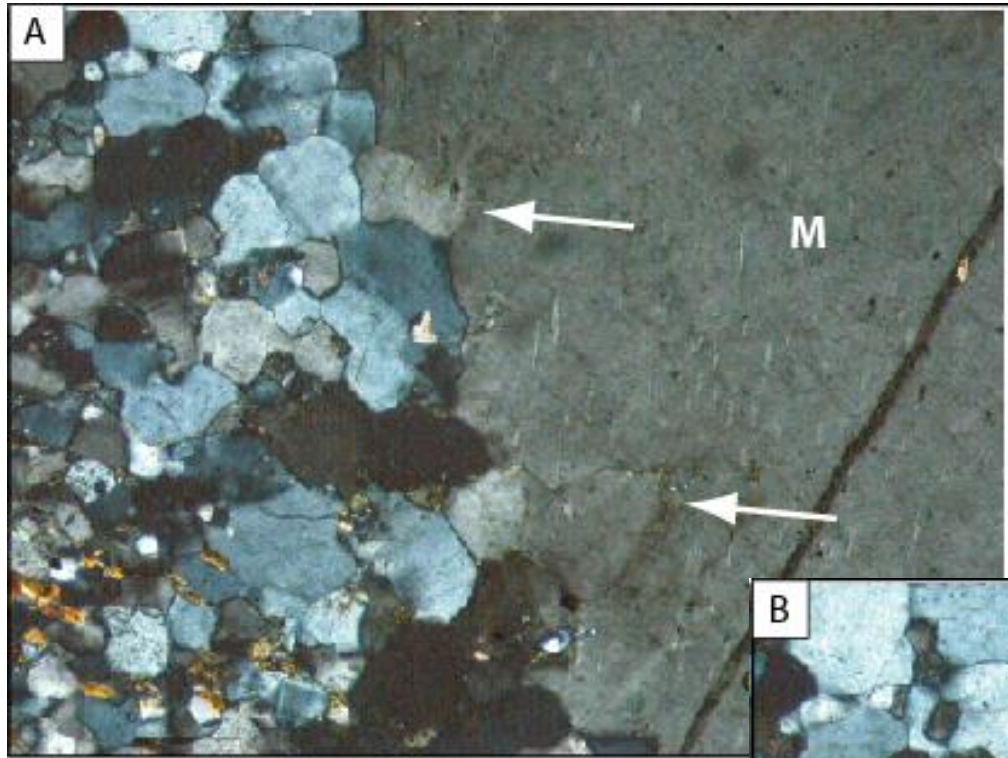
Result:

Formation of dislocation arrays /
subgrain boundaries

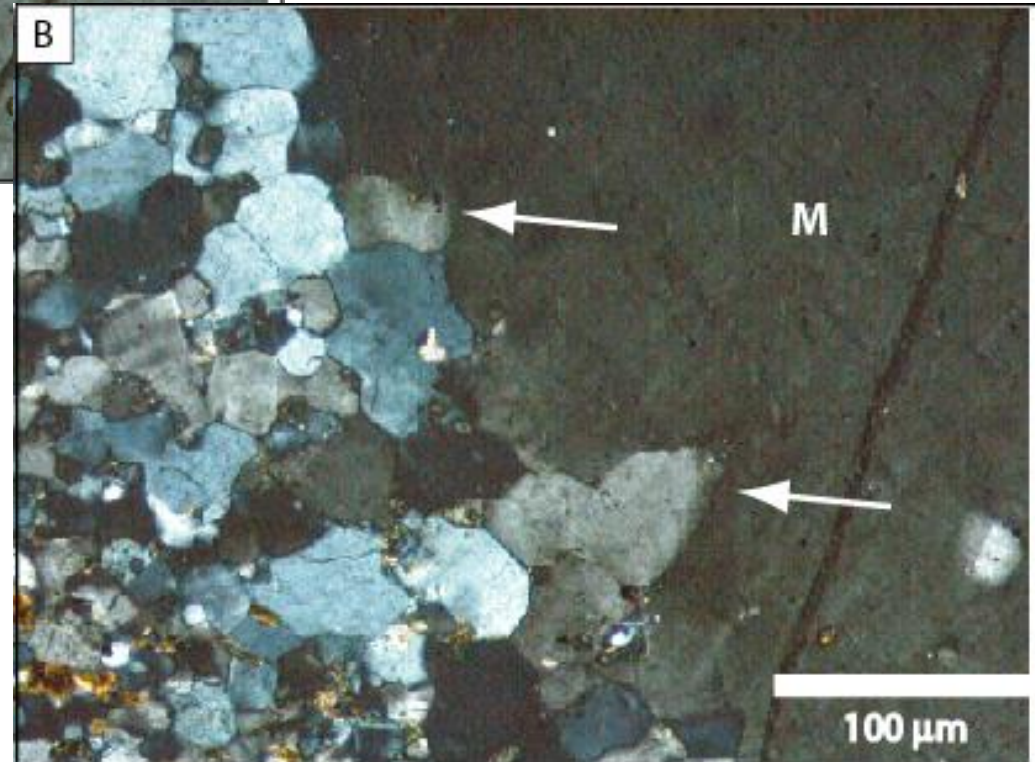
Temperature versus
Rate of Recovery



?



Subgrains



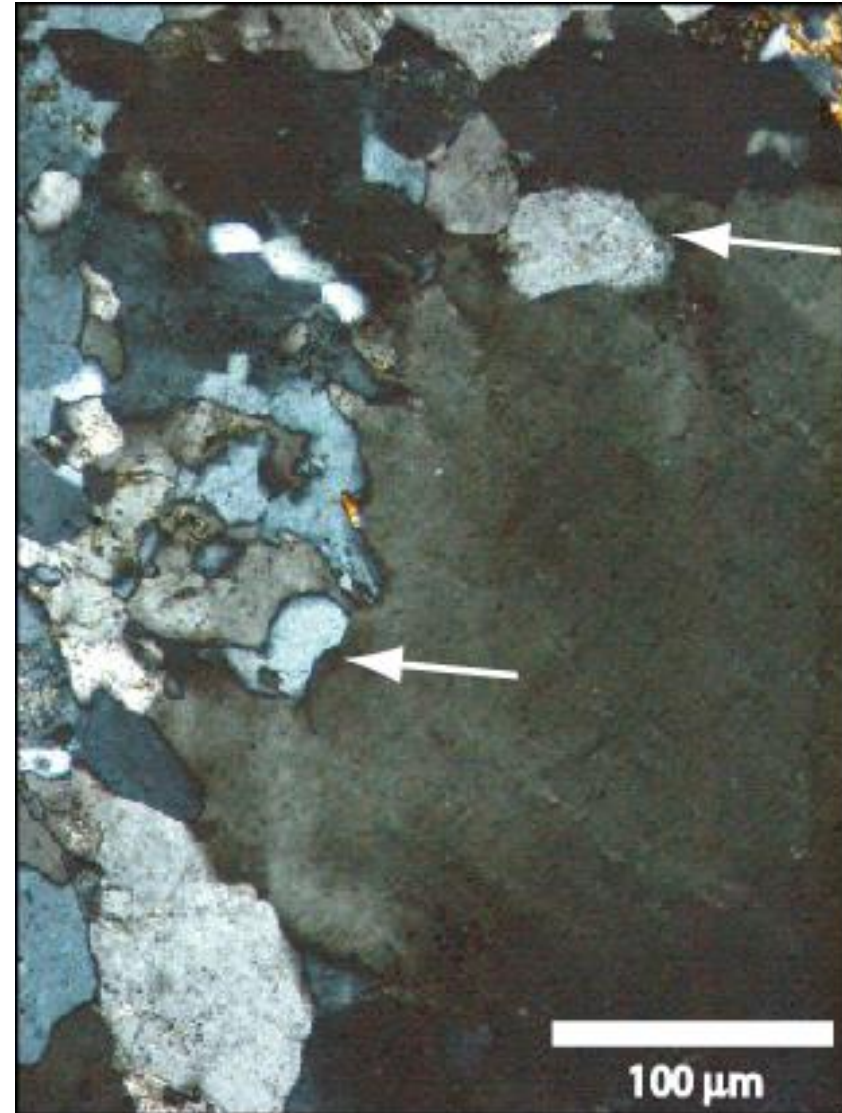
3 & 4) Appearance of new grains - recrystallization

Observation: appearance of
new grains

How?

3) Rotational
Recrystallization

4) Recrystallization by
nucleation



3) New grains – rotational recrystallization

Observation: new grains

How?

1) dislocations within the crystal

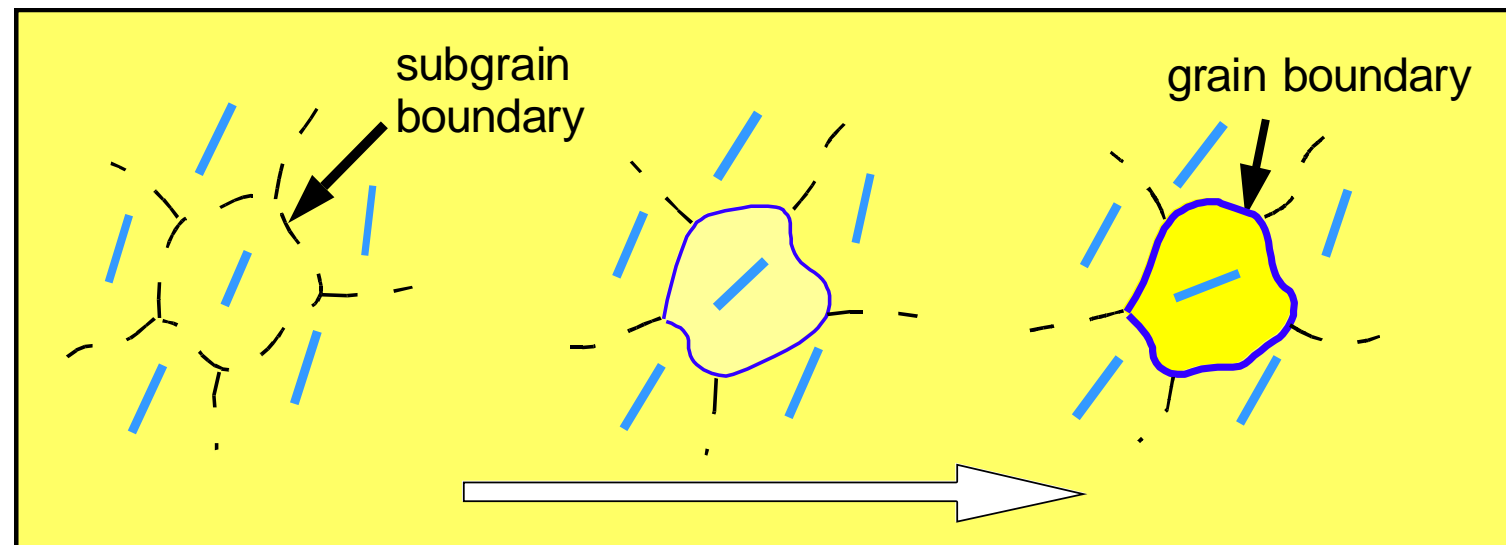
2) Free energy in the system is high

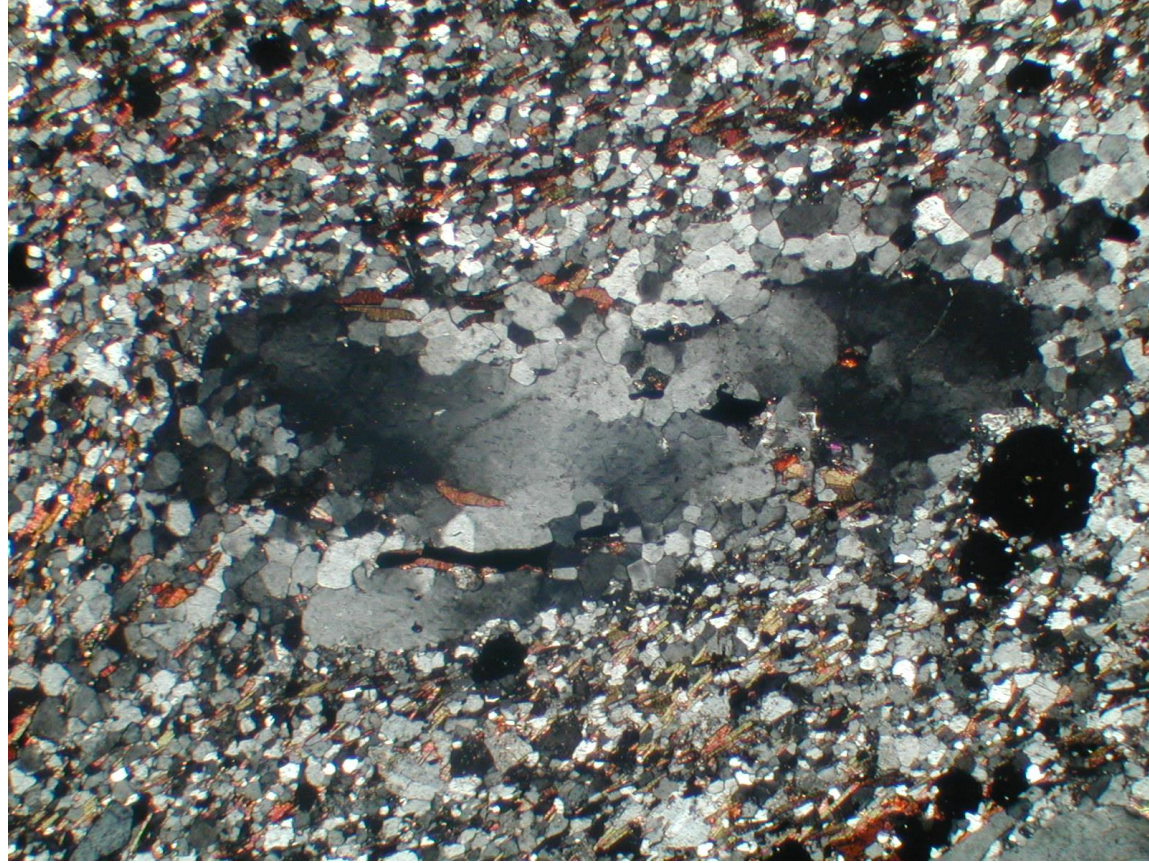
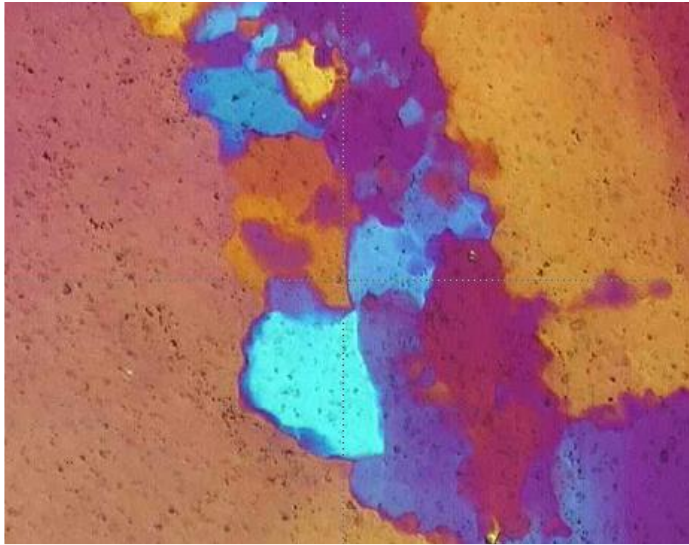
→ lower energy by putting more and more dislocations into the subgrain boundary

→ Rotation of subgrain

Result:

New grain
lower dislocation density





*Note: Angle of Mismatch to distinguish between subgrain
and grain boundary is mineral dependent*



Qtz $\approx 10^\circ$

Fsp $\approx 5 - 10^\circ$

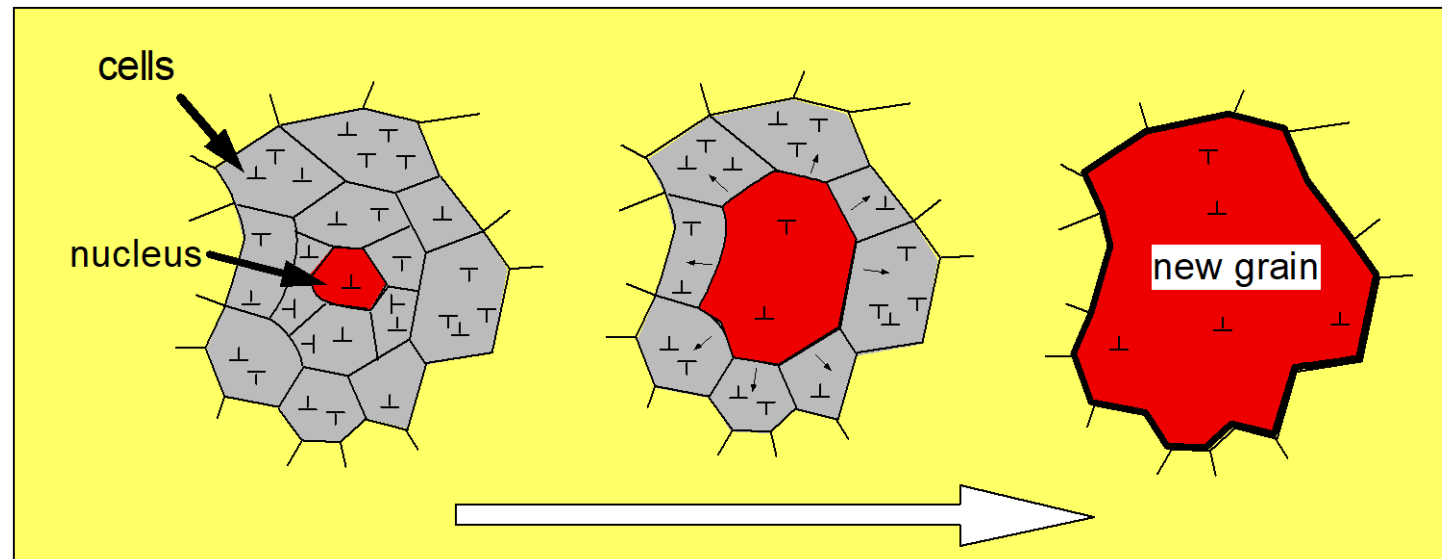
3) New grains – recrystallization by nucleation

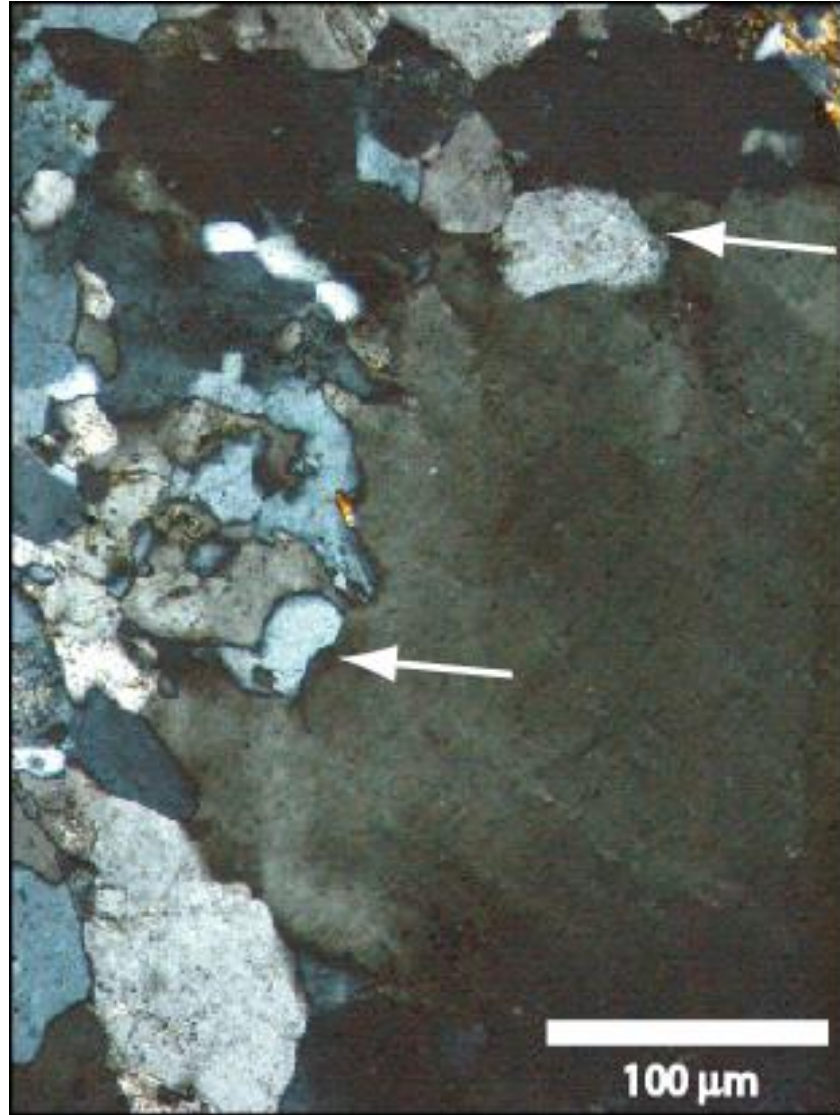
Observation: new grains

How?

- 1) dislocations within the crystal  small cells develop
- 2) These cells have different amount of dislocations
 rapid growth of nucleus

Result:
New
grain,
Low
disloca-
tion
density



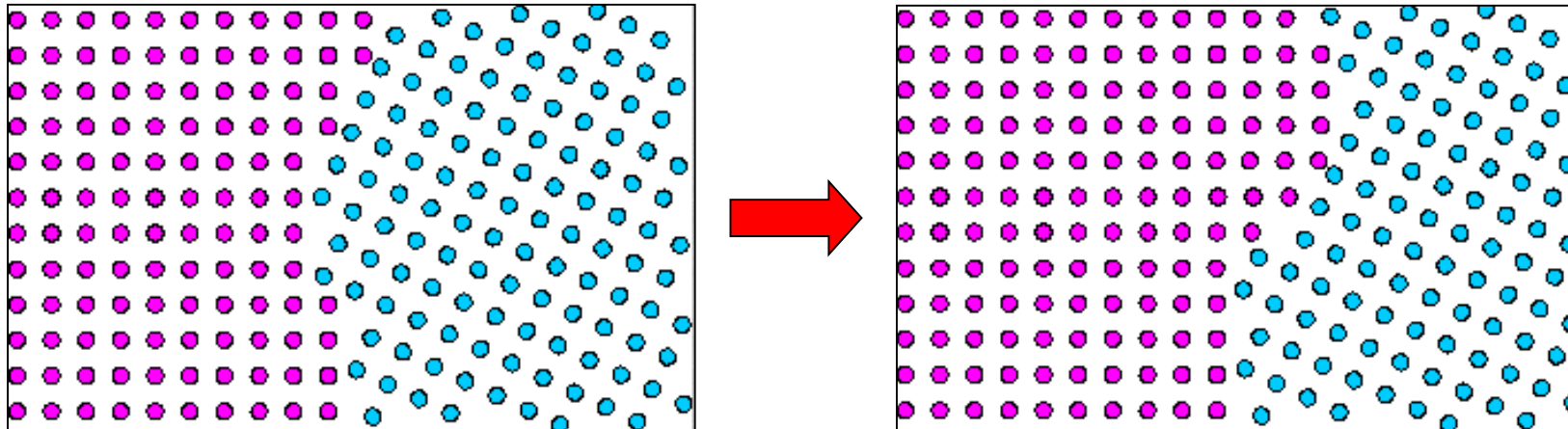


5) Grain boundary migration

Observation: grain boundaries move/migrate

How?

- 1) One atom from one grain moves to next grain
- 2) Group of atoms jump from one to the next grain



Why?

1) System has high energy

 system wants to lower the energy

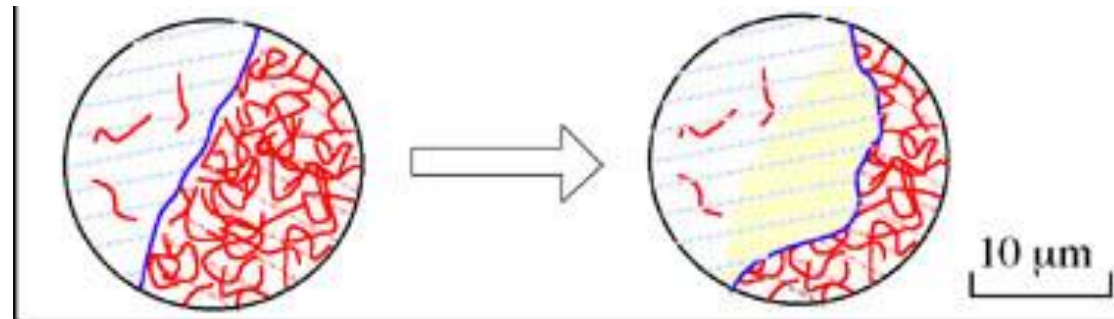
Reasons for high energy of system?

1. High dislocation density

2. Lots of boundaries

How to lower energy?

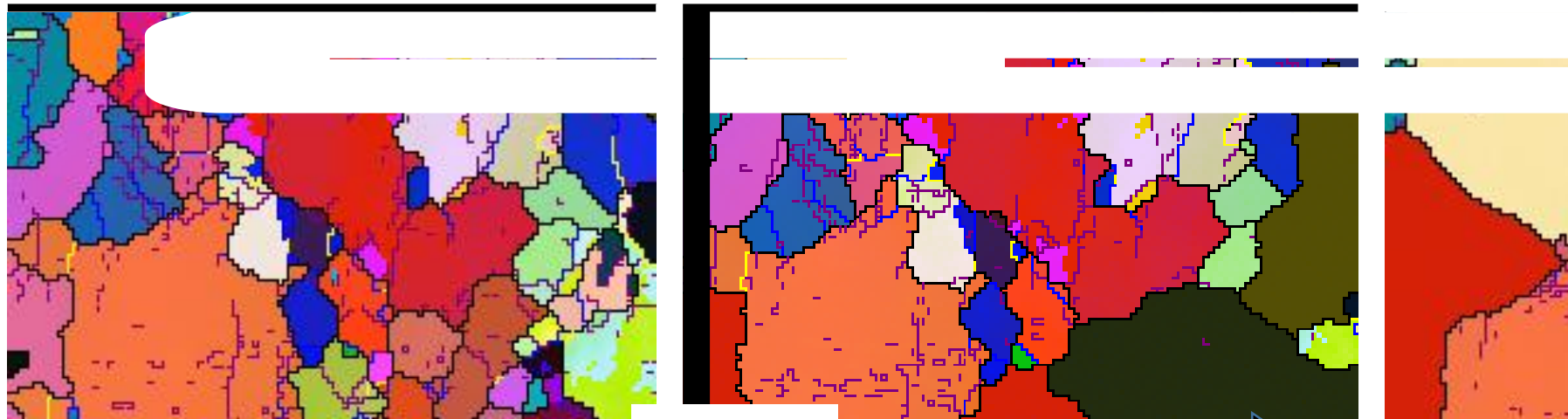
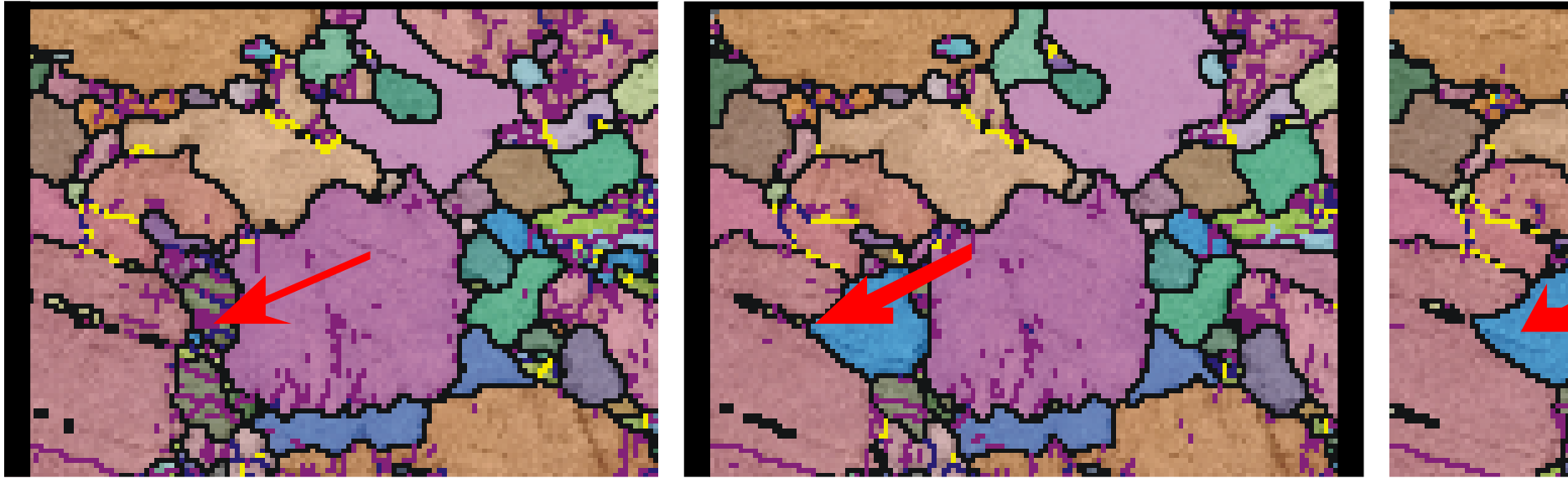
1. Reduction of dislocation density



 *Result:* less dislocations

In situ experiments in SEM
with EBSD analysis
Magnesium Alloy

Growth as energy reduction

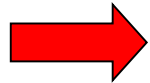
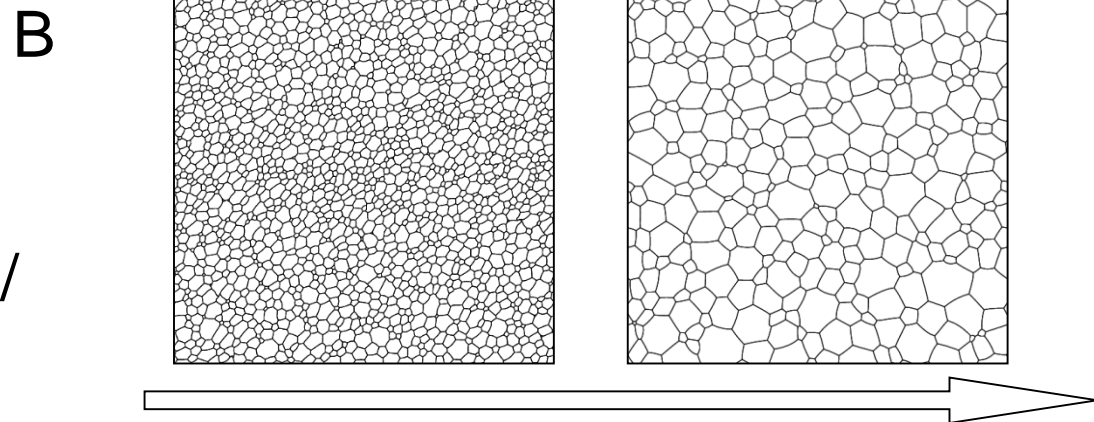
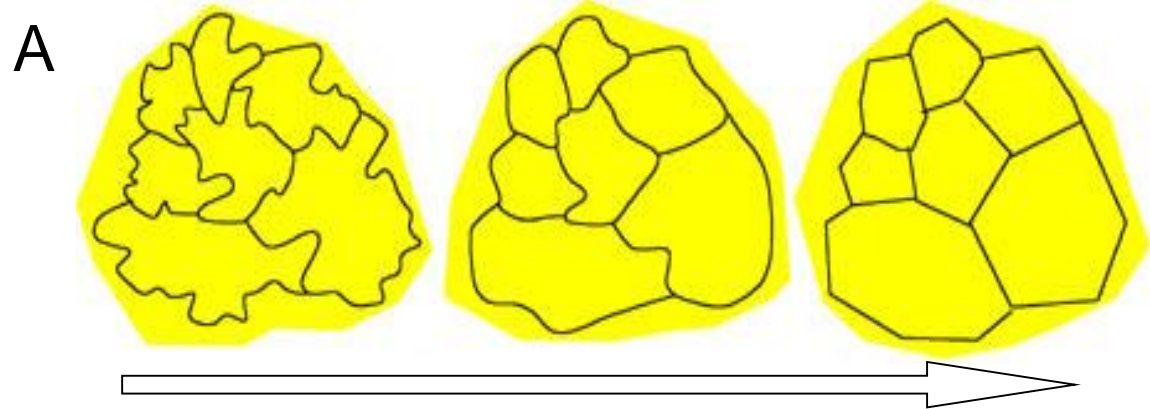


heating →

Piazolo et al. 2004

How to lower energy?

2) Reduction the length of boundaries



Result:
straight boundaries /
grain size increase

Rate of migration $\approx F$ (driving force) $\times M$ (mobility)

$$\text{Mobility} \approx M_{\min} * e^{(f(T, \text{fluid}))}$$

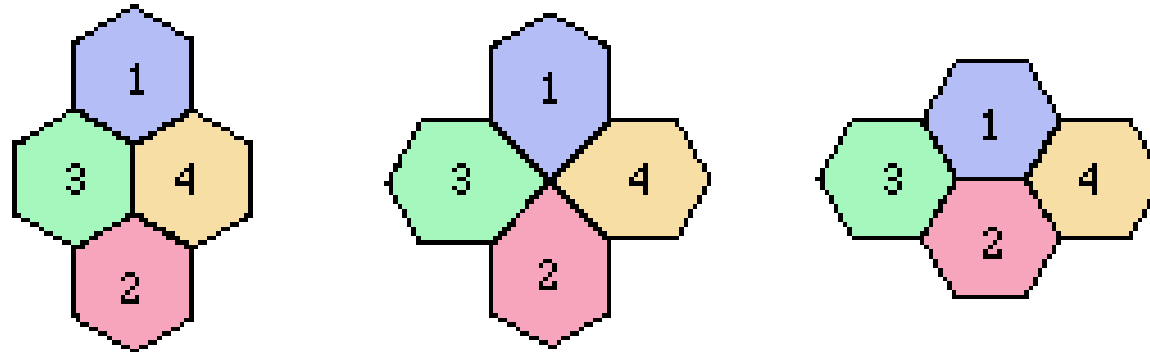
6) Grain boundary sliding

Observation: grains slide past each other in experiments

How?

- Grain boundaries "break"
- Sliding accommodated by movement of dislocation / point defects or by chemical diffusion

 *Result – Example: Neighbour switches*



Try it yourself:

Bath foam bubbles squeezed between finger - thumb

How can we use our knowledge to derive conditions?

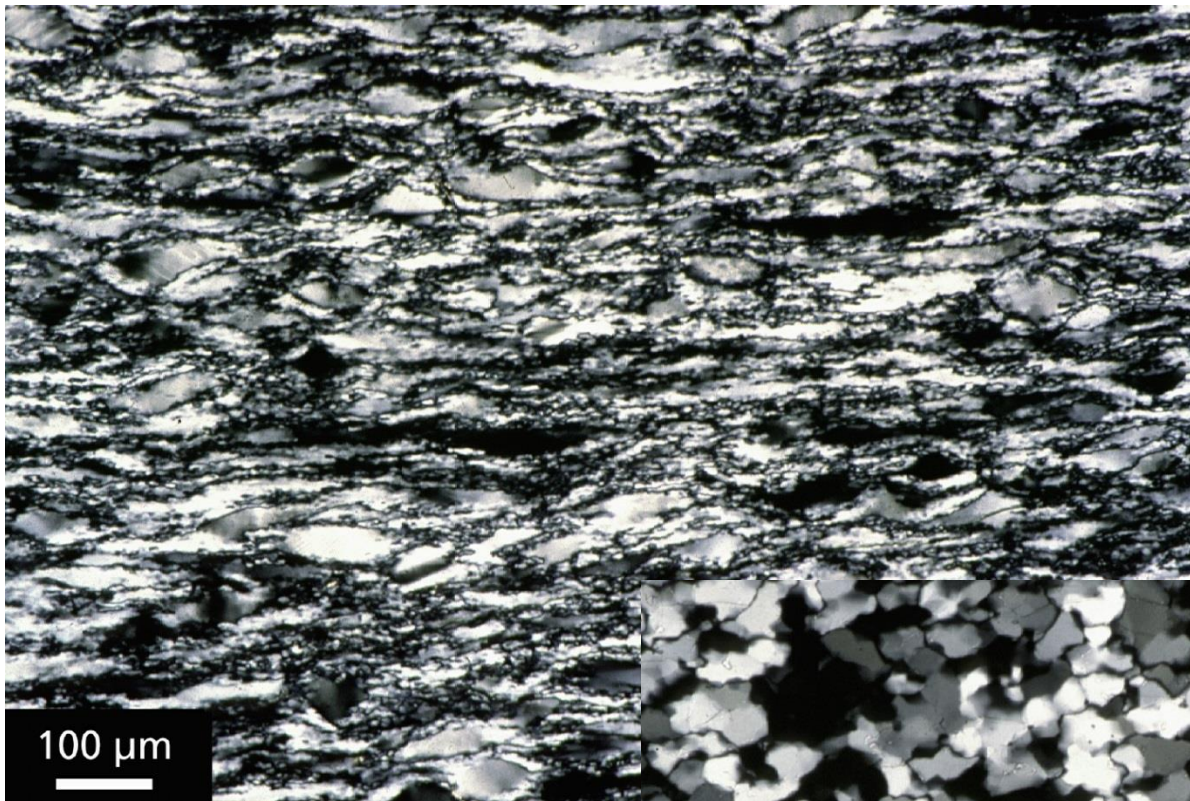
Different mechanisms at different rates at different conditions

 different effect on microstructural development

Rates depend on:

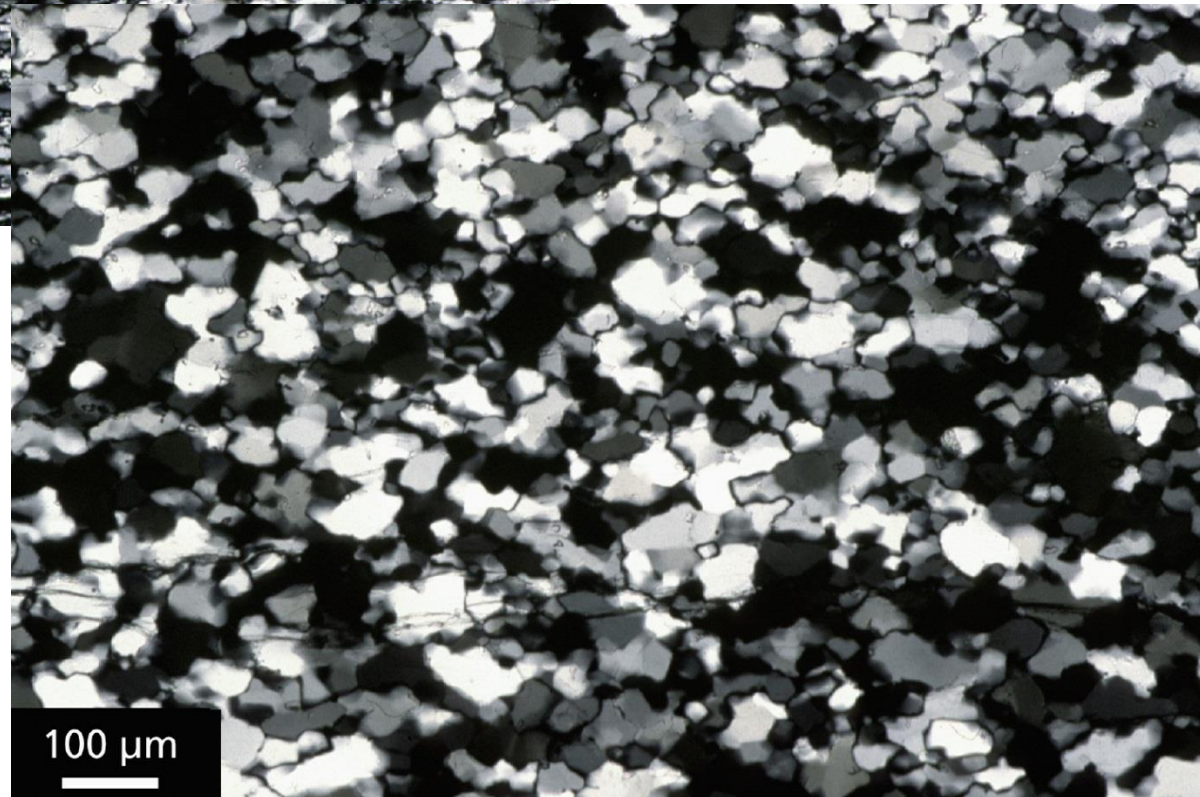
- 1) Stress
- 2) Strain rate / finite strain
- 3) Temperature
- 4) Fluid

Note: for dislocations to move and/or atoms to move we need T or fluid



Low T

Tullis, J., Stünitz, H.,
Teyssier, C. and Heilbronner,
R. 2000.



Thank you & Questions

High T