Helmholtz Young Investigators Group
“The effect of deformation mechanisms for ice sheet dynamics”

ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR- UND MEERESFORSCHUNG

Universiteit Utrecht

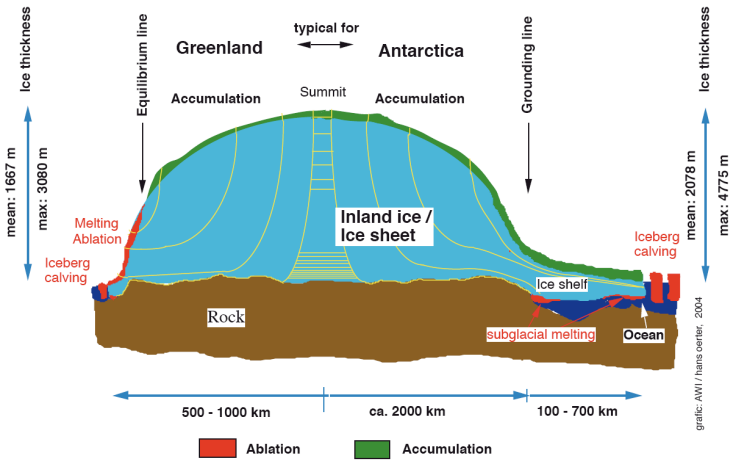
EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Microstructures in polar ice cores

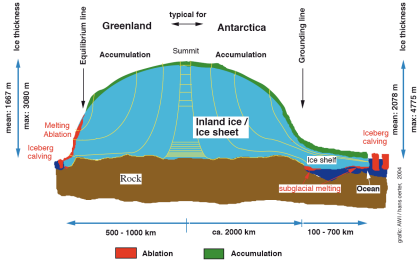
Ilka Weikusat

HELMHOLTZ ASSOCIATION

Schematic ice sheet



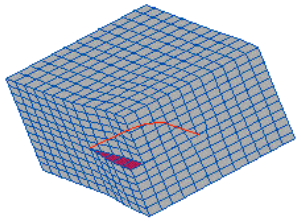
Ice sheet & sea level

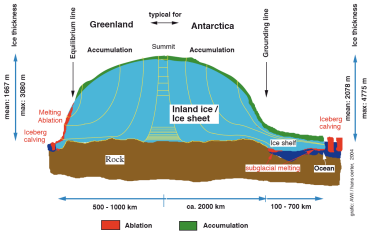


µ-physical processes

deformation:

- Natural ice:
  Dislocation creep





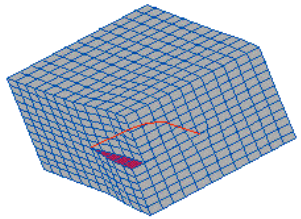
http://www.geo.lsa.umich.edu/~ydoluiim/animations/edgescrewglide.mov

µ-physical processes

deformation:

- Natural ice: Dislocation creep

Dislocation glide



http://www.geo.lsa.umich.edu/~wdpluijm/animations/edgescrewglide.mov

Dislocation climb

Jessell & Bons 2000

Flow relation

Glen's Flow Law (1952)

$$\dot{\varepsilon} = B \cdot \exp(-Q/RT) \cdot \sigma^n$$

$\dot{\varepsilon}$ = strain rate
σ = stress
T = temperature
R = ideal gas constant
B, n, Q = constants

Mostly: n=3
(1.5 to 4)

Intro
Deformation
Ice cores: c-axes
Recrystalli-zation
Ice cores: grain size
RX Diagram
GS-sensitive?
Summary

Flow relation
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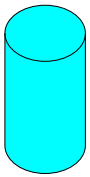

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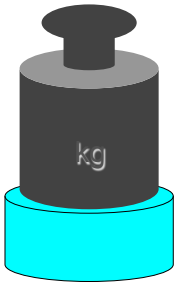

Creep tests
- Empirical
- 10-100x faster deformation than ice sheets

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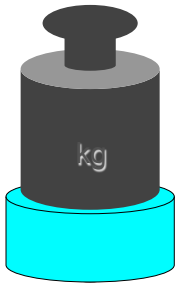

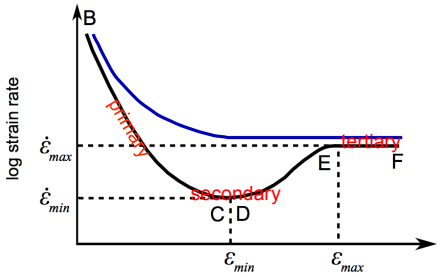

After Treverrow 2012

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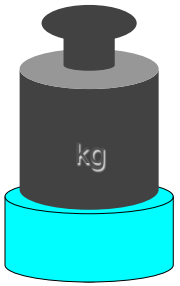

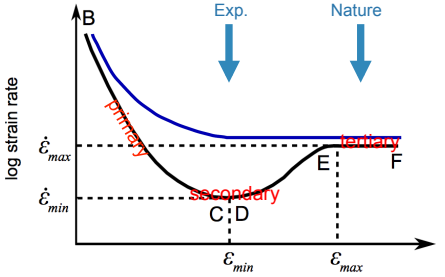

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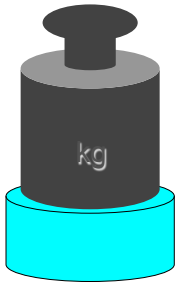

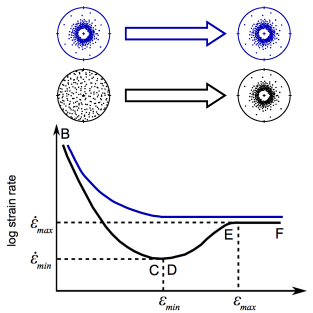

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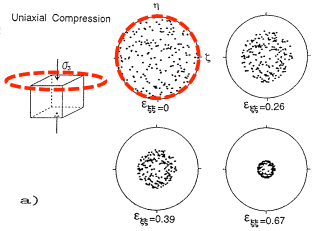
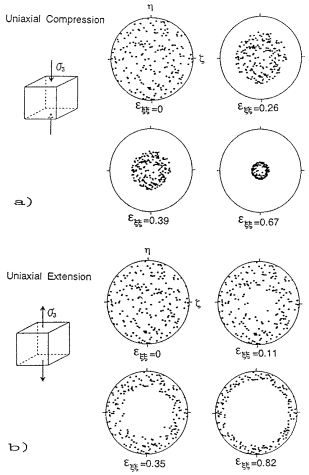


Azuma, 1994

Development of c-axes distributions



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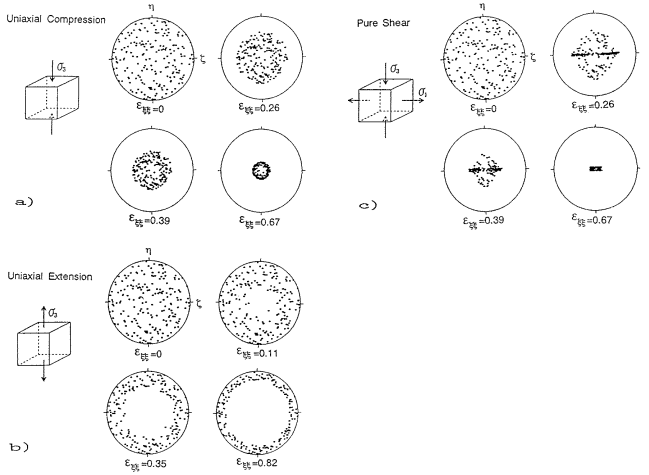

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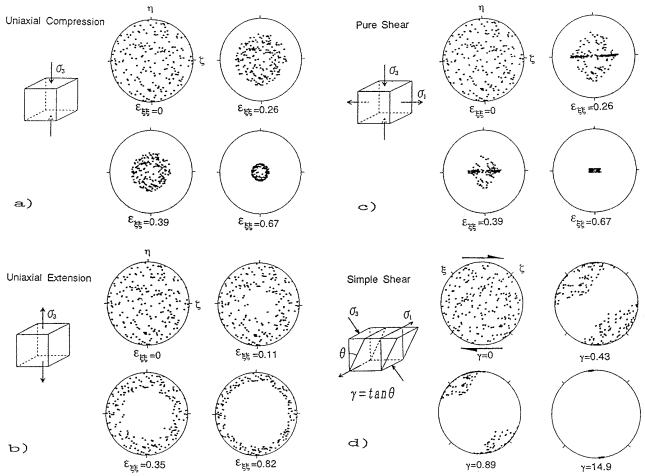

Azuma, 1994

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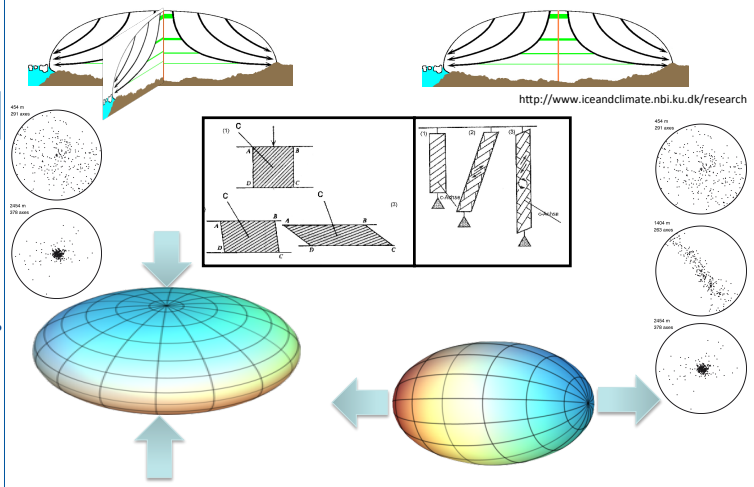
Dome position **C-axes** Ice divide or flank position

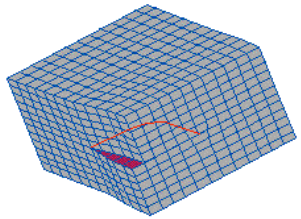


Microstructure evolution

deformation:

- Natural ice: Dislocation creep

Dislocation glide



Dislocation climb

Jessell & Bons 2000

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Microstructure evolution

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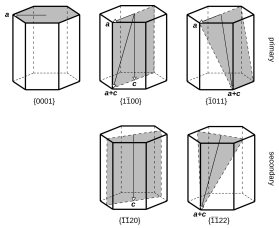

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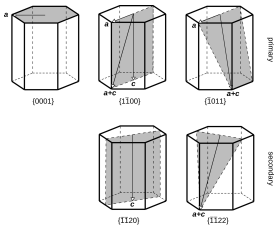
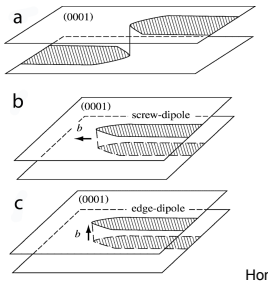




Hondoh 2010

→ Strong plastic anisotropy

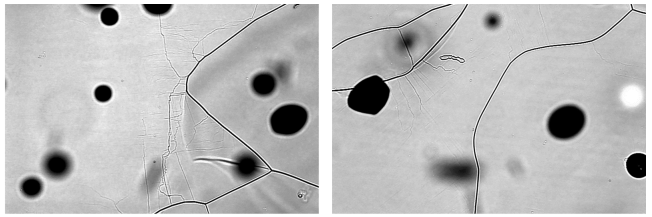
- Polycrystal:
  - high internal stresses & concentrated strain heterogeneities

Microstructure evolution

deformation:

- Natural ice: Dislocation creep → dislocation density

Heterogeneous strain



EDML 556m

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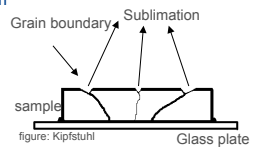


figure: Kipfstuhl

Light µScopy – sublimation etch grooving

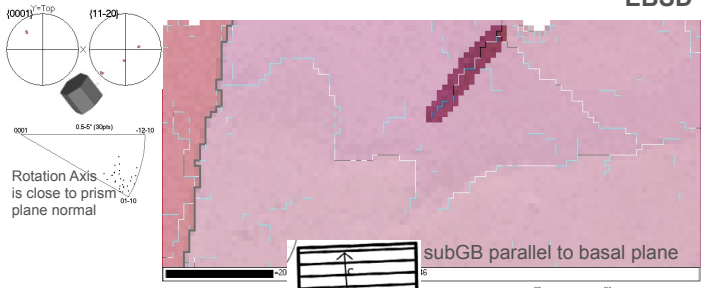
Microstructure evolution

deformation:

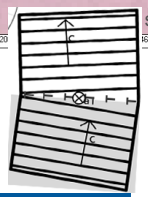
- Natural ice: Dislocation creep → dislocation density

Heterogeneous strain and non-basal slip

EBSD



sGB || basal plane
+
Rot. Axis || basal plane
=
Tilt boundary with non-basal edge dislocations
(b=c or b=c+a)



Microstructure evolution

deformation:

- Natural ice: Dislocation creep → dislocation density

Heterogeneous strain and non-basal slip

large internal stresses & heterogeneous strains

Rotation Axis: / Arrangement:	*c-axis as rotation axis*	*rotation axis in basal plane*	*arbitrary rotation axes*
basal plane normal (n and z-type)	3	$62^{[a]}$	18
basal plane parallel (p-type)	$7^{[b]}$	$66^{[a]}$	18
no particular arrangement to basal plane	7	30	16

sGB || basal plane
+
Rot. Axis || basal plane
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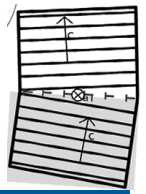
Tilt boundary with non-basal edge dislocations
(b=c or b=c+a)



Microstructure evolution

deformation:

- Natural ice: Dislocation creep → dislocation density

large internal stresses & heterogeneous strains

Hot material

In natural conditions:

- Homologous temperatures → 0.9 and 0.7

Microstructure evolution

deformation:

- Natural ice: Dislocation creep → dislocation density

recrystallization:

- Static: Normal grain growth (**NGG**)
  - Motion of GB
  - → driving force: GB area

  Reduction (& assoc. free energy)

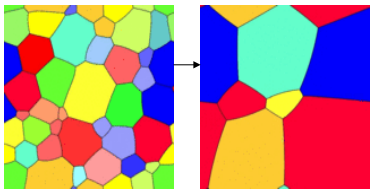
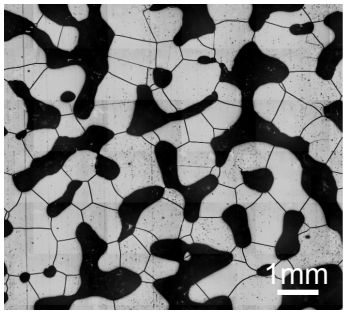


Image: ELLE, Bons



EDML 40m

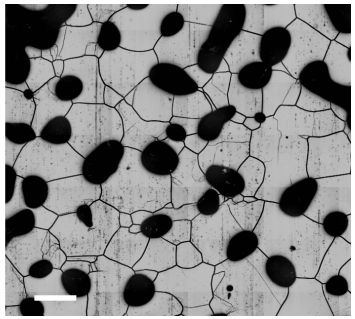
Microstructure evolution

deformation:

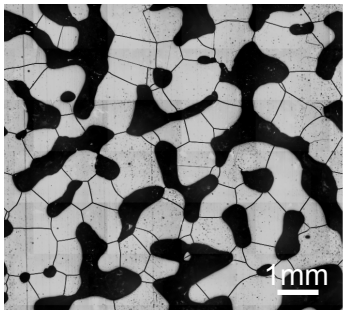
- Natural ice: Dislocation creep → dislocation density

recrystallization:

- Static → driving force: GB surface reduction (**NGG**)
- Dynamic →



70m



EDML 40m

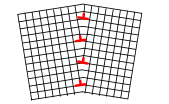
Microstructure evolution

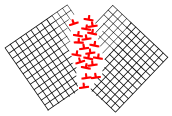
deformation:

- Natural ice: Dislocation creep → dislocation density

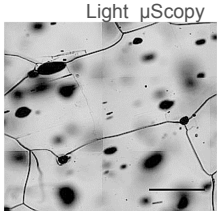
recrystallization:

- Static → driving force: GB surface reduction (**NGG**)
- Dynamic → driving force: dislocation density reduction
  - Motion of dislocations → rotation recrystalization (**RRX**)

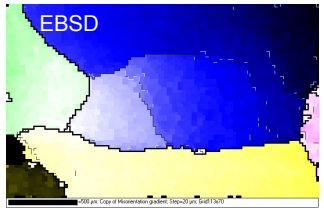




Light µScopy



EDC 685m



EDML 2386m

Microstructure evolution

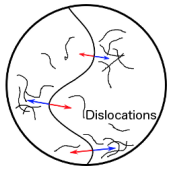
deformation:

- Natural ice: Dislocation creep → dislocation density

recrystallization:

large internal stresses & heterogeneous strains

- Dynamic → driving force: dislocation density reduction
  - Motion of dislocations → rotation recrystalization (**RRX**)
  - Motion of GB → strain-induced grain boundary migration (**SIBM**)



Binder 2014

Microstructure evolution

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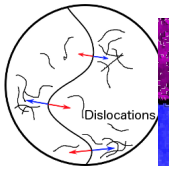
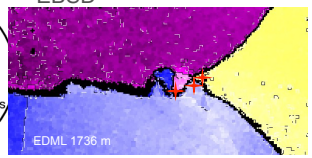
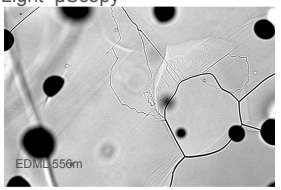
  - Motion of GB → strain-induced grain boundary migration (**SIBM-N/-O**)



EBSD



Light µScopy



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Nucleation

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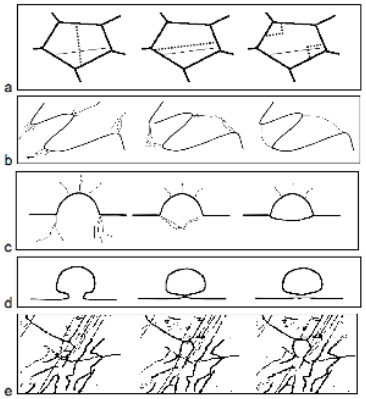
recrystallization:

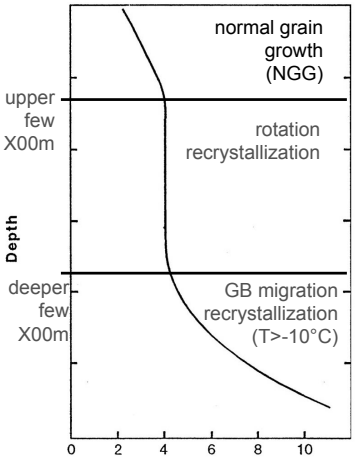
- Static → driving fc
- Dynamic → drivin
  - Motion of di
  - Motion of G

(SIBM-N/-O)



Kipfstuhl et al., unpublished

μS evolution – *tripartite paradigm*



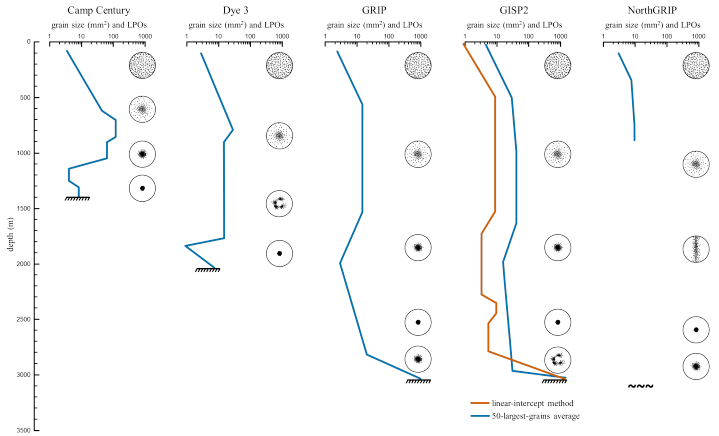
(modified after: De La Chapelle et al. 1998)

NGG

RRX

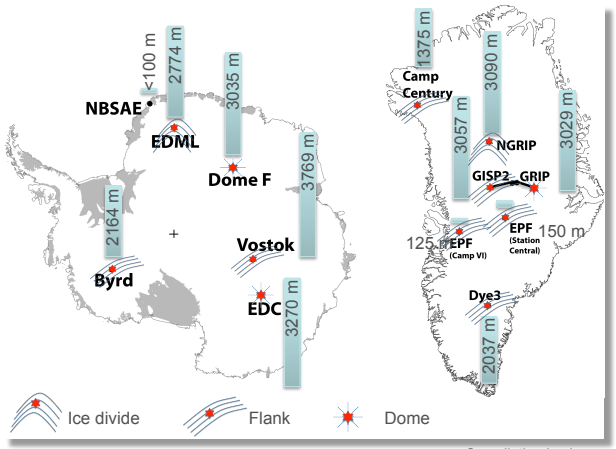
SIBM (-N / -O)

μS in long ice cores Greenland

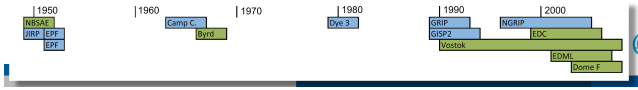


Faria et al. 2014

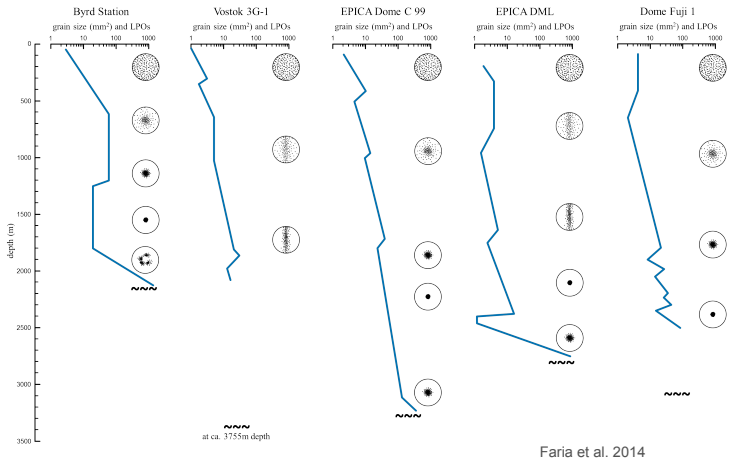
μS in long ice cores Antarctica & Greenland



Compilation by Jansen et al. 2013



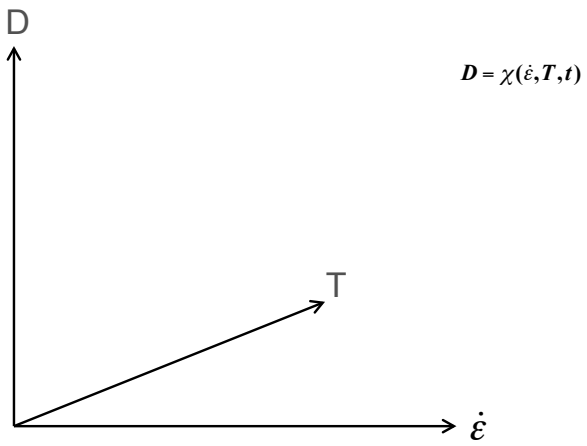
μS in long ice cores Antarctica



Faria et al. 2014

Tripartite paradigm?

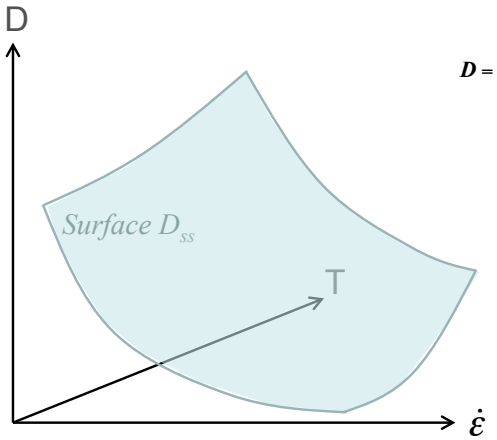
Recrystallization Diagram



$D = \chi(\dot{\varepsilon}, T, t)$

D	Mean grain size
$\dot{\varepsilon}$	Strain rate
T	Temperature
t	time

Recrystallization Diagram



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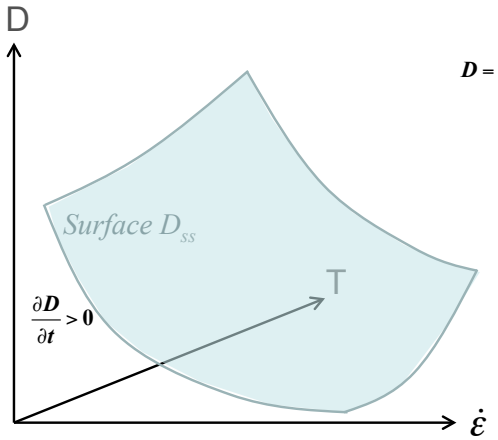
Recrystallization Diagram

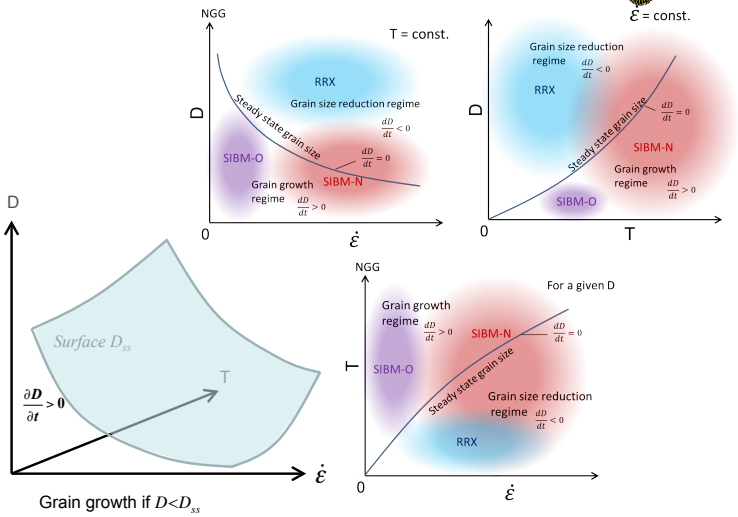


$D = \chi(\dot{\varepsilon}, T, t)$

Grain growth if $D < D_{ss}$

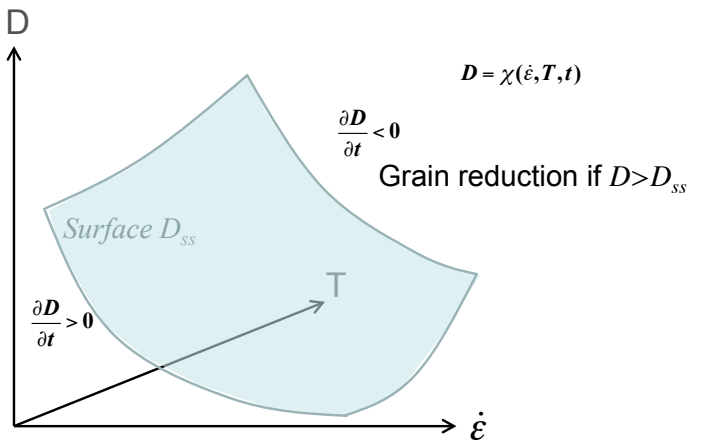
D	Mean grain size
$\dot{\varepsilon}$	Strain rate
T	Temperature
t	time

Recrystallization Diagram



D Mean grain size
$\dot{\varepsilon}$ Strain rate
T Temperature
t time

Recrystallization Diagram



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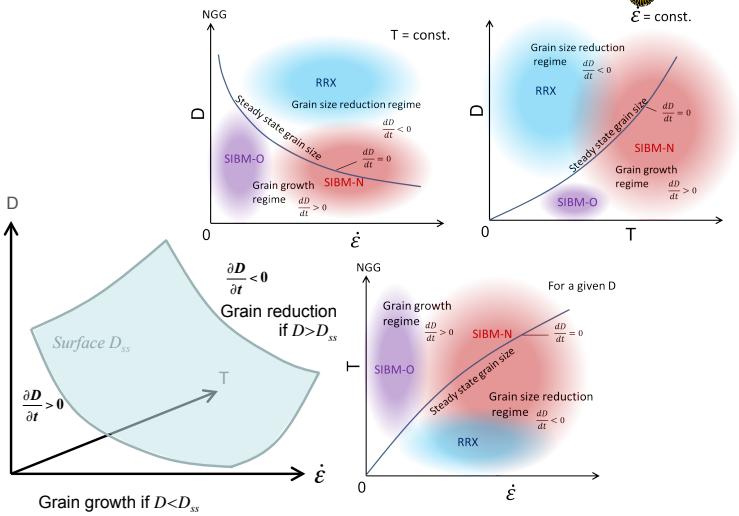
Recrystallization Diagram



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$\dot{\varepsilon}$ Strain rate
T Temperature
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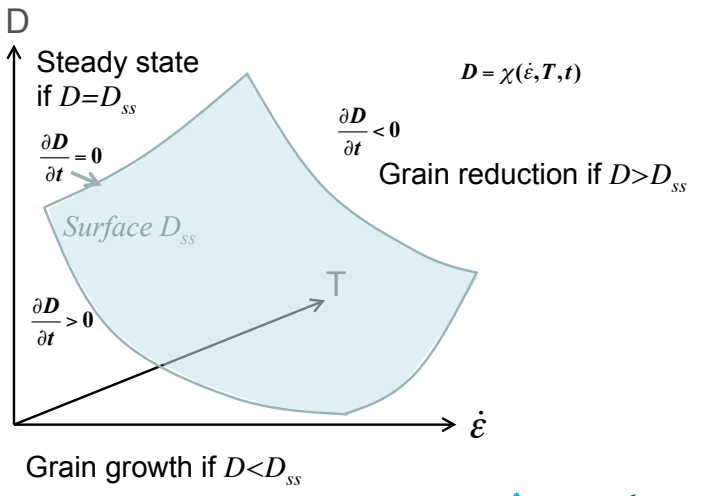
Recrystallization Diagram



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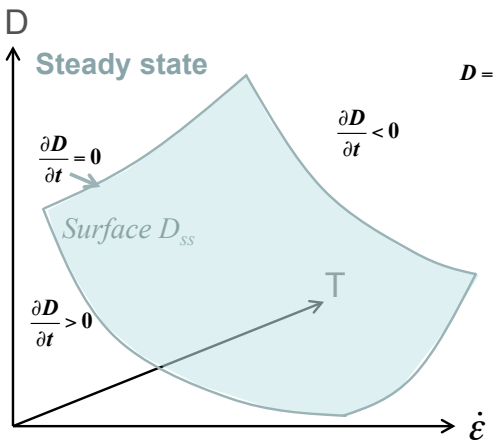
Recrystallization Diagram



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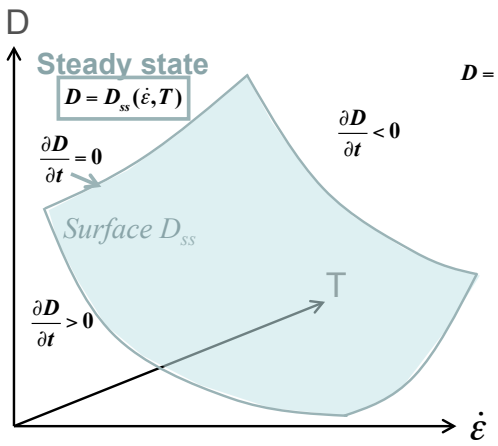
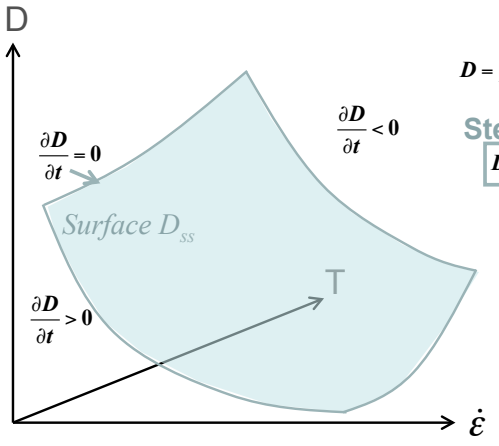
$\dot{\varepsilon}$ Strain rate
T Temperature
t time

Recrystallization Diagram



D Mean grain size
$\dot{\varepsilon}$ Strain rate
T Temperature
t time

Recrystallization Diagram

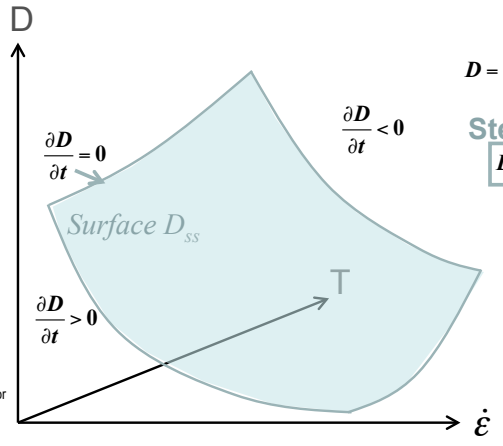


$D^2_{ss} = \frac{\varphi}{\sigma^3}$ Jacka & Li 1994

D Mean grain size
$\dot{\varepsilon}$ Strain rate
T Temperature
t Time
φ Dimensional factor
σ stress

Recrystallization Diagram

D Mean grain size



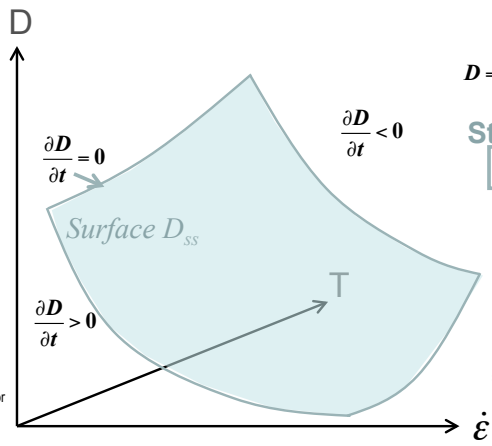
$D^2_{ss} = \frac{\varphi}{\sigma^3}$ Jacka & Li 1994

$\dot{\varepsilon} = A\sigma^n$ Glen 1955

$A \approx \alpha e^{-Q/k_b T}$

$\dot{\varepsilon}$ Strain rate
T Temperature
t Time
φ Dimensional factor
σ Stress
Q Act. Energy
α Const.
k Boltzmann's const.

Recrystallization Diagram



$D = \chi(\dot{\varepsilon}, T, t)$

Steady state

$D = D_{ss}(\dot{\varepsilon}, T)$

$D_{ss}^2 = \frac{\varphi}{\sigma^3}$ Jacka & Li 1994

$\dot{\varepsilon} = A\sigma^n$ Glen 1955

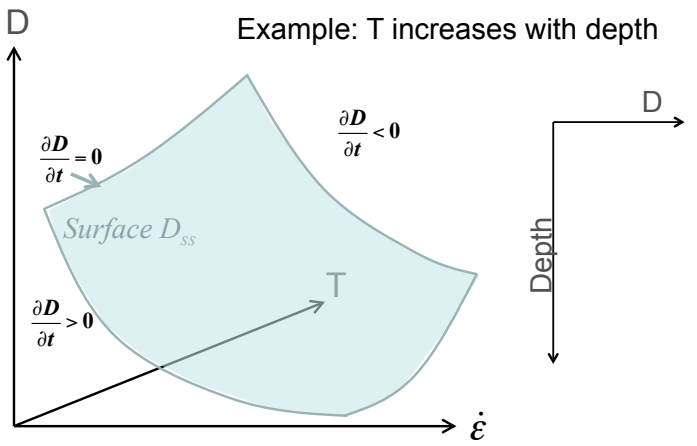
$A \approx \alpha e^{-Q/k_b T}$

$\Rightarrow D_{ss}(\dot{\varepsilon}, T) = \left(\frac{\alpha\varphi}{\dot{\varepsilon}}\right)^{\frac{1}{2}} e^{\frac{-Q}{2kT}}$

D Mean grain size
$\dot{\varepsilon}$ Strain rate
T Temperature
t Time
φ Dimensional factor
σ Stress
Q Act. Energy
α Const.
k Boltzmann's const.

Recrystallization Diagram

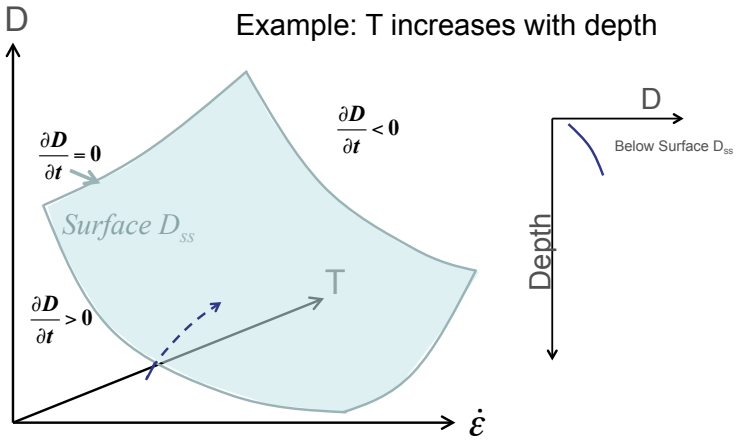
Example: T increases with depth



Faria et al. 2014

Recrystallization Diagram

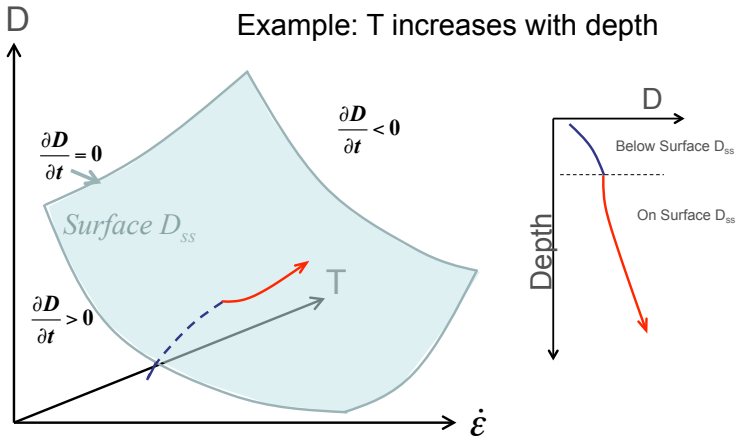
Example: T increases with depth



Faria et al. 2014

Recrystallization Diagram

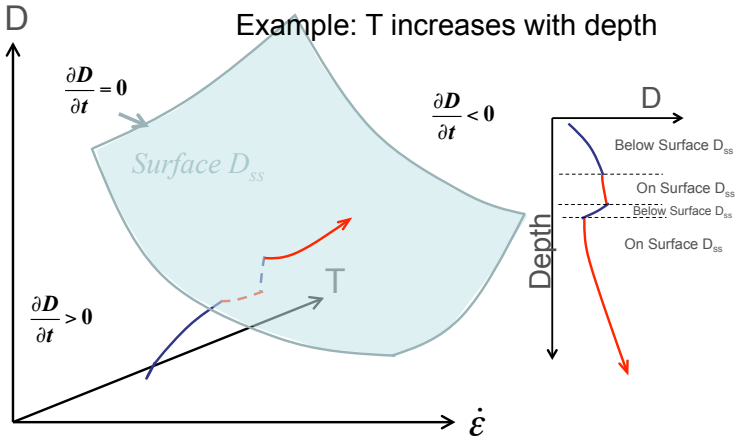
Example: T increases with depth



Faria et al. 2014

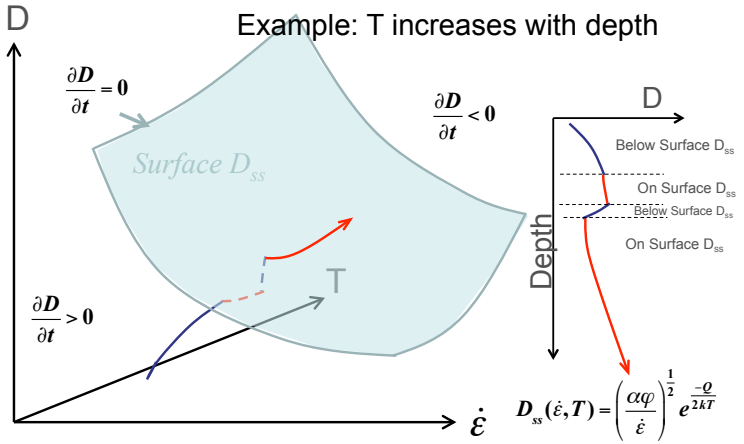
Recrystallization Diagram

Example: T increases with depth



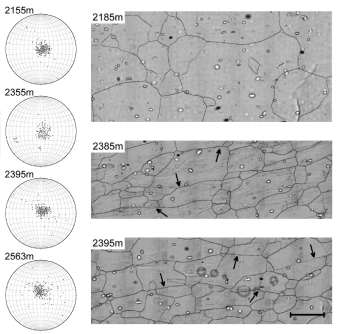
Recrystallization Diagram

Example: T increases with depth

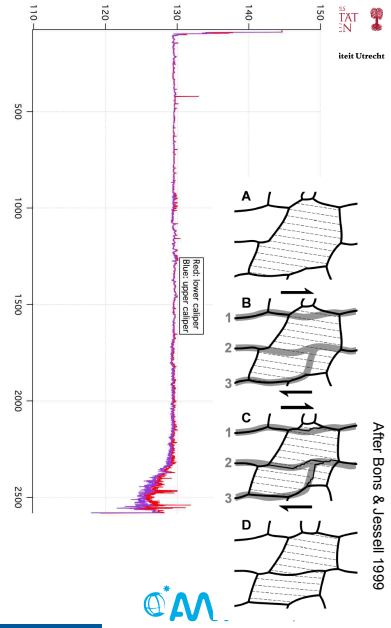


EDML Drill hole

- Drill hole closure
- „brickwall pattern"
- microshear



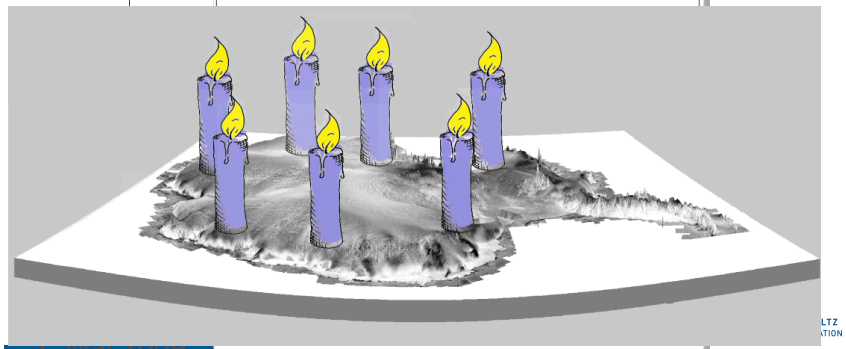
Faria et al. 2006



After Bons & Jessell 1999

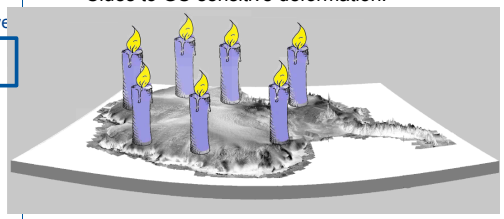
Max-Planck-Institut
für Mathematik
in den Naturwissenschaften
Leipzig

Is Antarctica like a birthday cake?



Summary

- Ice: hexagonal; highly anisotropic (mainly basal glide).
- Deformation: dislocations (and more).
- Non-basal dislocations form subGB.
- Dynamic recrystallization significant (hot, heterogeneous strains).
- Recrystallization regimes in temperature - strain rate - grain size state space.
- Dynamic grain growth caused by strain-induced GB migration.
- Grain size reduction by rotation recrystallization.
- Competition of the recrystallization processes results in a steady-state grain size as surface in the state space.
- Clues to GS-sensitive deformation.



Sérgio Faria, Nobby Azuma, Sepp Kipfstuhl, Martyn Drury, Daniela Jansen

Thanks

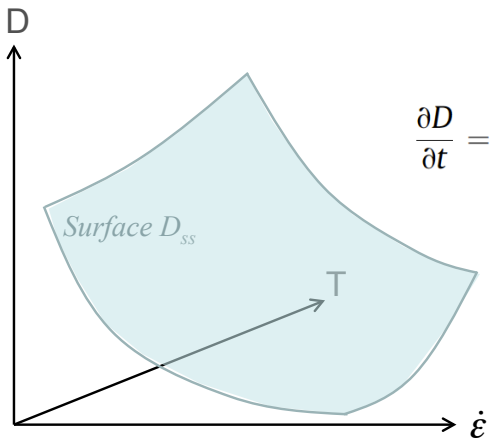
bc3

Microstructure evolution – *tripartite paradigm* does not work - what else?

Bla

- NGG
- RRX
- SIBM (-N / -O)

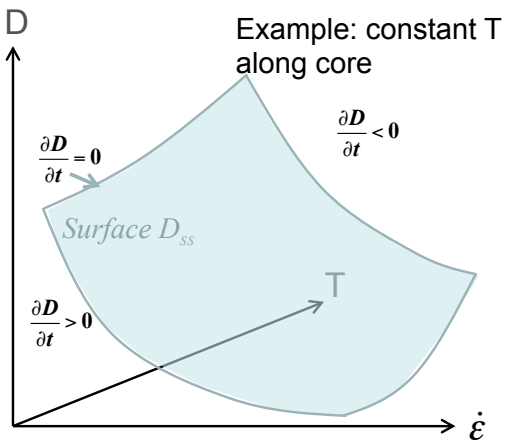
Diagram



$$\frac{\partial D}{\partial t} = \frac{\partial}{\partial t}\chi(\dot{\varepsilon}, T, t) \neq 0$$

D	Mean grain size
$\dot{\varepsilon}$	Strain rate
T	Temperature
t	time

Diagram



Diagram