Schematic ice sheet

Intro
Deformation heterog. ε
Hot material
Recrystallization
NGG
RRX
SIBM
Diagram
Summary
Microstructure evolution

deformation:

- Natural ice: Dislocation creep → dislocation density
Microstructure evolution

**deformation:**

- Natural ice: Dislocation creep $\rightarrow$ dislocation density

$\rightarrow$ Strong plastic anisotropy
  - Polycrystal:
    - high internal stresses & concentrated strain heterogeneities
Microstructure evolution

deformation:

- Natural ice: Dislocation creep $\rightarrow$ dislocation density

large internal stresses & heterogeneous strains

Hot material

In natural conditions:

- Homologous temperatures $\rightarrow$ 0.9 and 0.7
Microstructure evolution

deformation:

- Natural ice: Dislocation creep $\rightarrow$ dislocation density

recrystallization:

- Static $\rightarrow$ driving force: GB surface reduction (NGG)
- Dynamic $\rightarrow$ driving force: dislocation density reduction
  - Motion of dislocations $\rightarrow$ rotation recrystalization (RRX)
Microstructure evolution

deformation:

- Natural ice: Dislocation creep $\rightarrow$ dislocation density

recrystallization:
- Static $\rightarrow$ driving force: GB surface reduction (NGG)
- Dynamic $\rightarrow$ driving force: dislocation density reduction

Motion of dislocations $\rightarrow$ rotation recrystallization (RRX)

Novel approaches and ice core μS data from different optical methods

See Poster: Binder et al.

EGU2014-12098
Microstructure evolution

deformation:

- Natural ice: Dislocation creep $\rightarrow$ dislocation density

recrystallization:

large internal stresses & heterogeneous strains

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

Binder 2014
Microstructure evolution

defformation:

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

![EBSD and Light µScopy Images](image.png)

- Dislocations
- Misorientation to reference point

- >0.75°
- >1°
- >10°

Width of image: 2.5mm
Microstructure evolution

deformation:

- Natural ice: Dislocation creep → dislocation density

recrystallization:

- μS modelling of combined crystal plasticity deformation + recrystallization

See Poster: Llorens et al. → EGU2014-12880
Schematic ice sheet

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μS in long ice cores
Antarctica

Diagram

Summary

Tripartite paradigm?

Faria et al. 2014
Diagram

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

- **D**: Mean grain size
- **\dot{\varepsilon}**: Strain rate
- **T**: Temperature
- **t**: Time
Grain growth if $D < D_{ss}$

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

$\frac{\partial D}{\partial t} > 0$

Diagram

$D$ Mean grain size

$\dot{\varepsilon}$ Strain rate

$T$ Temperature

$t$ time
Diagram

- Intro
- Deformation heterog. $\varepsilon$
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- NGG
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- SIBM

Diagram

Summary

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

Grain growth if $D < D_{ss}$

$\frac{\partial D}{\partial t} > 0$

Surface $D_{ss}$

NGG

$T = \text{const.}$

RRX

Steady state grain size

$\frac{dD}{dt} < 0$

$\frac{dD}{dt} = 0$

$\frac{dD}{dt} > 0$

SIBM-O

SIBM-N

Grain size reduction regime

For a given $D$

Grain growth regime

SIBM-O

SIBM-N

Steady state grain size

RRX

$\dot{\varepsilon} = \text{const.}$
**Diagram**

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

\[ \frac{\partial D}{\partial t} < 0 \]

Grain reduction if \( D > D_{ss} \)

\[ \frac{\partial D}{\partial t} > 0 \]

Grain growth if \( D < D_{ss} \)

- \( D \): Mean grain size
- \( \dot{\varepsilon} \): Strain rate
- \( T \): Temperature
- \( t \): Time

**Summary**
Diagram

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

- Grain growth if $D < D_{ss}$
- Grain reduction if $D > D_{ss}$

- Steady state grain size $D_{ss}$

- Diagram showing the relationship between grain size ($D$), strain rate ($\dot{\varepsilon}$), and temperature ($T$) with regions for different conditions:
  - NGG
  - RRX
  - SIBM

- Conditions for different regimes:
  - $\frac{\partial D}{\partial t} < 0$
  - $\frac{\partial D}{\partial t} > 0$
  - $\frac{dD}{dt} = 0$
  - $\frac{dD}{dt} = \frac{d\dot{\varepsilon}}{dt} < 0$
  - $\frac{dD}{dt} = \frac{dT}{dt} > 0$
  - $\frac{dD}{dt} = \frac{dT}{dt} = 0$

- For a given grain size $D$, different regimes with transition curves.
Diagram

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

- **Steady state** if \( D = D_{ss} \)
  \[ \frac{\partial D}{\partial t} = 0 \]

- **Grain reduction** if \( D > D_{ss} \)
  \[ \frac{\partial D}{\partial t} < 0 \]

- **Grain growth** if \( D < D_{ss} \)
  \[ \frac{\partial D}{\partial t} > 0 \]

**Diagram Labels:**
- \( D \): Mean grain size
- \( \dot{\varepsilon} \): Strain rate
- \( T \): Temperature
- \( t \): time

**Legend:**
- Surface \( D_{ss} \)
Diagram

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

$\frac{\partial D}{\partial t} = 0$

$\frac{\partial D}{\partial t} > 0$

$\frac{\partial D}{\partial t} < 0$

Surface $D_{ss}$

Mean grain size $D$

Strain rate $\dot{\varepsilon}$

Temperature $T$

Time $t$

Intro

Deformation heterogeneity $\varepsilon$

Hot material

Recrystallization

NGG

RRX

SIBM

Summary
Diagram

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

\[ \frac{\partial D}{\partial t} = 0 \]

\[ \frac{\partial D}{\partial t} > 0 \]

\[ \frac{\partial D}{\partial t} < 0 \]

\( D \) Mean grain size
\( \dot{\varepsilon} \) Strain rate
\( T \) Temperature
\( t \) time
Diagram

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

\[ \frac{\partial D}{\partial t} = 0 \]

\[ \frac{\partial D}{\partial t} > 0 \]

\[ \frac{\partial D}{\partial t} < 0 \]

\[ D_{ss}^2 = \frac{\varphi}{\sigma^3} \]

Mean grain size

\( \dot{\varepsilon} \)

Strain rate

Temperature

Time

Dimensional factor

Steady state

Surface \( D_{ss} \)

\( t \)

\( \dot{\varepsilon} \)

\( \sigma \)

stress

Jacka & Li 1994
Intro
Deformation heterog. $\varepsilon$

Hot material

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Diagram

$D$ Mean grain size
$\dot{\varepsilon}$ Strain rate
$T$ Temperature
t Time
$\varphi$ Dimensional factor
$\sigma$ Stress
$Q$ Act. Energy
$\alpha$ Const.
k Boltzmann’s const.

Diagram

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

$\frac{\partial D}{\partial t} = 0$

$\frac{\partial D}{\partial t} > 0$

$\frac{\partial D}{\partial t} < 0$

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

$A \approx \alpha e^{-Q/k_bT}$
Diagram

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

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

Glen 1955

\[ \dot{\varepsilon} = A\sigma^n \]

\[ A \approx \alpha e^{-Q/k_BT} \]

\[ D_{ss}(\dot{\varepsilon}, T) = \left( \frac{\alpha \varphi}{\dot{\varepsilon}} \right)^{\frac{1}{2}} e^{-\frac{Q}{2k_BT}} \]

Jacka & Li 1994

- Mean grain size \( D \)
- Strain rate \( \dot{\varepsilon} \)
- Temperature \( T \)
- Time \( t \)
- Dimensional factor \( \varphi \)
- Stress \( \sigma \)
- Act. Energy \( Q \)
- Const. \( \alpha \)
- Boltzmann’s const. \( k \)
Example: T increases with depth

\[
\frac{\partial D}{\partial t} > 0
\]

\[
\frac{\partial D}{\partial t} = 0
\]

\[
\frac{\partial D}{\partial t} < 0
\]

Surface \( D_{ss} \)

Faria et al. 2014
Example: \( T \) increases with depth

\[
\frac{\partial D}{\partial t} < 0
\]

\[
\frac{\partial D}{\partial t} = 0
\]

\[
\frac{\partial D}{\partial t} > 0
\]

Surface \( D_{ss} \)

Faria et al. 2014
Example: T increases with depth

\[ \frac{\partial D}{\partial t} < 0 \]

\[ \frac{\partial D}{\partial t} = 0 \]

\[ \frac{\partial D}{\partial t} > 0 \]

Faria et al. 2014
Example: T increases with depth

\[ \frac{\partial D}{\partial t} = 0 \]

\[ \frac{\partial D}{\partial t} < 0 \]

\[ \frac{\partial D}{\partial t} > 0 \]
Diagnosis

- Intro
- Deformation heterogeneity $\varepsilon$
- Hot material
- Recrystallization
- NGG
- RRX
- SIBM

Diagram

- Example: $T$ increases with depth

\[
\frac{\partial D}{\partial t} = 0 \quad \text{Above Surface } D_{ss}
\]

\[
\frac{\partial D}{\partial t} < 0 \quad \text{Below Surface } D_{ss}
\]

\[
\frac{\partial D}{\partial t} > 0 \quad \text{On Surface } D_{ss}
\]

\[
D_{ss}(\varepsilon, T) = \left(\frac{\alpha}{\varepsilon}\right)^{1/2} \cdot \frac{-Q}{e^{2kT}}
\]
Summary

- Dynamic recrystallization significantly influences material properties (hot, heterogeneous strains).
- Strain-induced boundary migration can lead to dynamic grain growth.
- Rotation recrystallization leads to grain size reduction.
- With their driving causes recrystallization regimes can be situated in (temperature-strain rate-grain size) state space.
- Competition of the recrystallization processes gives a steady-state grain size as surface in the state space.
Summary

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Thanks