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

Recrystallization Diagram for Polar Ice

Ilka Weikusat, Nobuhiko Azuma, Sérgio H. Faria

EGU, 30/4/2014

Schematic ice sheet

Intro

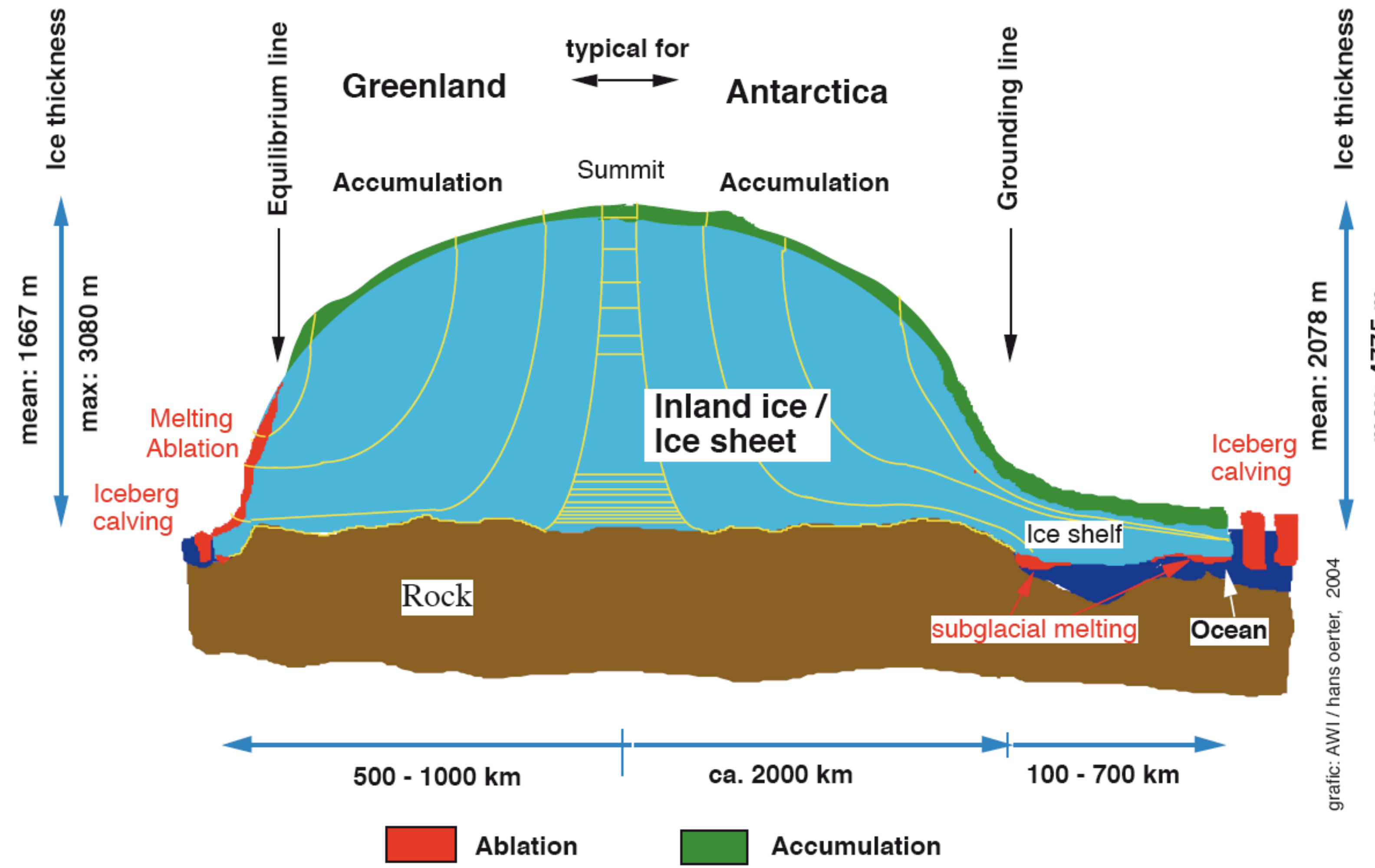
Deformation
heterog. ε

Hot material

Recrystalli-
zation
NGG
RRX
SIBM

Diagram

Summary



Microstructure evolution

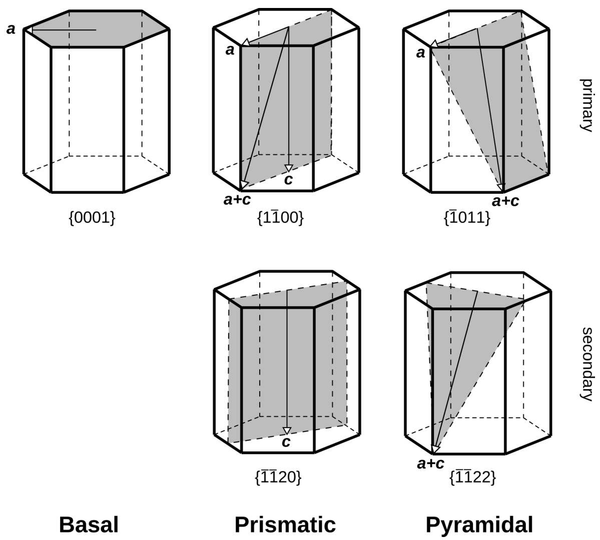
deformation:

- Natural ice: Dislocation creep → dislocation density

Microstructure evolution

deformation:

- Natural ice: Dislocation creep → dislocation density



→ Strong plastic anisotropy

- Polycrystal:
  - high internal stresses & concentrated strain heterogeneities

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

Intro

Deformation
heterog. ε

Hot material

Recrystallization
NGG
RRX
SIBM

Diagram

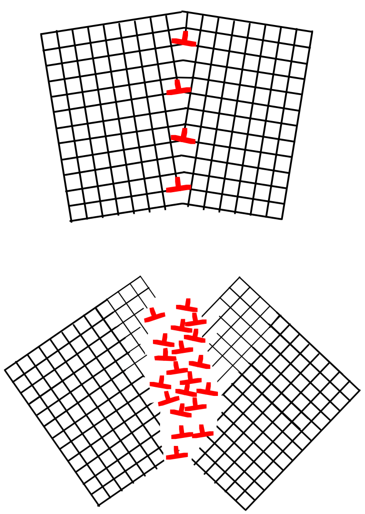
Summary

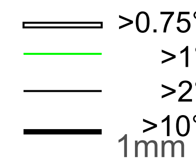
deformation:

- Natural ice: Dislocation creep → dislocation density

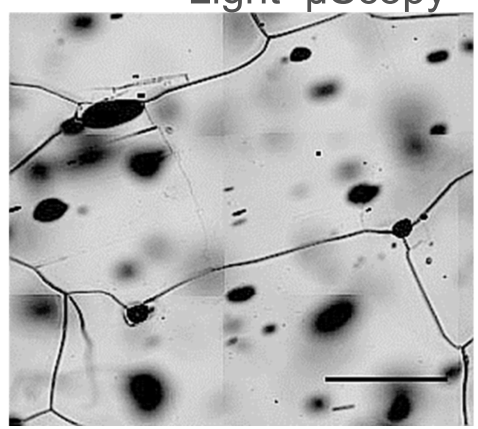
recrystallization:

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

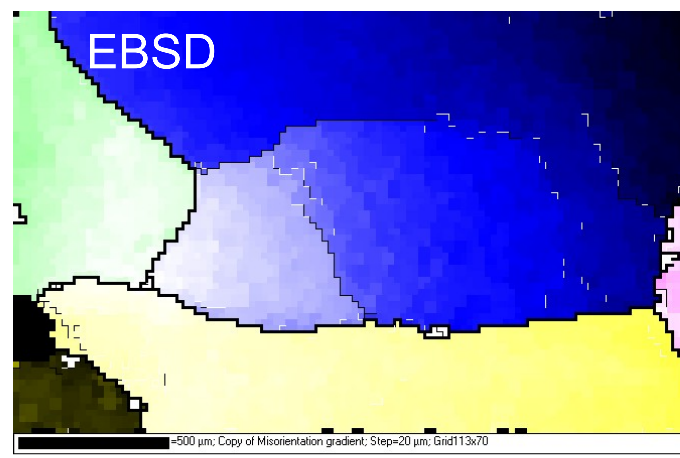




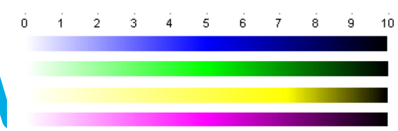
Light µScopy



EDC 685m



EDML 2386m



Microstructure evolution

deformation:

- Natural ice: Dislocation creep → dislocation density

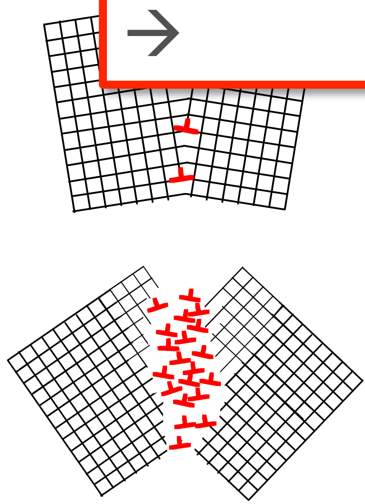
rec

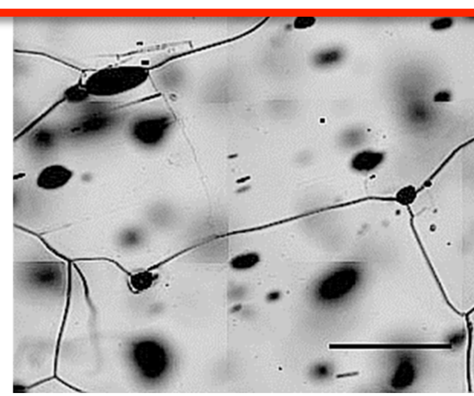
- s
- I

Novel approaches and ice core µS data from different optical methods

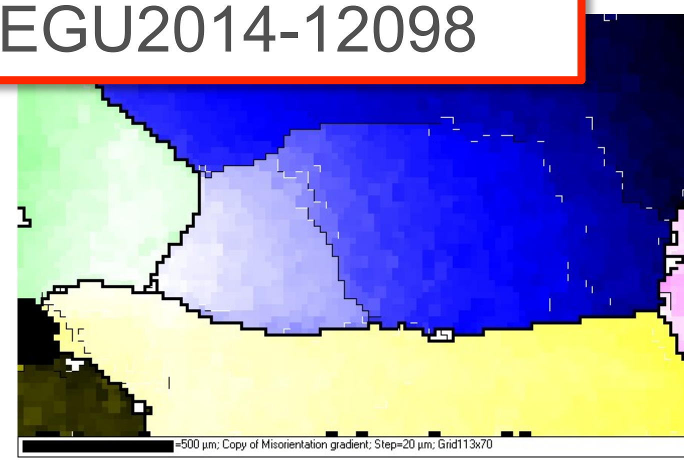
See Poster: Binder et al.

→ EGU2014-12098

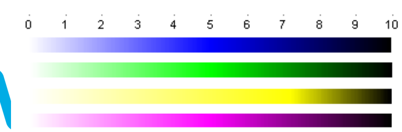




EDC 685m



EDML 2386m



Microstructure evolution

Intro

Deformation
heterog. ε

Hot material

Recrystalli-
zation
NGG
RRX
SIBM

Diagram

Summary

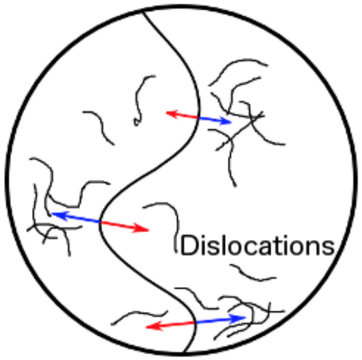
deformation:

- 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

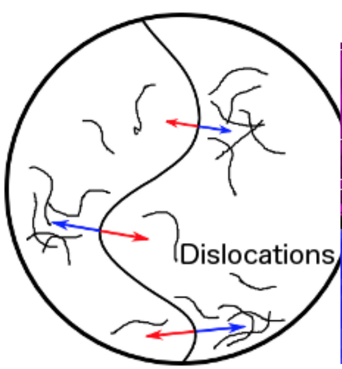
Microstructure evolution

deformation:

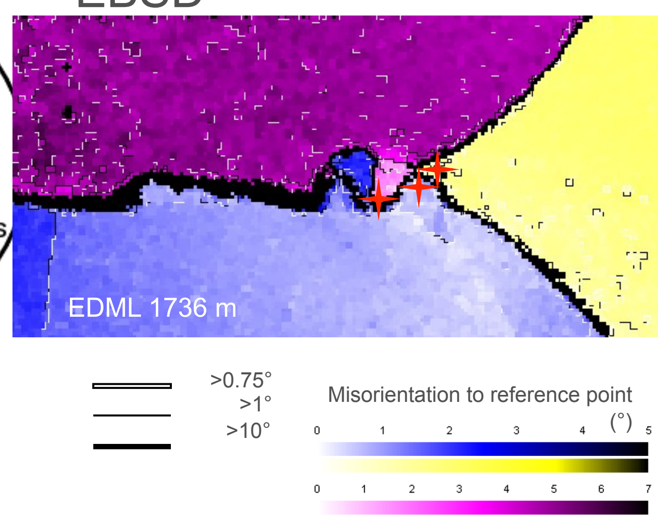
- Natural ice: Dislocation creep → dislocation density

recrystallization:

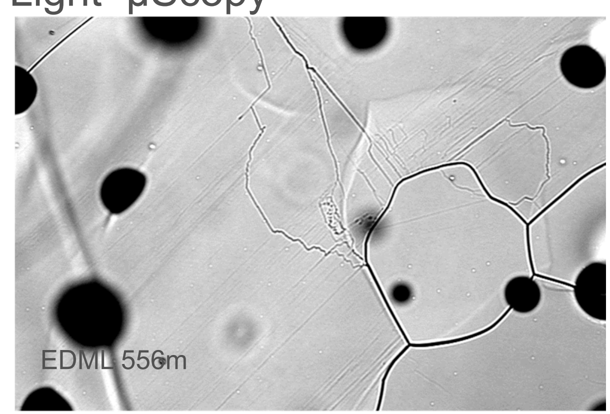
- Static → driving force: GB surface reduction (NGG)
- Dynamic → driving force: dislocation density reduction
  - Motion of dislocations → rotation recrystalization (RRX)
  - Motion of GB → strain-induced grain boundary migration (SIBM-N/-O)



EBSD



Light µScopy



Width of image: 2.5mm

Microstructure evolution

Intro

Deformation
heterog. ε

Hot material

Recrystalli-zation
NGG
RRX
SIBM

Diagram

Summary

deformation:

- Natural ice: Dislocation creep → dislocation density

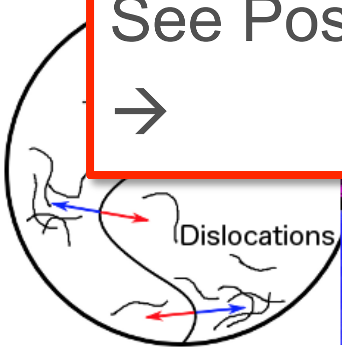
recrystallization:

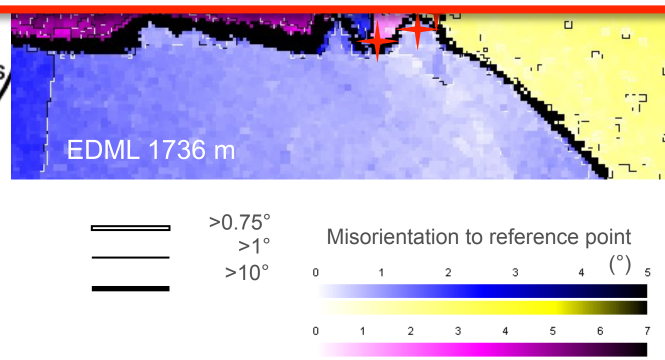
-
-

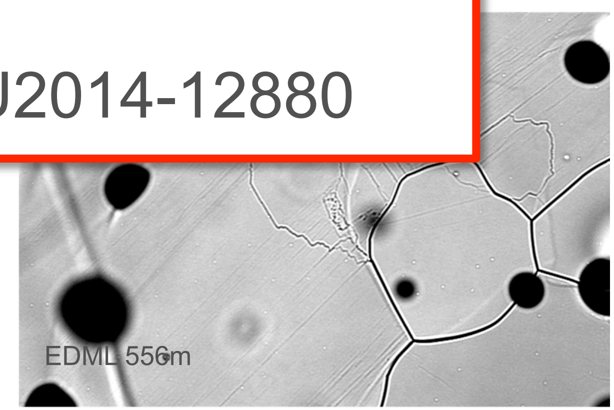
-O)

µS modelling of combined
crystal plasticity deformation + recrystallization

See Poster: Llorens et al.
→ EGU2014-12880







Width of image: 2.5mm

Schematic ice sheet

Intro

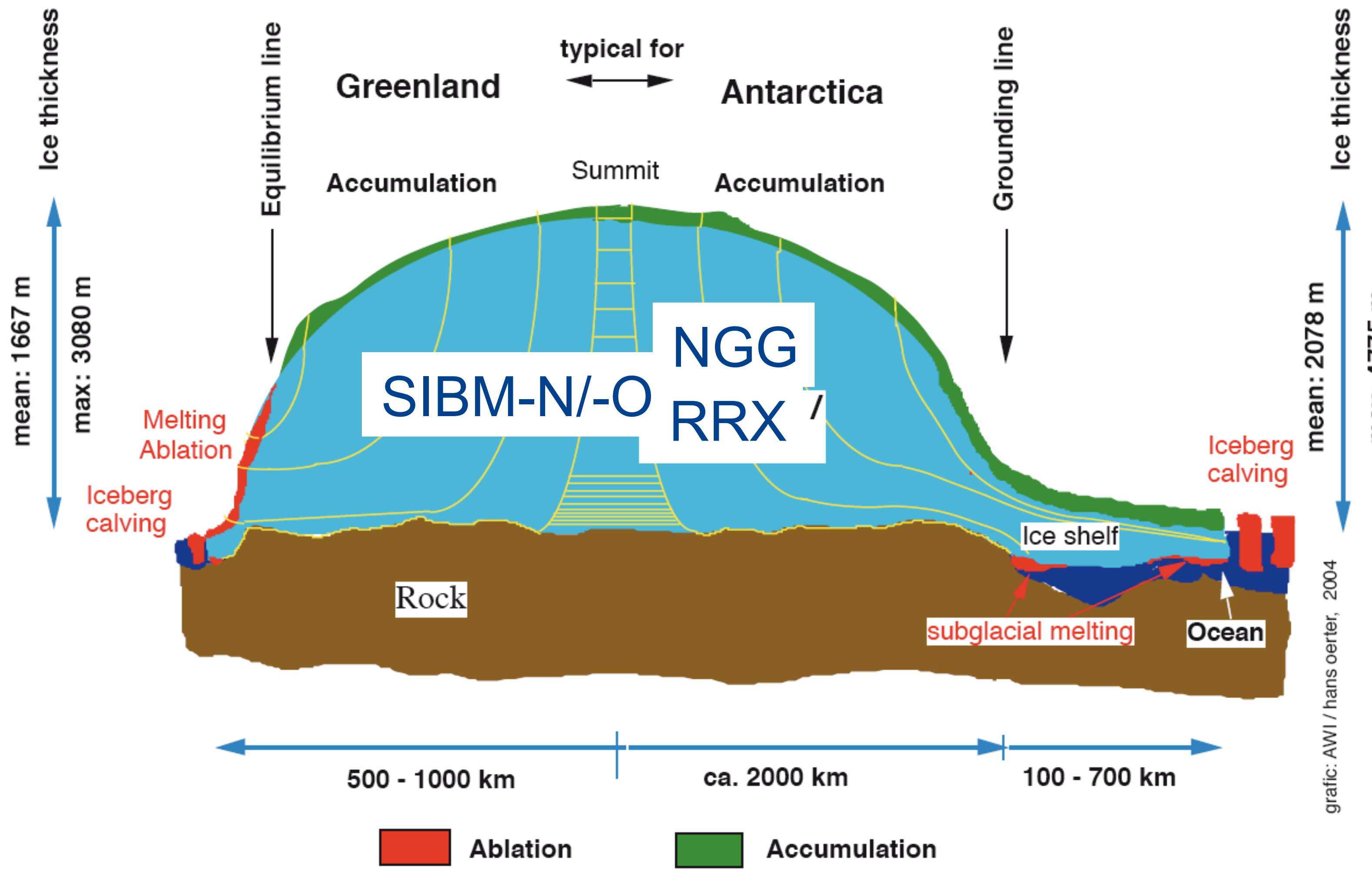
Deformation
heterog. ε

Hot material

Recrystalli-zation
NGG
RRX
SIBM

Diagram

Summary



µS in long ice cores Antarctica

Intro

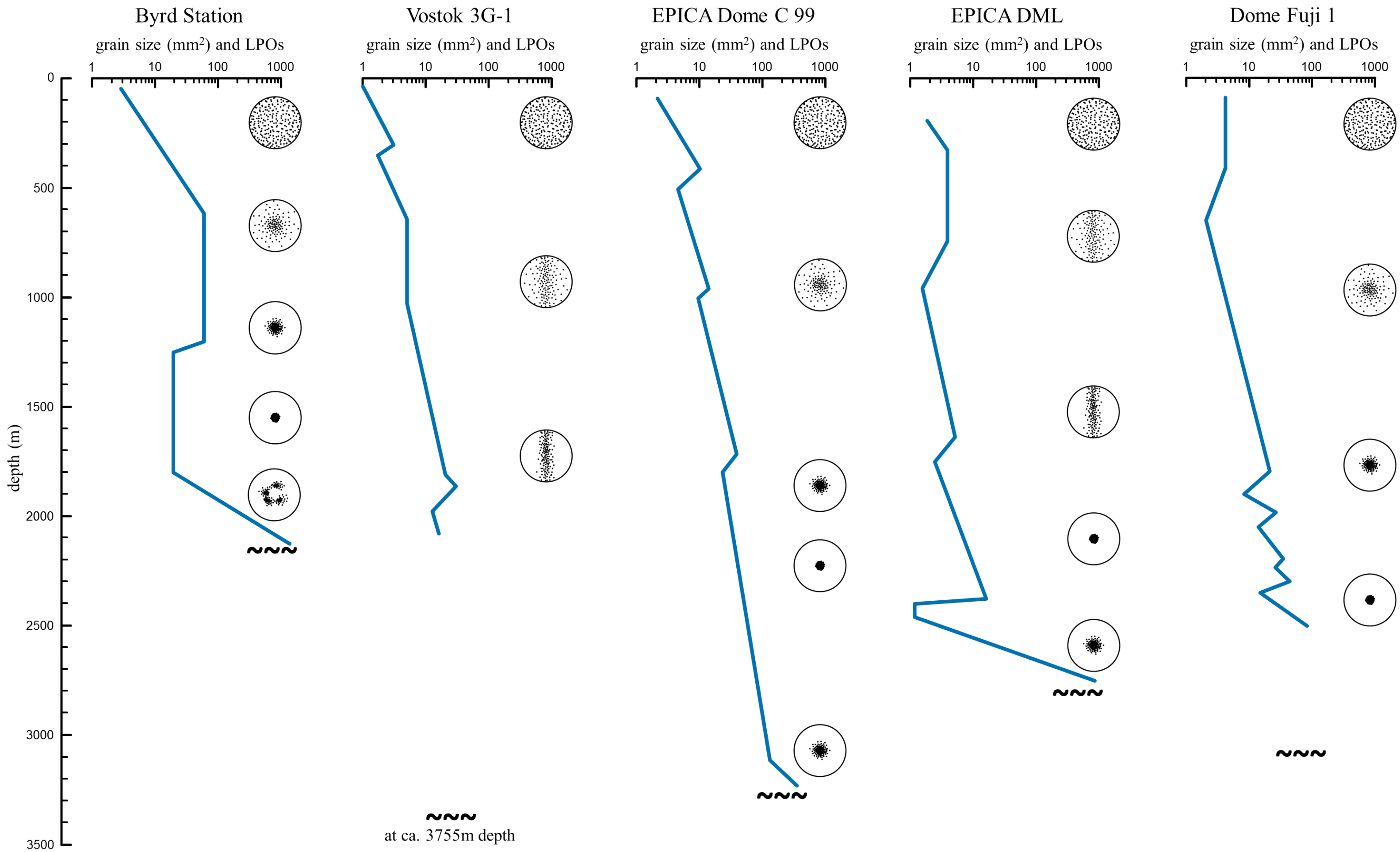
Deformation
heterog. ε

Hot material

Recrystalli-
zation
NGG
RRX
SIBM

Diagram

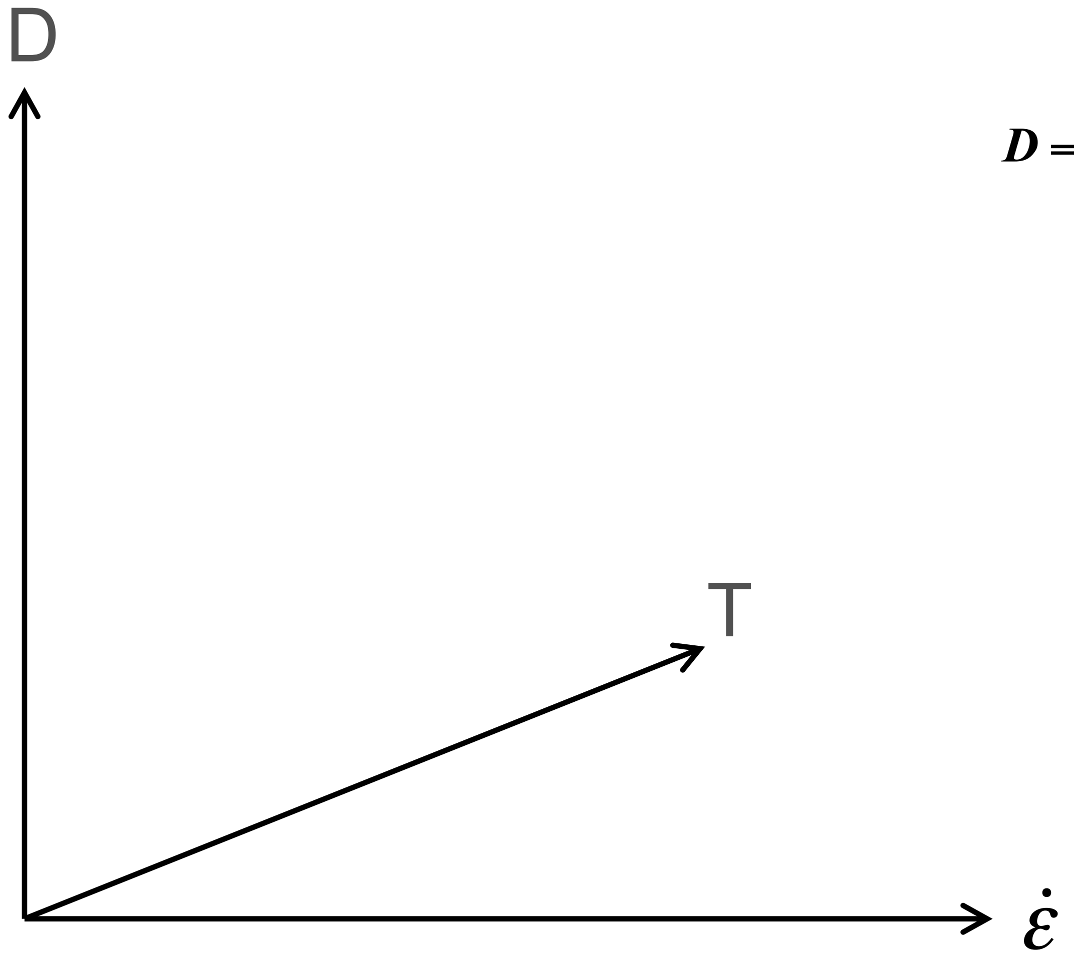
Summary



Faria et al. 2014

Tripartite paradigm?

Diagram



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

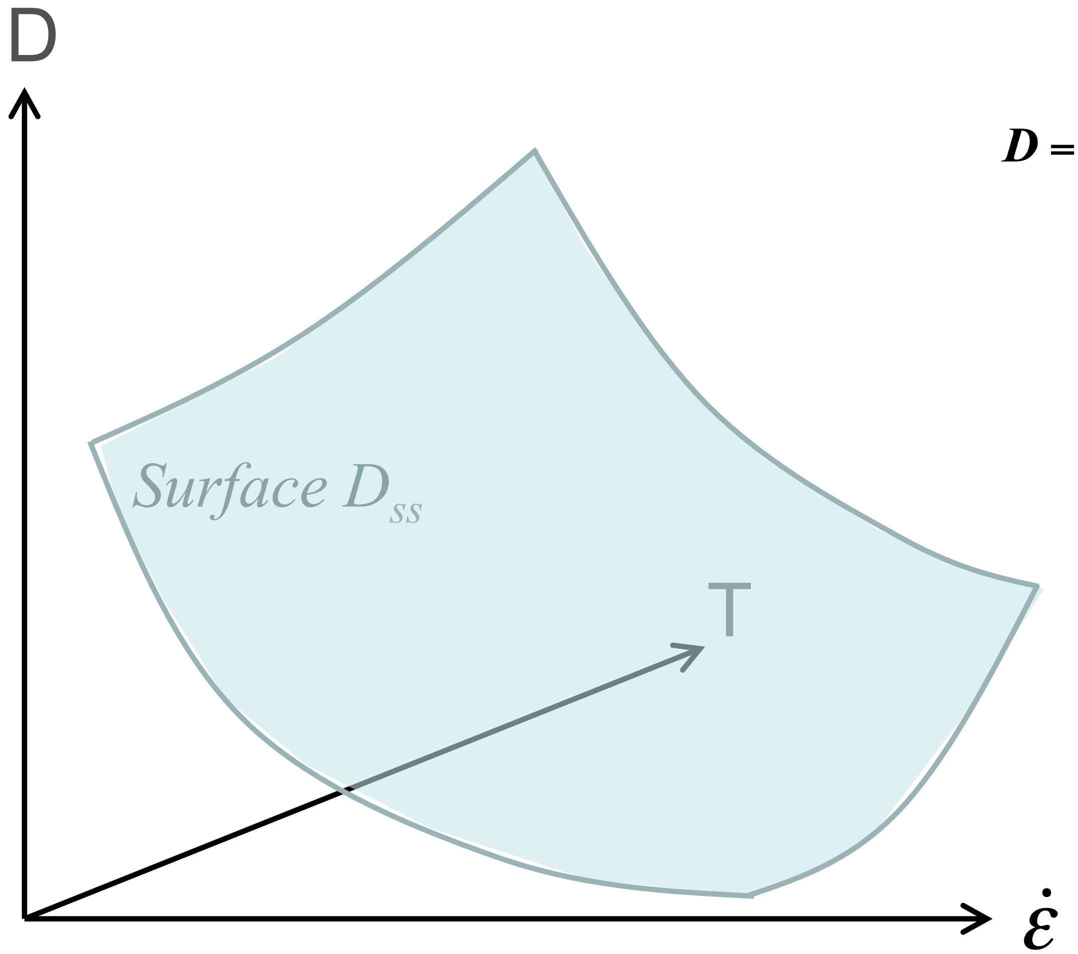
D Mean grain size

$\dot{\varepsilon}$ Strain rate

T Temperature

t time

Diagram



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

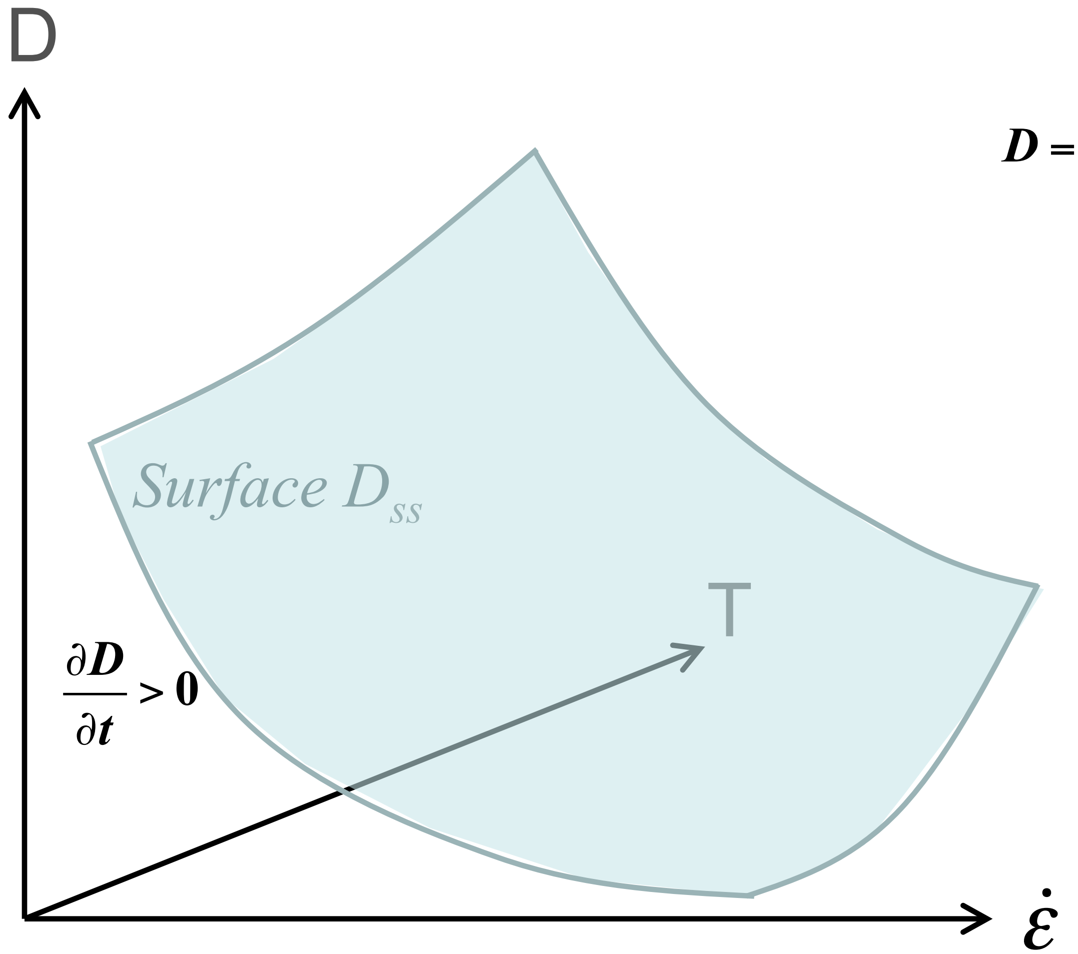
D Mean grain size

$\dot{\varepsilon}$ Strain rate

T Temperature

t time

Diagram



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

Grain growth if $D < D_{ss}$

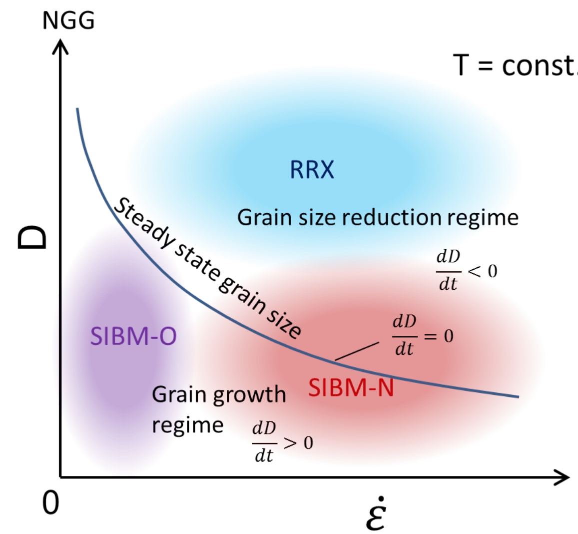
D Mean grain size

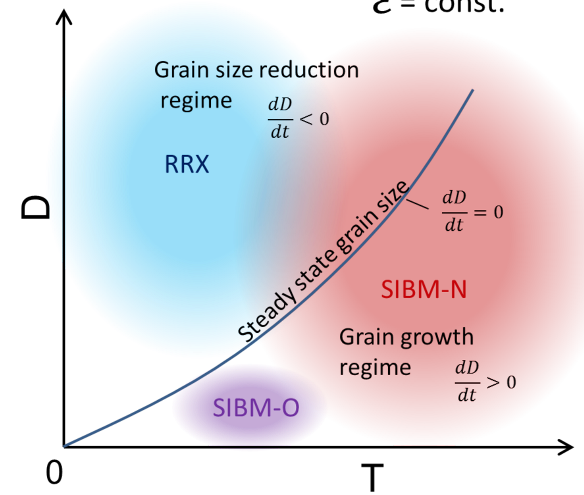
$\dot{\varepsilon}$ Strain rate

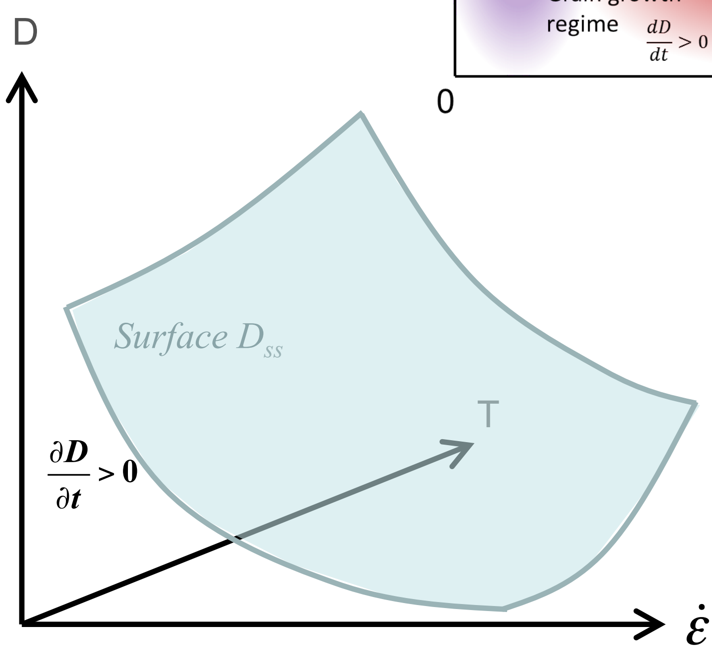
T Temperature

t time

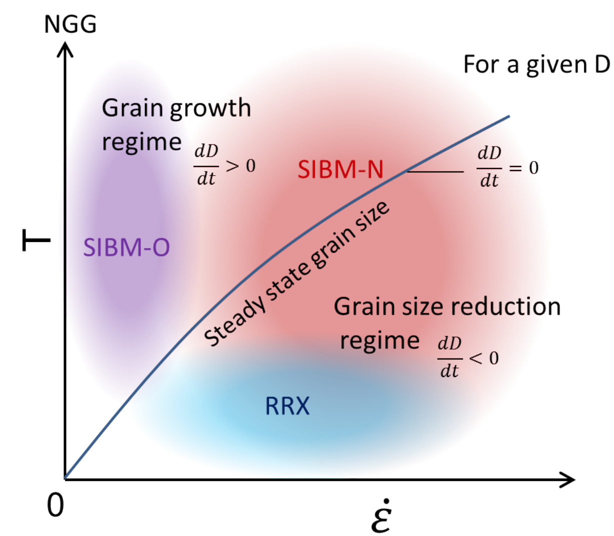
Diagram







Grain growth if $D<D_{ss}$



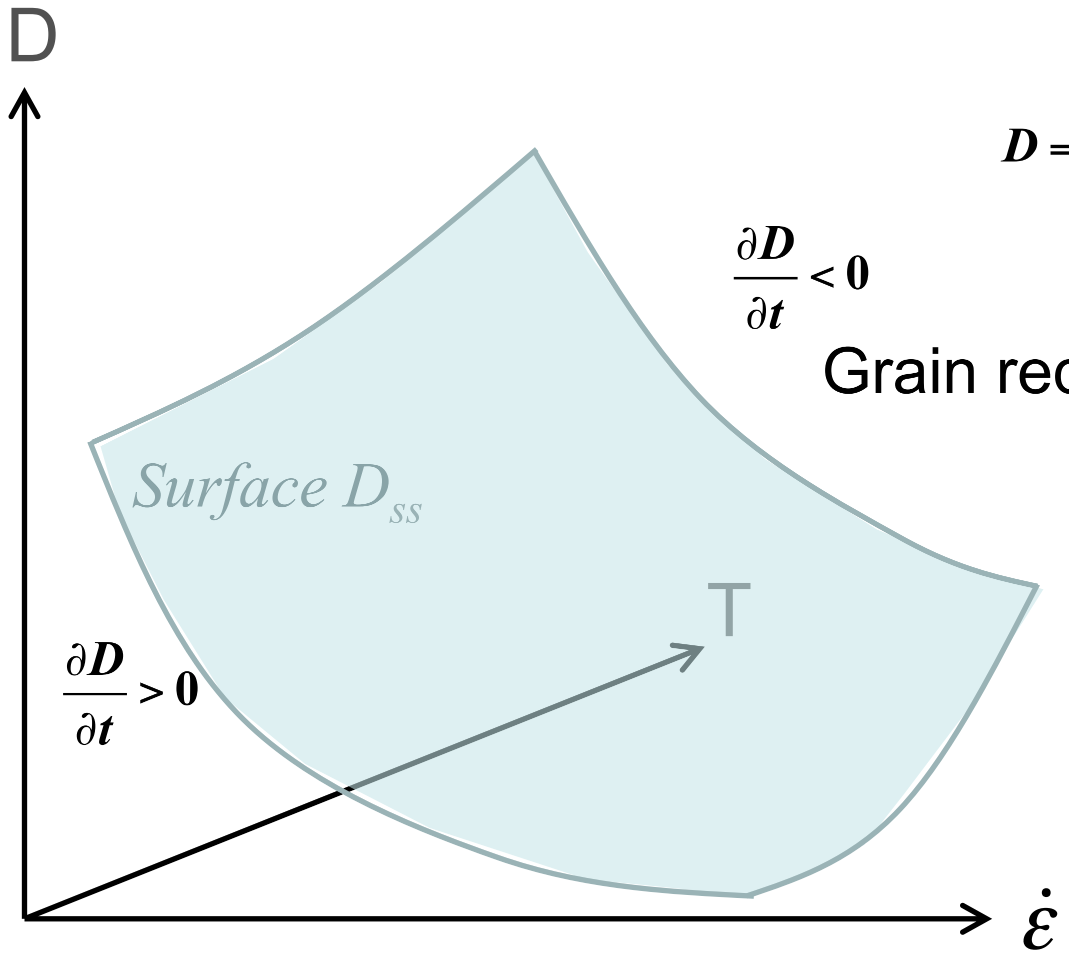
D Mean grain size

$\dot{\varepsilon}$ Strain rate

T Temperature

t time

Diagram



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

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

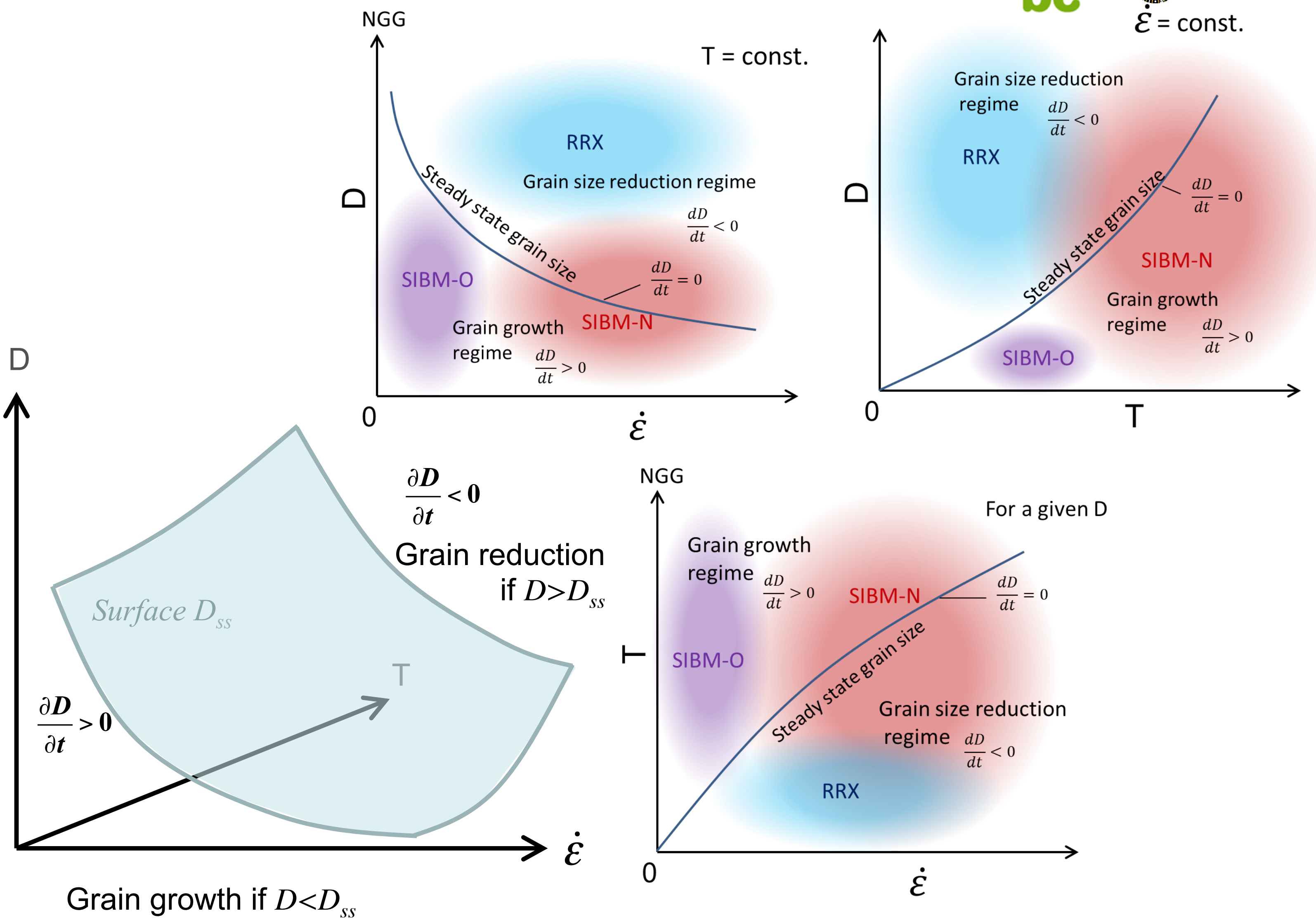
Grain reduction if $D > D_{ss}$

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

Grain growth if $D < D_{ss}$

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

Diagram



D Mean grain size

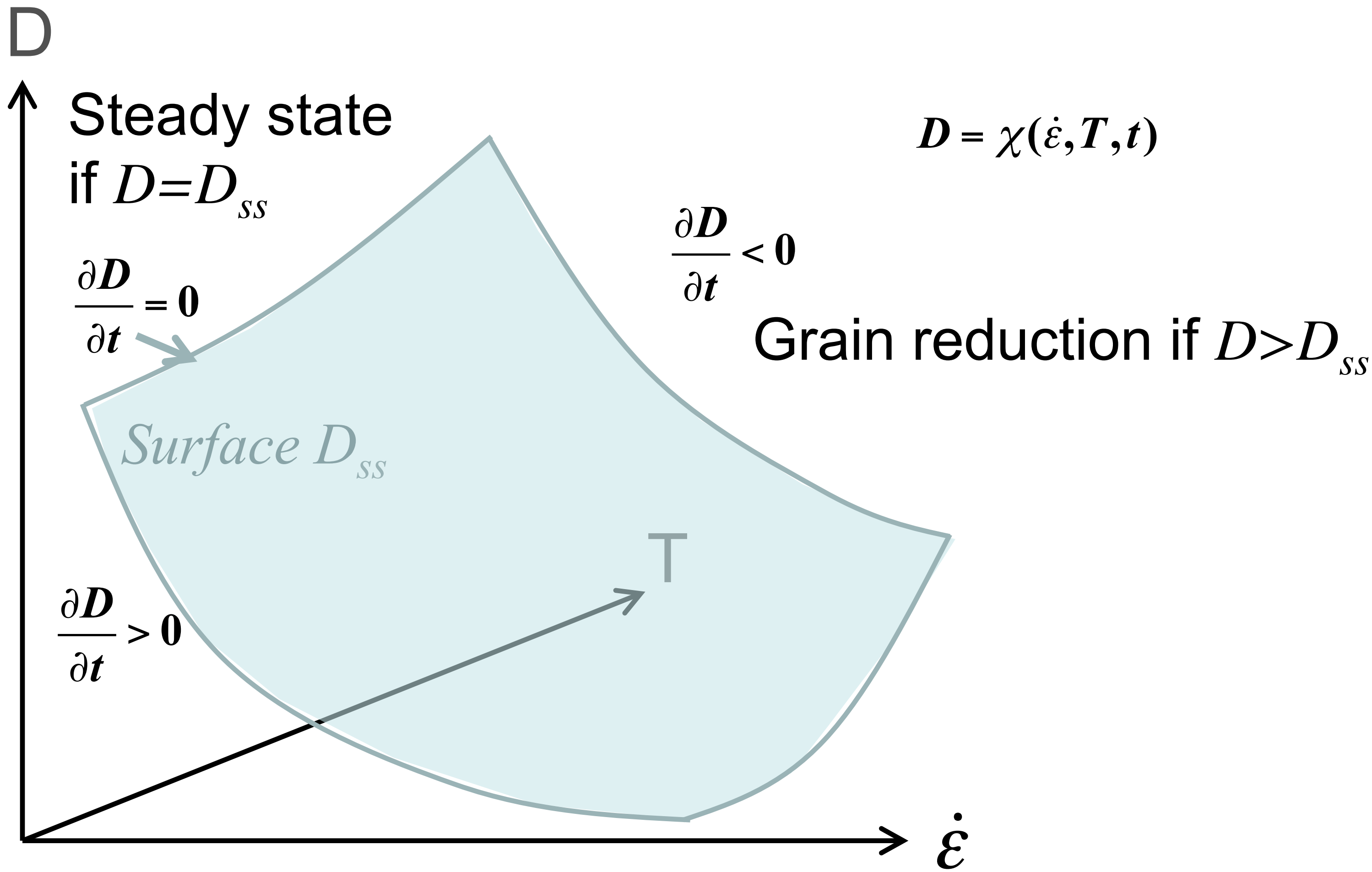
$\dot{\varepsilon}$ Strain rate

T Temperature

t time

Diagram

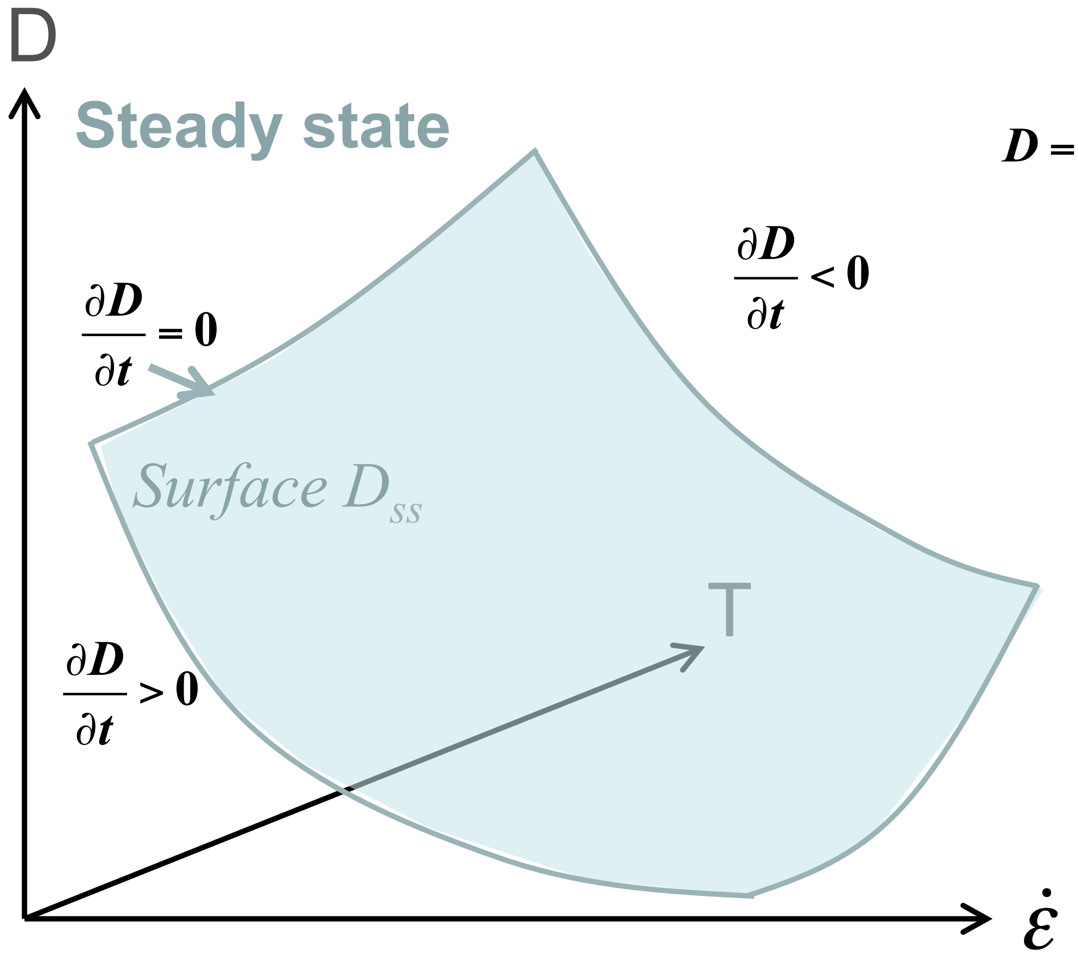
$$D = \chi(\dot{\varepsilon}, T, t)$$



Grain growth if $D<D_{ss}$

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

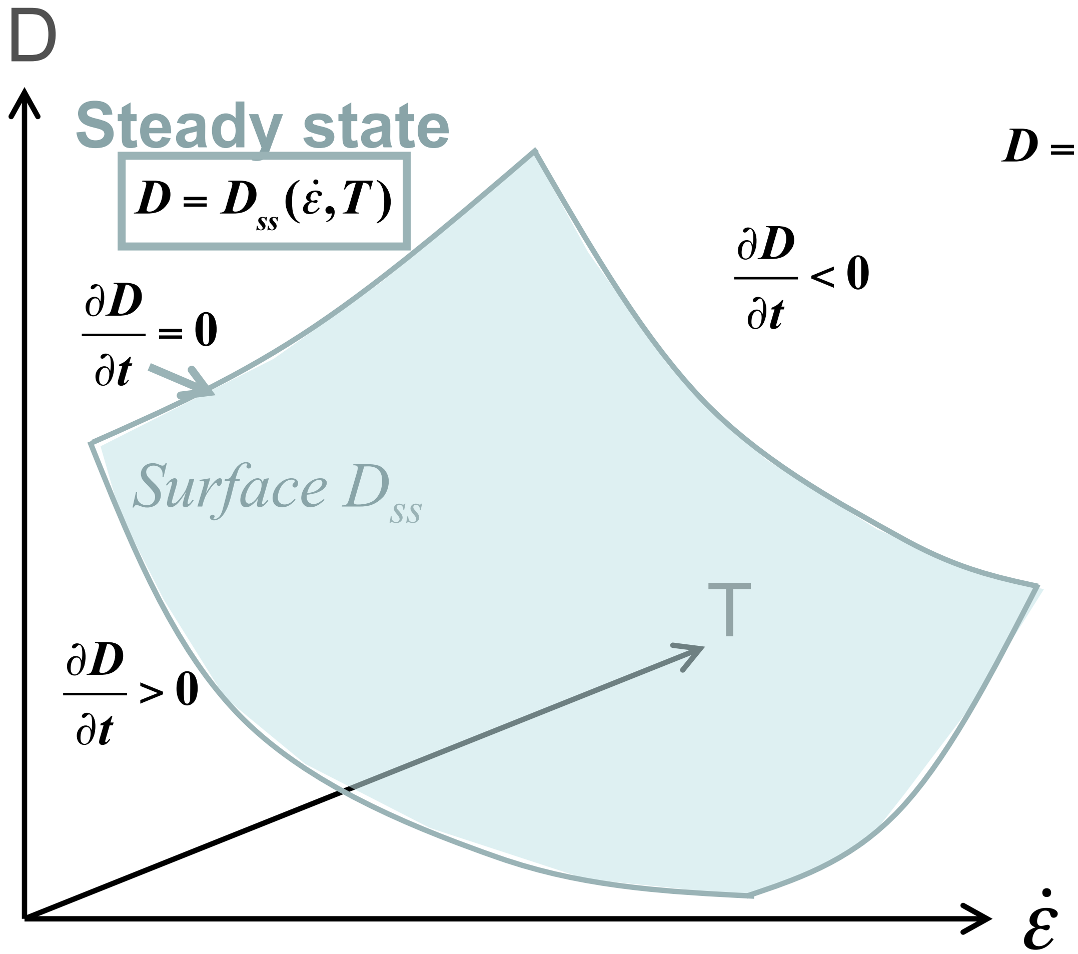
Diagram



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

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

Diagram



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

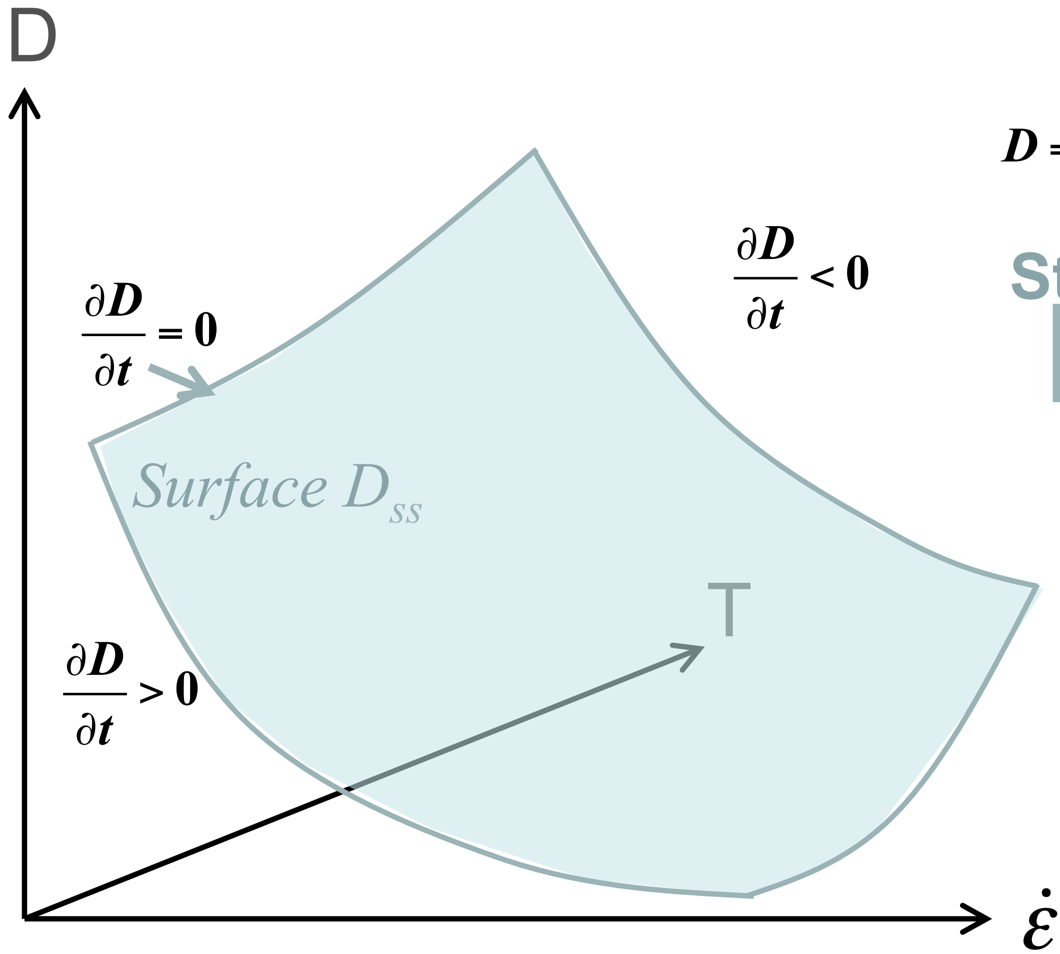
D Mean grain size

$\dot{\varepsilon}$ Strain rate

T Temperature

t time

Diagram



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

Steady state

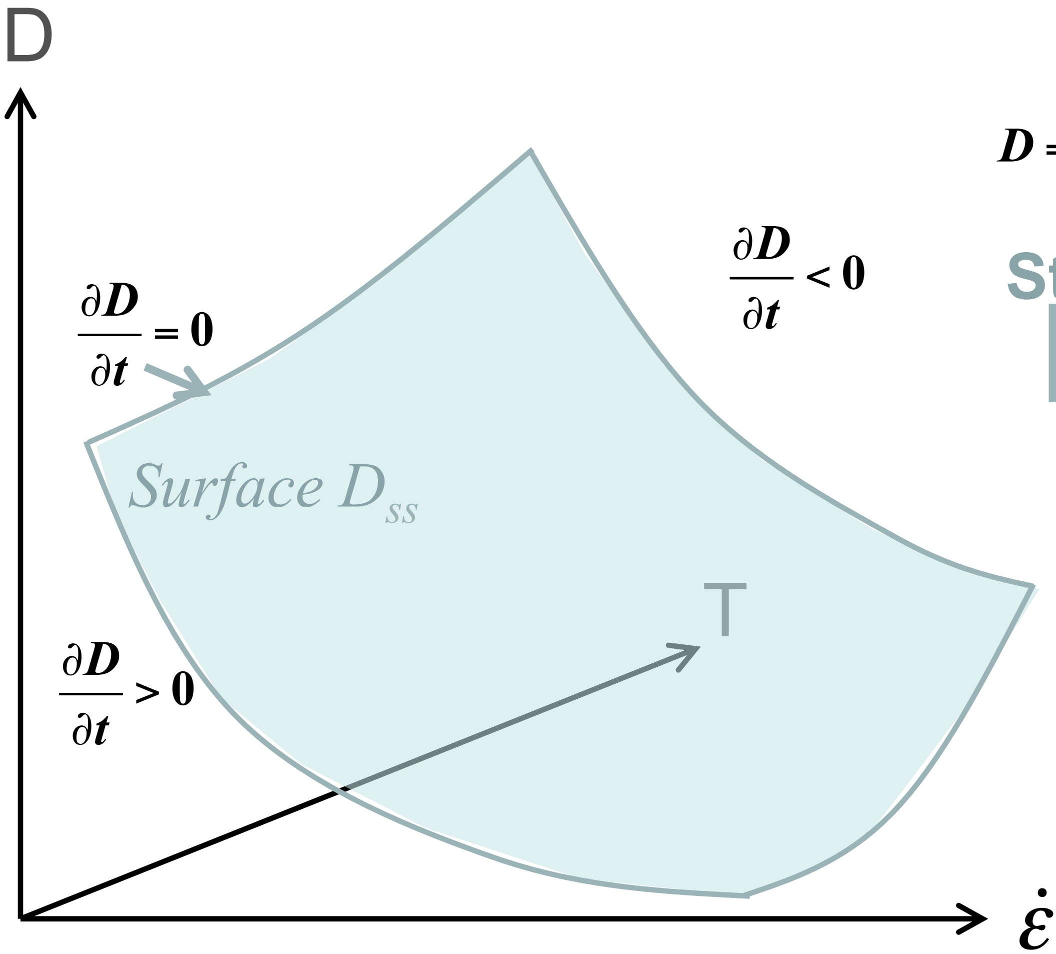
$$D = D_{ss}(\dot{\varepsilon}, T)$$

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

Jacka & Li 1994

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

Diagram



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

Steady state

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

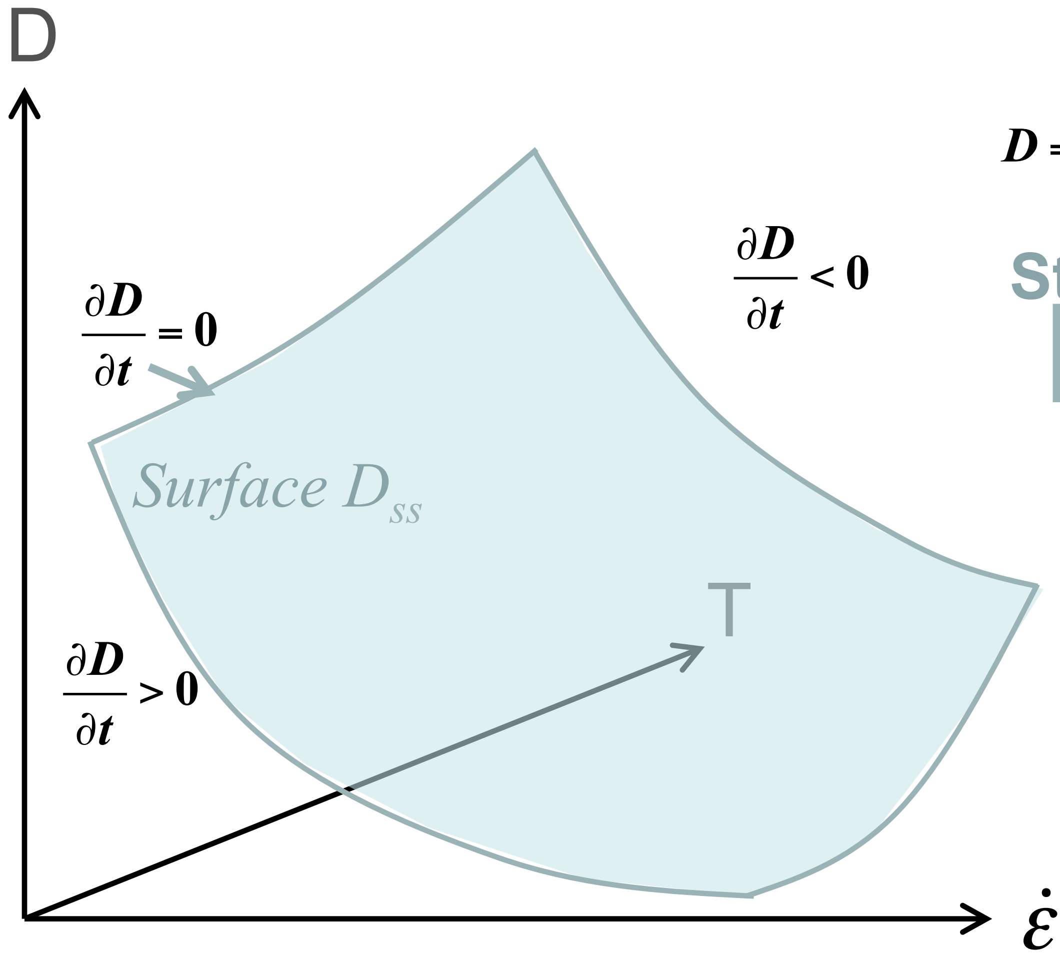
$$D_{ss}^2 = \frac{\varphi}{\sigma^3}$$ Jacka & Li 1994

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

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

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.

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

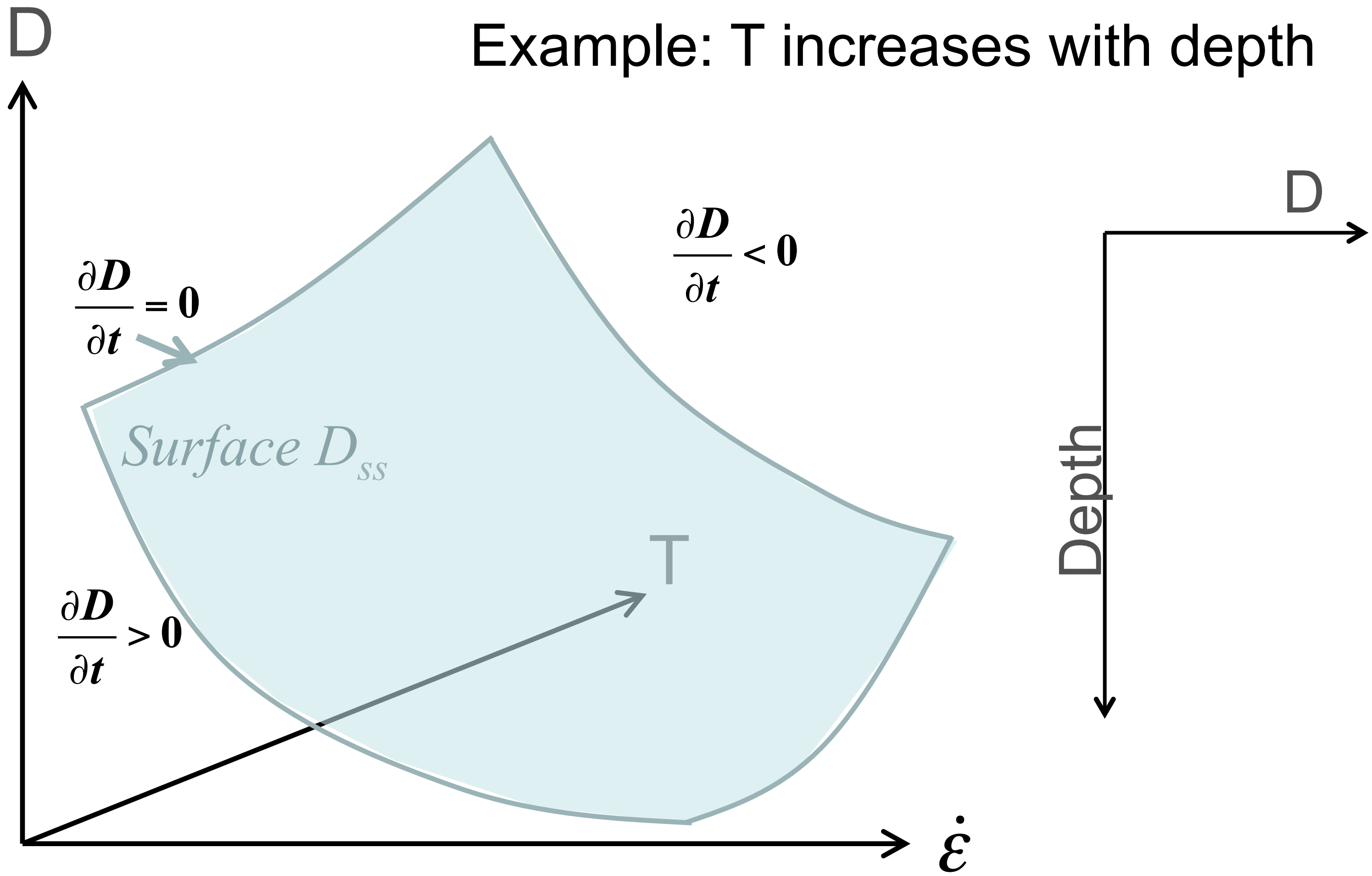
$$A \approx \alpha e^{-Q/k_b T}$$

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

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.

Diagram

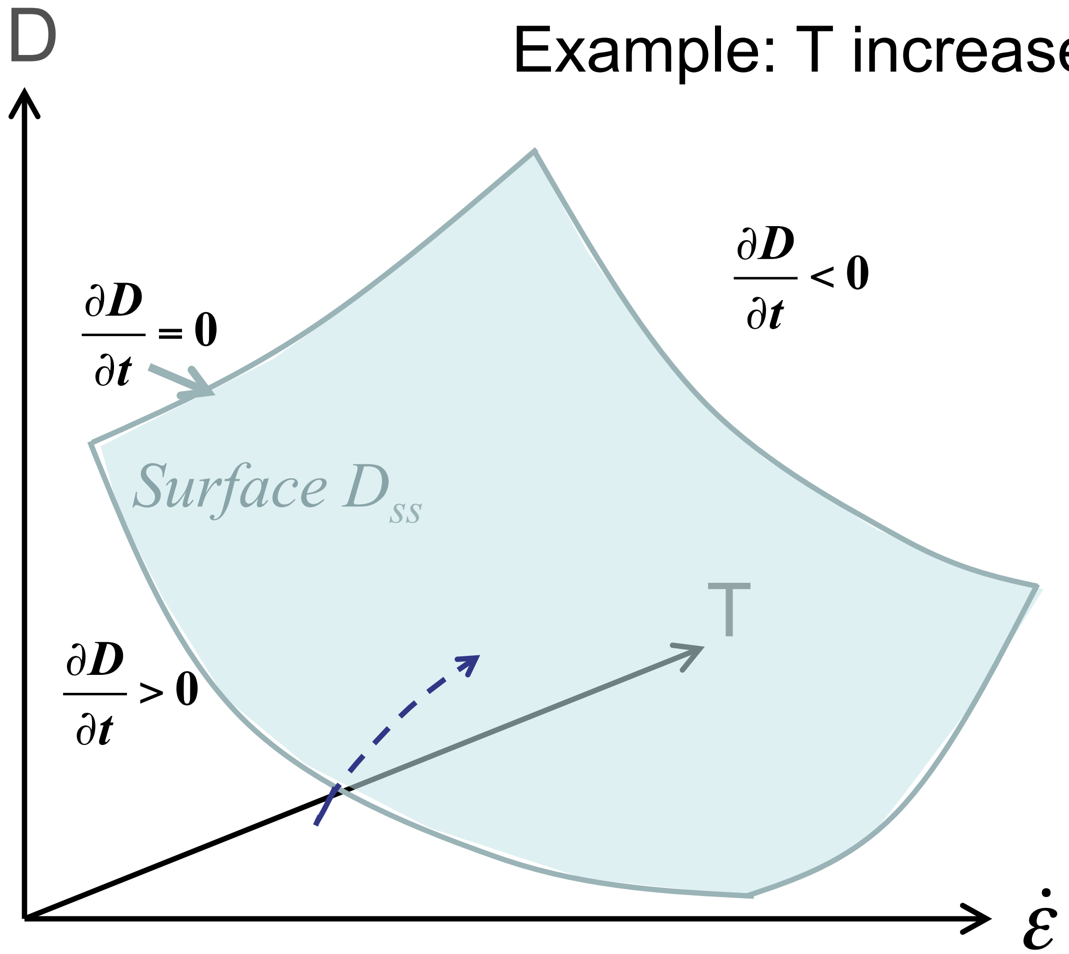
Example: T increases with depth

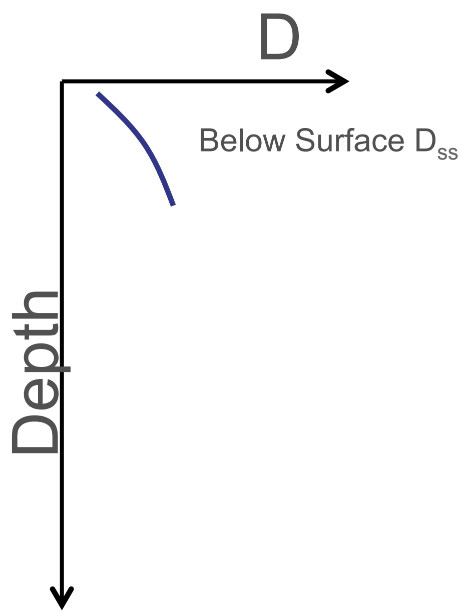


Faria et al. 2014

Diagram

Example: T increases with depth



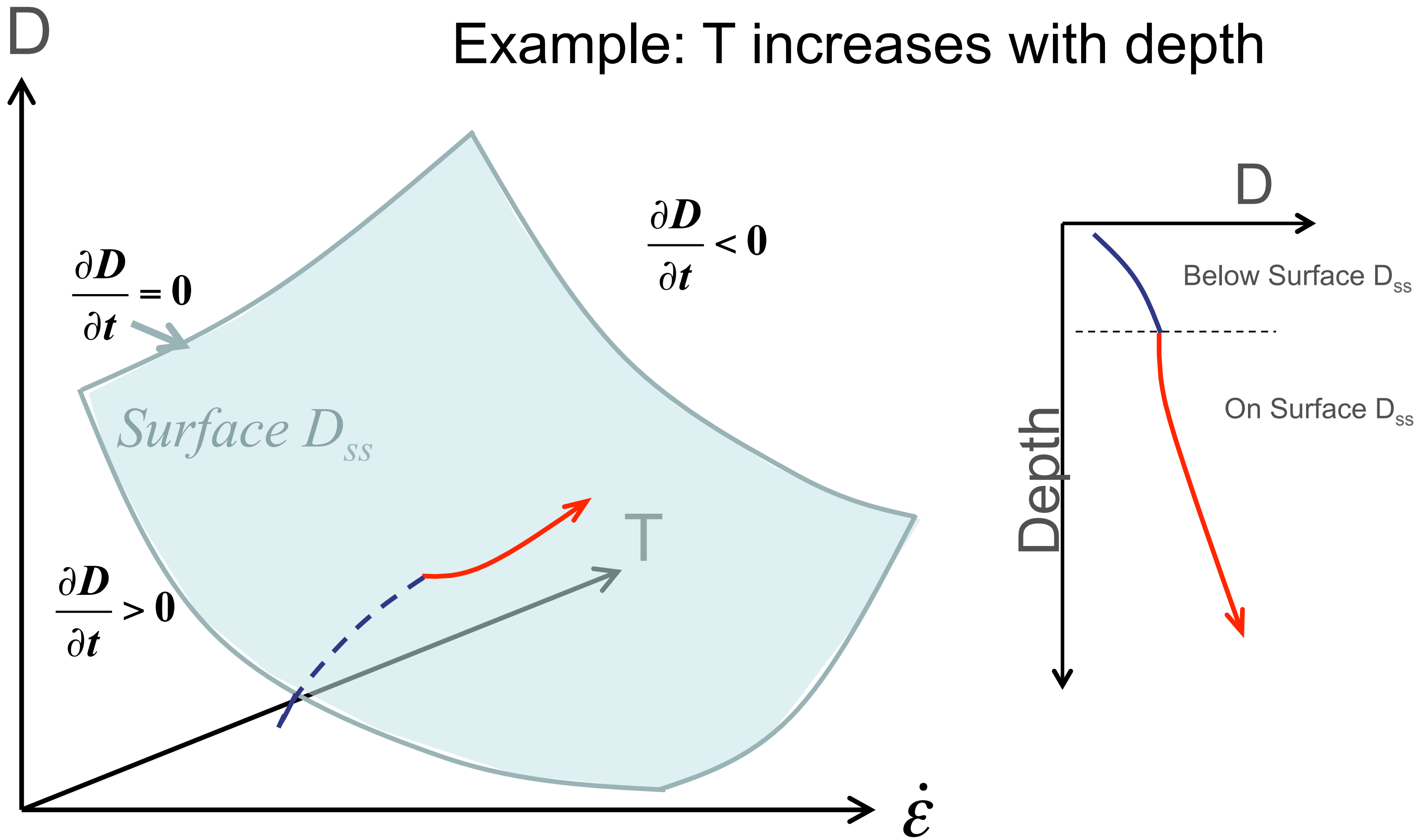


Faria et al. 2014

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

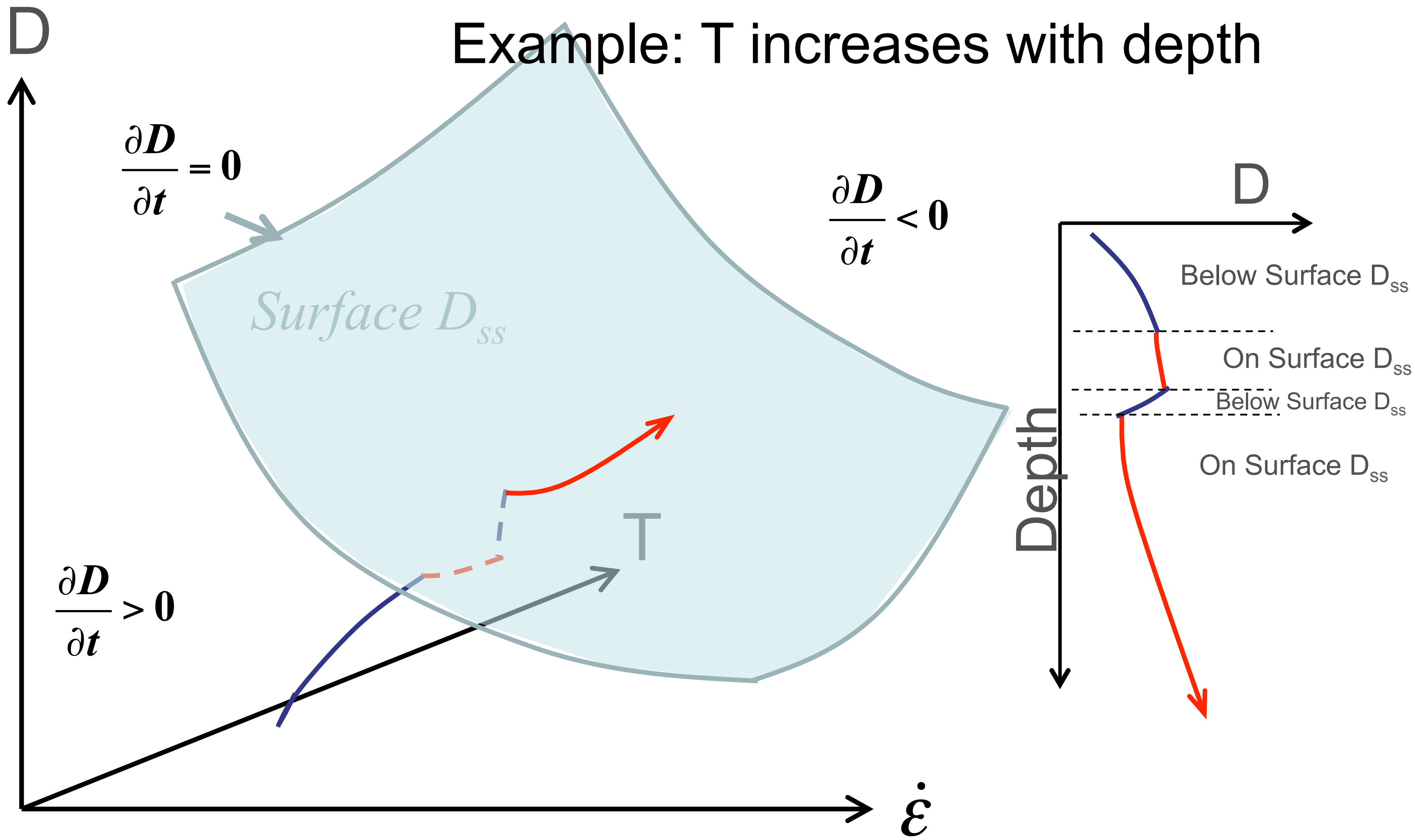
Diagram

Example: T increases with depth



Faria et al. 2014

Diagram


D
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}
T
$\dot{\varepsilon}$
D
Depth
Below Surface D_{ss}
On Surface D_{ss}
Below Surface D_{ss}
On Surface D_{ss}

Diagram

Intro

Deformation heterog. ε

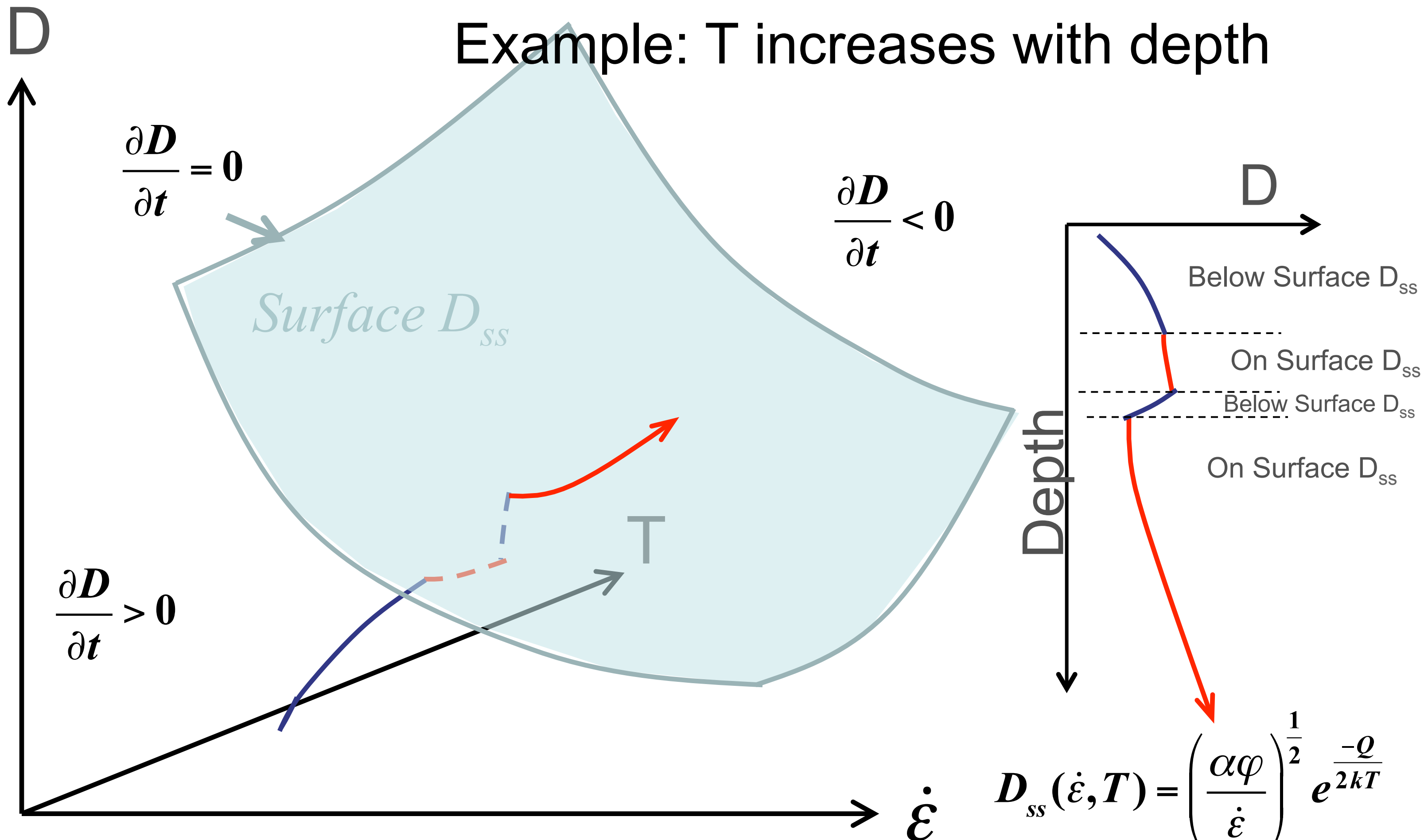
Hot material

Recrystalli-zation
NGG
RRX
SIBM

Diagram

Summary

Example: T increases with depth



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

Summary

Intro

Deformation
heterog. ε

Hot material

Recrystalli-
zation
NGG
RRX
SIBM

Diagram

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

Intro

Deformation
heterog. ε

Hot material

Recrystalli-zation
NGG
RRX
SIBM

Diagram

- 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.