Anisotropy in ice sheets - some types and causes

Ilka Weikusat

Ilka Weikusat:
"**Anisotropy in ice sheets - some types and causes",** Neutrino-astronomy meets ice drilling and glaciology, 30 September 2017 *Humboldt University*
List of references with full biblio info

Faria, S. H.; Weikusat, I. & Azuma, N. The Microstructure of Polar Ice. Part I: Highlights from ice core research Journal of Structural Geology , 2014, 61, 2-20. http://dx.doi.org/10.1016/j.jsg.2013.09.010

IPCC Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 2014, 151, ISBN 978-92-9169-143-2.

Glen, J. W. The creep of polycrystalline ice Proc. Roy. Soc. London, 1955, A228, 519-538
Griera, A.; Llorens, M.-G.; Gomez-Rivas, E.; Bons, P. D.; Jessell, M. W.; Evans, L. A. & Lebensohn, R. Numerical modelling of porphyroclast and porphyroblast rotation in anisotropic rocks Tectonophysics , 2013, 587, 4 - 29, http://dx.doi.org/10.1016/j.tecto.2012.10.008

Bartels-Rausch, T.; Bergeron, V.; Cartwright, J. H. E.; Escribano, R.; Finney, J. L.; Grothe, H.; Gutierrez, P. J.; Haapala, J.; Kuhs, W. F.; Pettersson, J. B. C.; Price, S. D.; Sainz-Diaz, C. I.; Stokes, D.; Strazzulla, G.; Thomson, E. S.; Trinks, H. & Uras-Aytemiz, N. Ice structures, patterns, and processes: A view across the icefields Reviews of Modern Physics, 2012, doi: 10.1103/RevModPhys.84.885.

Thorsteinsson, T. Textures and fabrics in the GRIP ice core, in relation to climate history and ice deformation Universitaet Bremen, 1996, http://epic.awi.de/26383/

Llorens, M.-G.; Griera, A.; Steinbach, F.; Bons, P. D.; Gomez-Rivas, E.; Jansen, D.; Roessiger, J.; Lebensohn, R. A. & Weikusat, I. Dynamic recrystallization during deformation of polycrystalline ice: insights from numerical simulations Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, The Royal Society, 2017, 375, 20150346 (1-24), doi: 10.1098/rsta.2015.0346.

Bons, P. D.; Jansen, D.; Mundel, F.; Bauer, C. C.; Binder, T.; Eisen, O.; Jessell, M. W.; Llorens, M.-G.; Steinbach, F.; Steinhage, D. & Weikusat, I. Converging flow and anisotropy cause large-scale folding in Greenland's ice sheet Nat Commun, 2016, 7, 11427, doi: 10.1038/ncomms11427.

Jansen, D.; Llorens, M.-G.; Westhoff, J.; Steinbach, F.; Kipfstuhl, S.; Bons, P. D.; Griera, A. & Weikusat, I. Small-scale disturbances in the stratigraphy of the NEEM ice core: observations and numerical model simulations The Cryosphere, 2016, 10, 359-370, doi: 10.5194/tc-10-359-2016.

Weikusat, I.; Jansen, D.; Binder, T.; Eichler, J.; Faria, S. H.; Wilhelms, F.; Kipfstuhl, S.; Sheldon, S.; Miller, H.; Dahl-Jensen, D. & Kleiner, T. Physical analysis of an Antarctic ice core - towards an integration of micro- and macrodynamics of polar ice Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, The Royal Society, 2017, 375, 20150347 (1-27), doi: 10.1098/rsta.2015.0347.

Llorens, M.-G.; Griera, A.; Bons, P. D.; Lebensohn, R. A.; Evans, L. A.; Jansen, D. & Weikusat, I. Full-field predictions of ice dynamic recrystallisation under simple shear conditions Earth and Planetary Science Letters , 2016, 450, 233 - 242, doi: 10.1016/j.epsl.2016.06.045.

Svensson, A.; Nielsen, S. W.; Kipfstuhl, S.; Johnsen, S. J.; Steffensen, J. P.; Bigler, M.; Ruth, U. & Röthlisberger, R. Visual stratigraphy of North Greenland Ice Core Project (NorthGRIP) ice core during the last glacial period J. Geophys. Res., 2005, D110, doi; 10.1029/2004JD005134.

Eichler, J.; Kleitz, I.; Bayer, M.; Jansen, D.; Kipfstuhl, S.; Shigeyama, W.; Weikusat, C. & Weikusat, I. Location and distribution of micro-inclusions in the EDML and NEEM ice cores using optical microscopy and in-situ Raman spectroscopy The Cryosphere, 2017, 11, 1075-1090, doi: 10.5194/tc-11-1075-2017.

- Why?
- Anisotropy
  - Intrinsic (ice itself)
    - Fabric (crystal preferred orientation)
    - Texture (grain shape preferred orientation)
  - Composite (second phases)
    - Air inclusions
    - Dust and salt particles

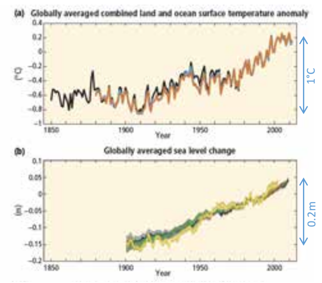
Bremerhaven

Located at estuary of river Weser into the North-Sea

Why should we care about anisotropy?

Sea level

IPCC - Intergovernmental Panel on Climate Change
(set up by UN to assess of the scientifc basis of climate change for policymakers)

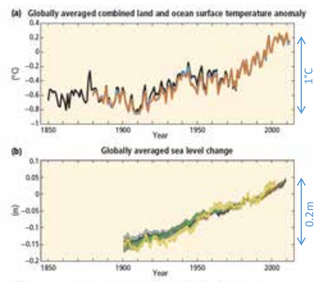


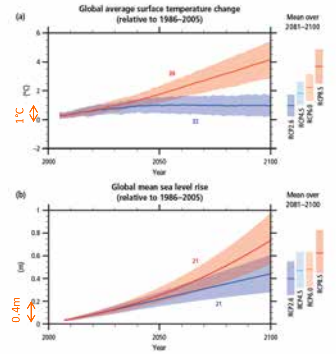
Observations (over ca. 100a)

IPCC 2014

Sea level

IPCC - Intergovernmental Panel on Climate Change
(set up by UN to assess of the scientifc basis of climate change for policymakers)





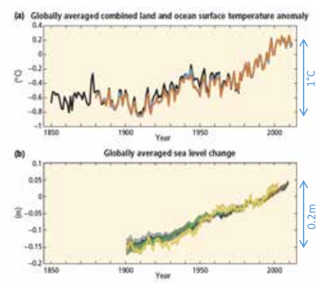
Observations (over ca. 100a)

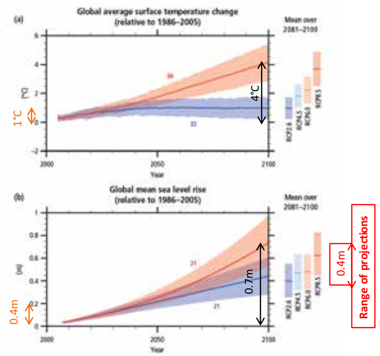
Projections (for ca. 100a)

IPCC 2014

Sea level

IPCC - Intergovernmental Panel on Climate Change
(set up by UN to assess of the scientifc basis of climate change for policymakers)





Observations (over ca. 100a)

Projections (for ca. 100a)

IPCC 2014

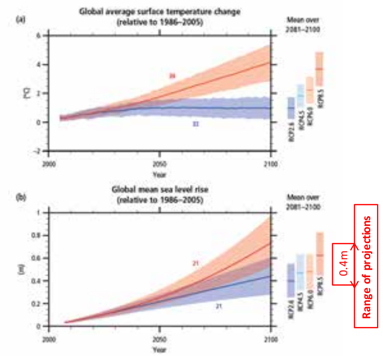
Ice sheets & Sea level

IPCC - Intergovernmental Panel on Climate Change
(set up by UN to assess of the scientifc basis of climate change for policymakers)

IPCC 2014:
-*low confidence* in the available models' ability to project **solid ice discharge**

-models *likely* underestimate **ice sheet contribution**

->underestimation of projected **sea level rise**



Projections (for ca. 100a)

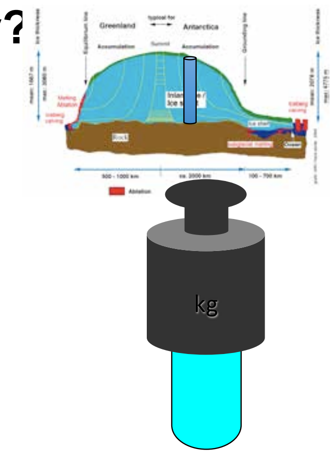
IPCC 2014

Why should we care about anisotropy?

Predictions by large scale flow models

Ice deformation

– Glaciology: ice discharge and sea level



Glen's flow law

Glen 1955

Why should we care about anisotropy?

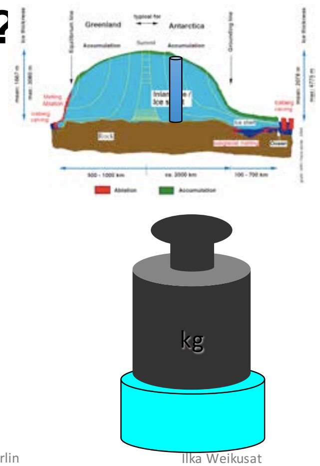
Predictions by large scale flow models

Ice deformation

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

$\dot{\varepsilon}$ = strain rate („How fast do we deform?")
σ = stress („How much do we press?")
T = temperature
R = ideal gas constant („general physical constant")
B, n, Q = **treated** as constant („tunig parameters")

– Glaciology: ice discharge and sea level



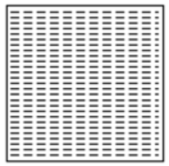
Glen's flow law

Glen 1955

Why should we care about anisotropy?

– Ice cube: optical scatter length

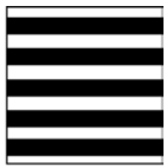
Anisotropy types



Intrinsic

Basically single material

- crystal orientation, crystal preferred orientation (CPO)
- crystal shapes, shape preferred orientation (SPO)



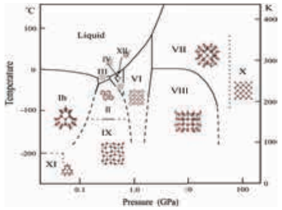
Composite

Two or more materials with different properties

- Isotropic or anisotropic in isolation
- E.g. stack of layers

Griera et al. 2013

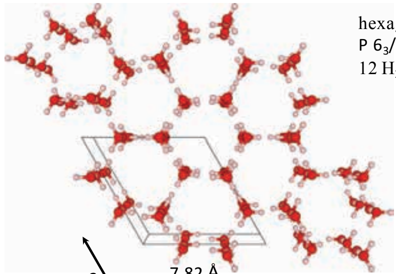
Intrinsic anisotropy -
Crystal preferred orientation

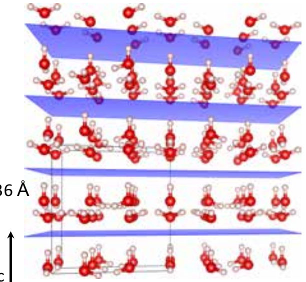


Bartels-Rausch et al. 2012

Ice Ih

hexagonal
P 6_3/mmc
12 H_2O in EZ

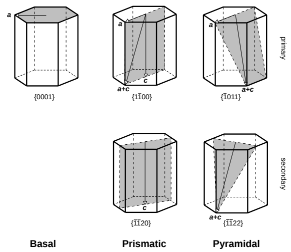




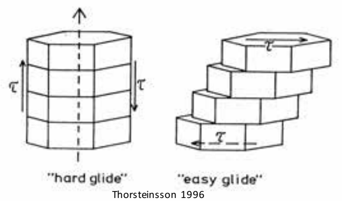
(slide (mod.) Ch. Weikusat)

Intrinsic anisotropy -
Crystal preferred orientation (fabric)

Possible dislocation slip systems in ice

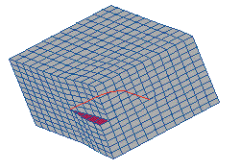


Faria et al. 2014



Thorsteinsson 1996

Dislocation:



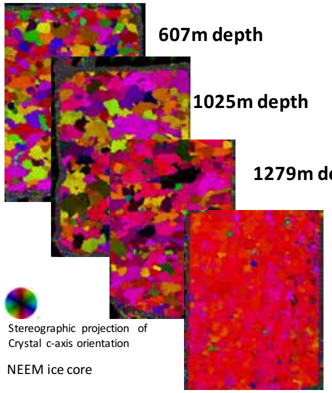
Screw dislocation: Lattice partly twisted

Edge dislocation: Extra half lattice plane

van der Pluijm , B., University of Michigan,
http://www.geo.lsa.umich.edu/~vdpluijm/animations/edgescrewglide.mov

Activation of non-basal slip: 60-100x higher stresses needed than for basal planes

Intrinsic anisotropy -
Crystal preferred orientation (fabric)



607m depth

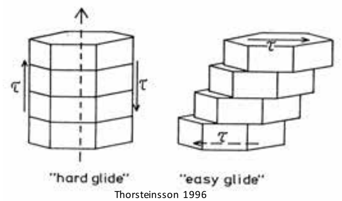
1025m depth

1279m depth

1757m depth

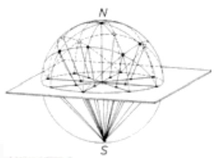
Stereographic projection of Crystal c-axis orientation

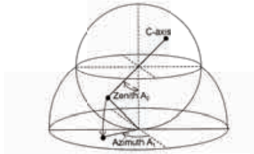
NEEM ice core



Thorsteinsson 1996

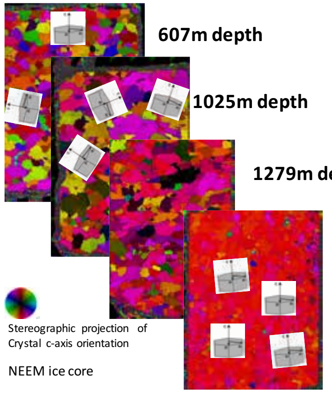
Stereographic projection





Method:
automated polarization microscopy
"fabric analyzer"

Intrinsic anisotropy -
Crystal preferred orientation (fabric)



607m depth

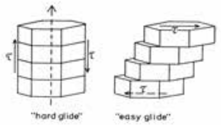
1025m depth

1279m depth

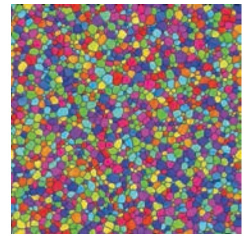
1757m depth

Stereographic projection of Crystal c-axis orientation

NEEM ice core



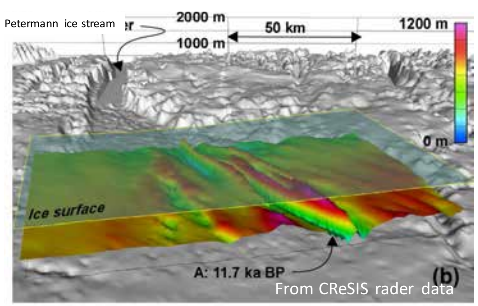
mechanistic approach

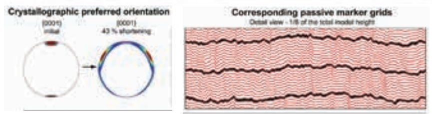


Llorens et al. 2016, 2017

microstructural modelling **(ELLE/FFT)**
- viscoplastic deformation of ice
- Recrystallization of ice

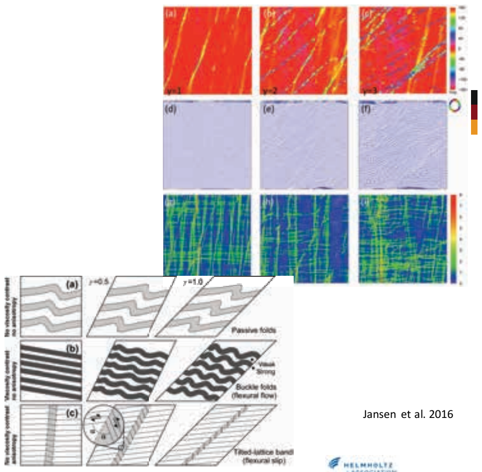
Folding partly caused by anisotropy





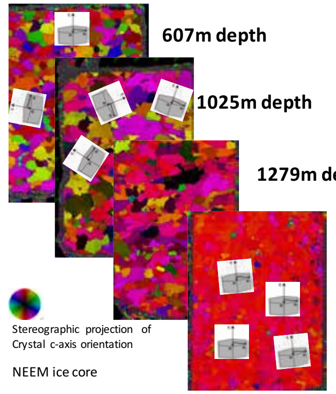
From viscoplastic modelling

Bons et al. 2016

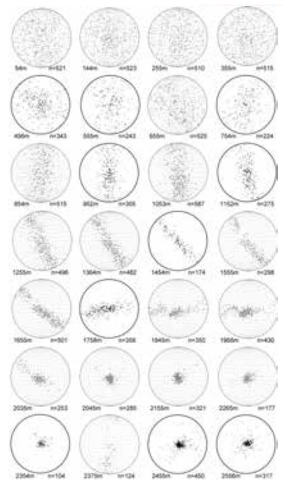


Jansen et al. 2016

Intrinsic anisotropy - Crystal preferred orientatior



NEEM ice core

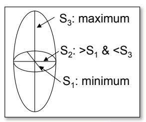


EDML ice core

Weikusat et al. 2017

Intrinsic anisotropy - CPO evolution with depth

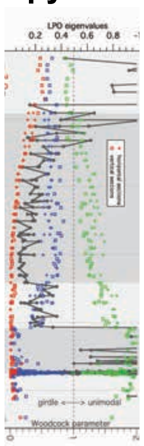
CPO (fabrics) as Eigenvalues of 2nd order orientation tensor

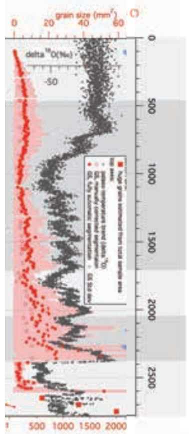


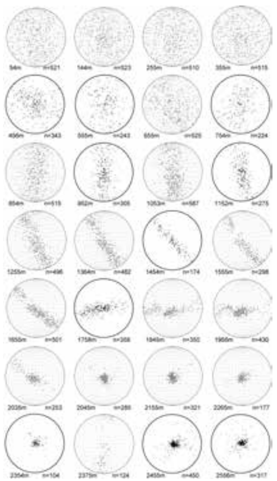
Random: $S_1 = S_2 = S_3 = 1/3$

Strong single maximum: $0 \leq s_1 = s_2 \leq 1/6$; $2/3 \leq s_3 \leq 1$

Girdle: $0 \leq s_1 \leq s_2 = 1/3 \leq s_3 \leq 2/3$





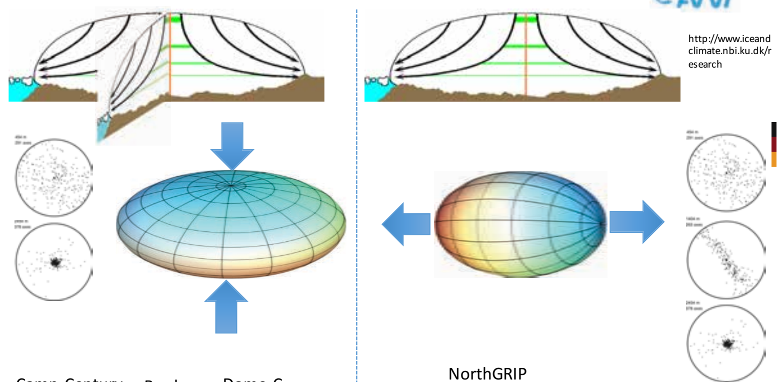


EDML ice core

Weikusat et al. 2017

Intrinsic anisotropy - CPO evolution with depth

History - deep ice cores for paleo-climate reconstruction
→ Low dynamic sites



Camp Century
Dye 3

Byrd
GRIP
GISPII

Dome C
Dome F

NorthGRIP
Vostok
EDML
NEEM

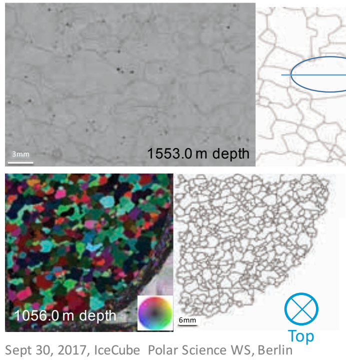
Intrinsic anisotropy - CPO evolution with depth

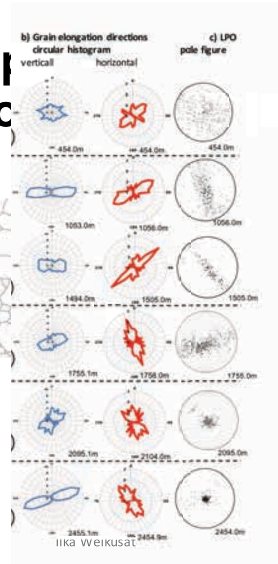
History - deep ice cores for paleo-climate reconstruction
→ Low dynamic sites

First physically motivated deep ice core:
EastGRIP – launched into the largest ice stream in Greenland

Intrinsic anisotrop Shape preferred o exture)

Weikusat et al. 2017

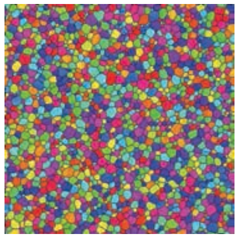




Distributions of grain elongation directions

EDML ice core

Intrinsic anisotropy - Shape preferred orientati

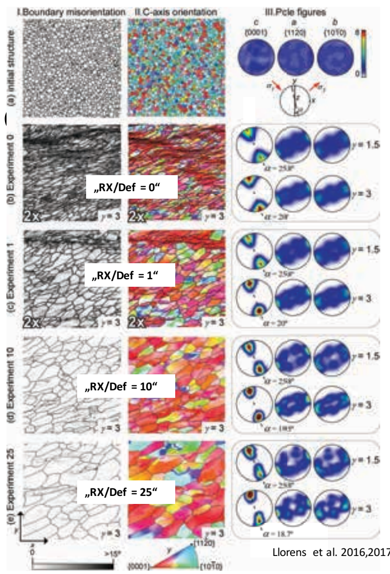


Ice in nature is a hot material
$T/T_m > 0.8$

→ Extensively recrystallizing

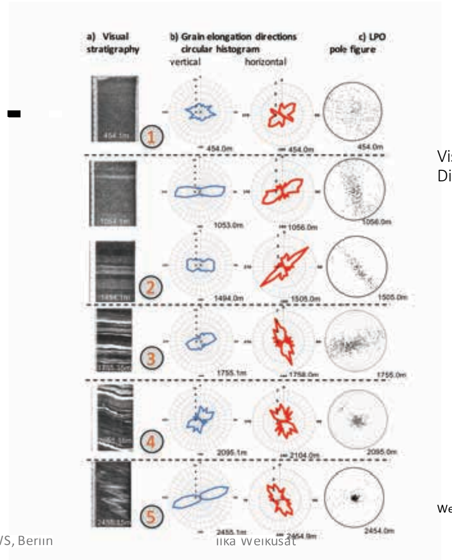
Llorens et al. 2016,2017

microstructural modelling
(ELLE/FFT)
- viscoplastic deformation of ice
- **Recrystallization of ice**



Llorens et al. 2016,2017

Intrinsic anisotropy - Shape preferred orientation



Visual stratigraphy
Distributions of grain elongations

EDML ice core

Weikusat et al. 2017

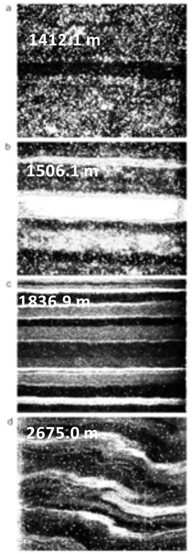
Composite anisotropy - Dusty layers – “cloudy bands“

Method:
Visual stratigraphy line scanner

TOP

Scatter object:
- Second phase particles
- Air bubbles
- Grain boundaries

EDML core



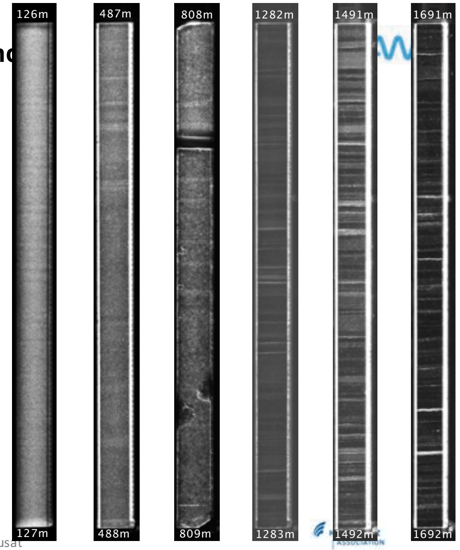
Composite anisotropy - Dusty layers – “cloudy band

NorthGRIP

Svensson et al. 2005

Method:
Visual stratigraphy line scanner

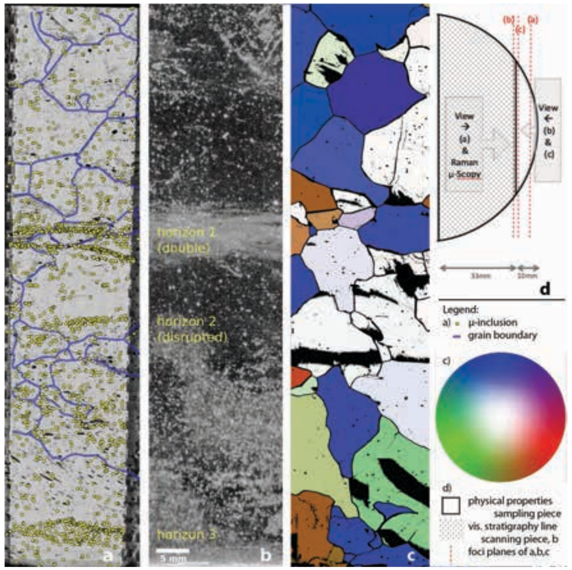
TOP



Scatter object:
- Second phase particles
- Air bubbles
- Grain boundaries

EDML core

“Dust“ distribution

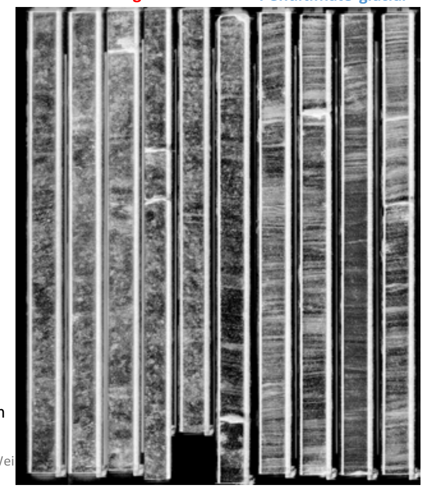


Eichler et al. 2017

Composite anisotropy - Dusty layers – “cloudy bands“

Last interglacial

Penultimate glacial



Scatter object:
- Second phase particles
- Air bubbles
- Grain boundaries

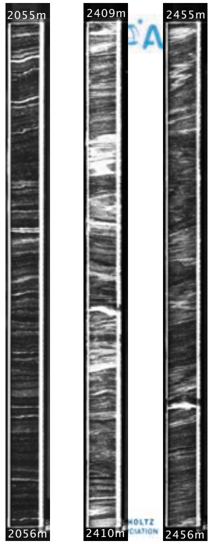
EDML below 2380-2390 m

Composite anisotropy -
Dusty layers – “cloudy bands“

Visual stratigraphy line scanner

TOP

Layers inclined and folded

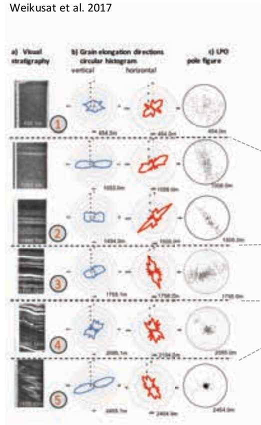


EDML core

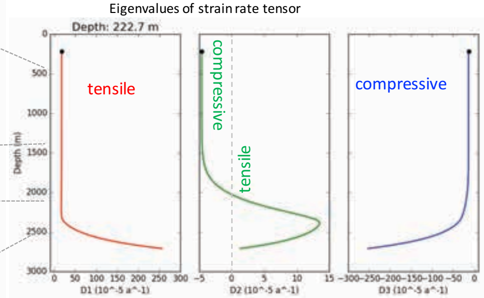
Layer deformation

Ice sheet flow model PISM at EDML site
Input:
-bed rock geometry
-surface T, AccRate
-geotermal heat flux

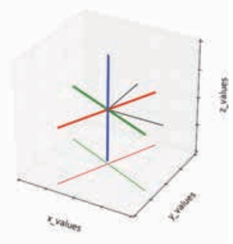
Weikusat et al. 2017



Eigenvalues of strain rate tensor



Eigenvectors' directions of strain rate tensor



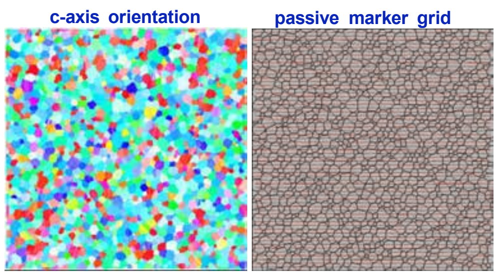
Thomas Kleiner
Flow model with isotropic flow description!

Anisotropy in ice cores – types and causes

Overview

Intrinsic anisotropy
- Extremely strong mechanical anisotropy in ice crystal.
- Evolution of crystal preferred orientation with depth depends on deformation mode (pure shear, simple shear etc.)
- Evolution of shape preferred orientation strongly masked by recrystallization, but can reveal deformation mode.

Composite anisotropy
- Layers of inclusions (air inclusions, dust) though in ppb range can change properties of layers significantly.



Llorens et al. 2016, 2017