Visual Stratigraphy of the EastGRIP Ice Core

Of the Lost Ice Core Orientation, Deformation Structures, Extreme Warm Events, and Trapped Ancient Air

PhD Thesis by Julien Westhoff

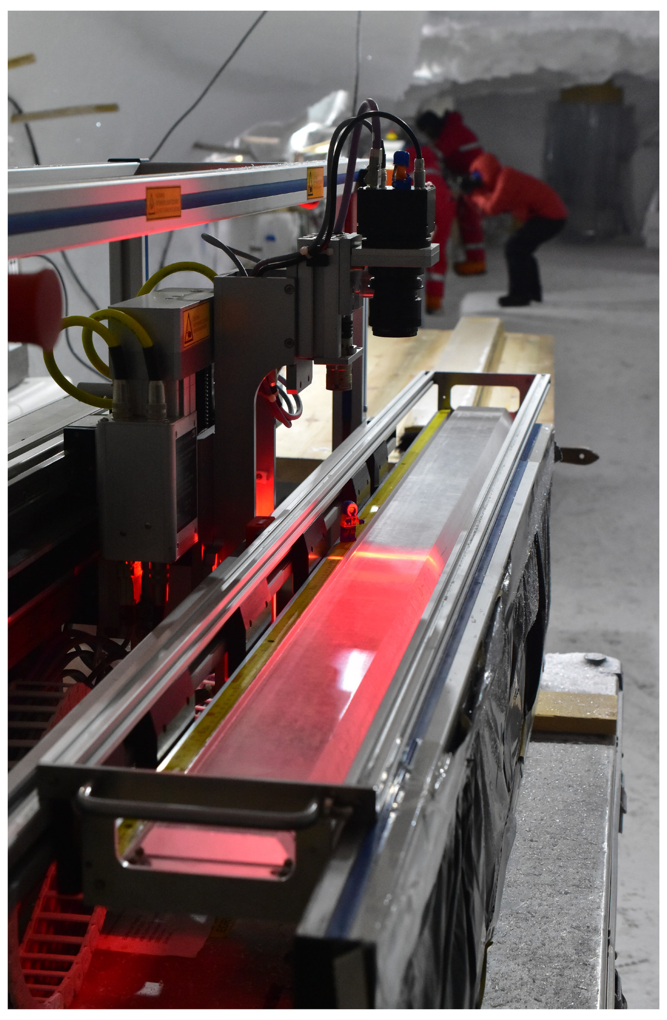
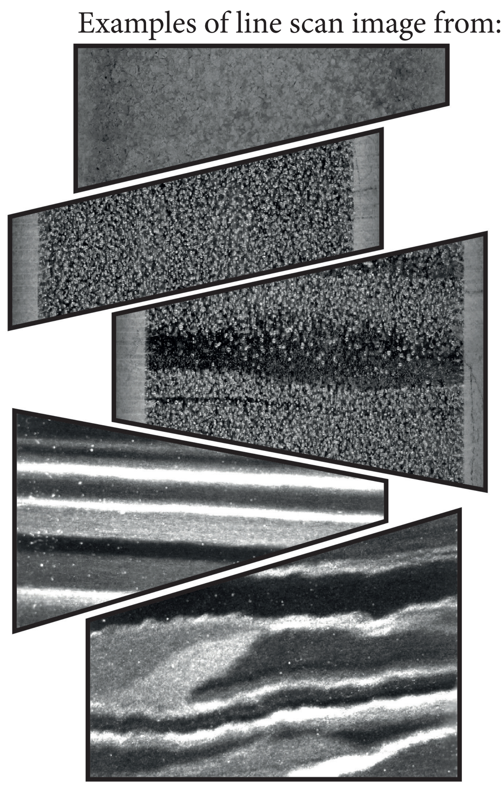


Fig. above: the line scanner illuminates the 165-cm ice core slab from below (red light) and scans the surface with a moving camera. This makes the stratigraphy visible.

Examples of line scan image from:



15.5 m depth (firn)

138.2 m depth ("normal" ice with bubbles)

138.9 m depth (986 CE melt layer)

1650.0 m depth (well stratified cloudy bands)

1650.7 m depth (deformation of cloudy bands)

PhD funded by:

In collaboration with:

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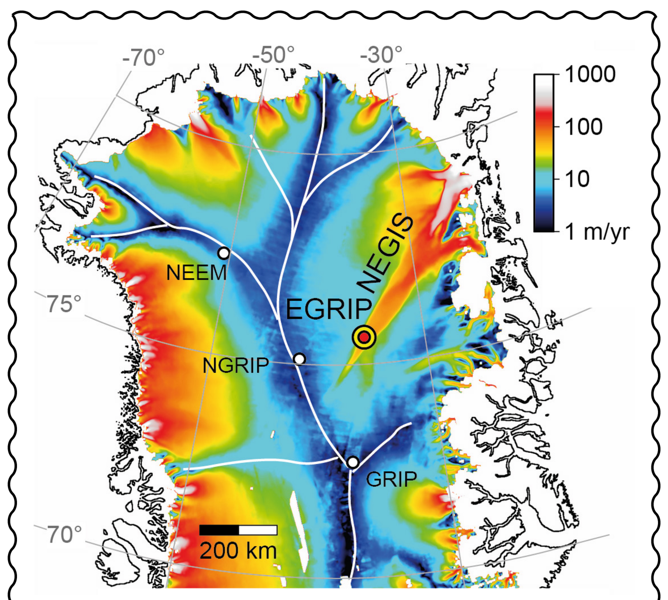
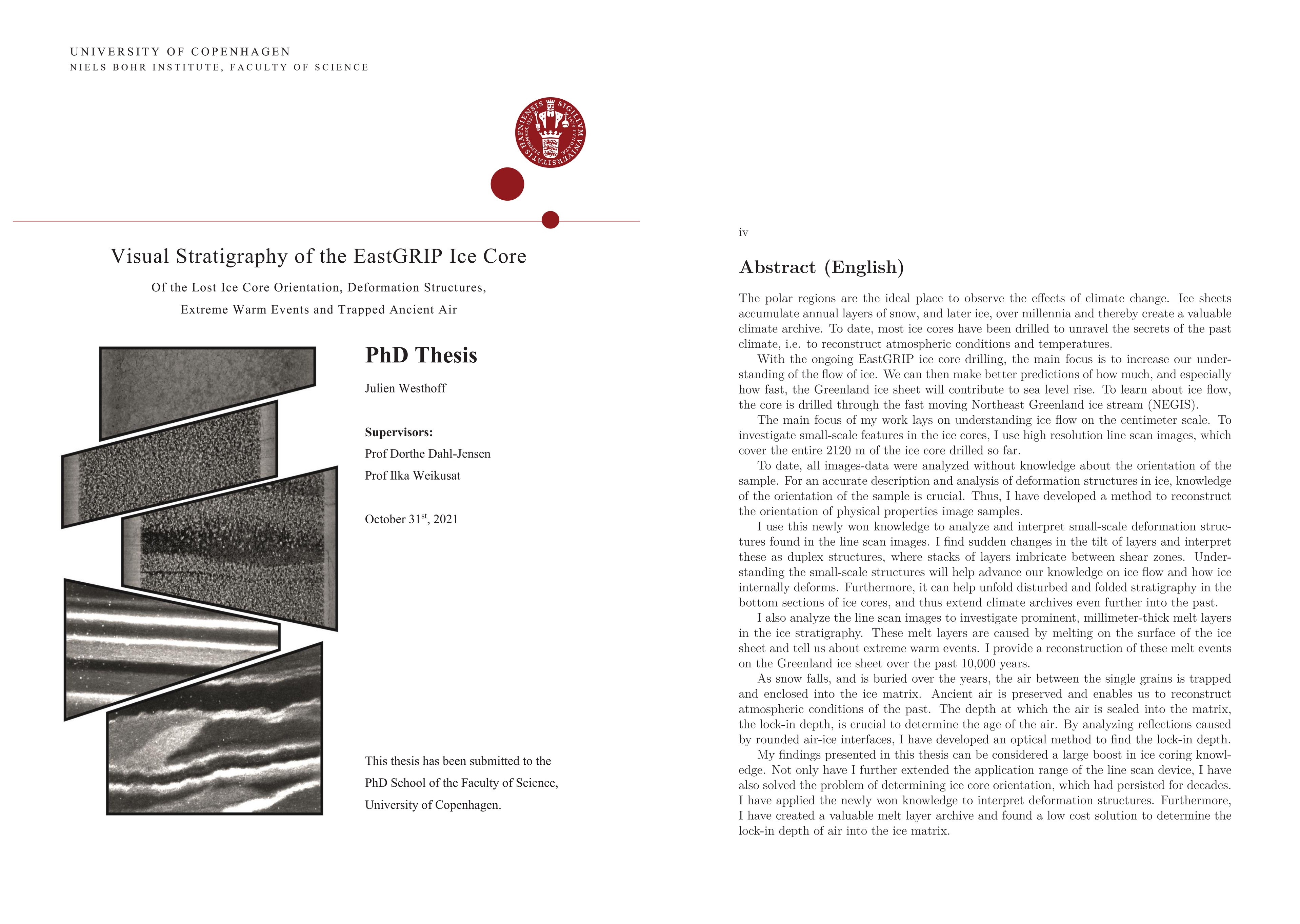


Fig. above: surface velocity map of Greenland and EastGRIP location. (Westhoff et al. 2021)



UNIVERSITY OF COPENHAGEN
NIELS BOHR INSTITUTE, FACULTY OF SCIENCE

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PhD Thesis

Julien Westhoff

Supervisors:
Prof Dorthe Dahl-Jensen
Prof Ilka Weikusat

October 31st, 2021

This thesis has been submitted to the PhD School of the Faculty of Science, University of Copenhagen.

iv

Abstract (English)

The polar regions are the ideal place to observe the effects of climate change. Ice sheets accumulate annual layers of snow, and later ice, over millennia and thereby create a valuable climate archive. To date, most ice cores have been drilled to unravel the secrets of the past climate, i.e. to reconstruct atmospheric conditions and temperatures.

With the ongoing EastGRIP ice core drilling, the main focus is to increase our understanding of the flow of ice. We can then make better predictions of how much, and especially how fast, the Greenland ice sheet will contribute to sea level rise. To learn about ice flow, the core is drilled through the fast moving Northeast Greenland ice stream (NEGIS).

The main focus of my work lays on understanding ice flow on the centimeter scale. To investigate small-scale features in the ice cores, I use high resolution line scan images, which cover the entire 2120 m of the ice core drilled so far.

To date, all images-data were analyzed without knowledge about the orientation of the sample. For an accurate description and analysis of deformation structures in ice, knowledge of the orientation of the sample is crucial. Thus, I have developed a method to reconstruct the orientation of physical properties image samples.

I use this newly won knowledge to analyze and interpret small-scale deformation structures found in the line scan images. I find sudden changes in the tilt of layers and interpret these as duplex structures, where stacks of layers imbricate between shear zones. Understanding the small-scale structures will help advance our knowledge on ice flow and how ice internally deforms. Furthermore, it can help unfold disturbed and folded stratigraphy in the bottom sections of ice cores, and thus extend climate archives even further into the past.

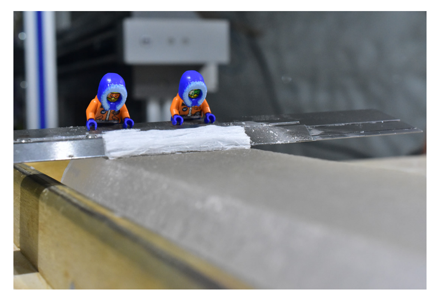
I also analyze the line scan images to investigate prominent, millimeter-thick melt layers in the ice stratigraphy. These melt layers are caused by melting on the surface of the ice sheet and tell us about extreme warm events. I provide a reconstruction of these melt events on the Greenland ice sheet over the past 10,000 years.

As snow falls, and is buried over the years, the air between the single grains is trapped and enclosed into the ice matrix. Ancient air is preserved and enables us to reconstruct atmospheric conditions of the past. The depth at which the air is sealed into the matrix, the lock-in depth, is crucial to determine the age of the air. By analyzing reflections caused by rounded air-ice interfaces, I have developed an optical method to find the lock-in depth.

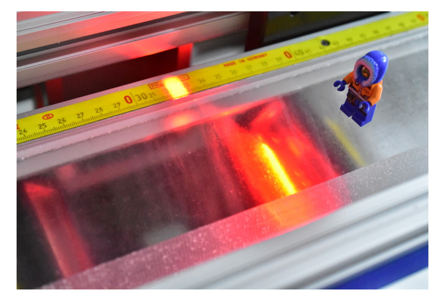
My findings presented in this thesis can be considered a large boost in ice coring knowledge. Not only have I further extended the application range of the line scan device, I have also solved the problem of determining ice core orientation, which had persisted for decades. I have applied the newly won knowledge to interpret deformation structures. Furthermore, I have created a valuable melt layer archive and found a low cost solution to determine the lock-in depth of air into the ice matrix.

Processing of Line scan samples:

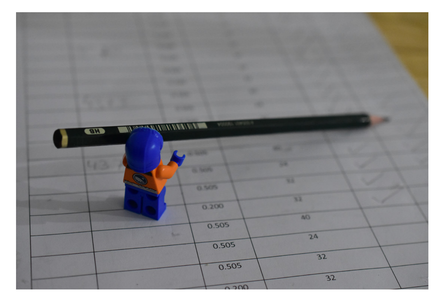
1. The ice core is cut into 3.6 x 165-cm pieces.



2. The upper and lower surfaces are polished with a microtome knife to remove scratches from the saws.



3. The sample is illuminated from below and the light is scattered on bubbles, breaks, or as seen here, impurities concentrated in cloudy bands.

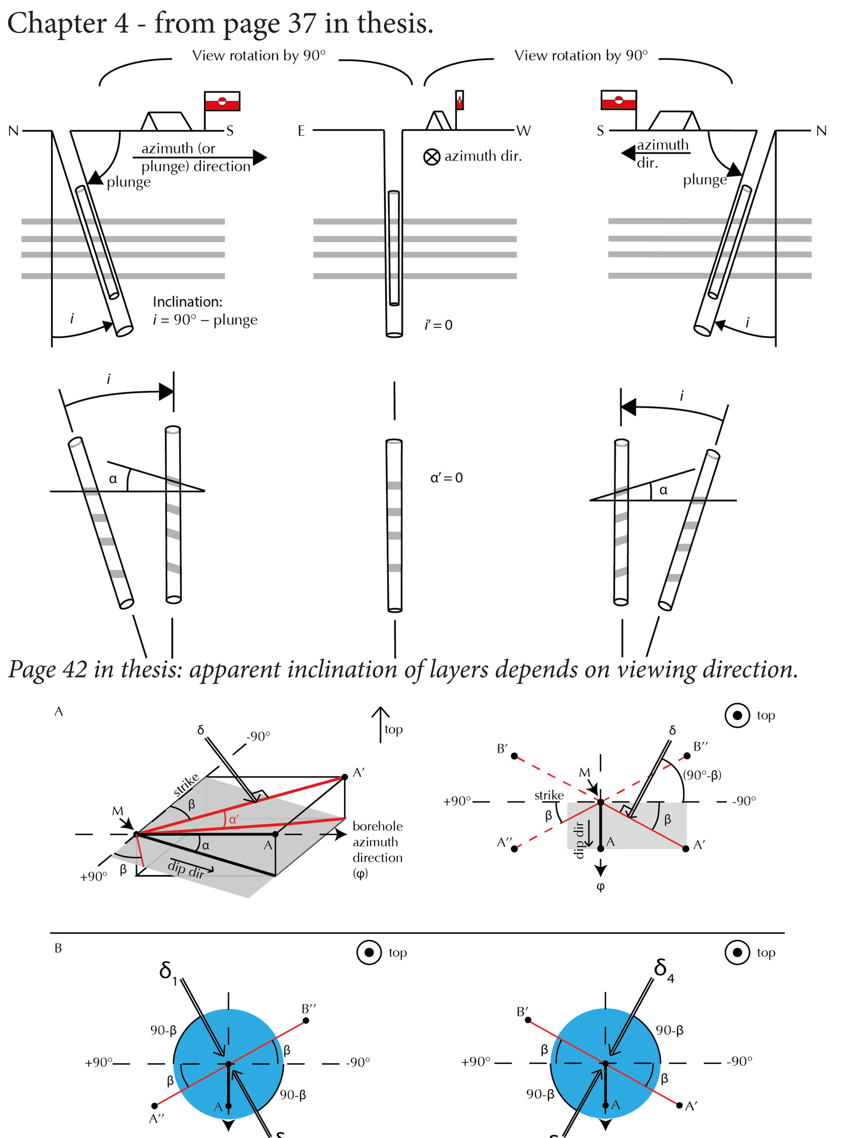


4. The settings of the camera are noted. We run four scans with different settings: two different integration times (controls brightness) and three different depths of focus below the ice core surface.

A stratigraphy-based method for reconstructing ice core orientation (2021)

Westhoff, J., Stoll. N., Franke, S., Weikusat, I., Bons, P., Kerch, J., Jansen, D., Kipfstuhl, S., and Dahl-Jensen, D.
Annals of Glaciology, Volume: 62, Issue: 85-86, pages: 192-202.

Chapter 4 - from page 37 in thesis.



Page 42 in thesis: apparent inclination of layers depends on viewing direction.

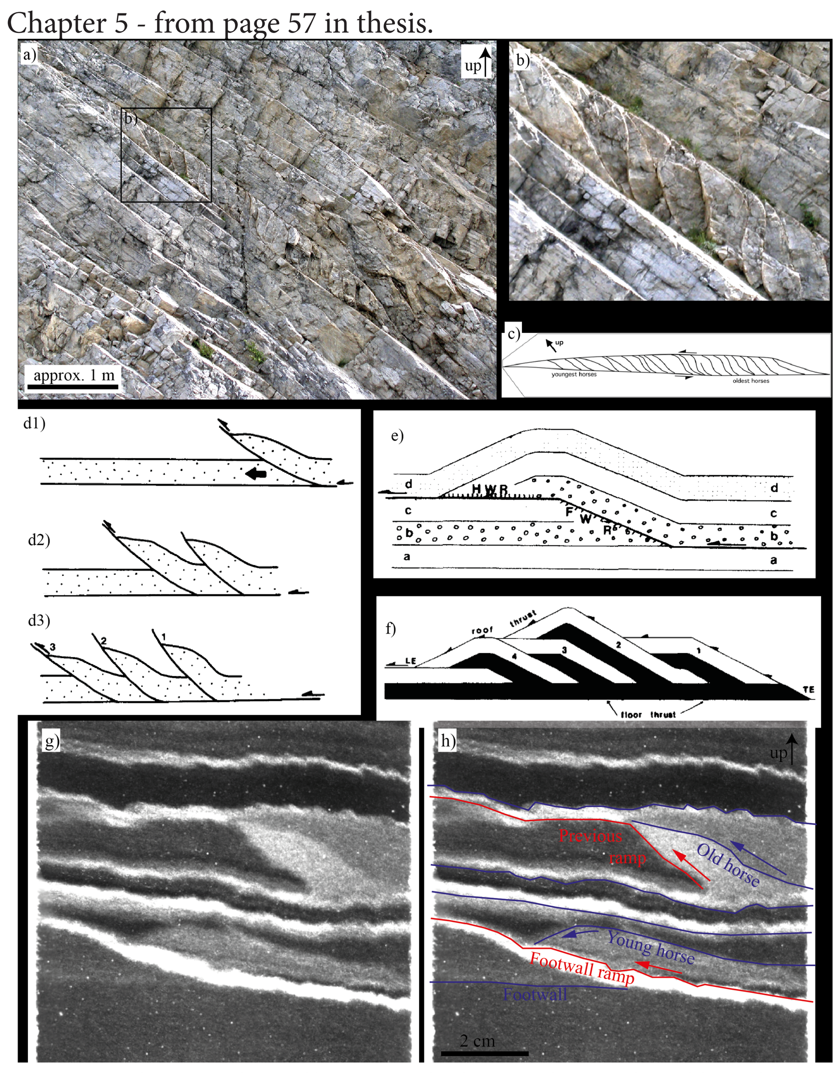
Page 44 in thesis: reconstruction of direction of view depending on apparent dip.

Short summary: We present a method to reconstruct the in-situ orientation of an ice core. The method uses input data from visual stratigraphy and borehole logging, and is based on the tilt of individual layers and the visible deformation structures.

Small-scale deformation structures in the EastGRIP ice core (in prep.)

Westhoff, J., Bons, P., Weikusat, I., Stoll, N., Streng, K., Jansen, D., and Dahl-Jensen, D.

Chapter 5 - from page 57 in thesis.



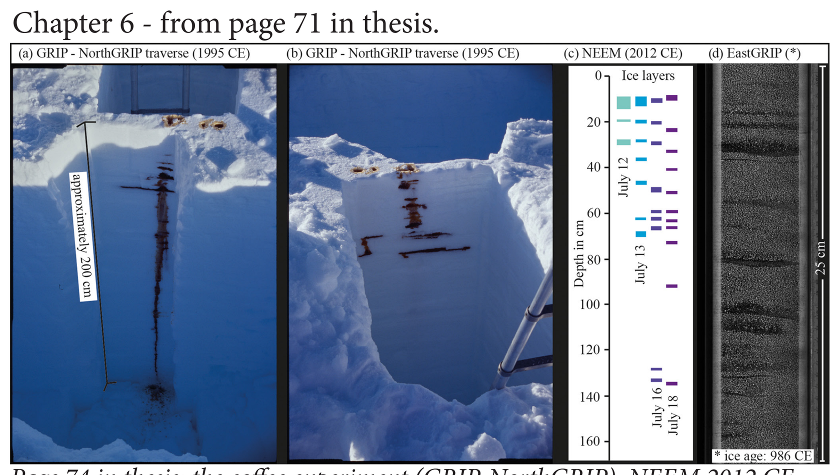
Page 66 in thesis: stacking of layers, i.e. duplicating the signal, visible in the ice core stratigraphy.

Short summary: We investigate cm-scale deformation structures and their influence on the integrity of climate-signal preservation in ice cores.

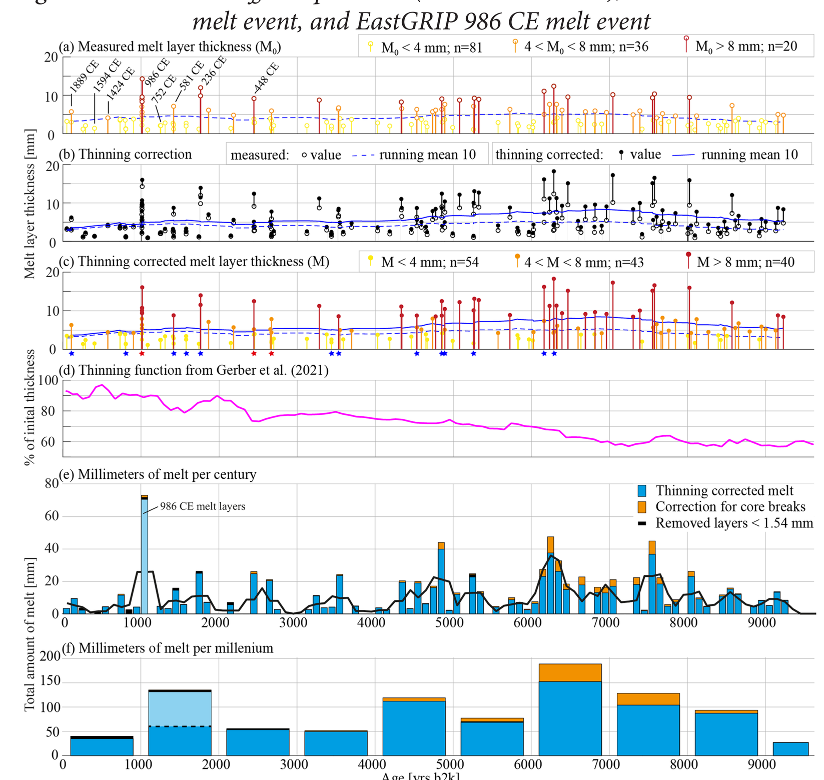
Melt in the Greenland EastGRIP ice core reveals Holocene warm events (2022)

Westhoff, J., Sinnl, G., Svensson, A., Freitag, J., Kjær, H. A., Vallelonga, P., Vinther, B., Kipfstuhl, S., Dahl-Jensen, D., and Weikusat, I.
Climate of the Past, 18, 1011–1034.

Chapter 6 - from page 71 in thesis.



Page 74 in thesis: the coffee experiment (GRIP-NorthGRIP), NEEM 2012 CE melt event, and EastGRIP 986 CE melt event



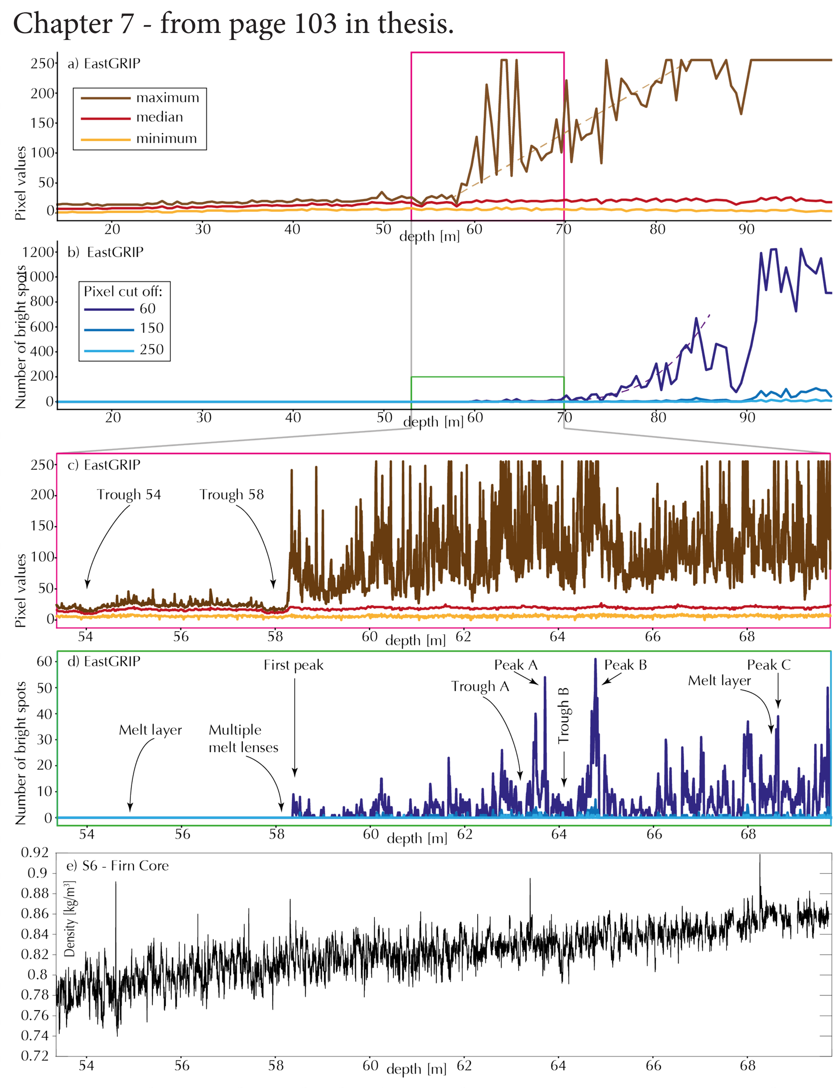
Page 84 in thesis: a-c) melt layer thickness of EastGRIP Holocene melt layers, d) thinning function, e,f) melt per century/millennium

Short summary: We present a melt layer record based on the visual stratigraphy of the EastGRIP ice core. We also investigate how melt layers correlate with tree ring growth anomalies and historic events.

An optical technique to finding the lock-in depth in ice cores (in prep.)

Westhoff, J., Freitag, J., Martinerie, P., Weikusat, I., Orsi, A., Dyonisius, M. N., Fain, X., Fourteau, K., and Blunier, T.
Almost ready to submit to Journal of Glaciology

Chapter 7 - from page 103 in thesis.



Page 108 in thesis: a-d) pixel value (grayscale) measurements on 1 x 5 cm line scan sections in the EastGRIP ice core, e) S6 density measurements

Short summary: We present a method to find the lock-in depth of gases into the ice matrix, which is solely based on the line scan images. The optical technique is thus a low cost alternative, or addition, to traditonal firn air pumping, modelling, and ^{15}N methods.

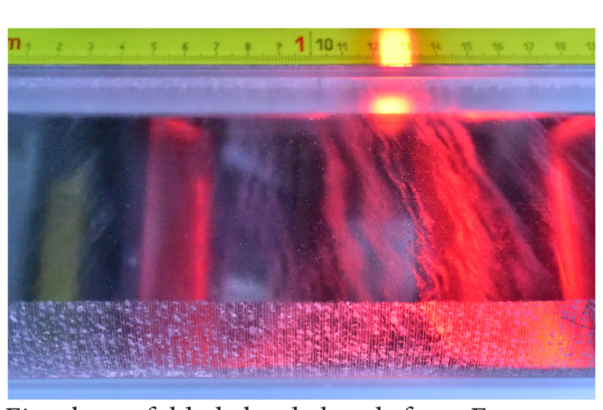


Fig. above: folded cloudy bands from EastGRIP depth approx. 2300m.

Notes, ideas, suggestions, and questions:

Line scan images around the poster:
from bag 2546 (1400.85 m) to bag 2477 (1361.80 m) starting in the top left corner, running counter-clockwise.
The visual stratigraphy shows the end of the Last Glacial Period and the beginning of the Bølling Allerød, visible by the change of brightness intensity of the cloudy bands.