Why do we care about snow pore structure ?

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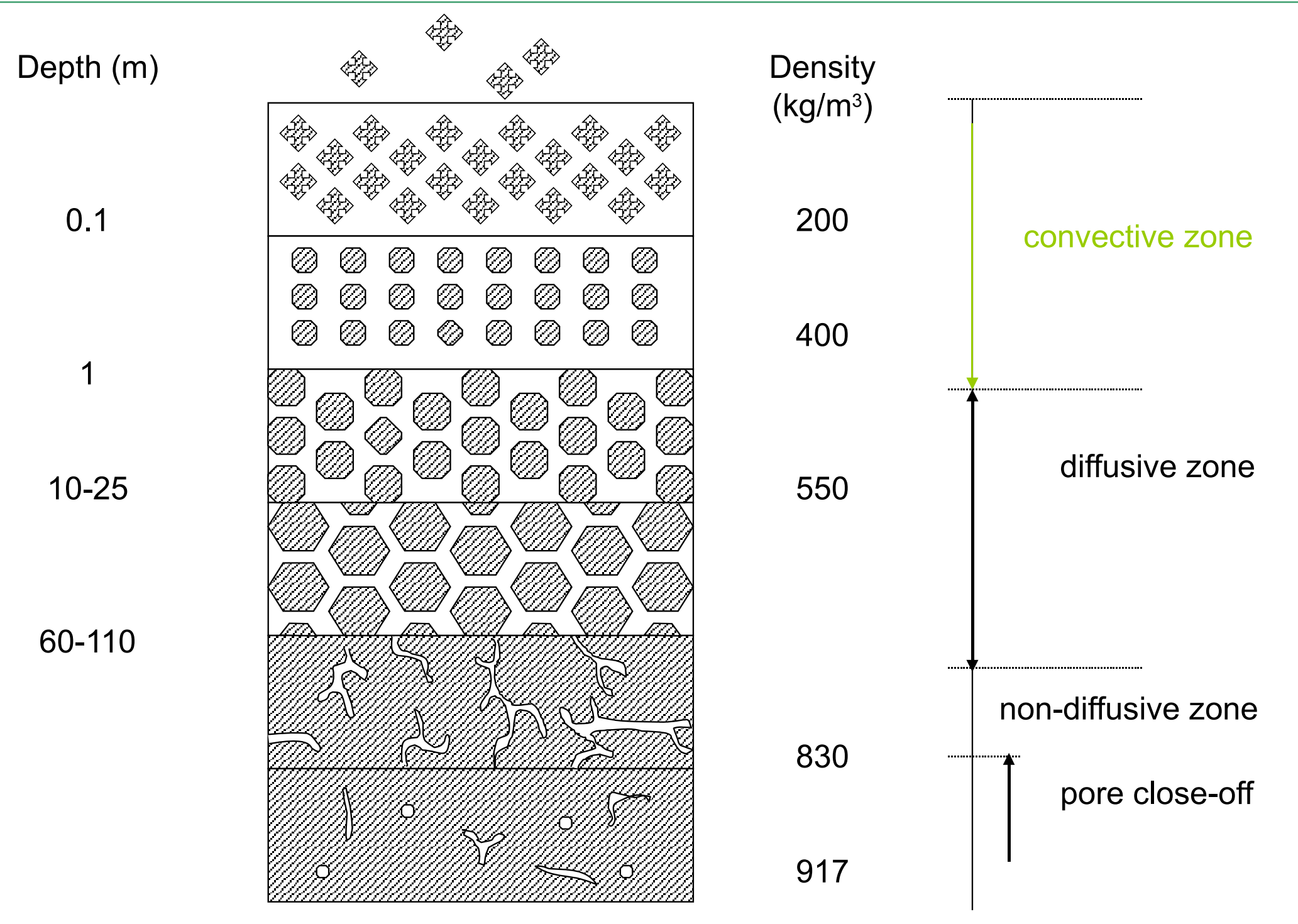
General Abstract

In polar regions precipitated snow does not melt. Layers accumulate and build up with time. The snow is slowly transformed to ice. The firn is highly porous and permeable and it is only in greater depths, between 60 to 110 meter, when the pore space gradually becomes discontinuous and the remaining air is confined into single air bubbles. The gas exchange in the firn is an important factor that determines the age of the entrapped air, which is important for ice core studies. In this study X-ray micro Computer Tomography is used to analyze 3D images of the firn and to derive an empirical relationship to permeability. We find an remarkable impact of near-surface processes on the connectivity of the pores.



Technical Abstract

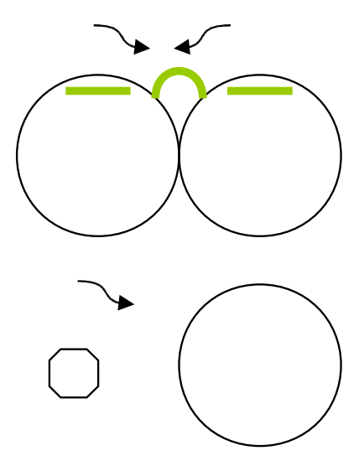
Polar firn forms a porous and permeable medium. We take 3D micro structural properties obtained by X-ray micro Computer-Tomography to model the measured permeability. The empirical relationship fairly well simulates low permeable layers and the stratigraphic induced variability of the measured profile, but fails for high permeable layers. By applying a sequence of morphological opening the connectivity function is obtained. High permeable layers are characterized by large well connected pores. The occurrence of these specific layers can be linked to the time, the firn was exposed to near-surface temperature gradient metamorphism, convection and coarsening.

Glossary Polar Firn

Firn /Firn Densification
Firn is snow, which survived one summer without melting. On glaciers and polar ice sheets, snow transforms and densifies by settling, sintering and creep until the density of ice is obtained and the pore space disintegrates into single, not connected air bubbles.

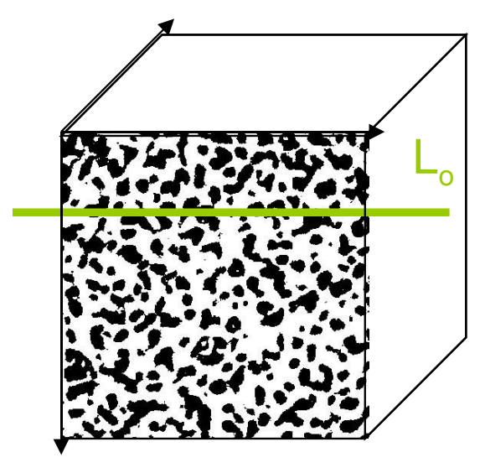
Pore close-off
Pore close-off is the process in polar firn, when the connected pore space starts to isolate into single air bubbles. The air gets enclosed in the ice and no further exchange is possible.

Snow Metamorphism
Snow metamorphism is the process of the transformation from snow to ice. Temperature gradient metamorphism is the by an applied temperature gradient occurring gradient in water vapor pressure, resulting in mass transfer from warm to cold. Equitemperature metamorphism is driven by the difference in curvature creating differences in water vapor pressure and resulting in a mass transfer from for example convex to concave surfaces.



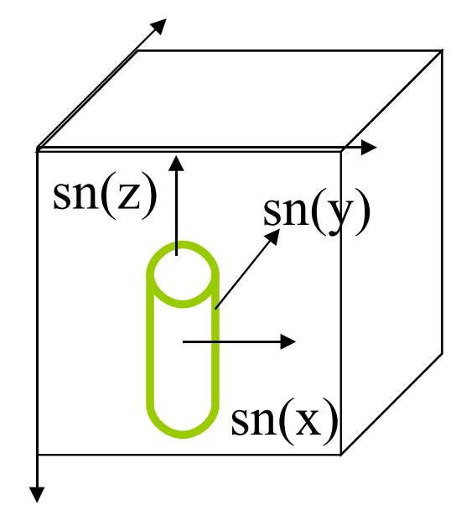
Glossary Volume Image Analysis

Chord Length
The mean chord length L_p of a phase p is the mean length of the intersections c of a line L_o. In 3D image analysis the chord length is obtained for different directions



$$L_p = \frac{L_o(p)}{c/2}$$

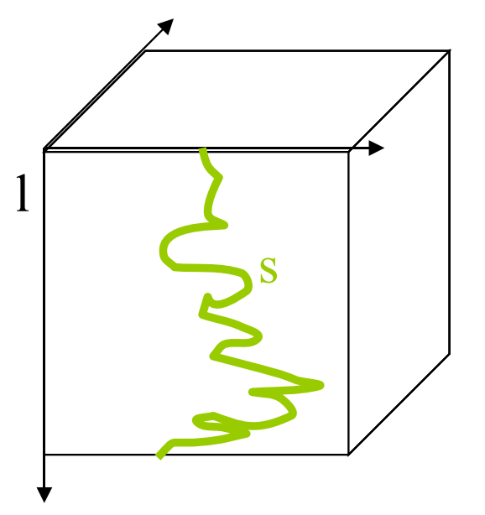
Specific Surface
The specific surface is the ratio of an objects surface to its volume. Fine grained snow has a large specific surface, coarse, large grained snow a small one.



$$\frac{\text{sn (x \& y)}}{\text{sn (z)}}$$

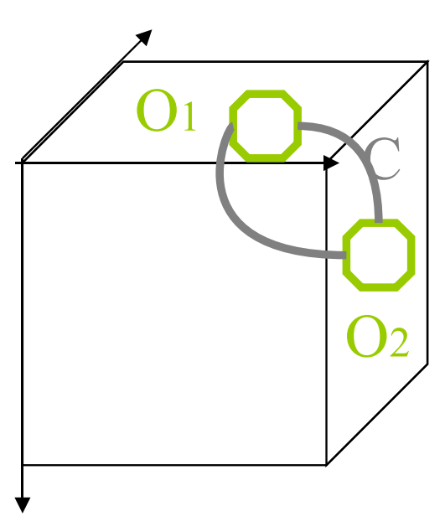
Snow Anisotropy
We consider the fraction of surface normal vectors pointing into a specific directions with an apex angle of 30°. The two horizontal directions and the vertical is defined as a measure of anisotropy of the firn texture.

Tortuosity
The tortuosity t is the ratio of the path length of the connected pore space s and the volume‘s side length l.



$$t = \frac{s}{l}$$

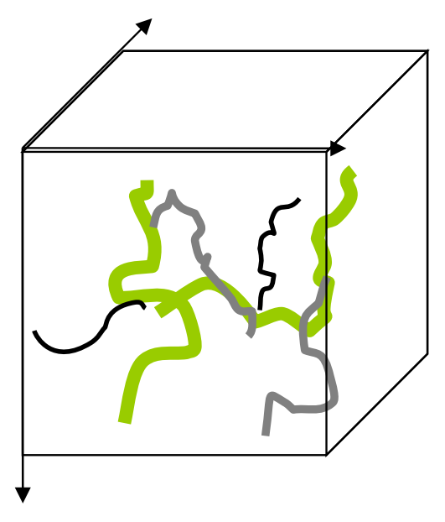
Specific Geometric Euler Number
The geometric Euler number χ is defined as the number of Objects *O*, minus the number of redundant connections *C* plus the number of Holes *H* (not valid for snow), divided by the volume *V.*



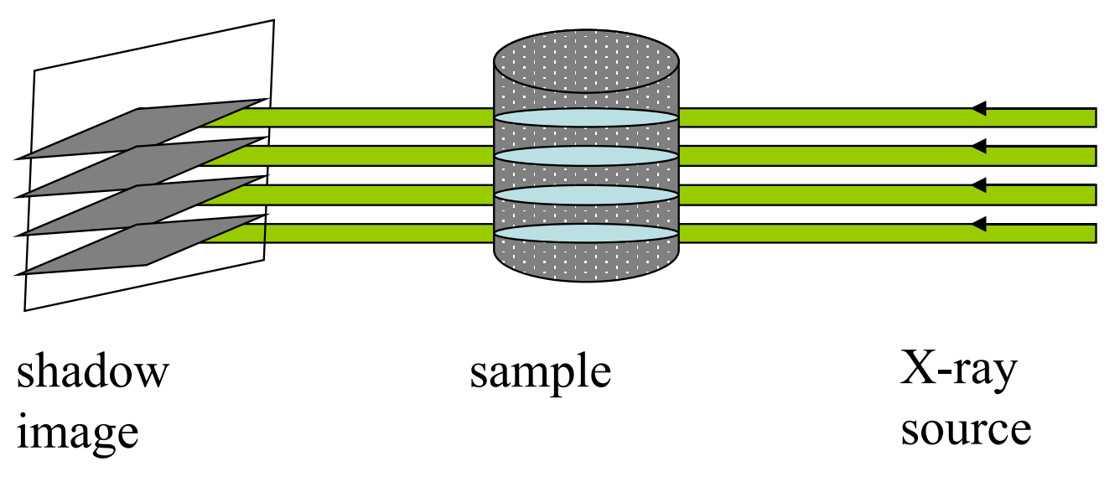
Morphological Opening
Morphological opening is a combination of erosion and dilation. The sequential use of opening with increasing radius of a disc as the structuring element simulates a sieving procedure for varying mesh width and can be used for the classification of the particle or pore sizes.

$$\chi = \frac{O - C + H}{V}$$

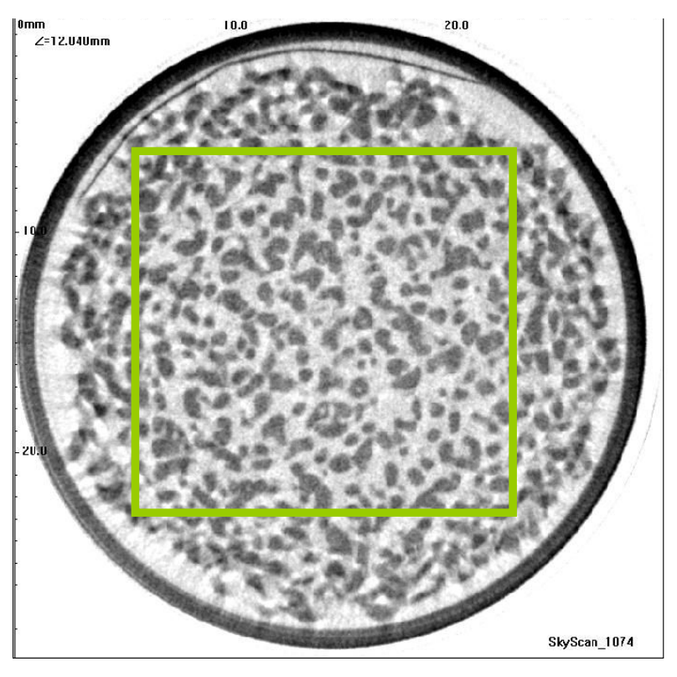
Connectivity Function
The connectivity function is defined as the progression of the Euler number as a function of pore connection size. In 3D image analysis the connectivity function can be obtained by morphological opening.

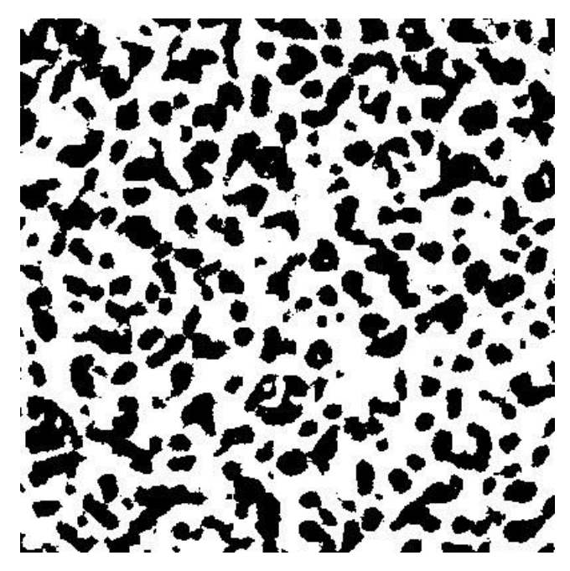


Methods

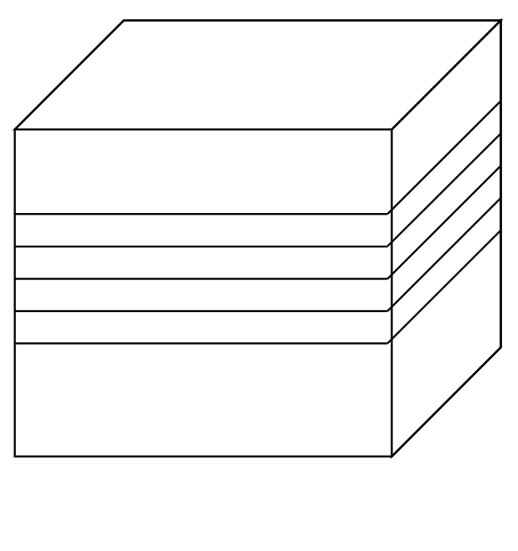


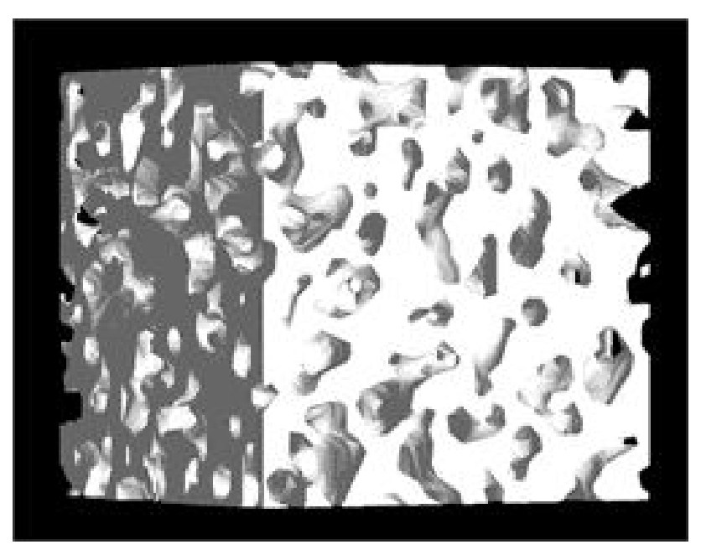
Firn samples are placed in front of a x-ray source and rotated by 0.9°. At each step a shadow image is created due to the difference in absorption of ice and air.





A cross section of a metamorphosed snow sample and a binarised and filtered cutout with a resolution of 40 µm per pixel.





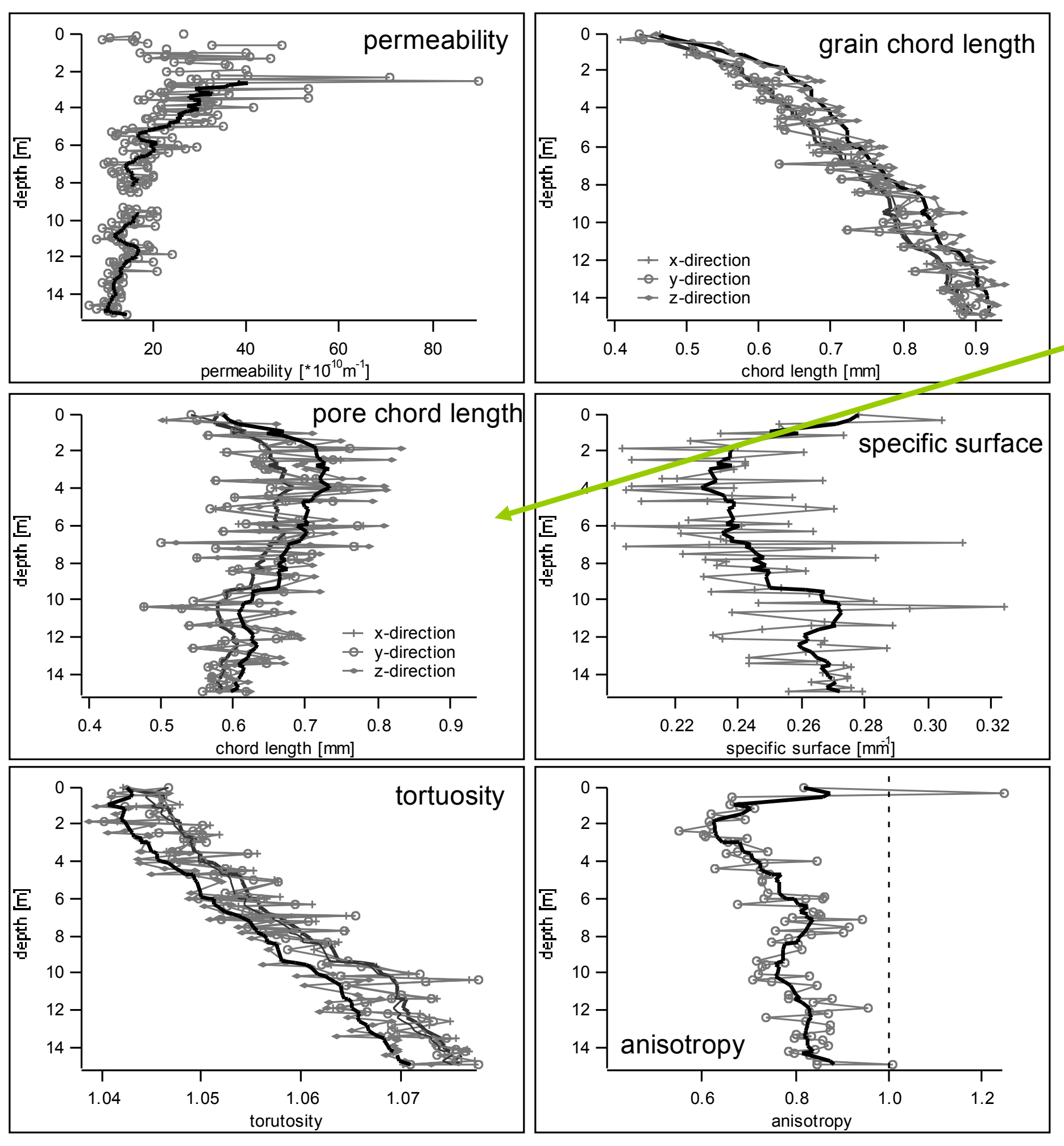
The analyzed cube is built of 400 cross sections with a distance of 40 µm. All filtering, segmentation and analysis procedures are applied to a 3-dimensional reconstruction of the pore or ice phase.

Results

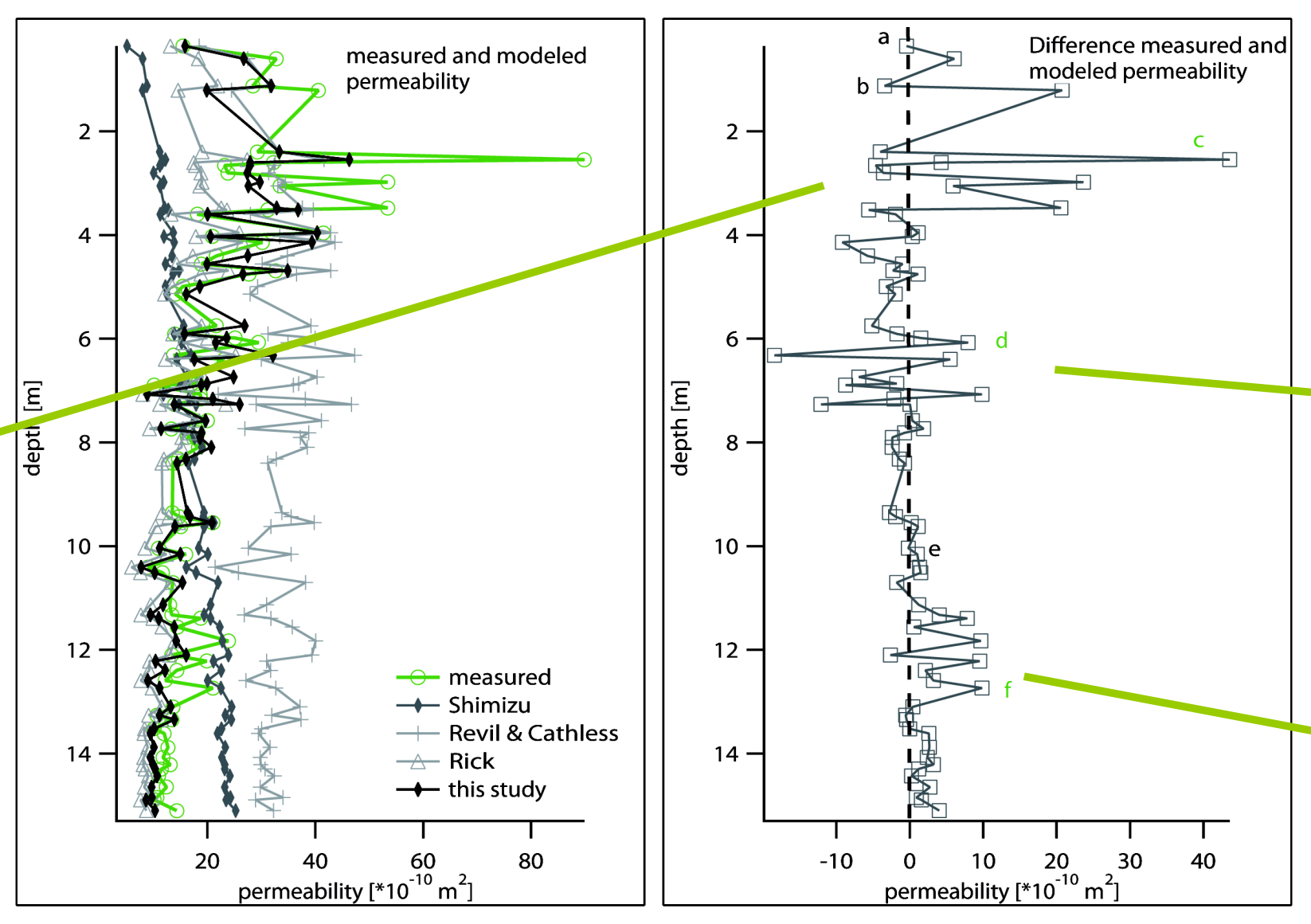
We find coarsening of the texture down to approximately 2.5 meter depth. This is accompanied by a maximum in air permeability and anisotropy at this depth. Using microstructure to model the permeability after Shimizu (1970), Revil and Cathless (1999), Rick (2004) and findings from this study results in fairly good results, apart from high permeable layers.

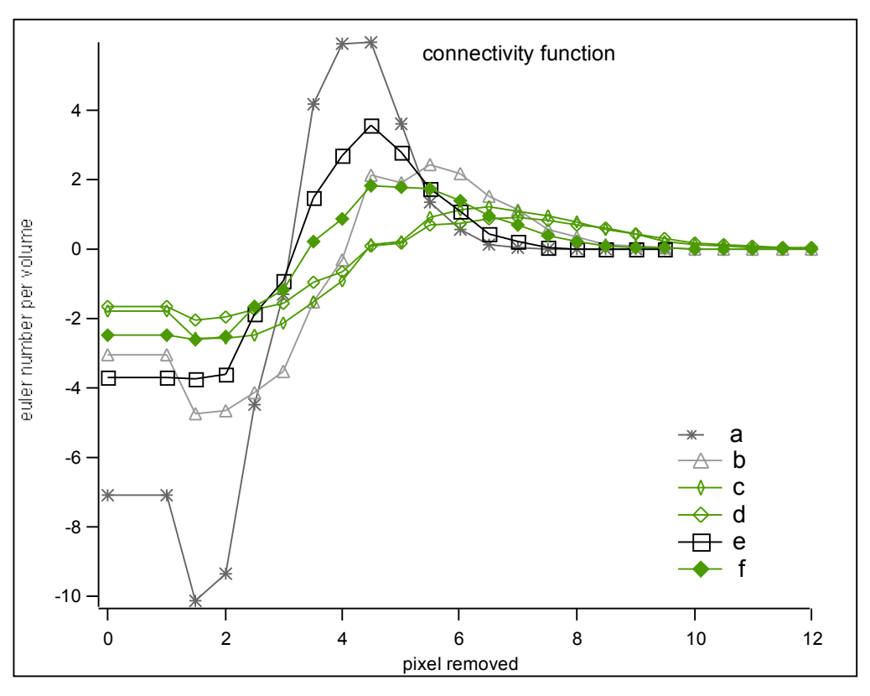
$$k = \frac{d_{pore} \cdot n^2 \cdot V \cdot a}{t_z \cdot 4 \cdot S}$$

Microstructure



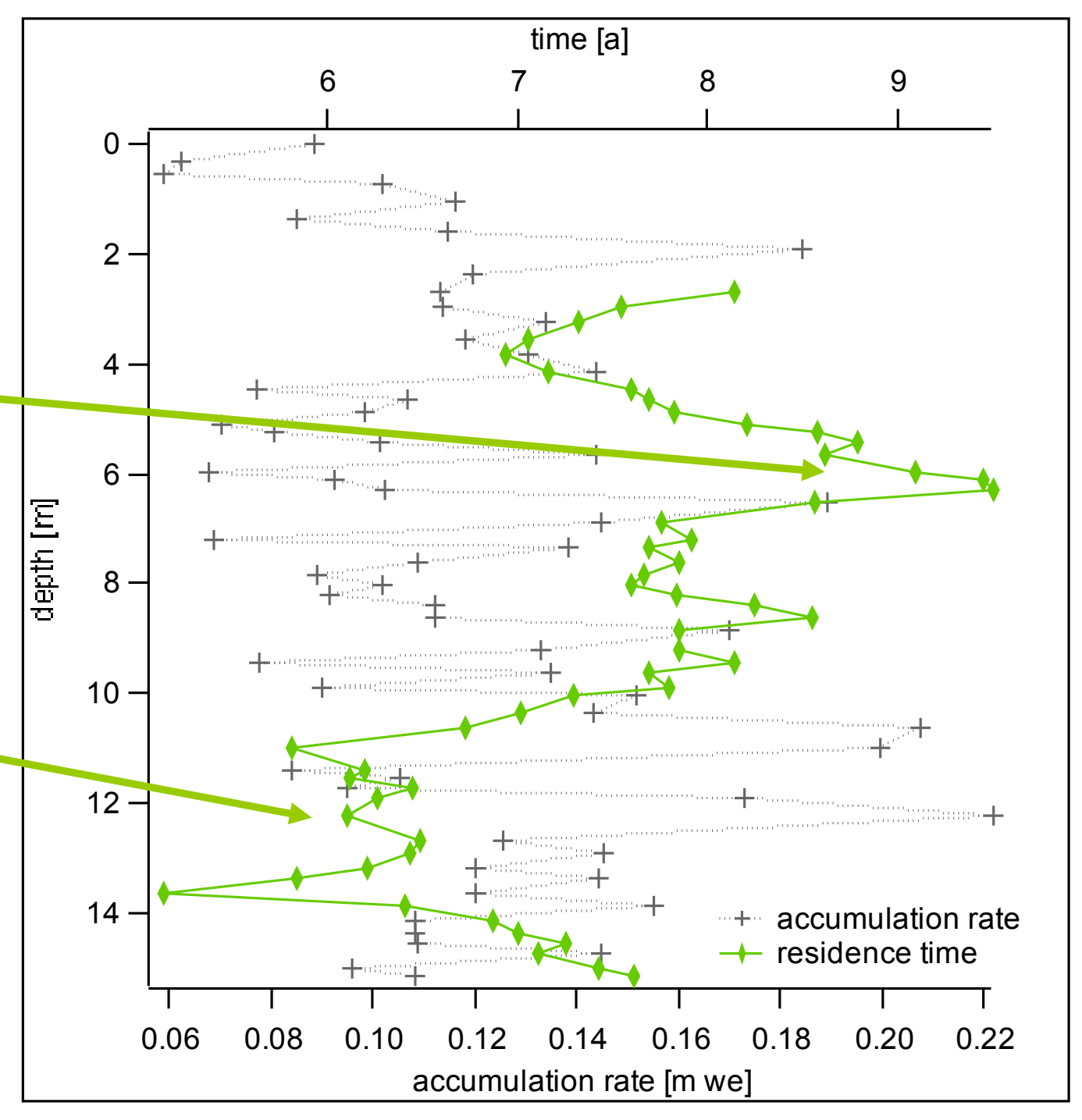
Modeling Permeability





The largest offset results from high permeable layers with large connected pores. These layers can be linked to relative increased residence times

The Residence Time



Increased residence times in the uppermost 2.5 meter stand for increased exposure to temperature gradient metamorphism of the firn and coarsening of the microstructure.

Summary

In the uppermost meters the exposure of firn layers to temperature gradients and metamorphism is the largest. Coarsening takes place, accompanied by an increase in air permeability.
An empirical relationship using micro structural properties can fairly well model the measured permeability but fails for high permeable firn layers. The connectivity function of these layers implies large connected pores. The occurrence of a well connected pore space can be linked to increased exposure of the firn to temperature gradient metamorphism and coarsening at near-surface depths.

References

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