Direct observations of pore close-off in stratified firn by means of large scale X-ray computer tomography

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Motivation

Very recently it has been observed, that in contradiction to former beliefs polar firn exhibits almost everywhere a significant layering at the firn-ice-transition (FIT). Even at low accumulation sites like Dome C (Antarctica) the porosity shows variations in adjacent layers of around 30% at the FIT (Hörhold et al, 2011). Because of this stratified structure impermeable layers occur within the firn and act like a sealing, so that the air is completely isolated from the overlying firn layers. It is out of question that this layering will alter the predicted age distribution of enclosed air as they are simulated by modelling the close-off in homogeneous firn columns. The study of of air enclosure in polar firn requires three dimensional observations of the firn structures.

One problem is to keep both, the spatial resolution and volume of investigation large enough to account for the layering on the cm-scale without loosing information about pore connectivity on the µm-scale. The interaction between layering (especially the thickness of certain layer) and the pore connectivity (amount of closed porosity) is illustrated in the figure on the right.

Here we present a first pilot study of large-scale-X-ray CT applied to the firn-ice transition of an Antarctic firn core (B37) drilled close to the EDML-drill site at Kohnen station. Gas-studies estimate a close-off depth at about 87m.

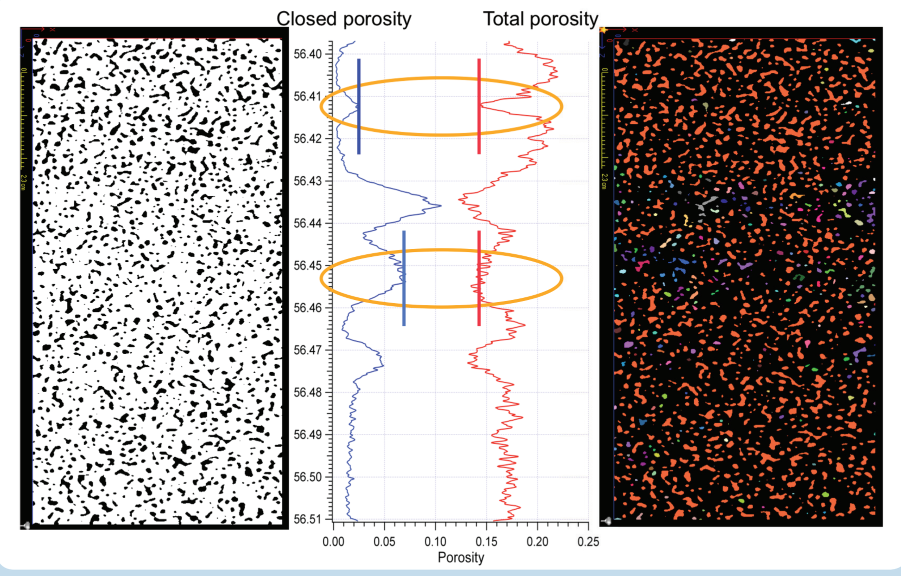


Figure 1: 10 cm long vertical cross section of a firn samplet from 56.4m-56.5m of the Greenlandic firn core B26 (X-CT with 56µm spatial resolution): (left: pores in black; right: color-coded pores of intra-connectivity (in red: open pore cluster). mid: profiles of total and closed porosity)

Measurement method

Fraunhofer EZRT

The large scale X-ray computer tomograph (AWI-ICE-CT) is a unique deviceadapted to the special requirements when you investigate ice. The whole measuring equipment is build in a cold lab with a temperature of -15°C.

Reachable resolution:
- 13 µm for ice cores of 10 cm diameter
- 1-2 µm for subvolumes

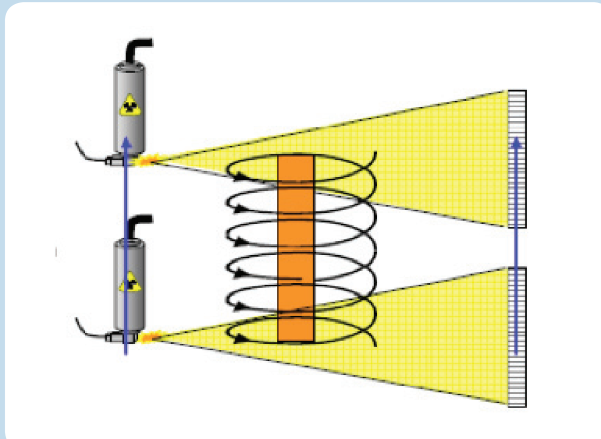


Figure 2: Sketch of the Helical-CT measurement method. Using a vertical feed during the rotation reduce the Feldkamp artifacts and allows measurements of theoretically arbitrary height.

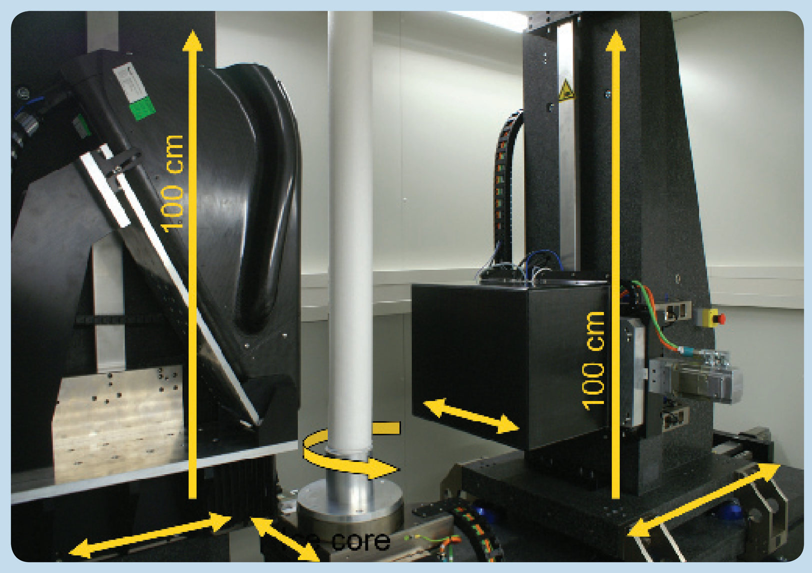


Figure 3: Detector (right) are equipped with climatic shielding (CFK, internal heater) and mounted on air puffered axes. An ice core piece of 1 m length is fixed on a rotation table seen in thInside the CT cold laboratory: The ICE-CT manipulator system is based on 3 heavy granite quaders. X-Ray tube (left) and e middle. 6 additional axis can be driven (yellow arrows).

Observations for the EDML core B36/37 (Kohnen) at the Firn-Ice-Transition

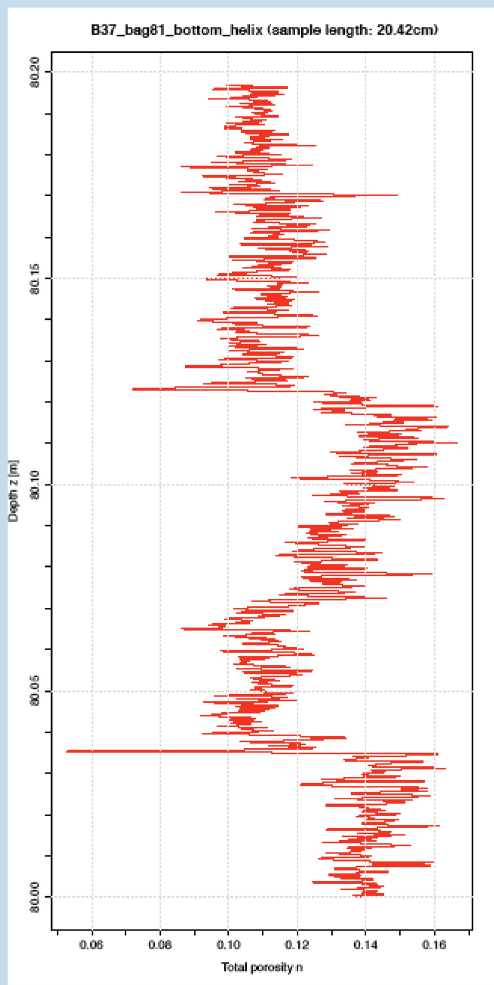


Figure 5: Porosity profile of bag81 (length 20,5cm) computed from a Helix-CT-measurement with a resolution of 15µm. In this depth region near the FIT a high variability can be observed.
The low porosity peaks around 81.035m and 81.123m can be indentified as windcrusts.

bag 81
(big volume above FIT)

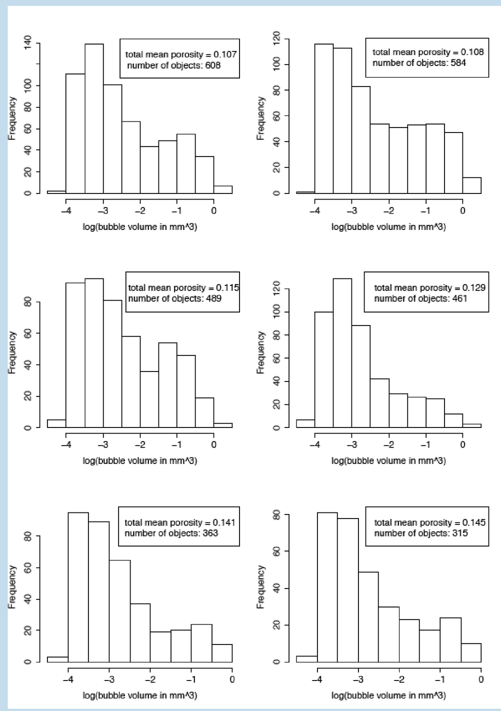


Figure 6: Size distributions of isolated pores in 10mm thick plateaus of bag 81. The plateaus are marked in figure 5. The fraction of small pores increases with rising total porosity.

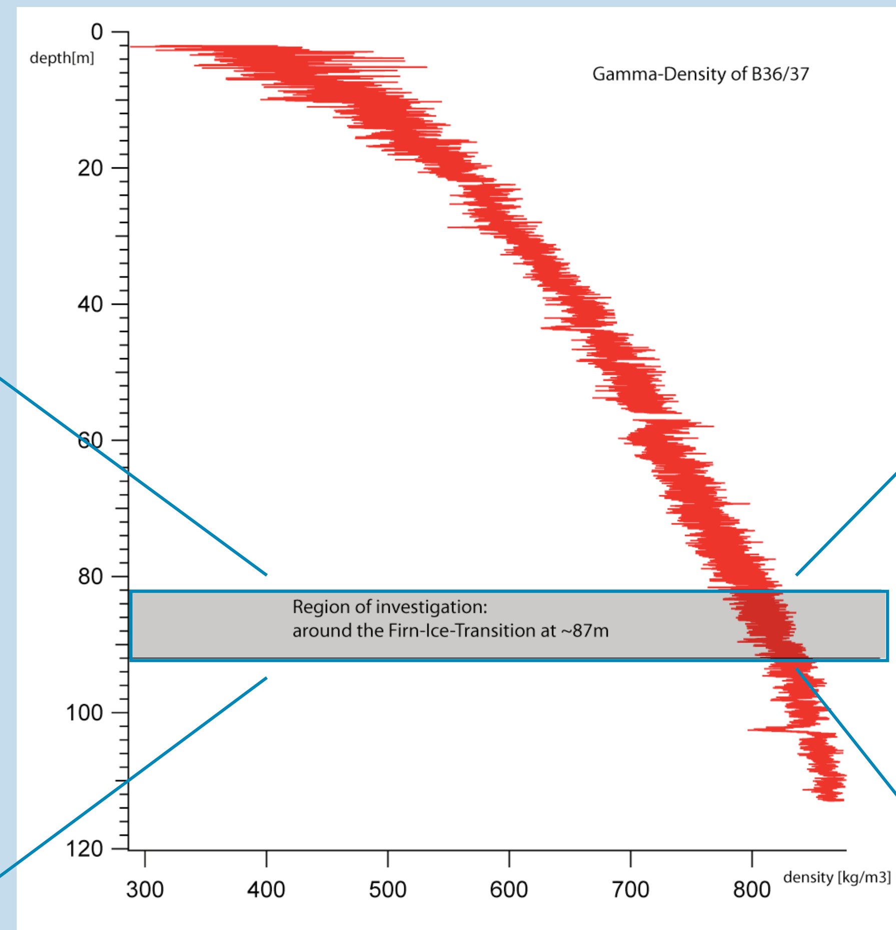


Figure 4: Density profile of firn core B36/37 drilled at Kohnen station (Antarctica) in 2005/2006, computed from Gamma-Absorption measurements (data from J. Freitag, M. Hörhold) with a vertical resolution of 3mm.

bag 87
(volume of the FIT)

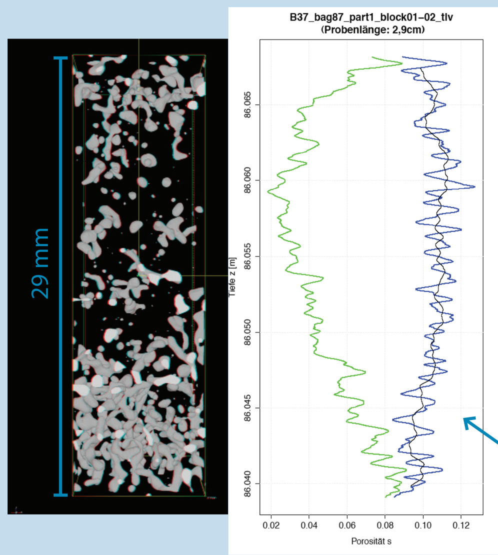


Figure 7b: A seleted porosity plateau (here in a maximum of n) from the profile of bag 87. The selection of the plateaus is made because the special features of the objects in these volumes: mostly closed pores or a percolating cluster of pores.

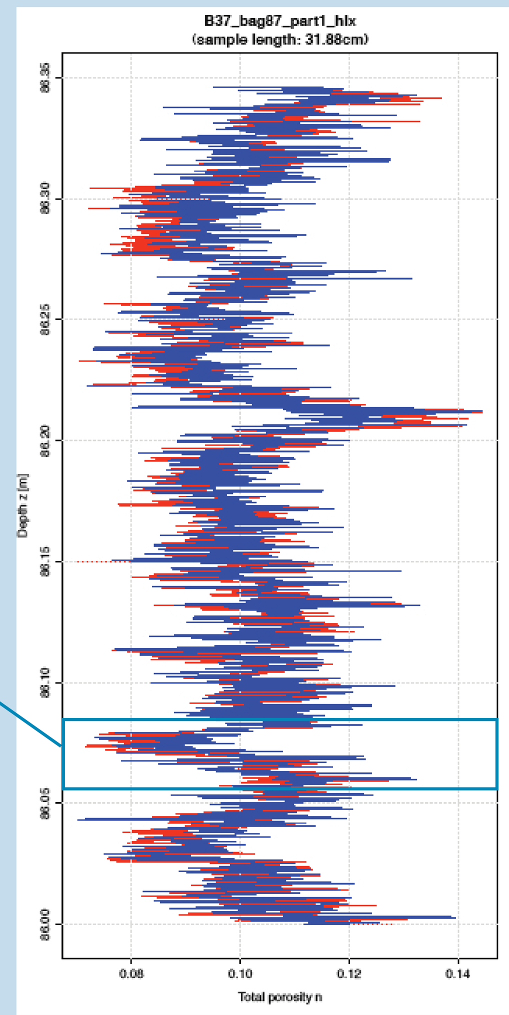
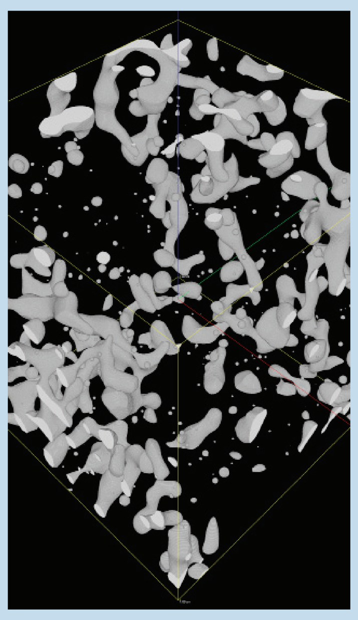
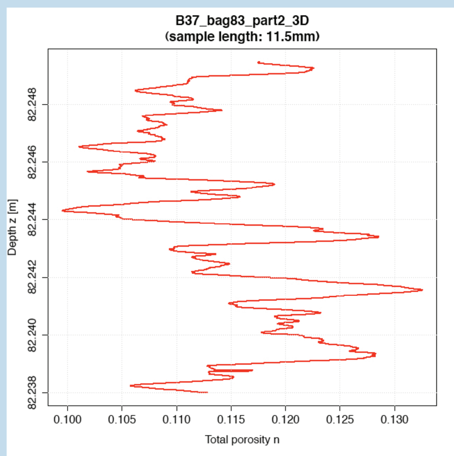


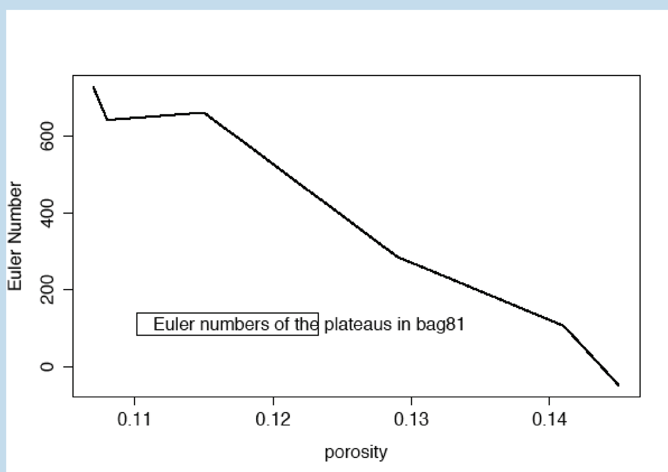
Figure 7a: Porosity profile of firn core B37 bag87 (length 31,9cm) computed from a Helix-CT-measurement with a resolution of 15µm.
Here the porosity of the same sample with different horizontal cuttings are compared (blue: cutting of 2cm edge length, red: cutting of 1 cm edge length): The variance of the porosity profile with the small ground area (1/4 of the original) rises with factor 2, the mean of both is the same.

bag 83
(volume above FIT)





Figures 7a(right), b(left): Firn core B37 bag83 (length 11,5mm) computed from a 3D-CT-measurement with a resolution of 7,2µm.
(a)Porosity profile, (b) 3D rendering view of the closed pores in the volume, closed pores are

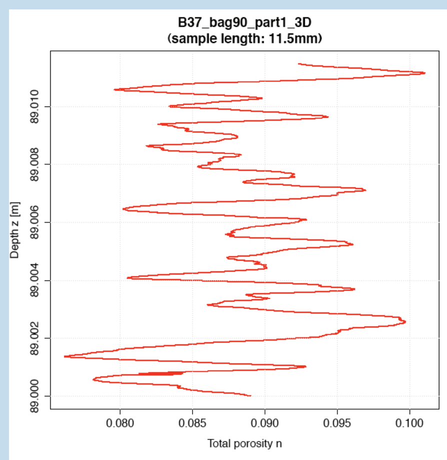


Figures 8: The Euler number is defined as the number of isolated objects minus redundant connections within objects and therefore a measure of pore connectivity. When the Euler number gets more positive, the pore network gets more separated. The positive Euler number for low porosities clearly show the dominance of separation against pore connectivity.

Structural change between these two depth regions also visually recognizable!

Note:
In the left 3D-view-picture of bag 81 also cutted objects on the border are shown. These are relicts of open pores from the neighbourhood of this volume.

bag 90
(volume under FIT)



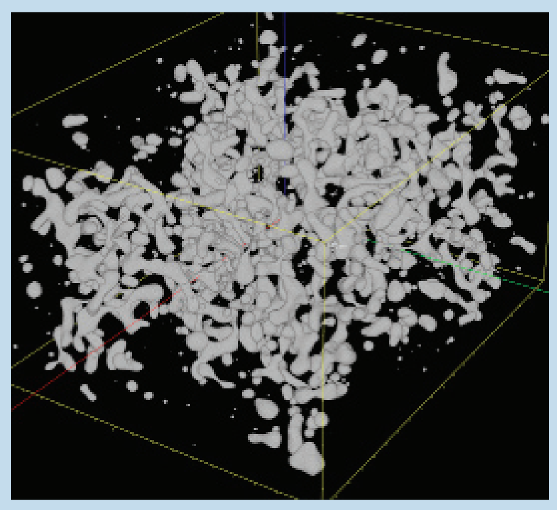


Figure 8 a(left), b(right): Firn core B37 bag90 (length 11,5mm) computed from a 3D-CT-measurement with a resolution of 7,2µm.
(a)Porosity profile, (b) 3D rendering view of the closed pores in the volume

Pore close-off as Percolation Problem: Closed Porosity Parametrization

MODEL

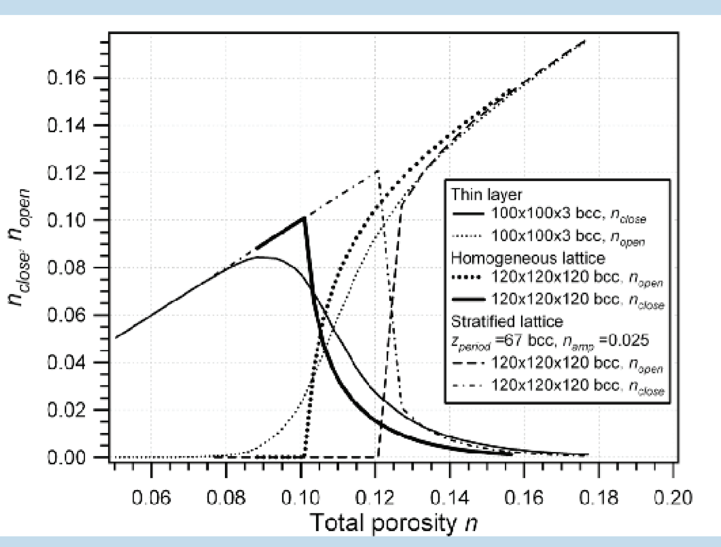


Figure 10: Closed and open porosity (probability) determined from a percolation model (J. Freitag). The pore-close off is supposed to be treated as a percolation process, that means that the air in the firn is gradually enclosed in bubbles.

MEASUREMENTS

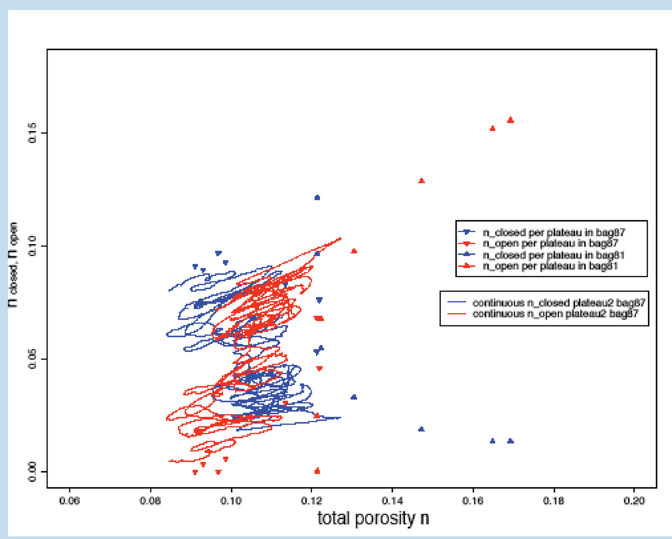


Figure 11: Closed and open porosity (plotted versus the total porosity) determined from selected palateaus (10mm height) from the measured profiles of bag81 and bag87.

Conclusion

- Technical aspect: Idea to develop an analysis procedure which enables us to analyse the volume data over a sliding window and decrease the expenditure of time, which is until now very high.
- Methodic aspect: Proof that the resolution of 15 µm is adequate to resolve small scale porosity and pore connectivity
- Estimate of small scale porosity show variations in porosity around a factor of 4 (n=0.07-0.14 for EDML)
- Previous approach to use the average porosity as the percolation threshold is questionable all the more
- Thin crusts are are permeable even with porosities less than 0.06 (see porosity profile of bag 81)
- Bubble size distributions show that the beginning of air enclosure is dominated by small pore fractions
- The relation between closed and total porosity is ongoing work

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