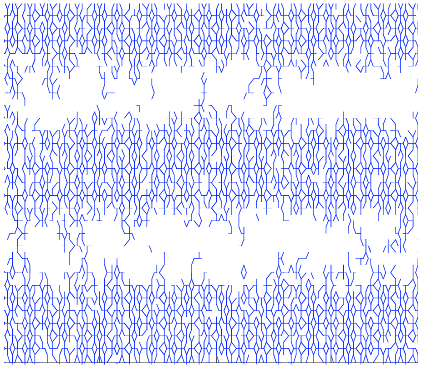
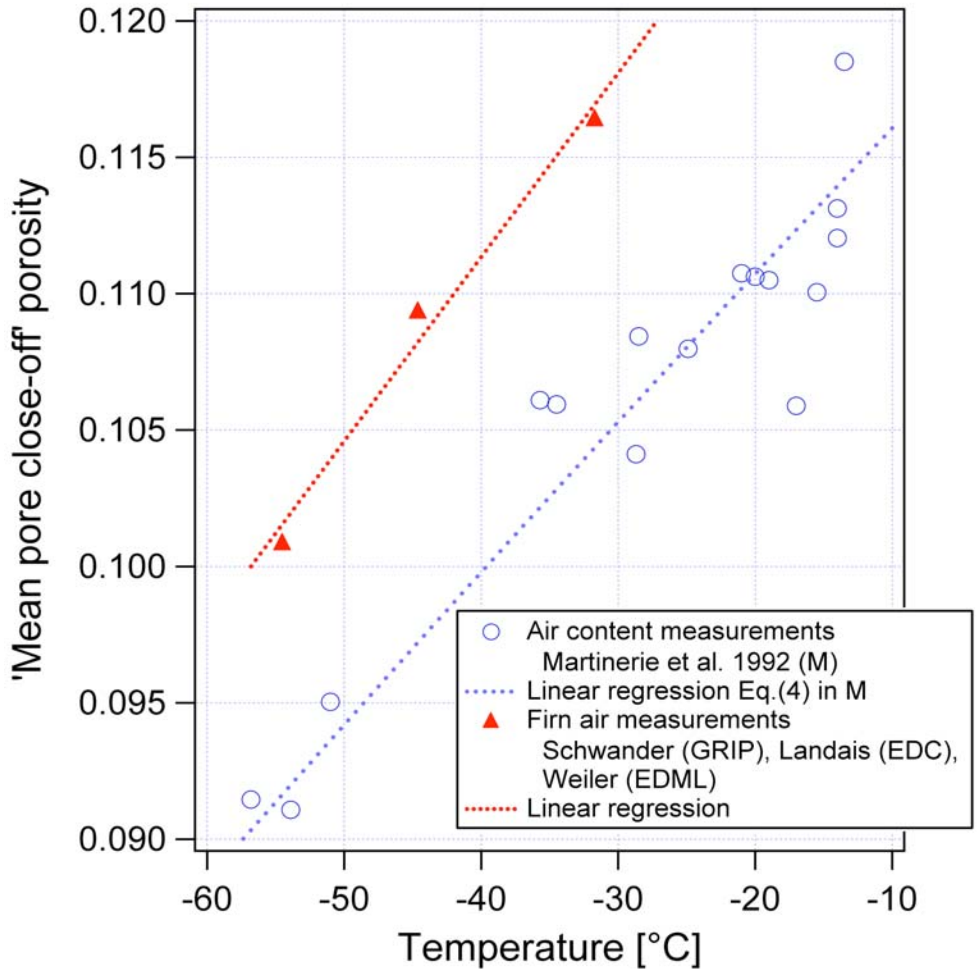
The layering of polar firn and its linkage to air trapping



Johannes Freitag
Sepp Kipfstuhl & Maria Hörhold

Alfred Wegener Institute (AWI)
Foundation for Polar and Marine Research
Bremerhaven

The air content in polar ice



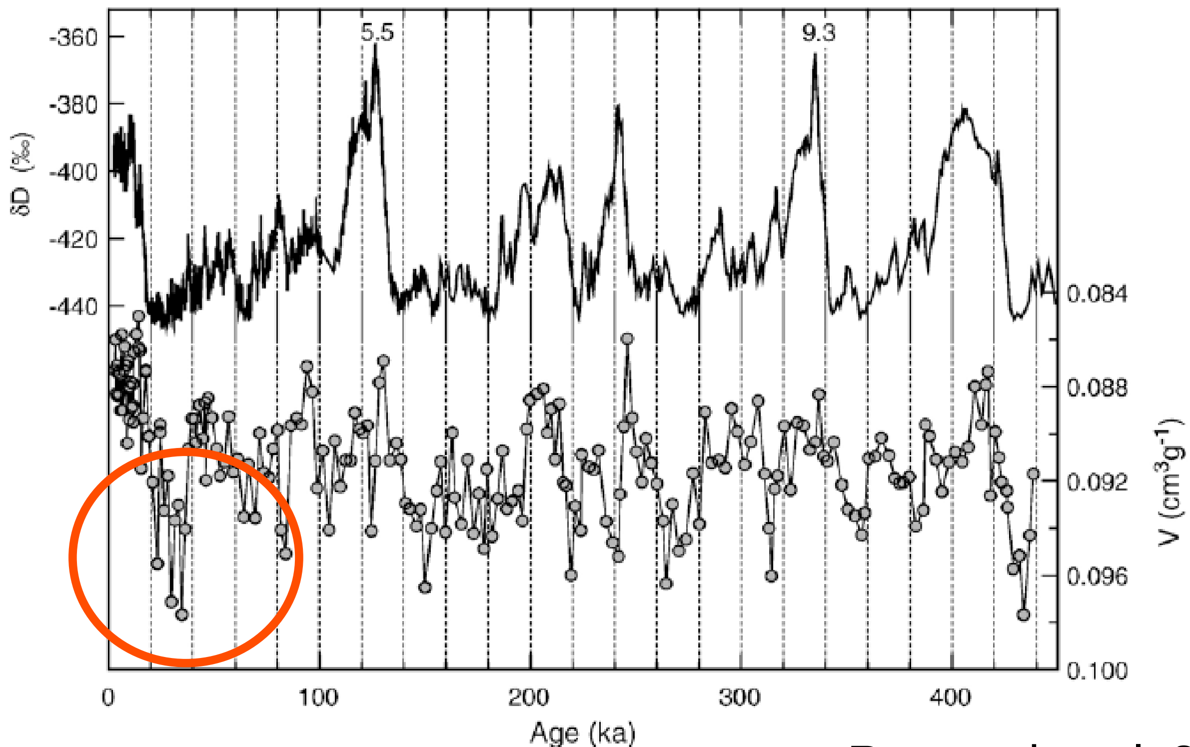
Linear relationship between pore close-off density (porosity) and temperature

Martinerie et al. (1992)

Reason?

Relation to microstructure properties?

Dome C (EDC) air content record



Raynaud et al. 2007

>80% of the variance in air content is not described by the n_{crit}(T)-relationship

Methods: µCT & Gamma-ray bench

Results:

- **Direct observations of air trapping**

An universal close-off porosity for polar firn?

- **The evolution of layering with depth**

Unexpected large layering at the firn-ice transition

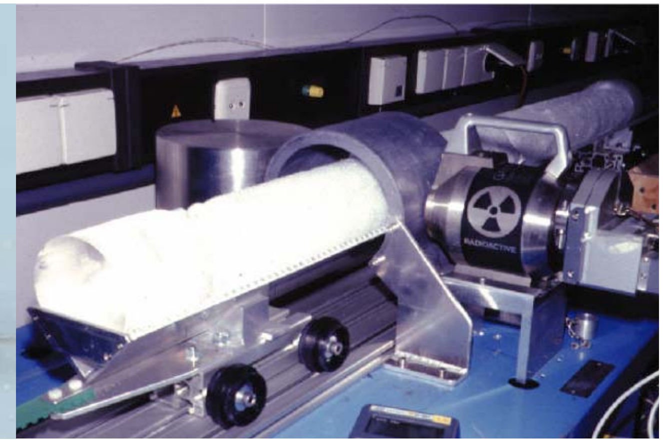
- **Simulations on stratified firn structures with a 3D-percolation model**

Variations of mean close-off porosities

Summary

X-ray-microfocus-computer-tomography (µCT) and Gamma-ray bench



µCT-SkyScan 1072,1074
Resolution: 8-20µm, 40µm

Point measurements on the cm-scale

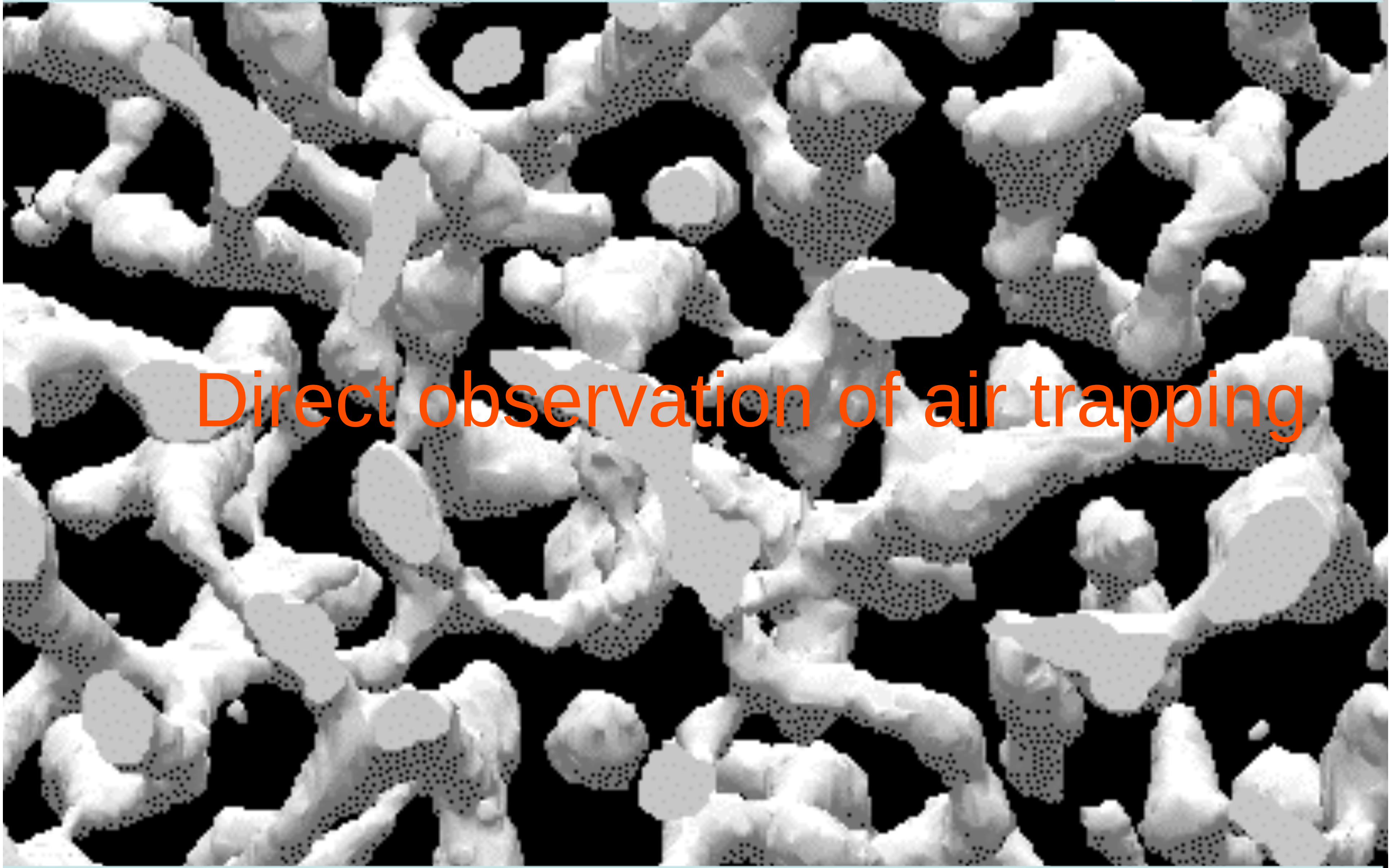
3D-volume processing:
Topological parameters: Euler number, coordination number.

Field measurements
Operation under cold conditions

Gamma-ray bench
Vertical resolution: ~3mm

Continuous porosity measurements along the whole firn column (30 min per meter)

Direct observation of air trapping



Firn cores:

B26

North Greenland (77°06‘N,49°06‘E)
T_{mean} = -30.6°C, Accumulation rate= 179mm w.eq. a^{-1}

B36

Kohnen station, EPICA, Dronning Maud Land Antarctica (75°00‘S,00°04‘E)
T_{mean} = -44.6°C, Accumulation rate= 62mm w.eq. a^{-1}

Dome C

Dome C, EPICA, Antarctica (75°06‘S,123°20‘E)
T_{mean} = -54.5°C, Accumulation rate= 25mm w.eq. a^{-1}

Euler number $E := B - L + H$ (1)

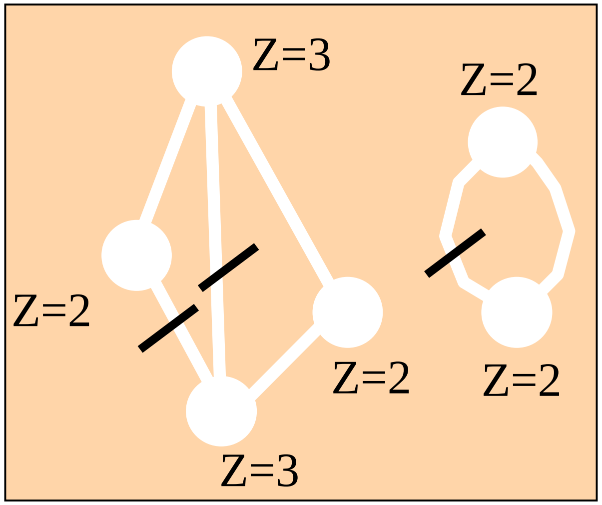
Coordination number $\bar{Z} = \dfrac{2(B_p - E)}{B_p}$ (2)

B: Isolated objects

L: Loops

H: Holes

Bp: Potential objects



B =2
L =3
H =0

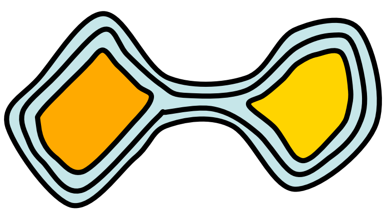
(1) ⇨ $E = B - L = 2 - 3 = -1$

$$\bar{Z} = \frac{(2+2+2+2+3+3)}{6} = 2.33$$

B_p=6 (1,2) ⇨ $\bar{Z} = \dfrac{2(6-(-1))}{6} = 2.33$

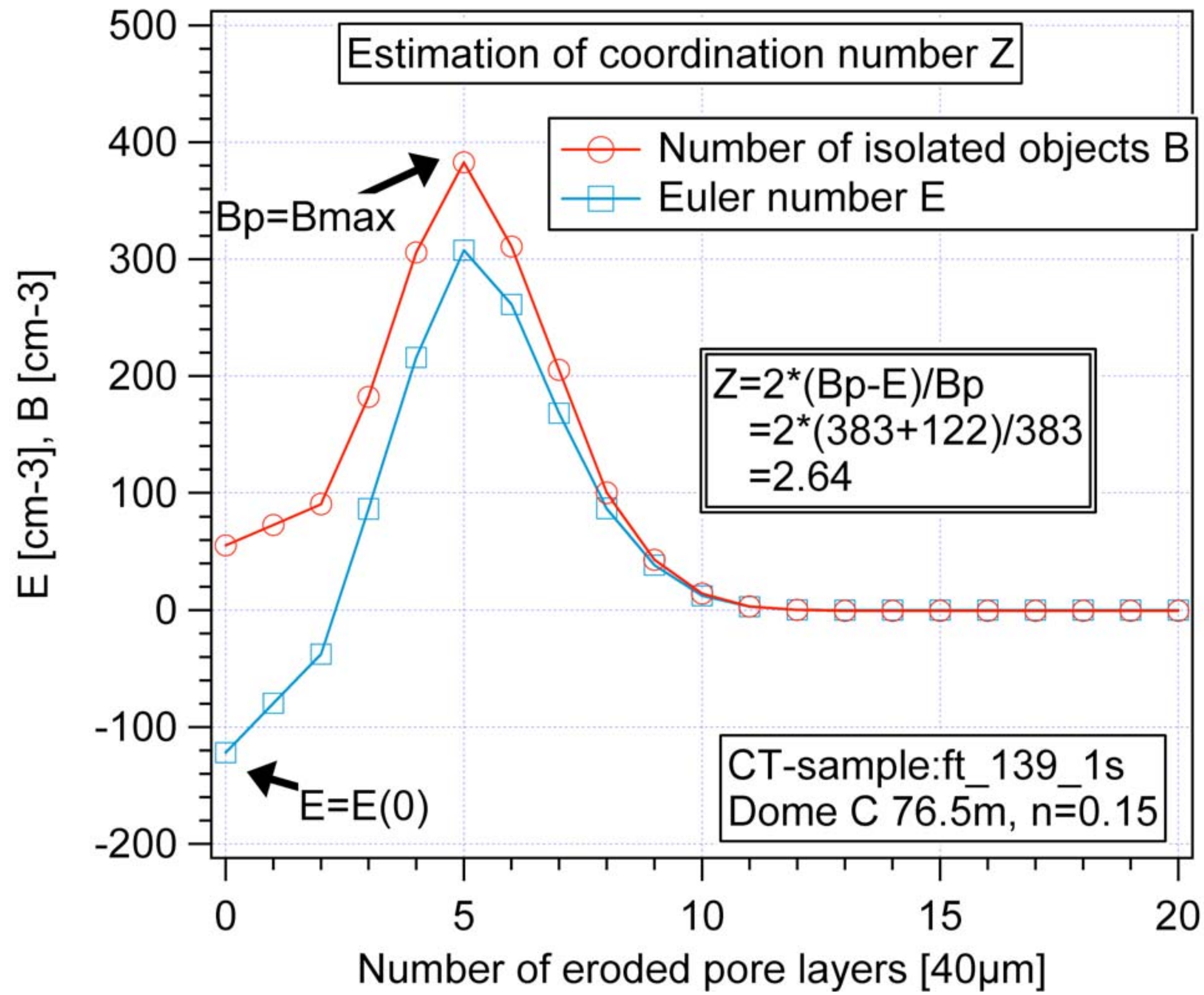
3D-image processing

$$\overline{Z} = \frac{2(B_p - E)}{B_p}$$



Erosion of pore space

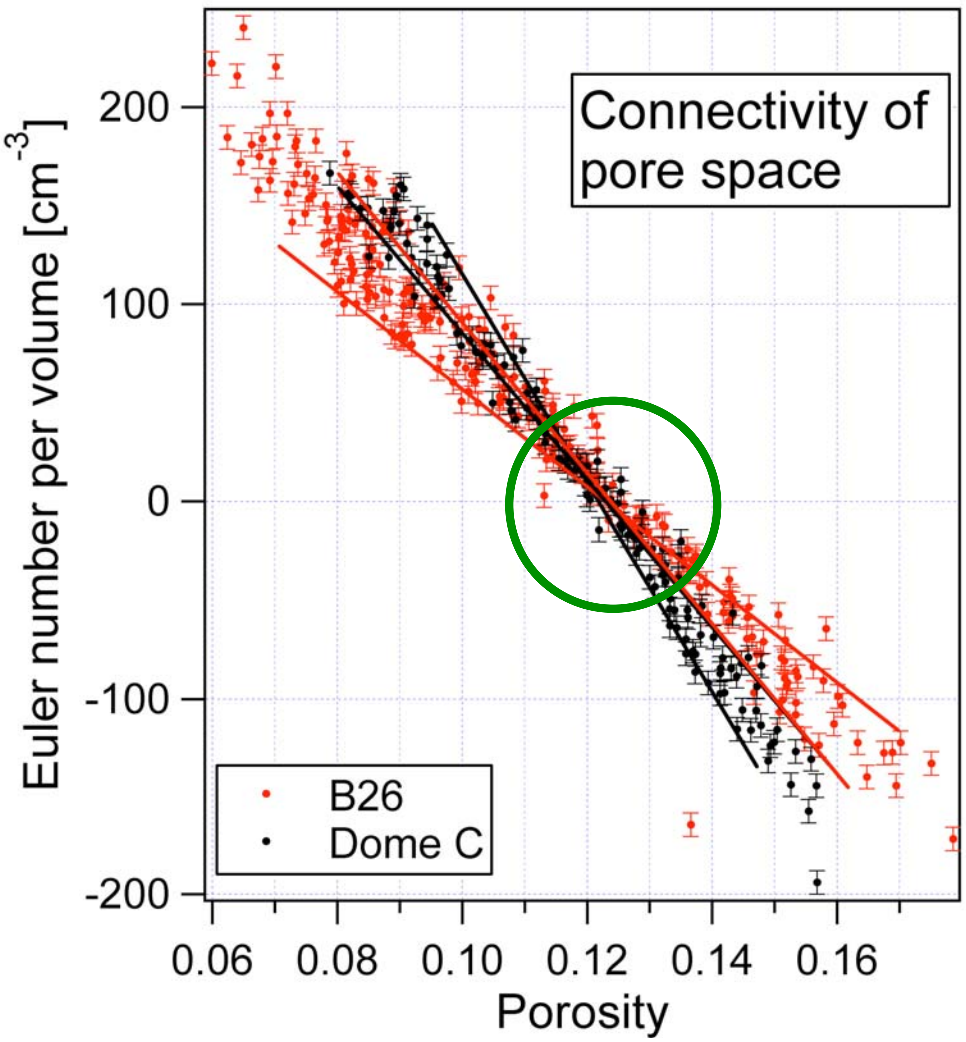
$$\overline{Z} = \frac{2(B_{max} - E(0))}{B_{max}}$$

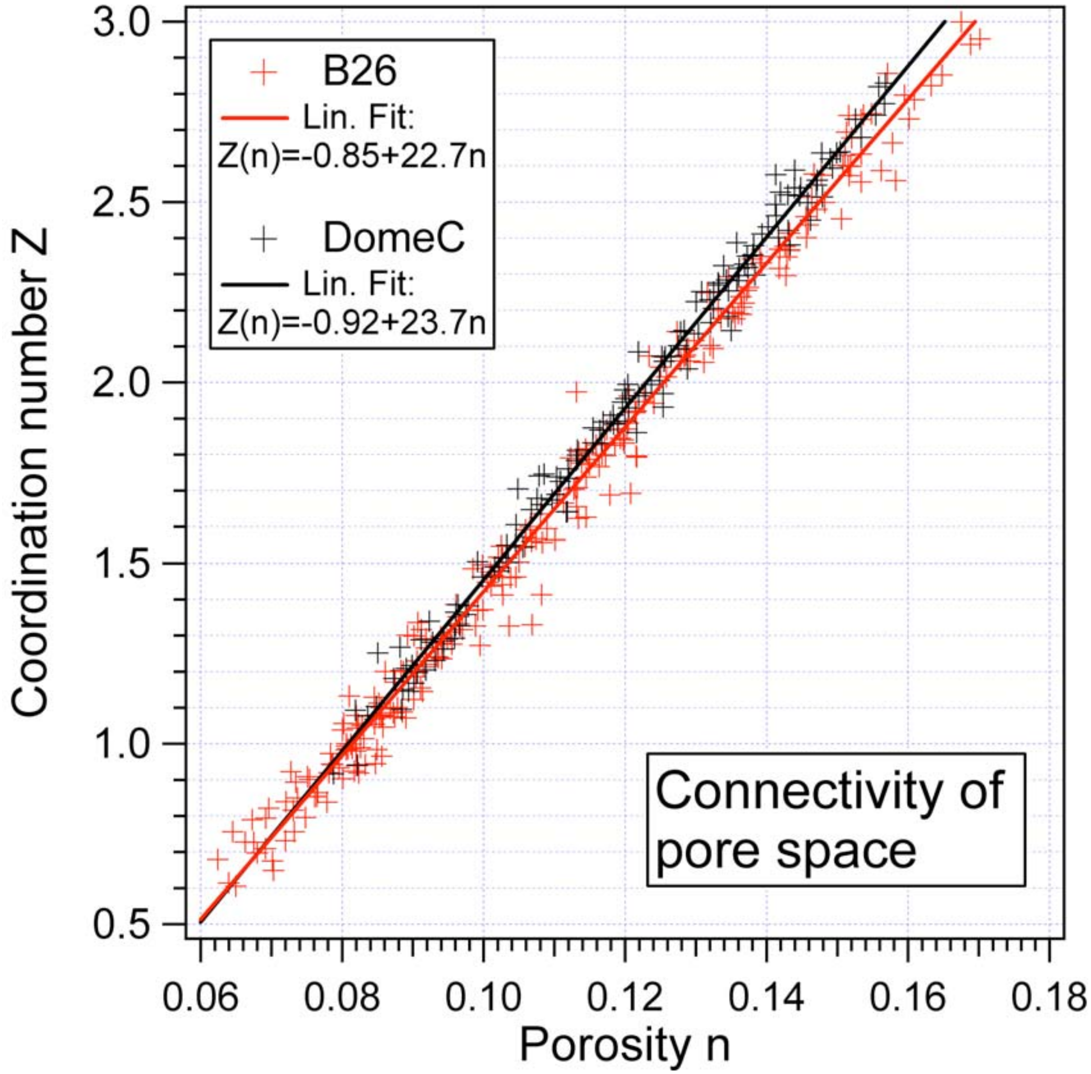


E~B (~ bubble density)

E=0 $\overset{(2)}{\Rightarrow}$ Z=2

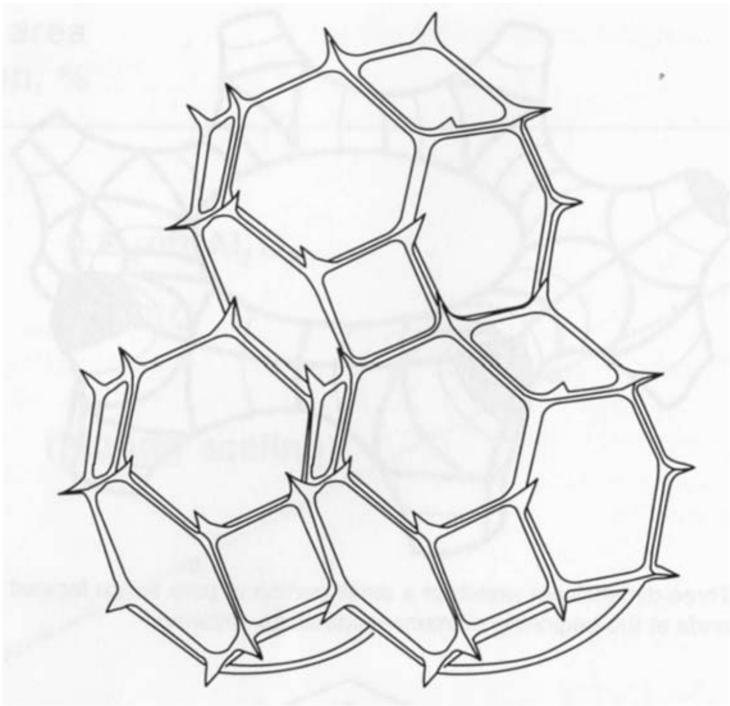
E~L (~ Loops)





⇨ Z(n)
linear relationship

Pore close-off as a percolation problem



Best lattice geometry for firn:
Sintered spheres (tetrakaidecahedrons),
grains are placed on a bcc-lattice

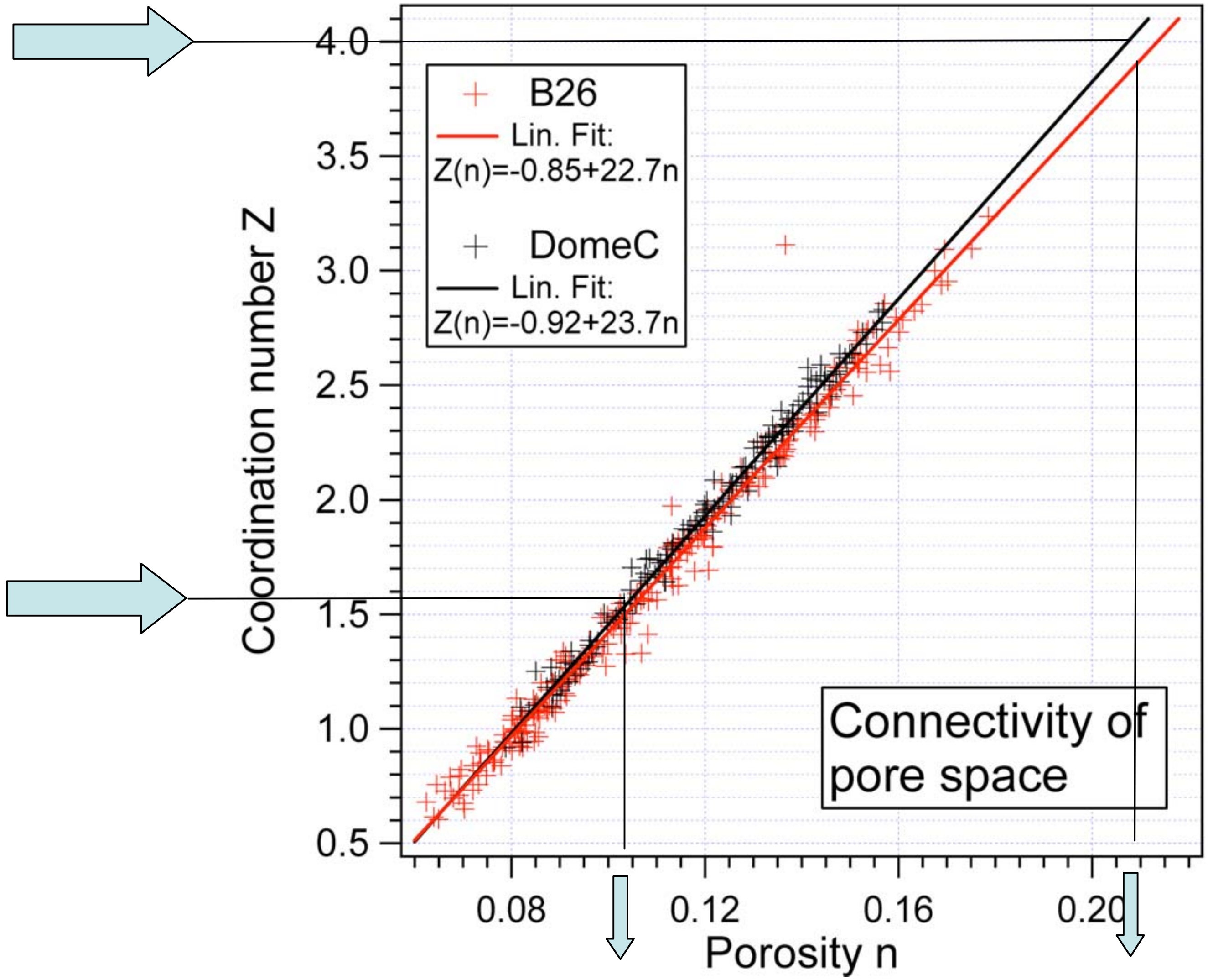
Fully occupied lattice (p=1):

$$Z=4$$

Lattice at the threshold from permeability to impermeability (percolation threshold p_{crit}~0.4)

$$Z\approx1.6$$

$Z(p) \approx$ linear

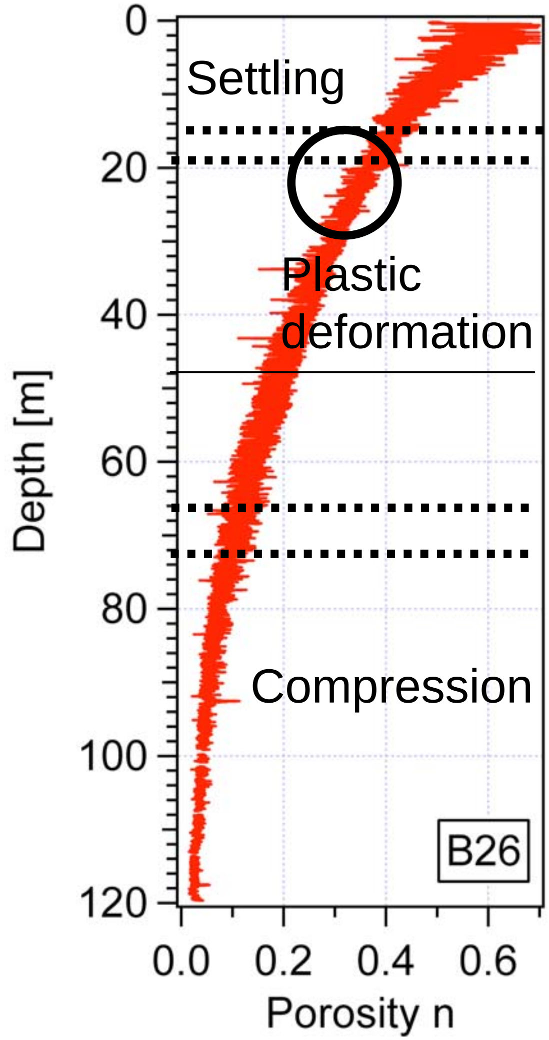


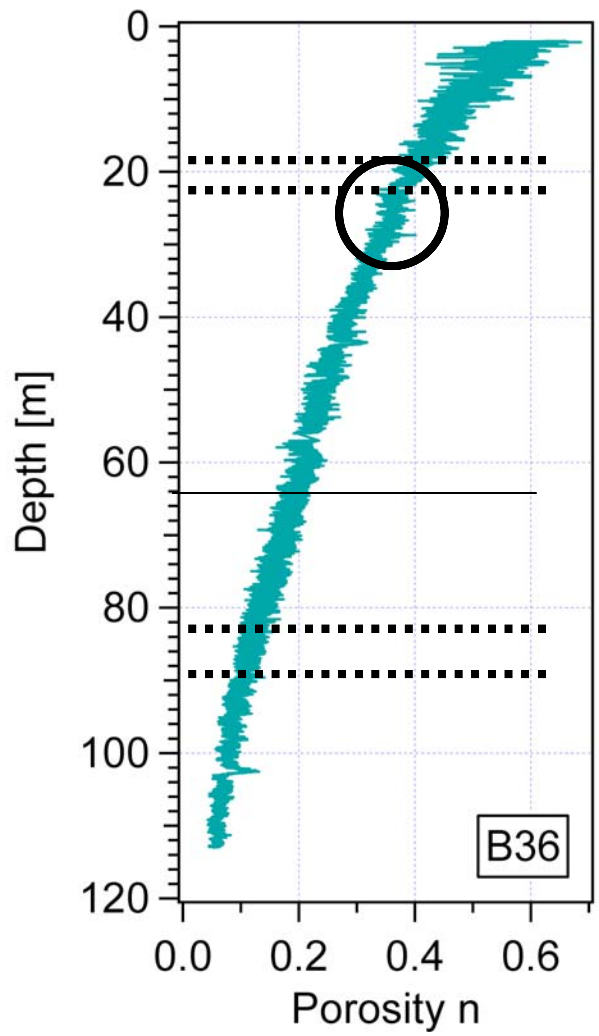
n=0.104 ~ ρ=822 kg/m³

n=0.208 ~ ρ=726 kg/m³

The evolution of layering

Image: S. Kipfstuhl

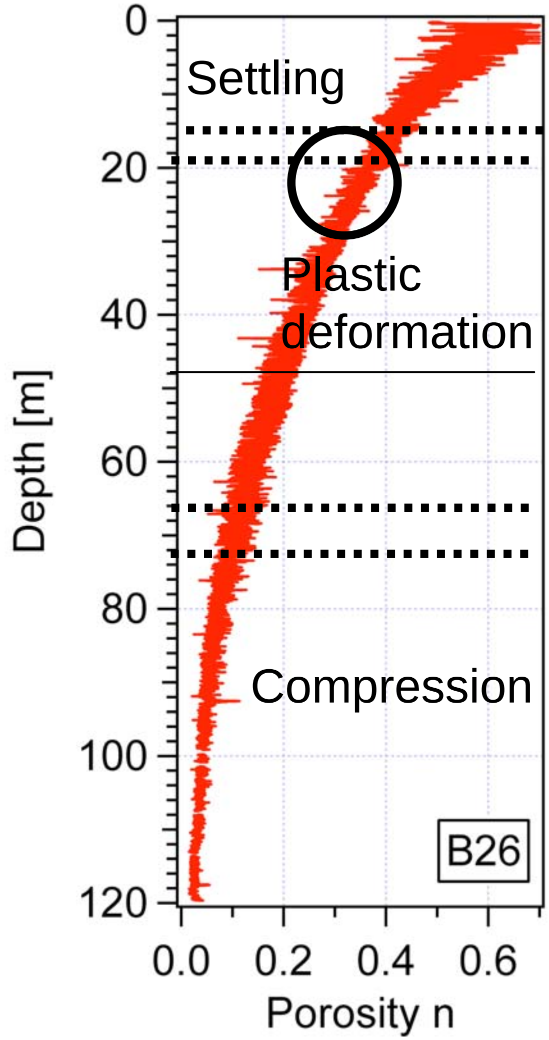


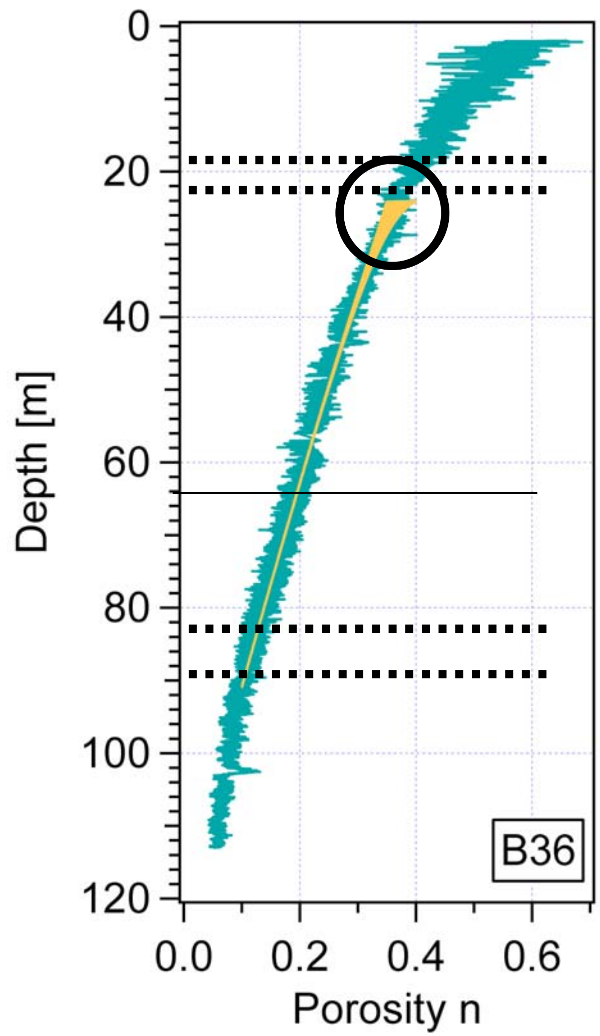


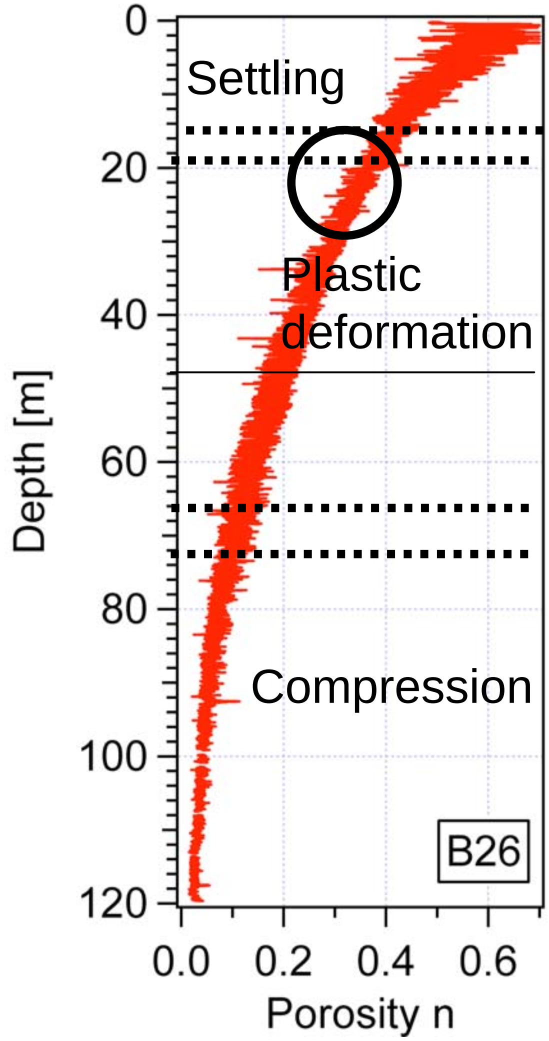
550 kg/m³ n=0.4

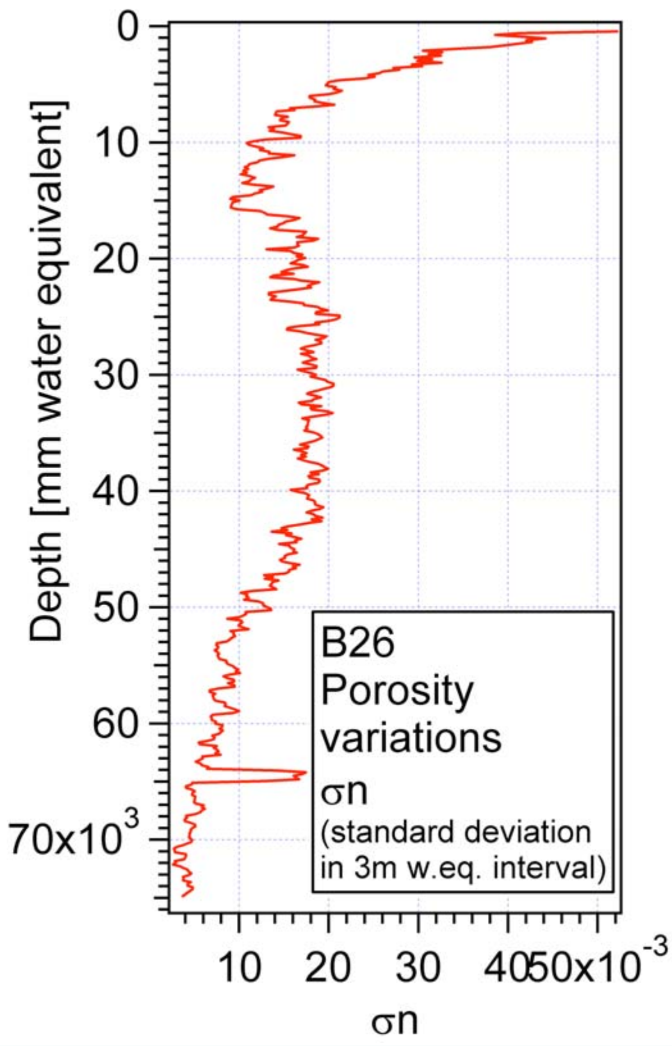
730 kg/m³ n=0.2

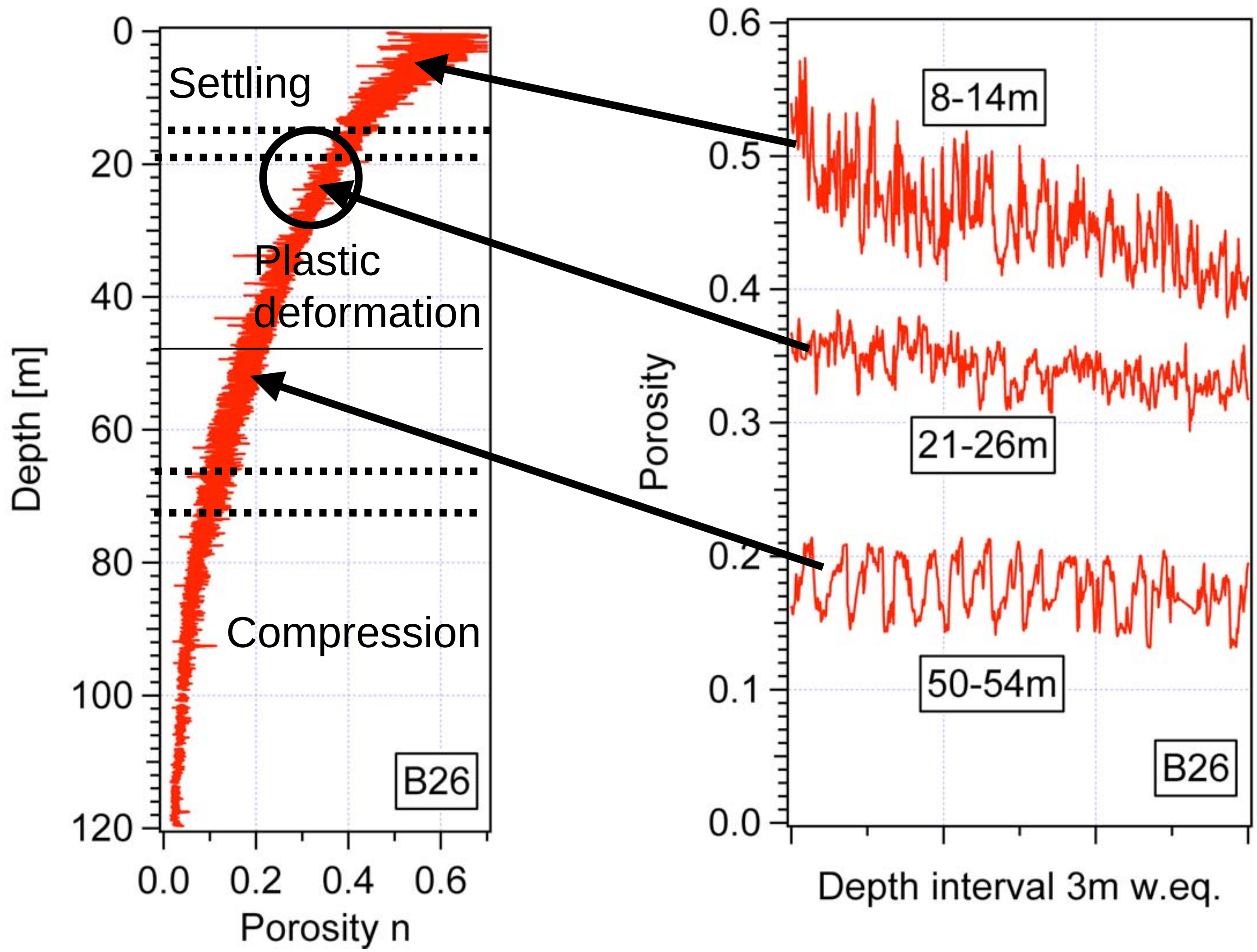
Firn-ice transition
820 kg/m³ n=0.1


Settling
Plastic deformation
Compression
Depth [m]
Porosity n
B26

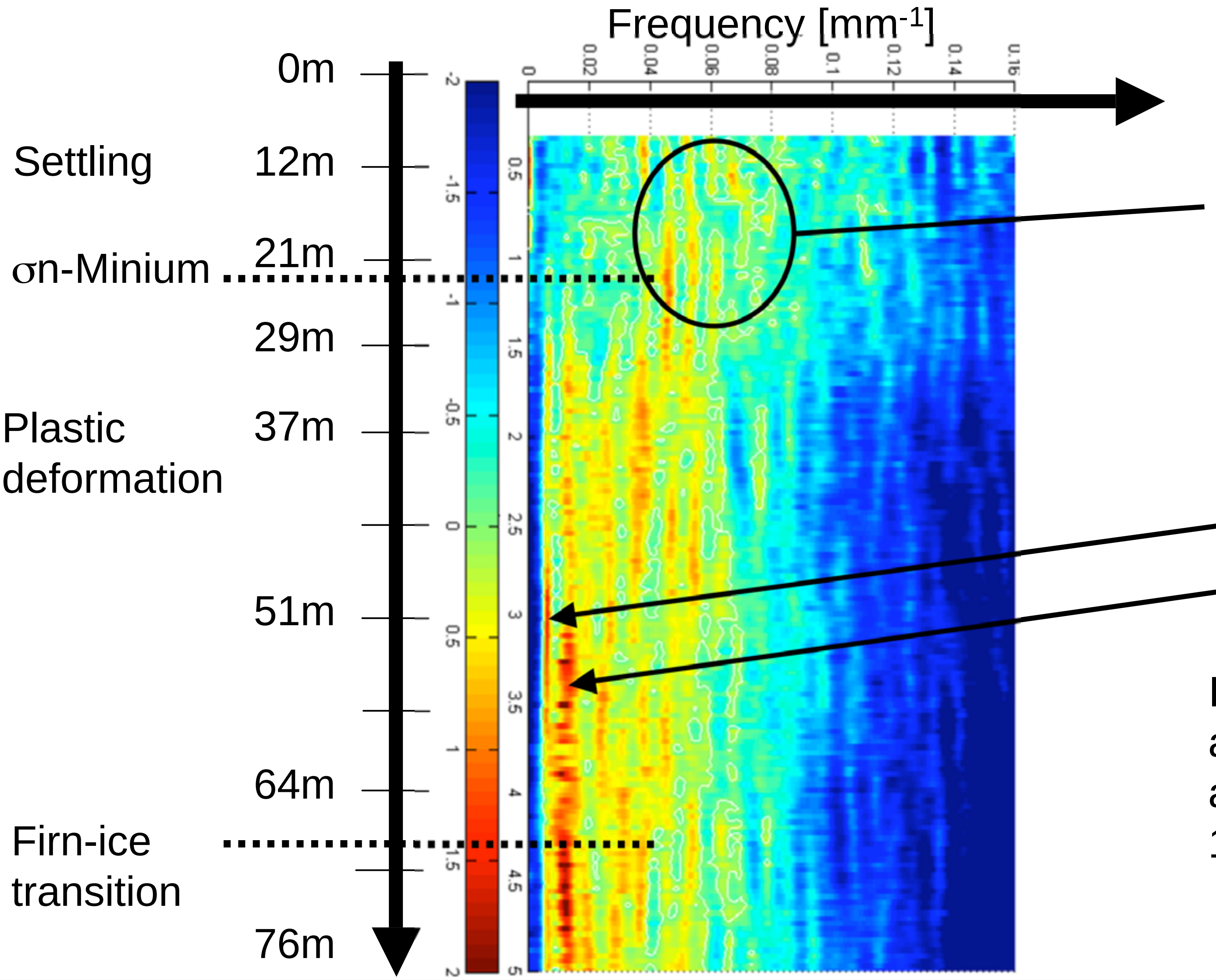

Depth [m]
Porosity n
B36
550 kg/m³ n=0.4
730 kg/m³ n=0.2
Firn-ice transition
820 kg/m³ n=0.1


Settling
Plastic deformation
Compression
B26
Depth [m]
Porosity n
0.0 0.2 0.4 0.6
0 20 40 60 80 100 120

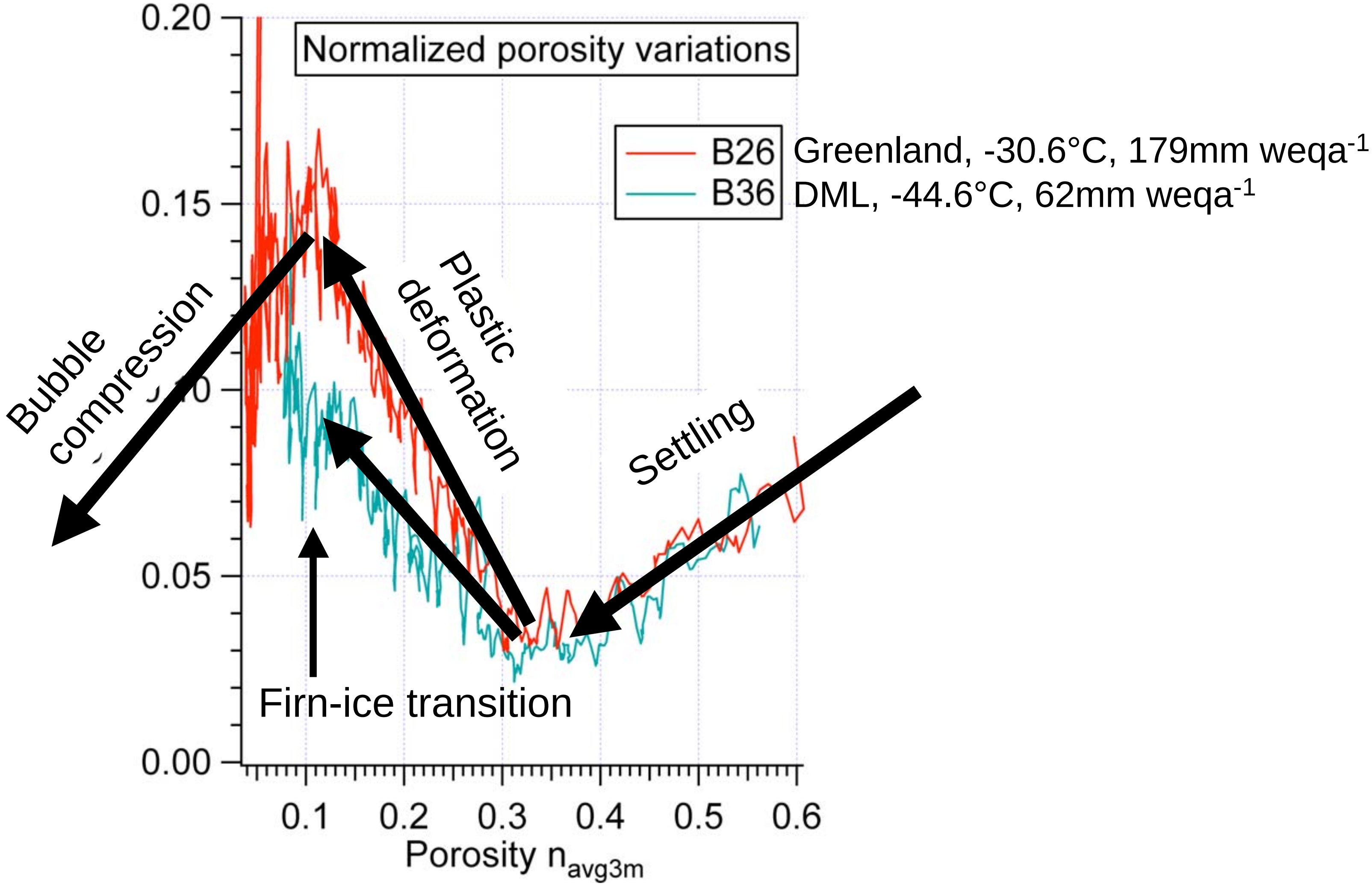

B26
Porosity variations
σn
(standard deviation in 3m w.eq. interval)
Depth [mm water equivalent]
0 10 20 30 40 50 60 70x10^3
σn
10 20 30 40 50x10^-3


Settling
Plastic deformation
Compression
B26
Depth [m]
0
20
40
60
80
100
120
0.0
0.2
0.4
0.6
Porosity n
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Porosity
8-14m
21-26m
50-54m
B26
Depth interval 3m w.eq.

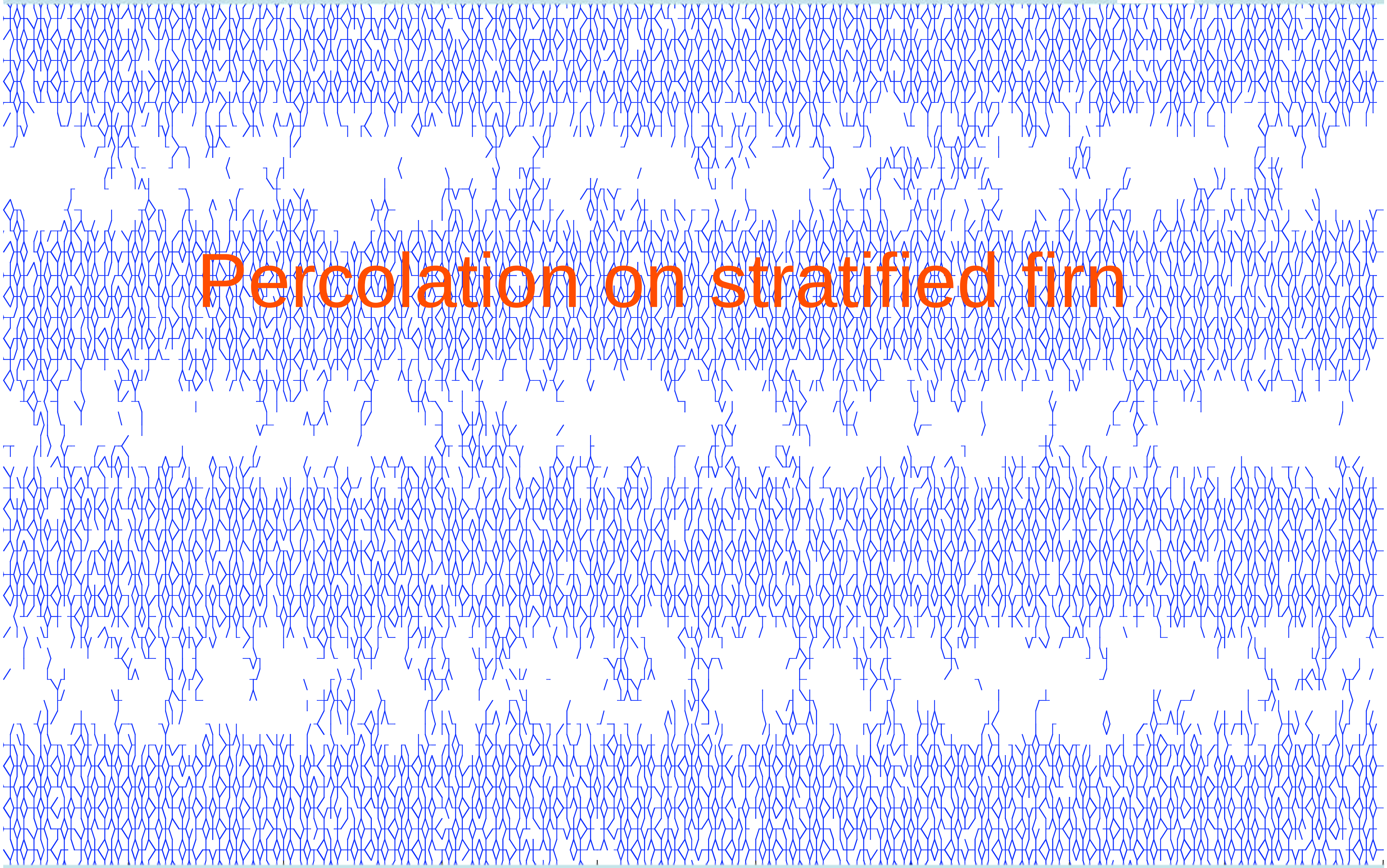
Evolutionary power spectrum of porosity (B26)



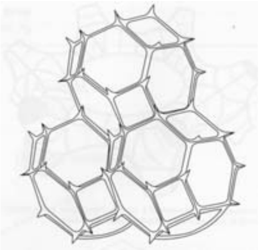
In comparison: accumulation rate at B26 about 179 mm w.eq.a^{-1}


Normalized porosity variations
B26 Greenland, -30.6°C, 179mm weqa-1
B36 DML, -44.6°C, 62mm weqa-1
0.20
0.15
0.10
0.05
0.00
0.1
0.2
0.3
0.4
0.5
0.6
Porosity n avg3m
Bubble compression
Plastic deformation
Settling
Firn-ice transition

Percolation on stratified firn



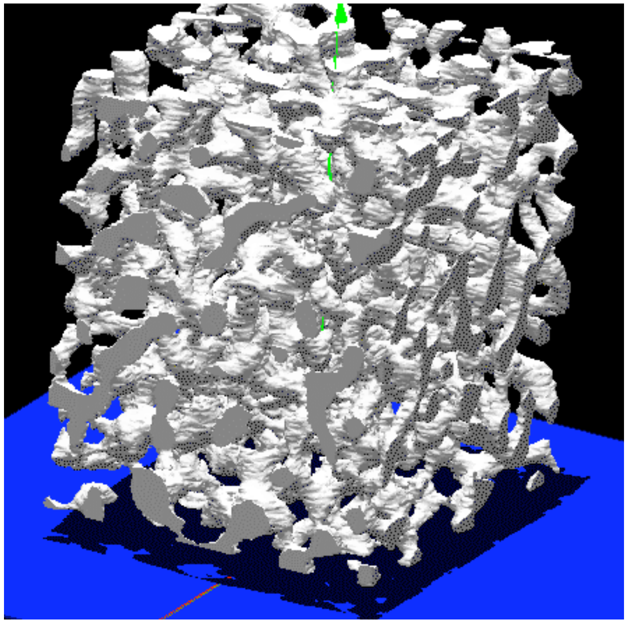
Adapting the percolation model on real firn pore structures



Step 1

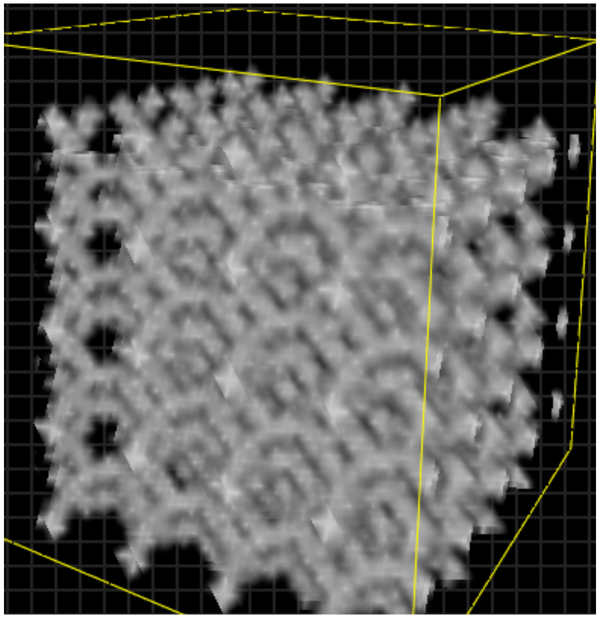
Introduction of a length scale
via the Euler number in fully occupied structures (Z=4):

Pore structure at n≈0.2



B26, 40m, E≈-650, 12x12x12mm³

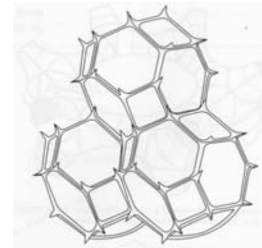
Lattice structure at p=1



BCC-lattice, 4x4x4 units, E≈-680

E(firn) ≈ E(lattice) ⇨ 1 bcc unit = 3 mm (B26),
= 2.7 mm (DomeC)

Adapting the percolation model on real firn pore structures



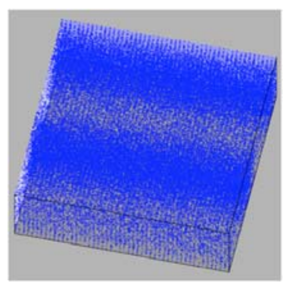
Step 2

Introduction of layering
via measured porosity variations at the firn-ice transitions

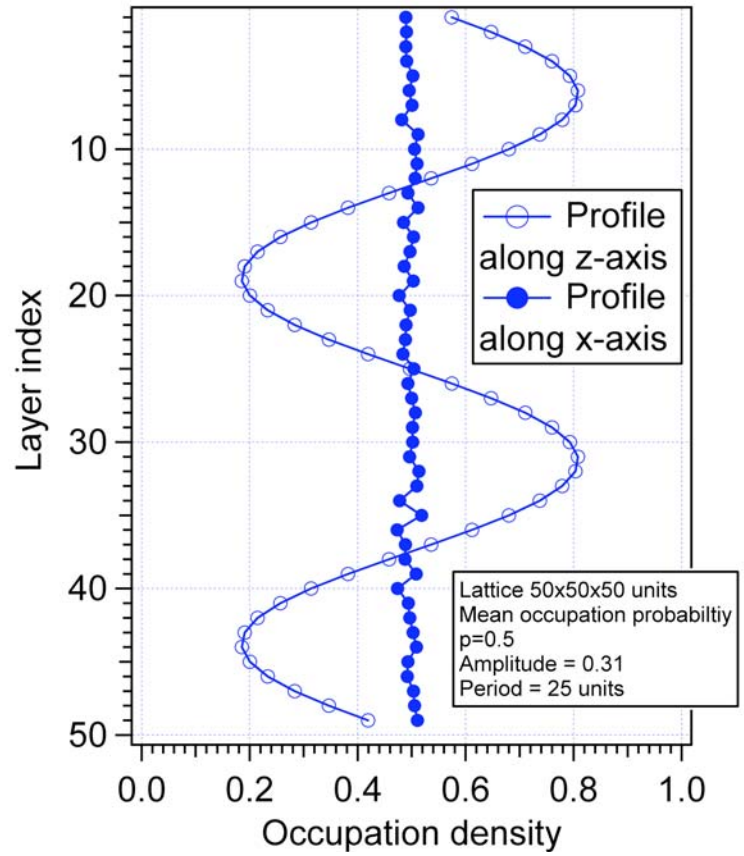
Assumption
Occupation probability varies periodically
in vertical direction (laterally homogenous)
Amplitude: σn
Wave lengths: year‘s accumulation
Conversion:

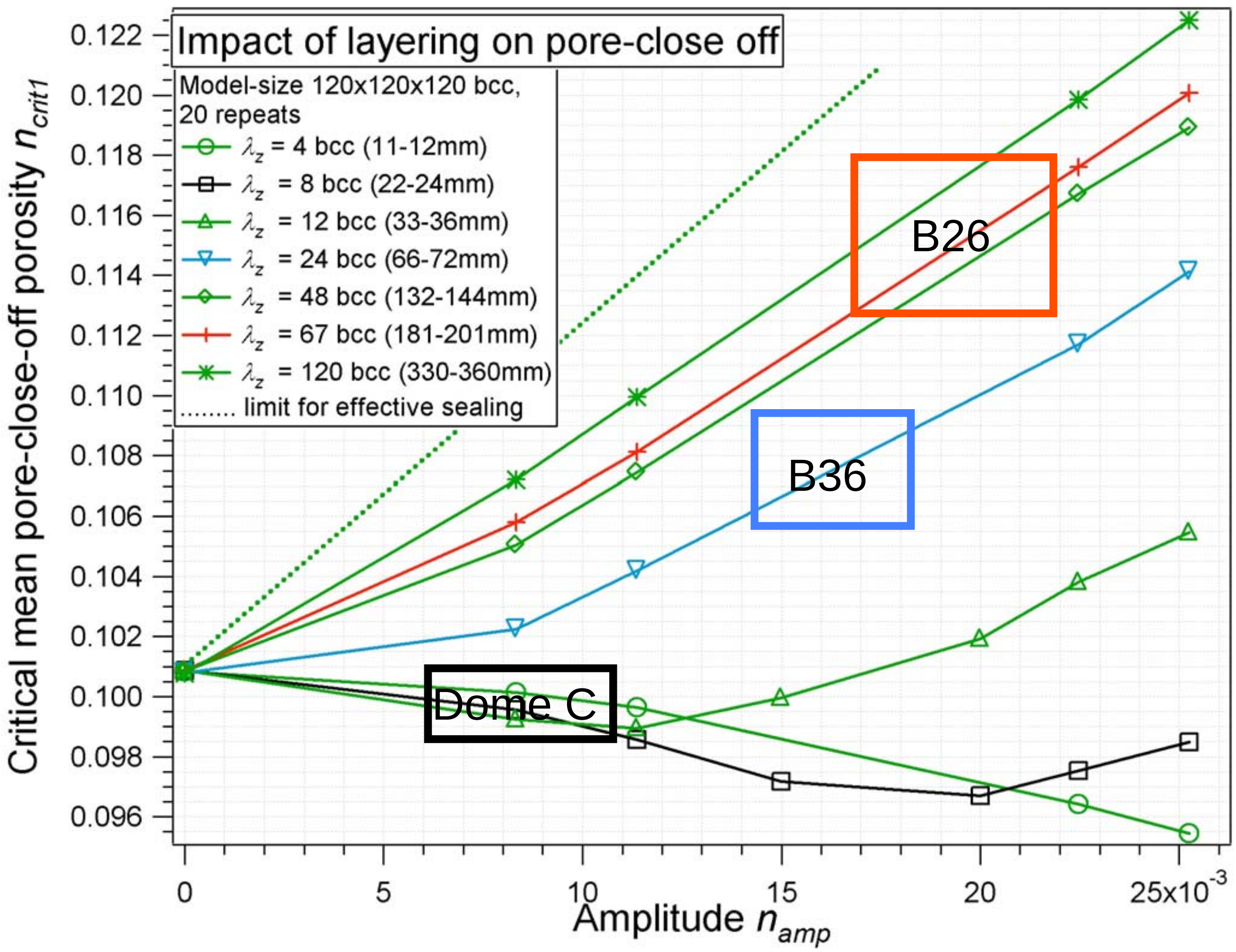
$$p(n) = -0.22 + 5.8n$$

(from the n(Z) and p(Z)-relation)



$$p(x,y,z) = p_{avg} + p_{amp} \sin \frac{2\pi z}{\lambda_z}$$





Firn air Pumping measurements

GRIP

B36

Dome C

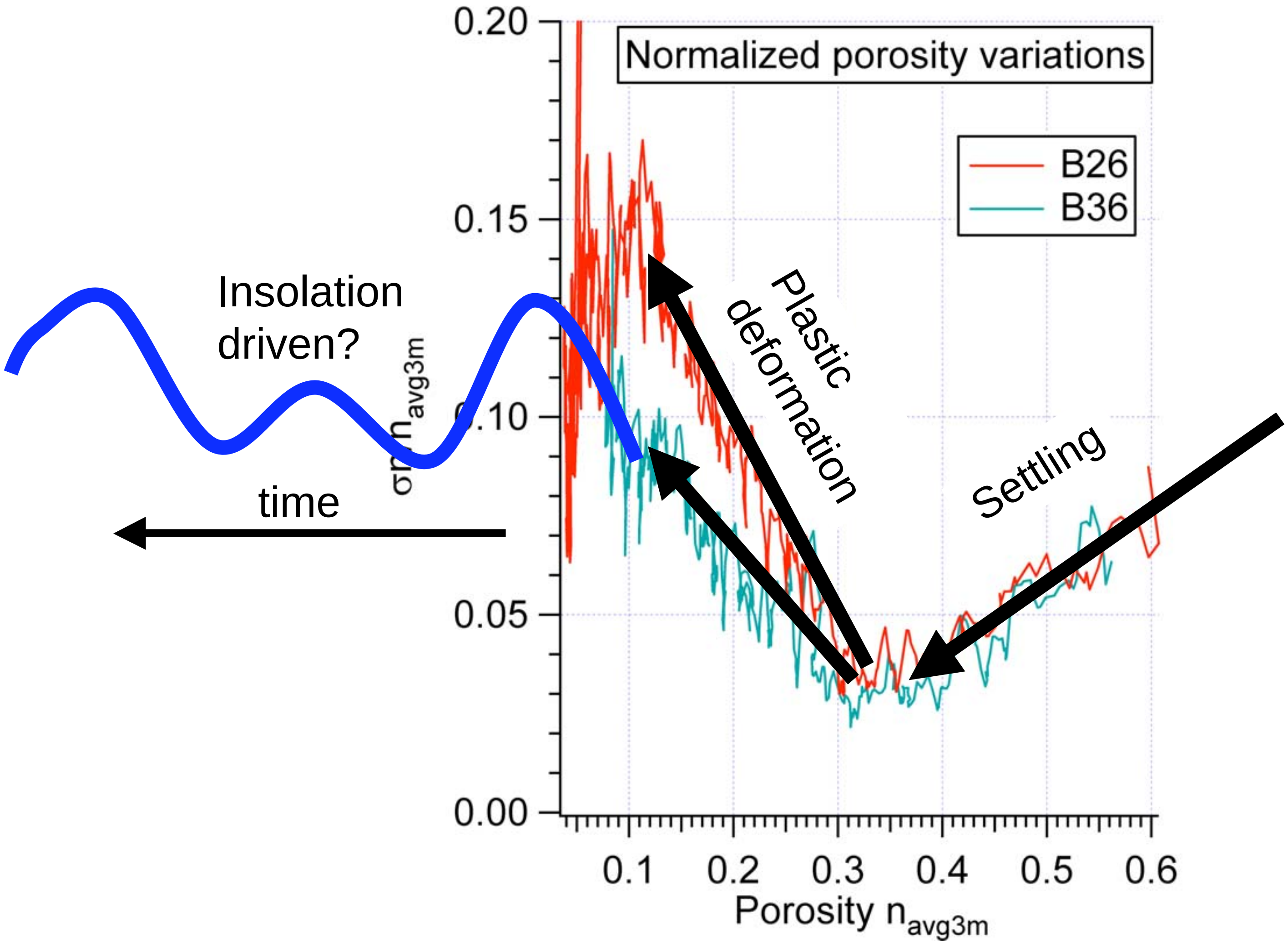
- Evidence for an universal close-off porosity for polar firn

- The 3D-percolation approach explains two critical porosities/densities (0.101 / 820 kg/m³ and 0.21 / 730 kg/m³) of polar firn

- Unexpected large layering at the firn-ice transition

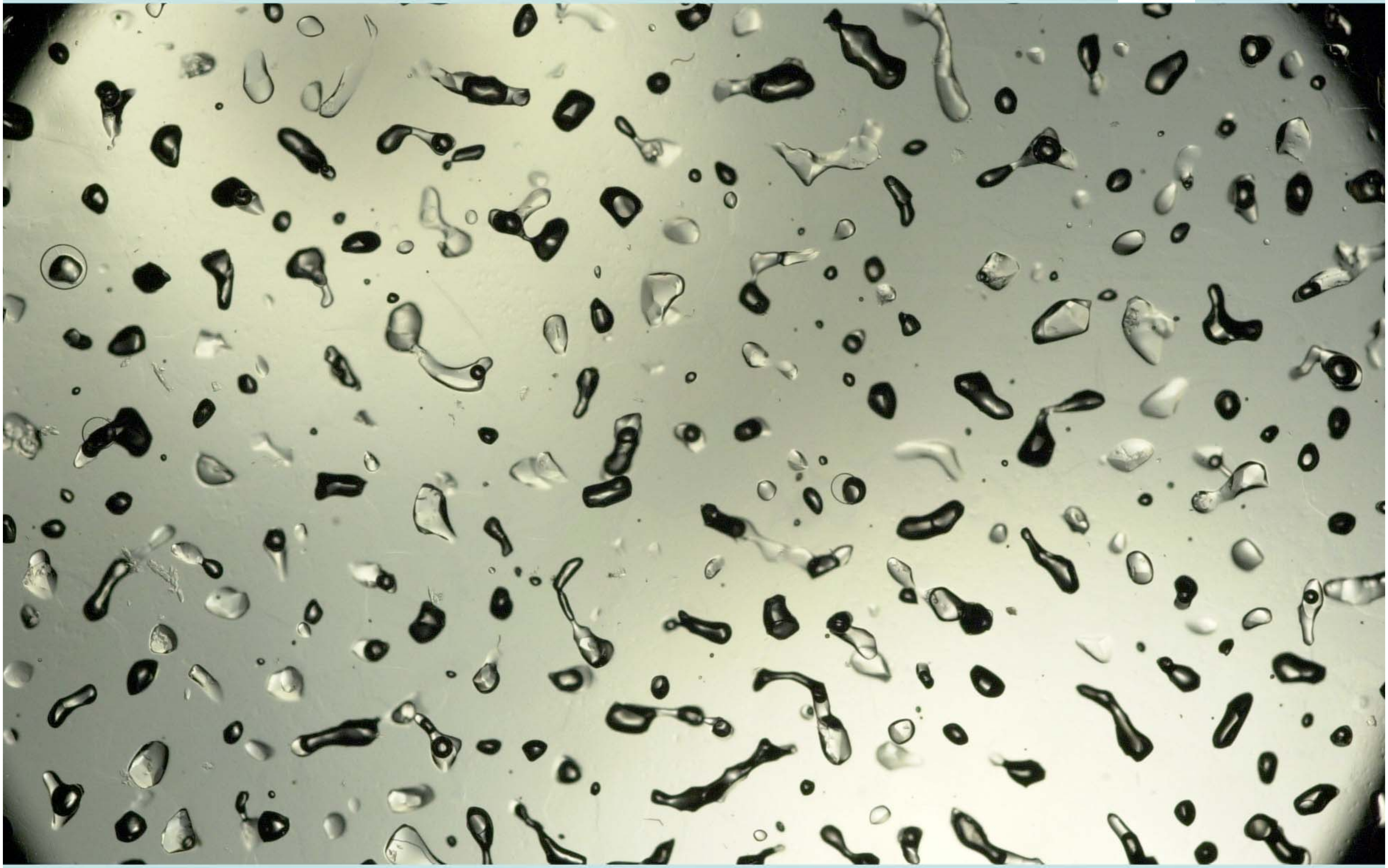
- Layering at firn-ice transition mainly results from different densification rates in seasonal layers in the stage of plastic deformation (stage II). The variations start to synchronize with the seasonal cycle. Are they chemically induced?

- Recent variations of mean close-off porosities at different sites can be exclusively explained by layering (amplitude and wave length are important)


Normalized porosity variations
B26
B36
0.20
0.15
0.10
0.05
0.00
0.1
0.2
0.3
0.4
0.5
0.6
Porosity n_{avg3m}
σn_{avg3m}
Plastic deformation
Settling
Insolation driven?
time

Thank you

J. Freitag



Open questions concerning the firn-ice transition

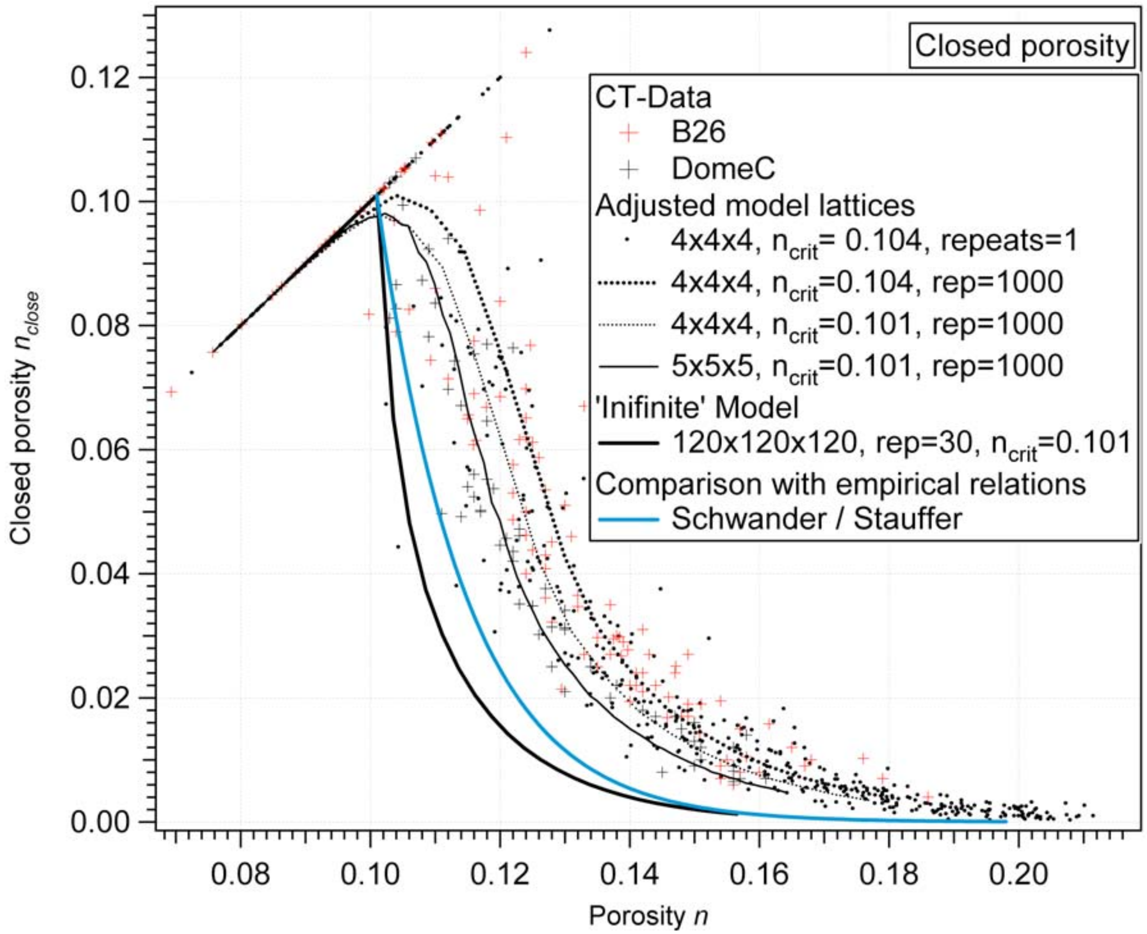
The physical link between insolation and N2/O2, air content (Duval?, Kawamura,..)

Large discrepancy between modelled close-off depths and $\delta^{15}N$ inferred lock-in depths under Glacial conditions in low accumultion sites (Landais et al, 2006).

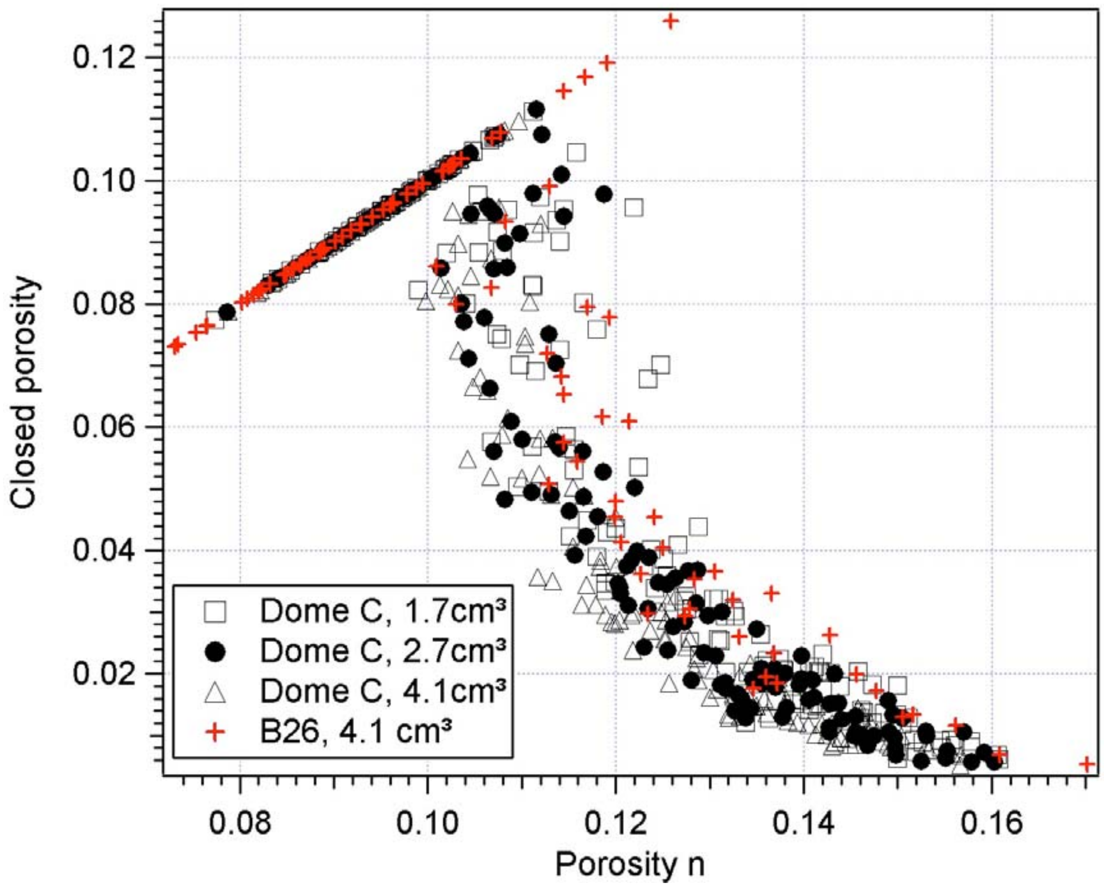
The nature of the non-diffusive zone

Why is the empirical relationship between pore close-off density (porosity) and temperature found by Martinerie et al. (1992) only valid for recent firn but not for paleo firn?

Closed porosity: model versus data



Closed porosity: size effect of data



...1961

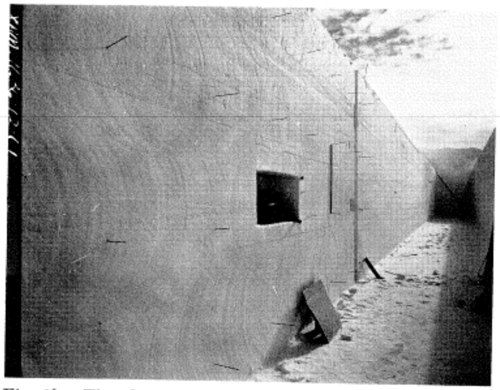


Fig. 6*b*. The first 6 meters of the study area with the layering accentuated by sunlight.

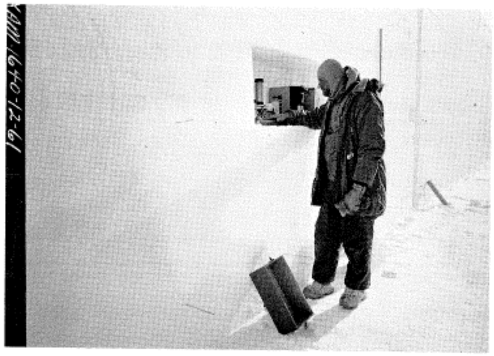
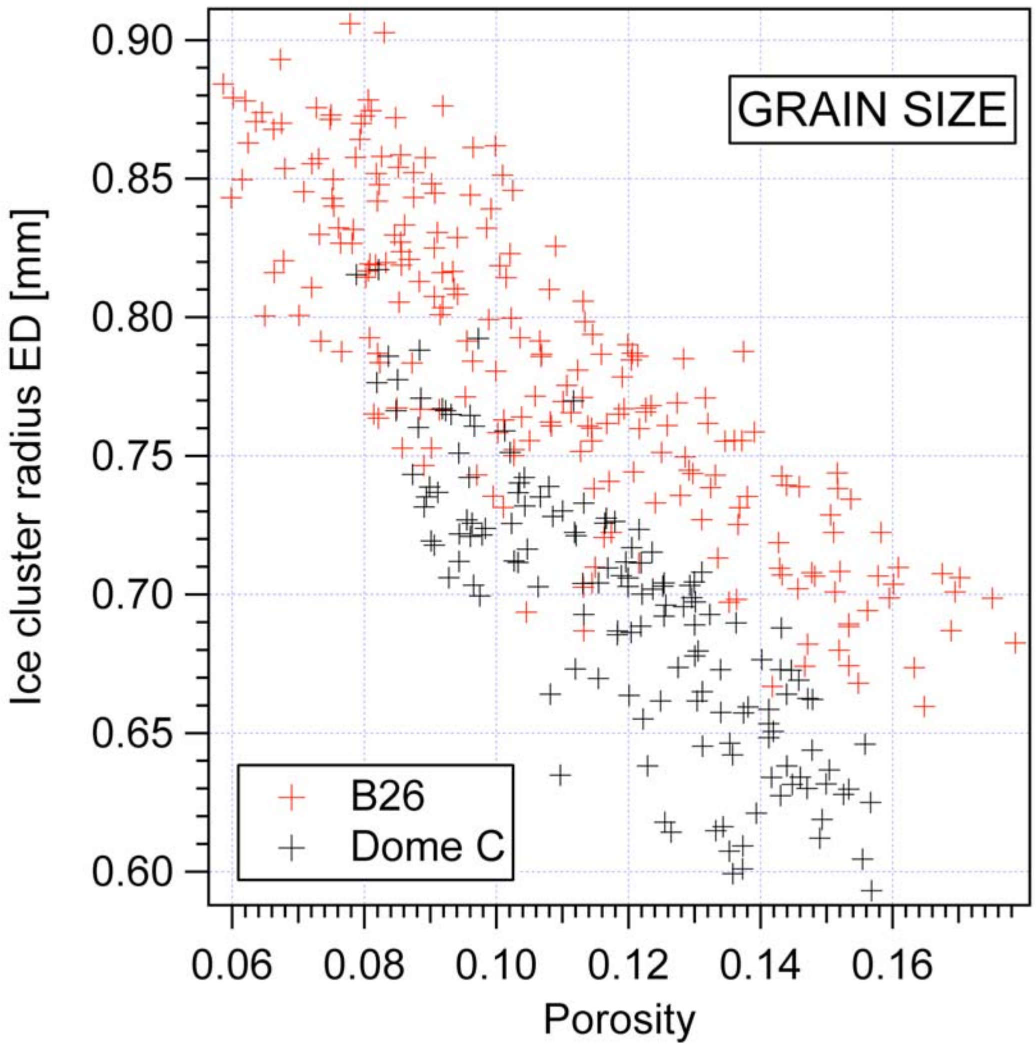


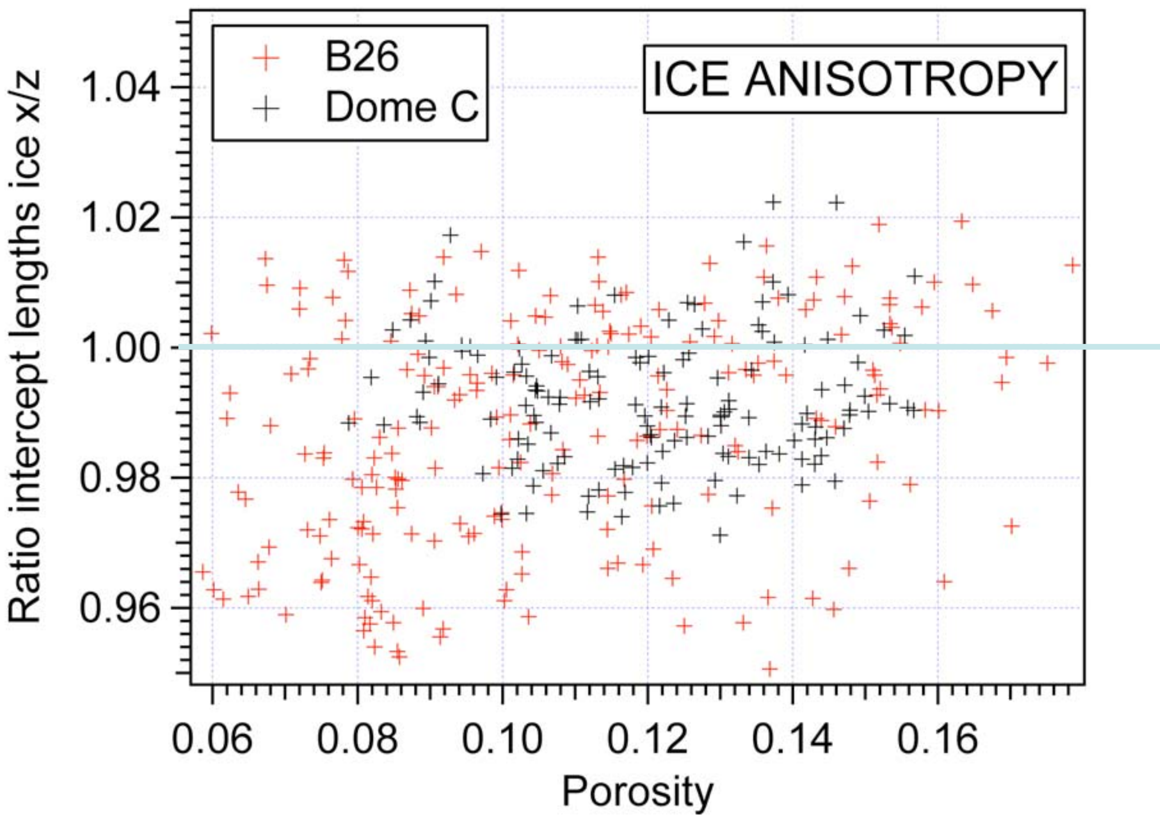
Fig. 6*d*. Density samples cut from the pit wall were weighed on a triple-beam balance mounted in the shelf shown here.

Stratigraphic studies at Byrd Station, Antarctica, by C. Benson.

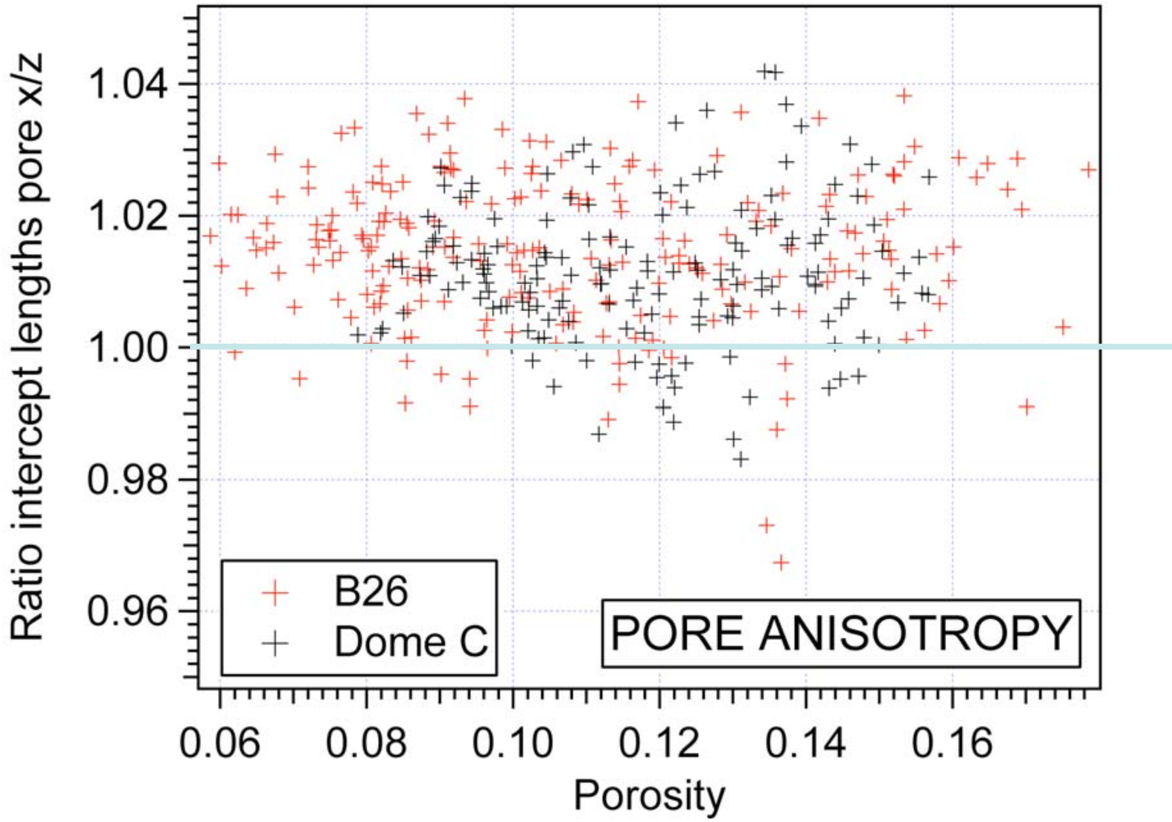
... 2008

Why are we still interested on firn layering?

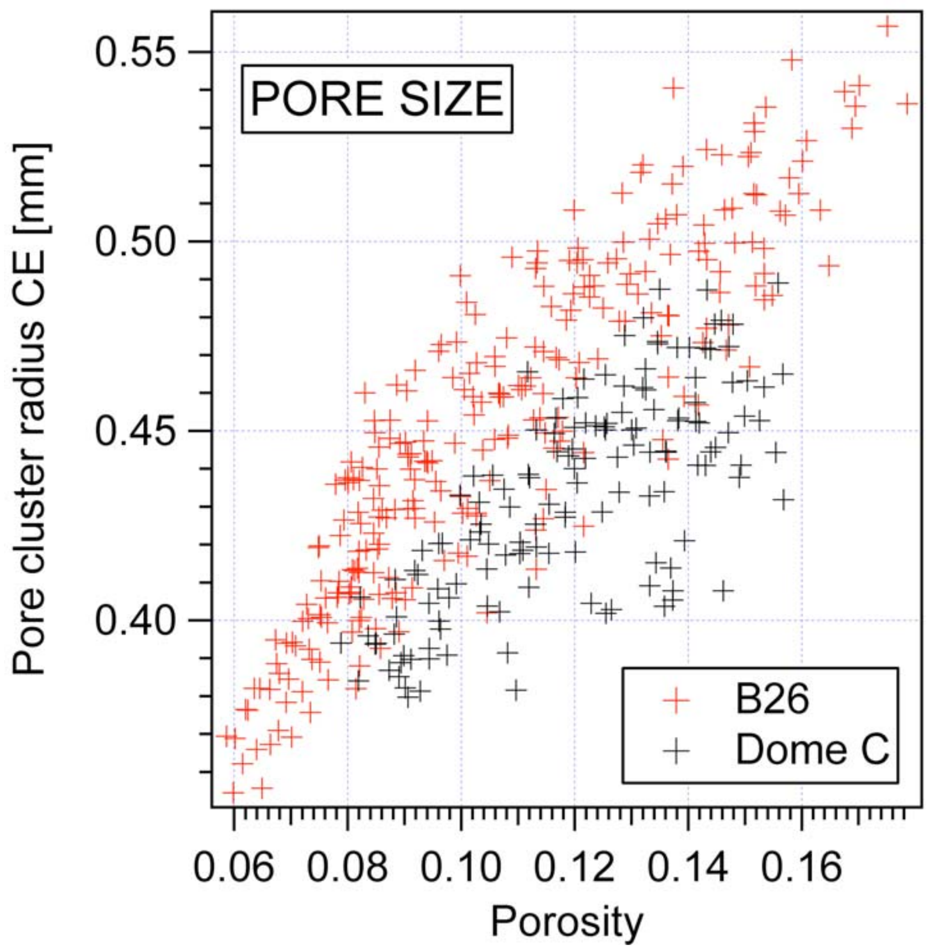

GRAIN SIZE
Ice cluster radius ED [mm]
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.06
0.08
0.10
0.12
0.14
0.16
Porosity
B26
Dome C

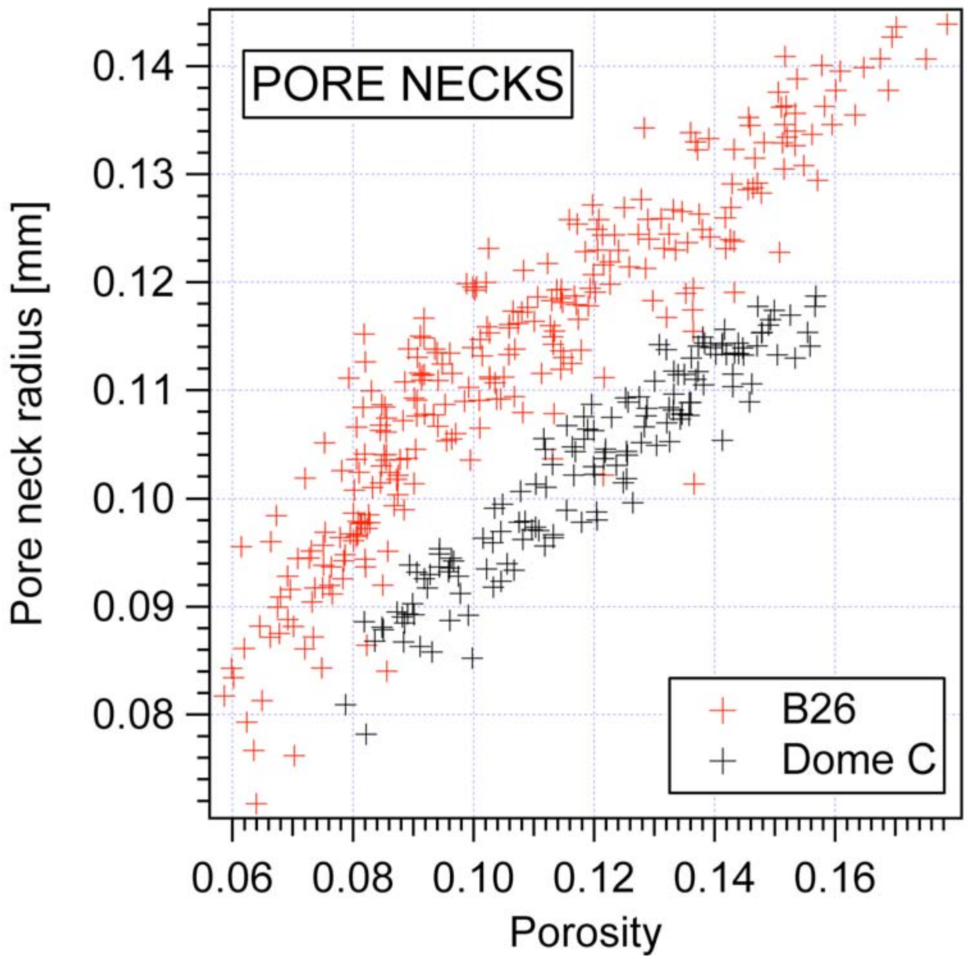


Ice phase is vertically elongated



Pore phase is vertically compressed


PORE SIZE
Pore cluster radius CE [mm]
0.55
0.50
0.45
0.40
0.06
0.08
0.10
0.12
0.14
0.16
Porosity
B26
Dome C

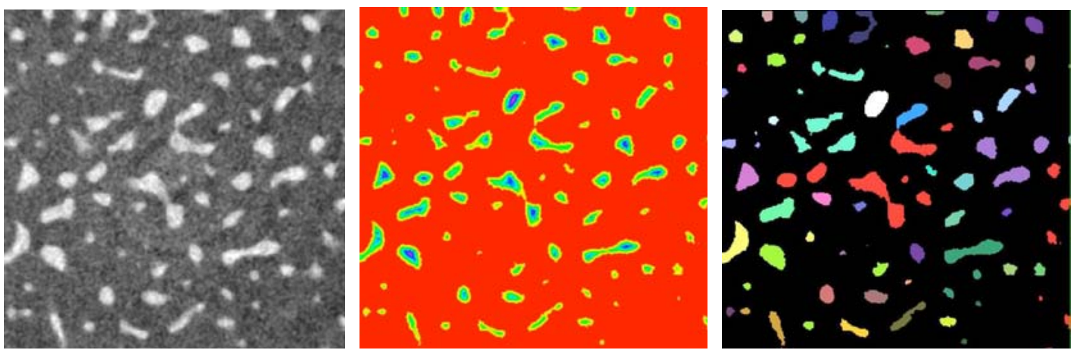

PORE NECKS
Pore neck radius [mm]
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.06
0.08
0.10
0.12
0.14
0.16
Porosity
B26
Dome C

X-ray-microfocus-computer-tomography (µCT)

SkyScan 1072
Resolution 8-20µm

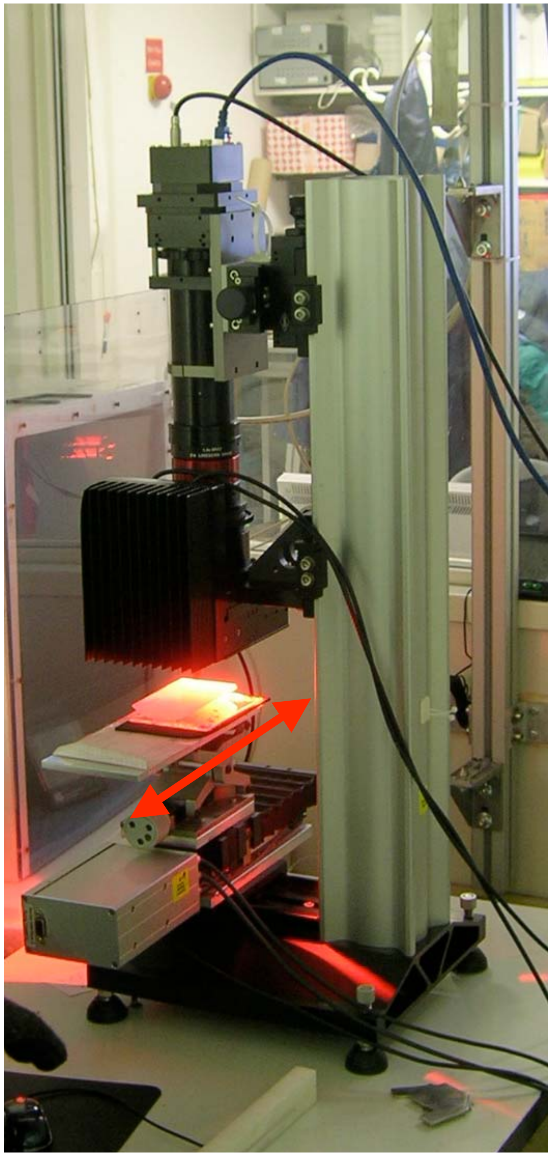
Field measurements

SkyScan 1074
Resolution: 40µm

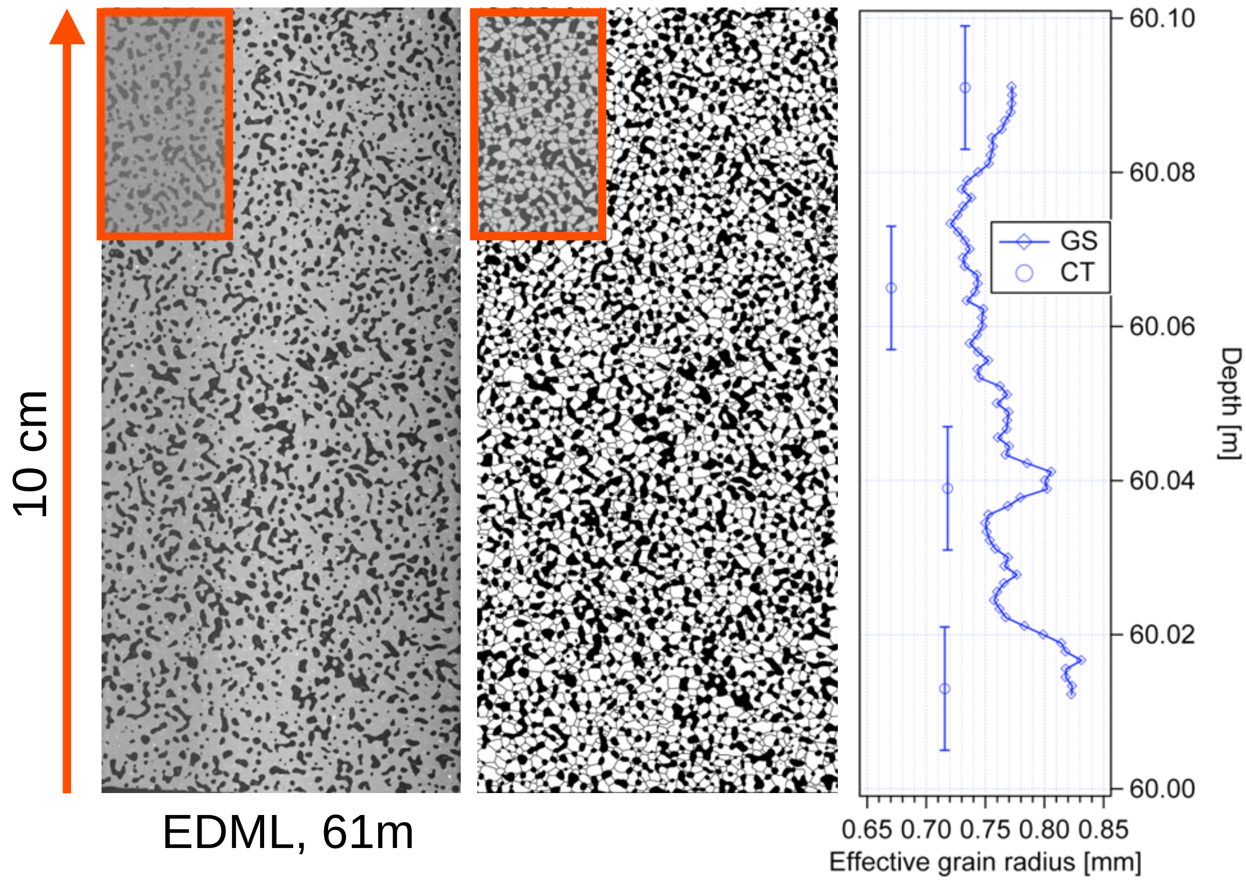


3D-volume processing:
open and closed porosity, pore and ice cluster size distributions, neck radii, coordination number, anisotropy, specific surface density, mean curvature…

Grain-size-Scanner



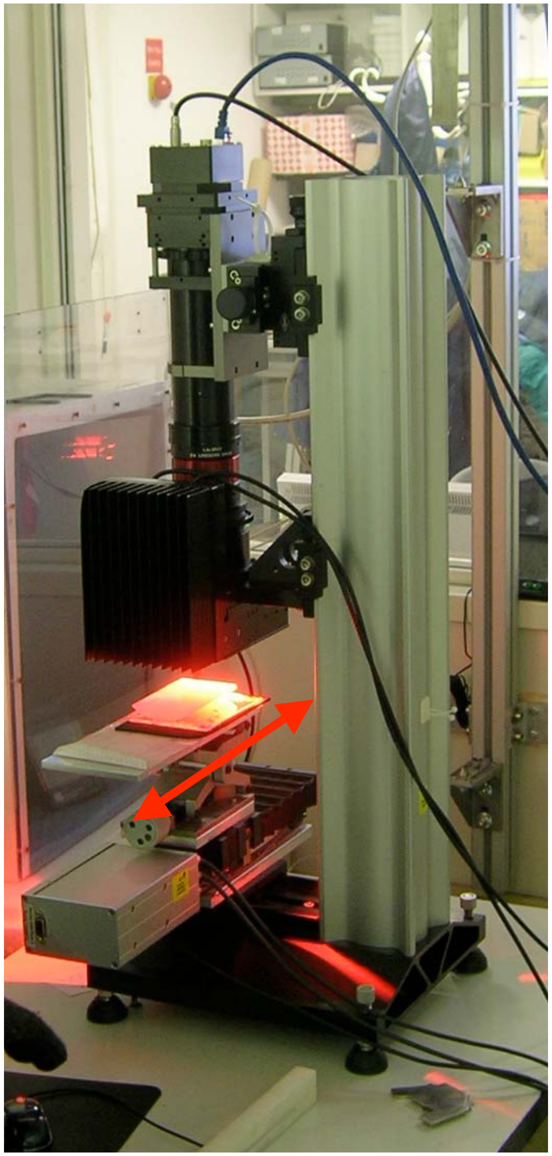
Intercomparison

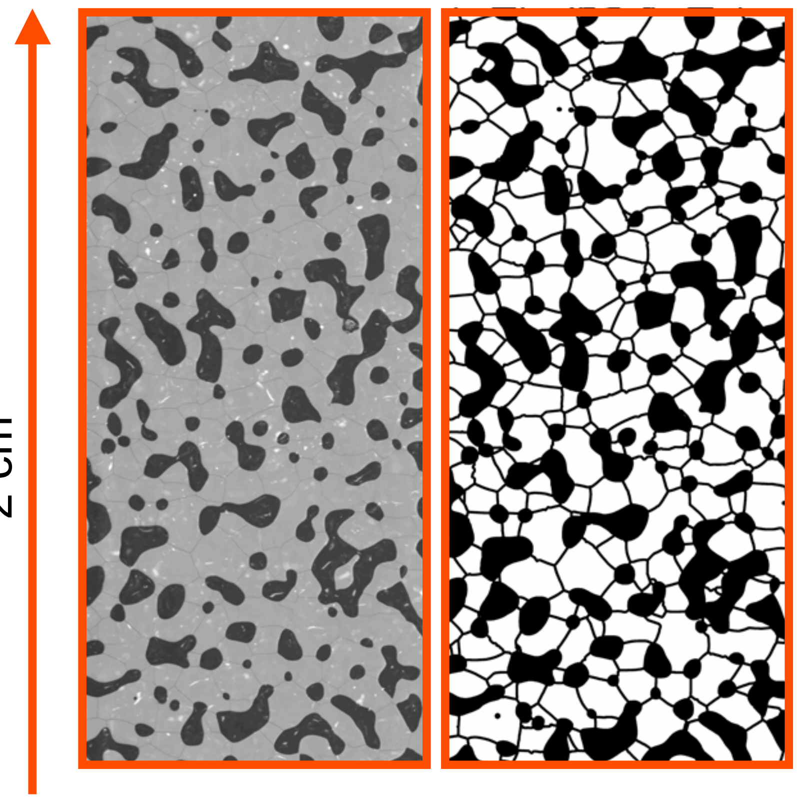


Resolution 5µm, 4cm scan width, v=1cm/s

(Schäfter&Kirchhoff, Hamburg)

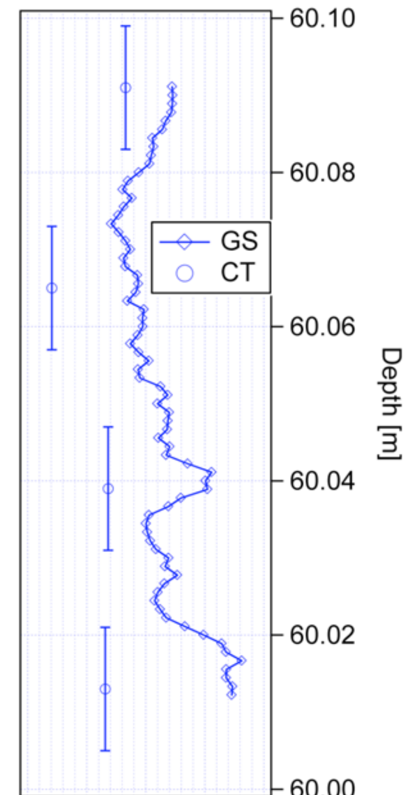
Grain-size-Scanner





EDML, 61m

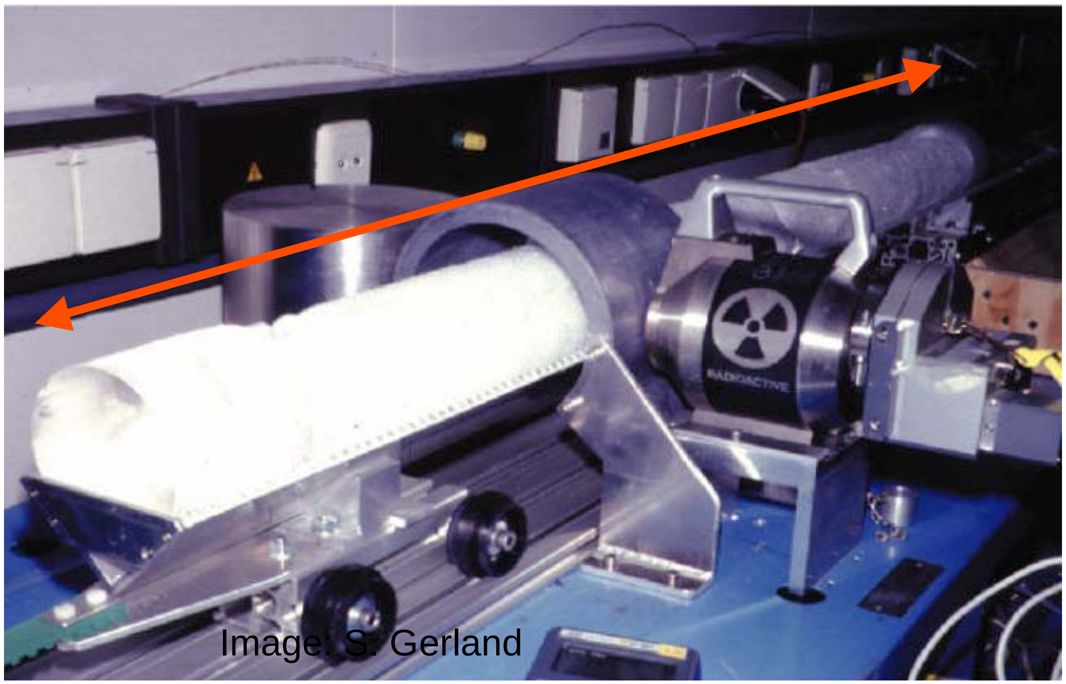
Intercomparison



Resolution 5µm, 4cm scan width, v=1cm/s

(Schäfter&Kirchhoff, Hamburg)

Gamma-bench for porosity measurements (GAMB)



Vertical resolution: ~3mm

Intercomparison