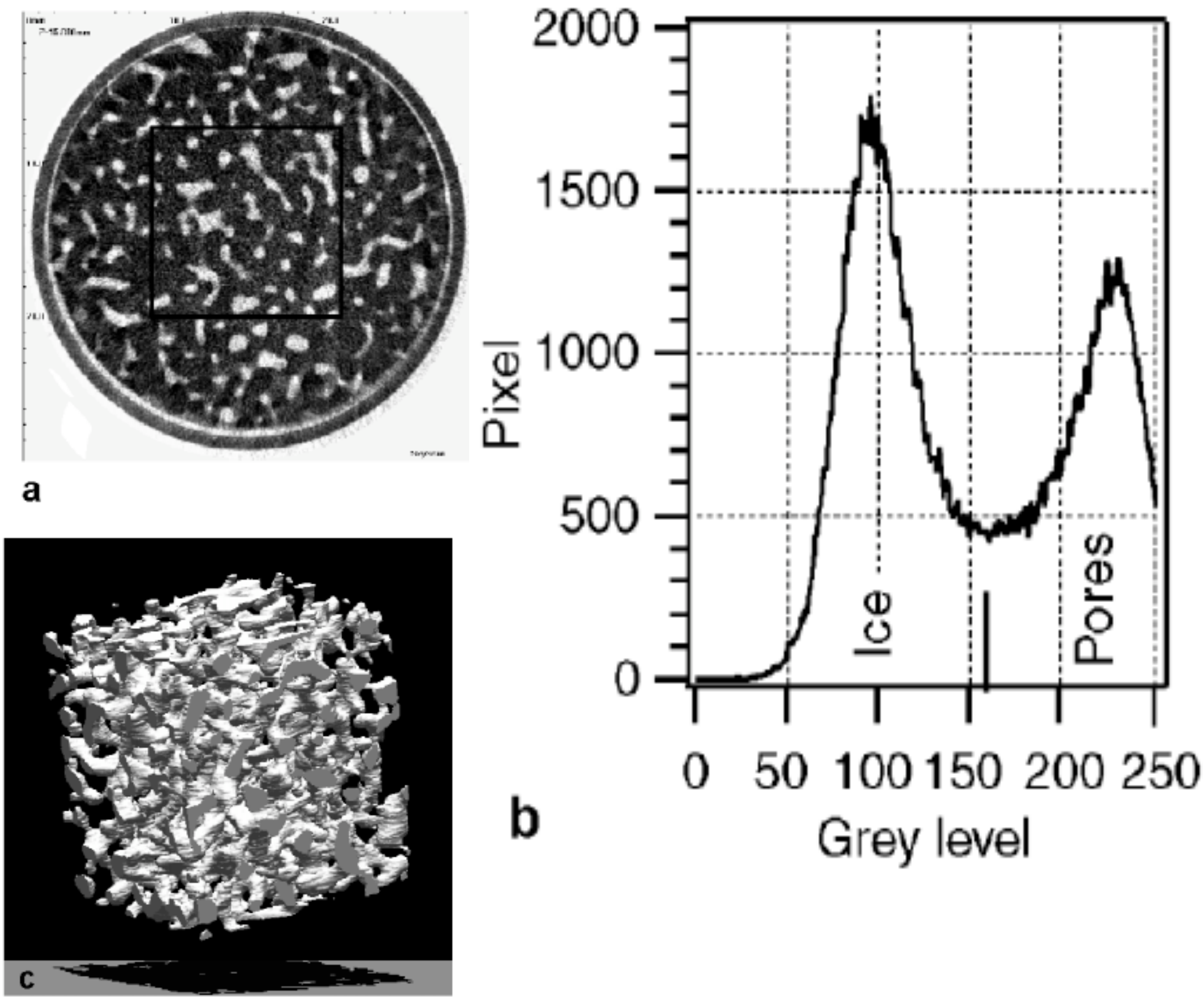
Microstructure-dependent densification via x-ray microtomography

Freitag, Wilhelms, Kipfstuhl 2004

- Coarse-grained firn and fine-grained firn densify at different rates, even after the "crossover point" where they have the same densification rate.
- This explains the minimum in density fluctuations around the depth of the "crossover point" (20-40m).
- A shift of the porosity vs. depth curve can account for the different critical densities of coarse- and fine-grained snow.

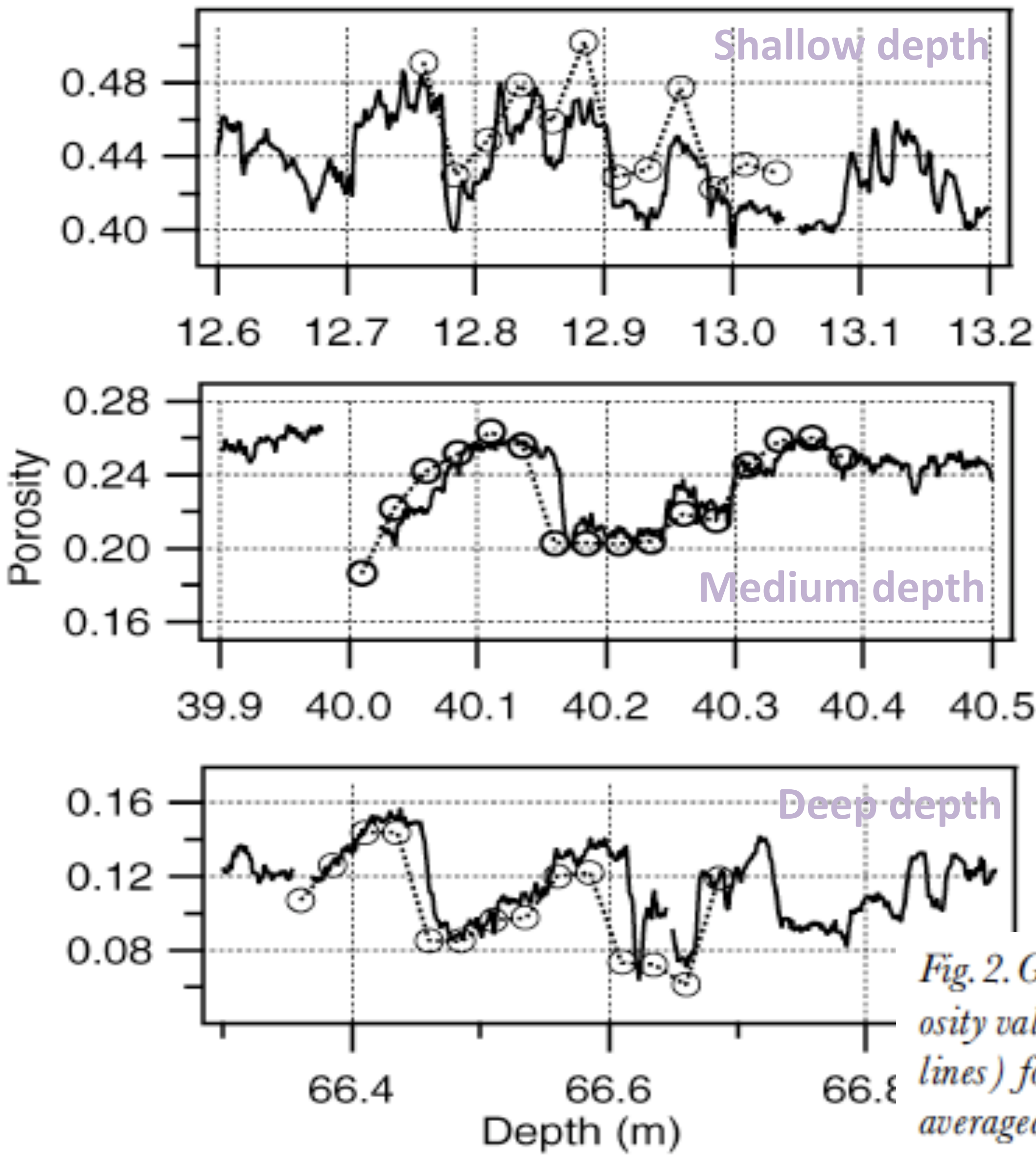


X-ray tomography processing

1. Reduce noise by a 3-voxel averaging filter
2. Set each voxel as pore (gray > 160) or ice (gray < 160)
3. Calculate porosity, density, surface area, pore size, cluster size.

Fig. 1. (a) Reconstructed horizontal cross-section through a cylindrical firn sample B26_51_1 from 51 m depth in raw data format. The pores appear in bright and the ice matrix in dark grey values. The outlined square indicates the 12 mm×12 mm area of interest for analytical processing. Notice the blurred pore areas close to the margin caused by the filling with fine snow after drilling. (b) Typical grey-level histogram of a single cross-section. (c) Binarized firn cube of B26_51_1. It is 12×12×12 mm^3 in size and built from a stack of 300 segmented images. The pore space is coloured in white, whereas the ice matrix is transparent.

Data Quality Control Patrol, part I



Validating the tomography method by density comparison: compare to the gamma radiation method

Circles / dots: XCT
Solid lines: γ radiation

Fig. 2. Gamma porosity (solid lines) in comparison to the porosity values measured by XCT (circles connected with dotted lines) for different depth intervals. The porosities of XCT are averaged over 12 mm depth intervals.

Data Quality Control Patrol, part II

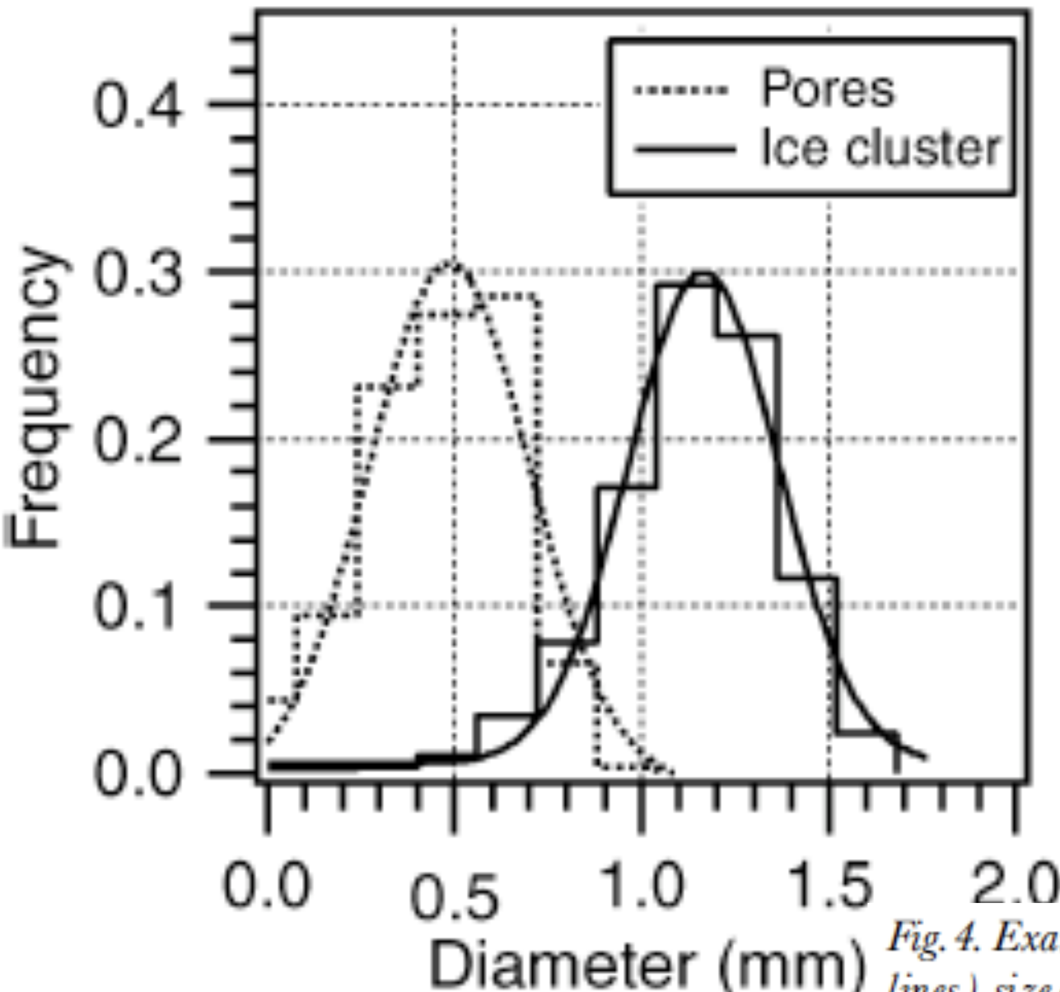
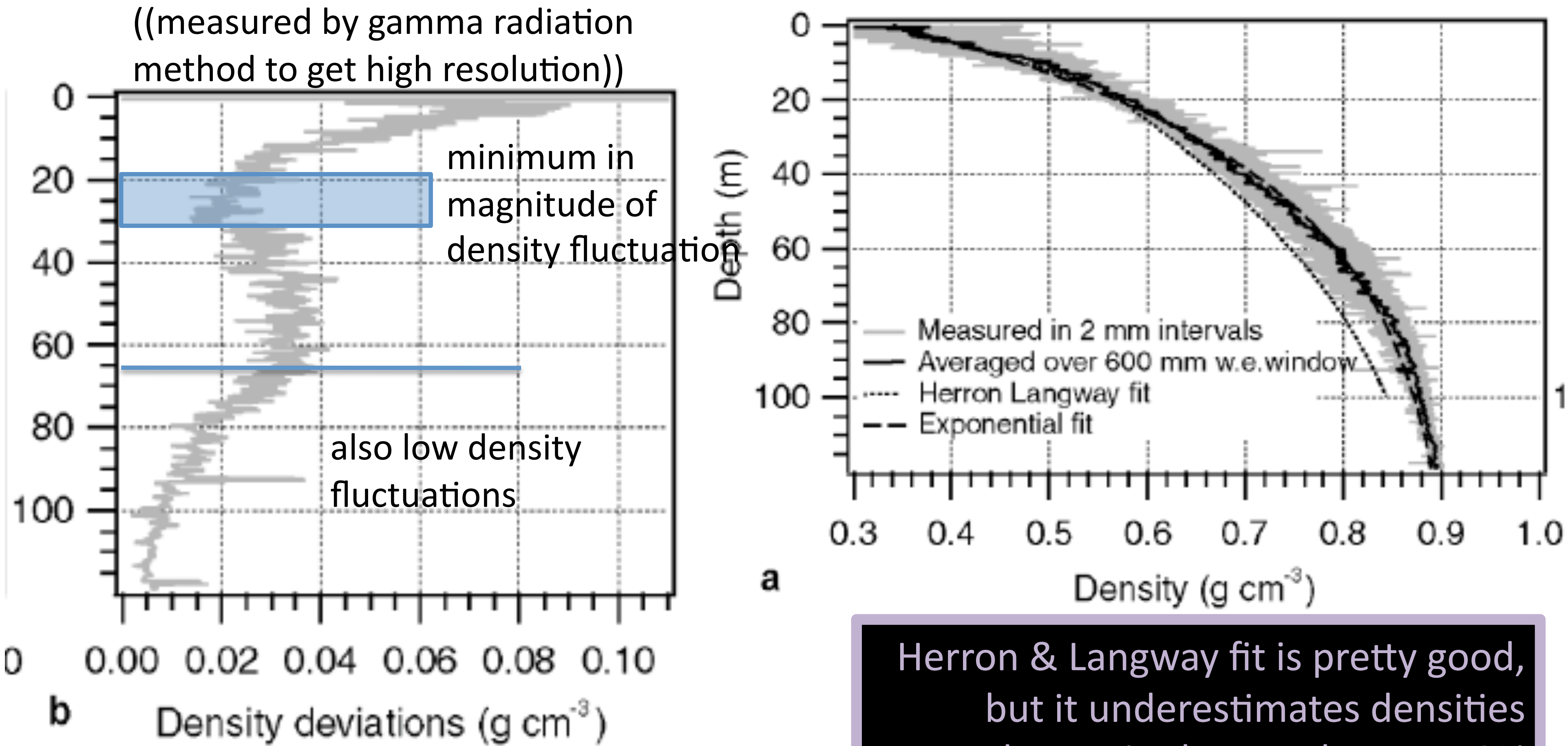


Fig. 4. Example of a pore (dotted lines) and ice-cluster (solid lines) size distribution fitted by Gauss functions. The estimations are performed on a reconstructed firn cube from the depth interval 51.260–51.272 m.

Sizes of air pores and ice clusters are have clear, separate Gaussian distributions

Gaussian width of pore size shrinks continuously with depth ✓

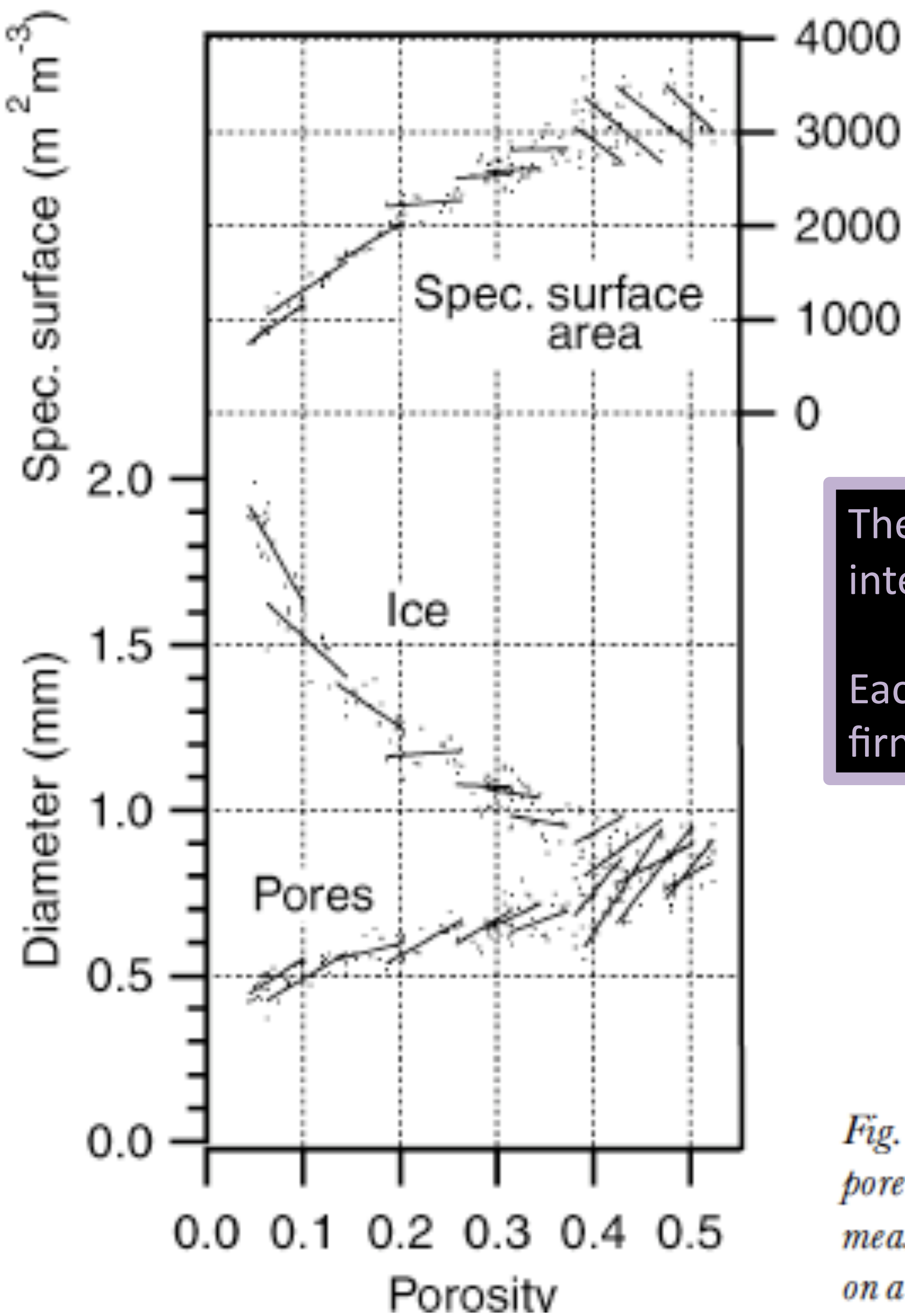
Gaussian width of ice cluster size shrinks only slightly with depth ✓

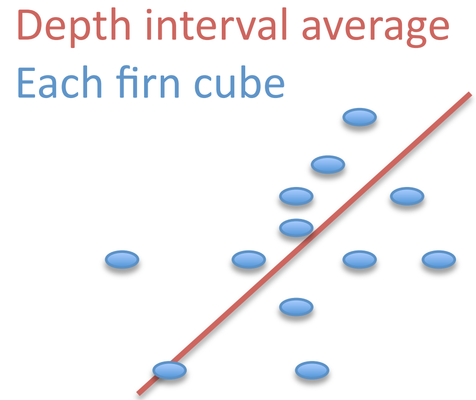


Herron & Langway fit is pretty good, but it underestimates densities deeper in the core by up to 8%

The minimum in density fluctuations at 20-30m is NOT explainable by seasonal variations à la Li and Zwally.

Fig. 3. (a) Highly resolved density profile of firn core B26 measured by gamma absorption. Additionally, the running mean over a 600 mm w.e. window and two model curves are plotted using the Herron and Langway (1980) approximation and an exponential fit. (b) Density fluctuations with depth indicated by the twofold standard deviation of the running mean in a 600 mm w.e. window. Notice the distinct minimum between 20 and 30 m.

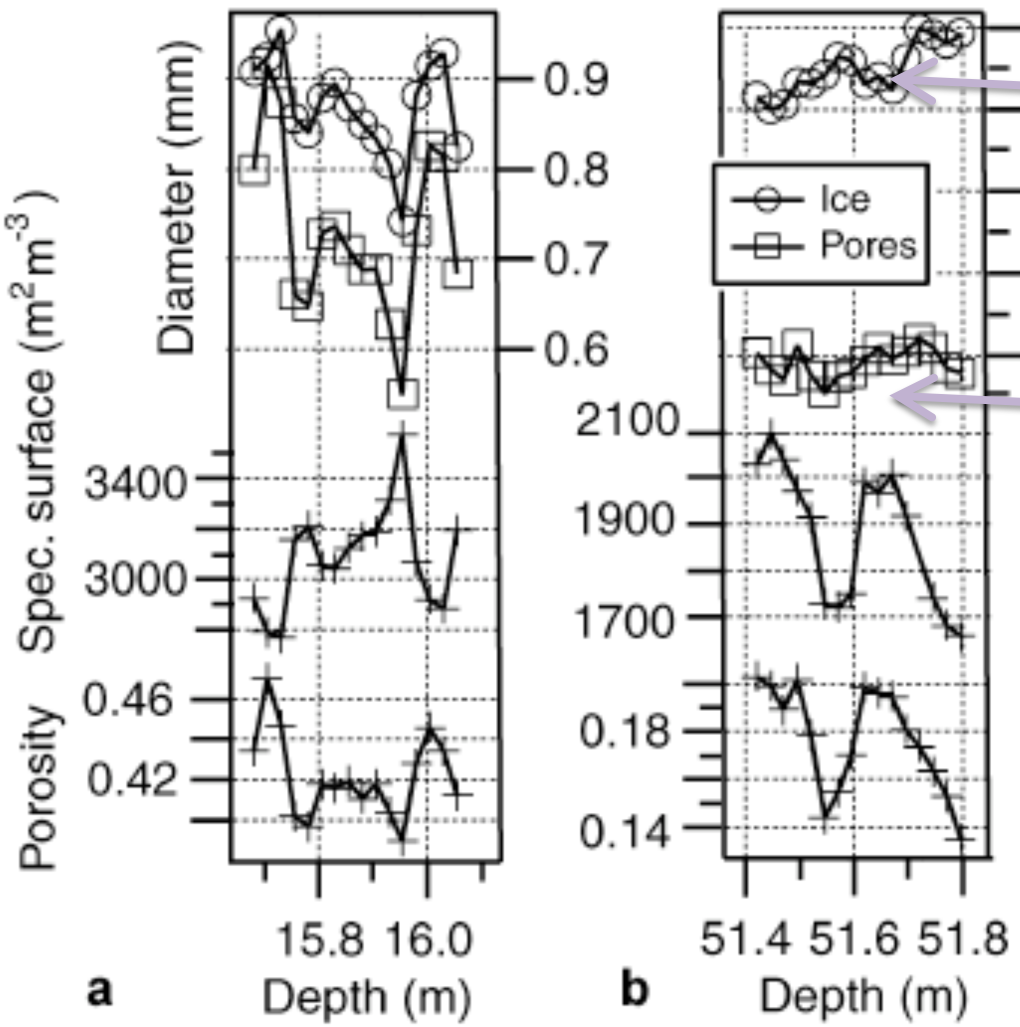




The core is divided into 13 different depth intervals, each 40cm long.

Each depth interval is processed as 16 different firn cubes, with side length 12mm.

Fig. 6. Specific surface area A_{spec}, mean ice cluster d_{ice} and pore diameter d_{pore} vs porosity n for all seasonal segments measured by XCT. Each of the segments is separately fitted on a linear regression curve.



The diameter of ice clusters increases with depth at all depths

The diameter of air pores stays relatively constant at depth

Fig. 5. Profiles of ice-cluster diameter d_{ice} (circles), pore diameter d_{pore} (squares), specific surface area A_{spec} (crosses) and porosity n (crosses, below) over firn intervals of 40 cm length at 15 m (a) and 51 m (b) depth.

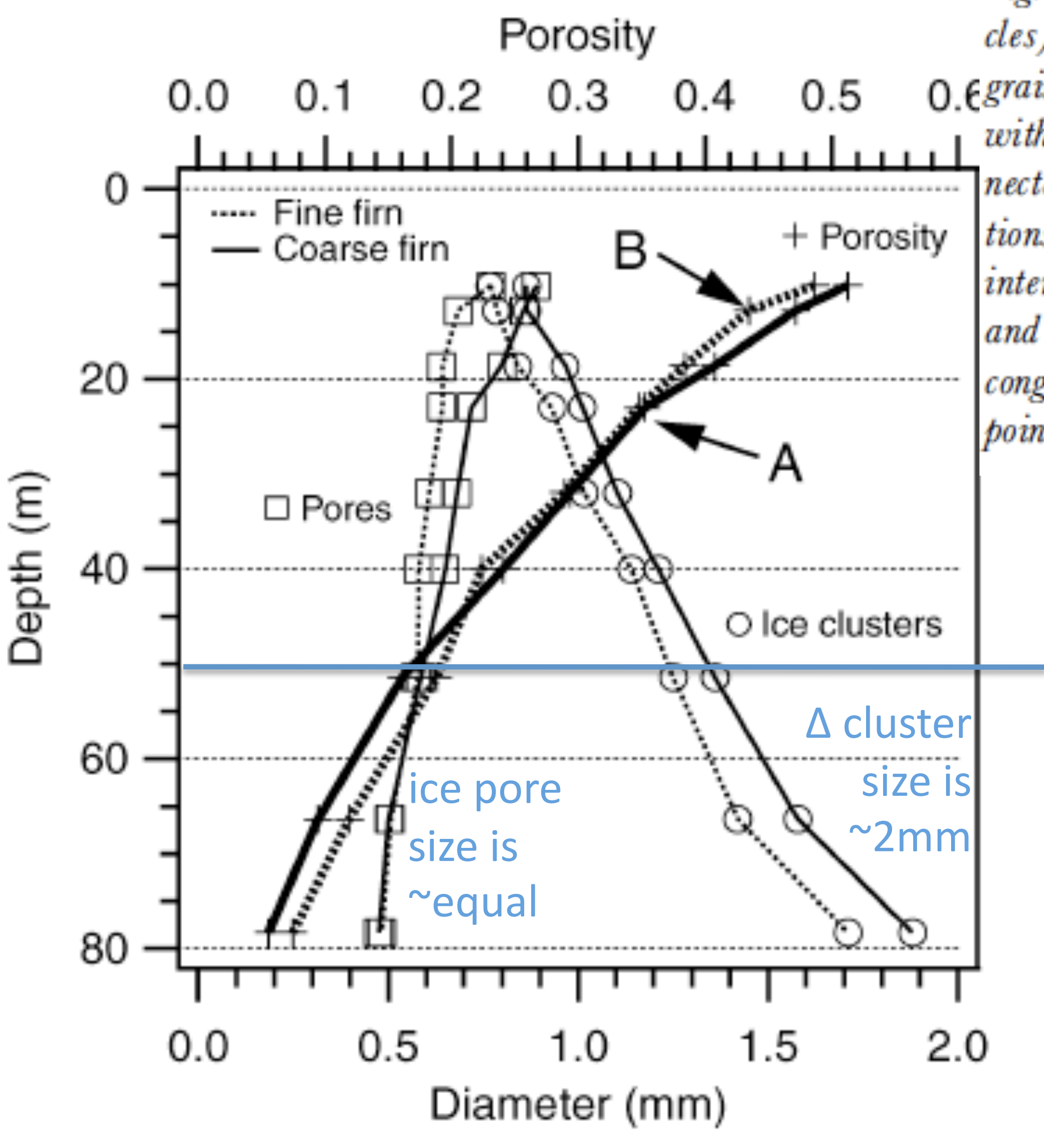


Fig. 7. Depth profiles of porosity (crosses), ice-cluster (circles) and pore (squares) diameter for fine- and coarse-grained firn. The data for fine-grained firn are connected with dotted lines. The data for coarse-grained firn are connected with solid lines. The arrows indicate the assumed positions of the critical porosities separating the initial and intermediate stage of densification for coarse-grained (A) and fine-grained (B) firn. Both porosity profiles become congruent by shifting the curve of fine-grained firn such that point B fits point A.

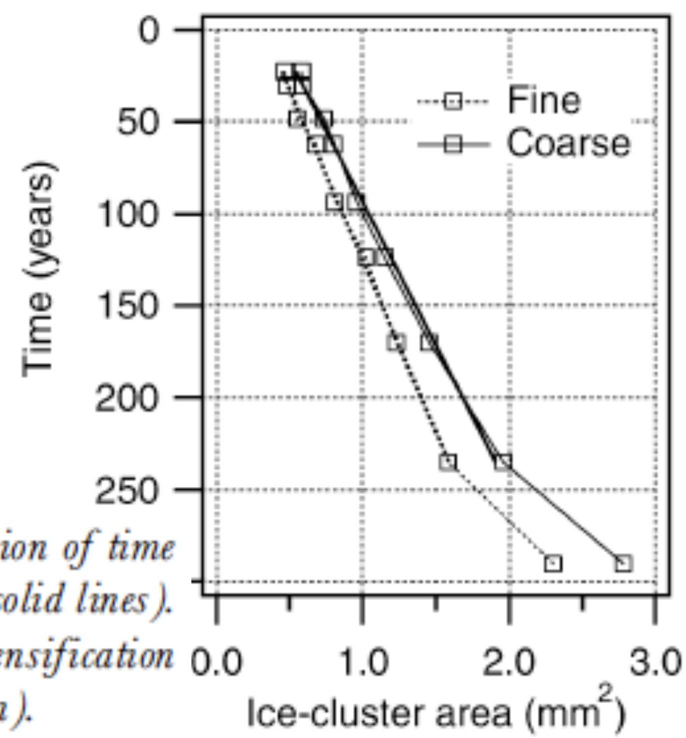
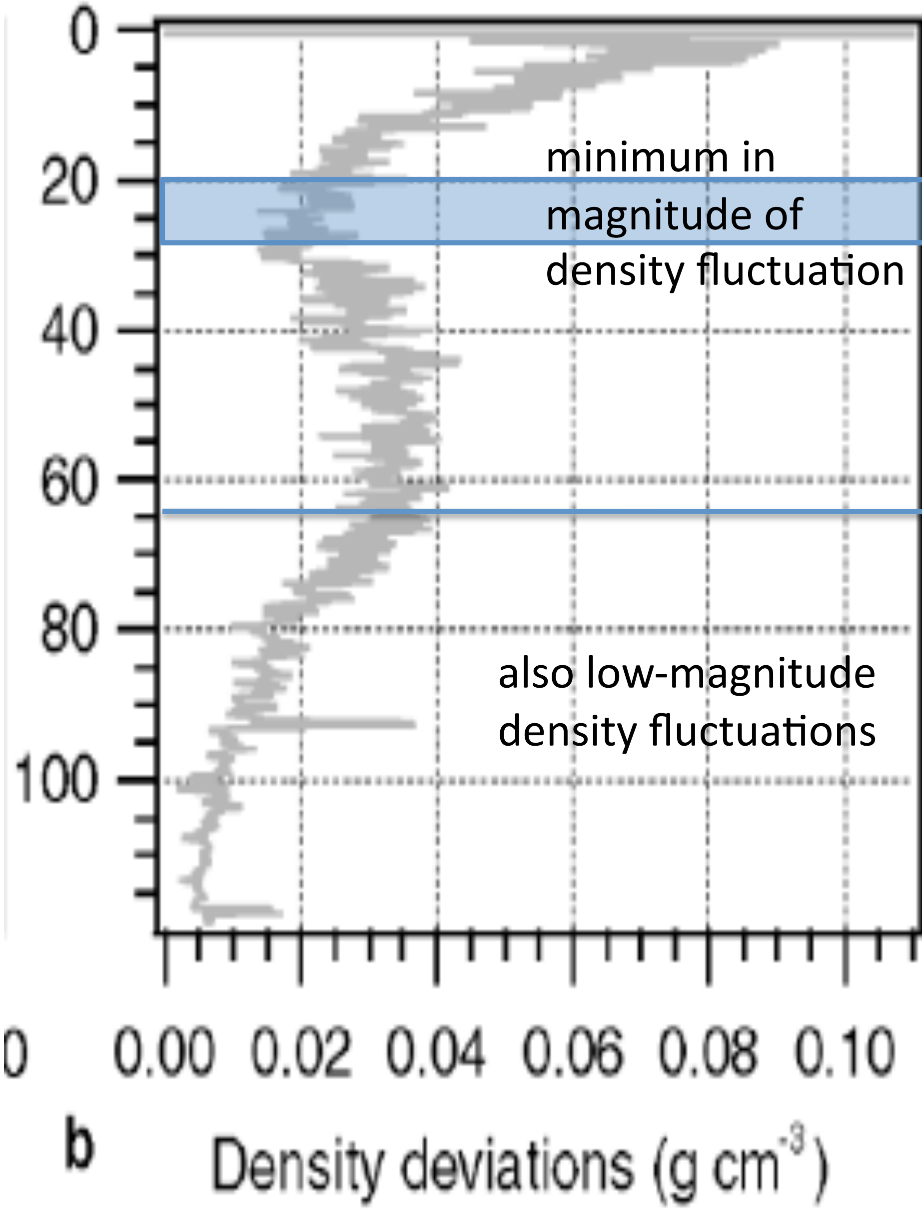
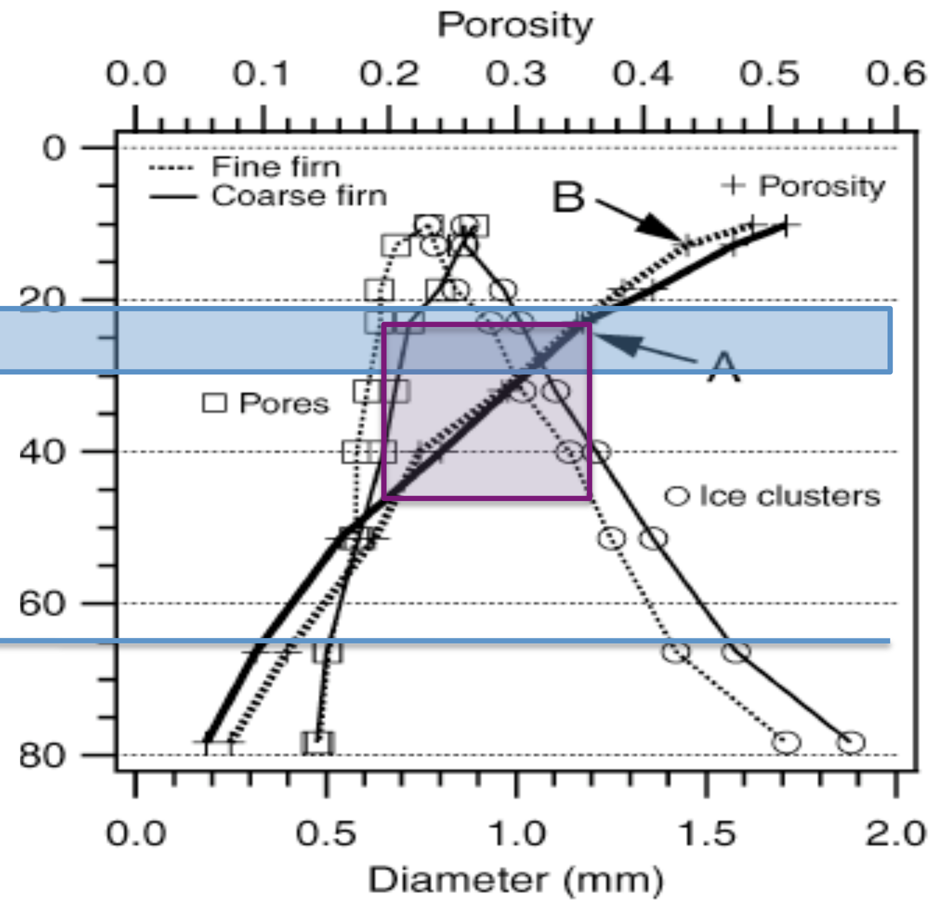


Fig. 8. Ice-cluster cross-sectional area as a function of time plotted for fine (dotted lines) and coarse firn (solid lines). The linear trends occur for the first 240 years of densification (which is equal to the first 66 m of the firn column).





"The porosity-depth profiles of fine- and coarse-grained firn display a crossover point in the range where the seasonal density variations reach their local minimum."

Firn Densification by Grain Boundary Sliding

Richard Alley, 1987

- Grain boundary sliding – not sintering! - explains the higher rate of densification at low densities.
- When enough intergranular bonds exist (N→6), grains cannot slide across each other. This is the critical point, ρ=0.6, where viscous creep becomes efficient / important.
- Activation energy for viscous creep is the SAME as the activation energy for grain diffusion.

N: coordination number
(Number of bonds per grain)

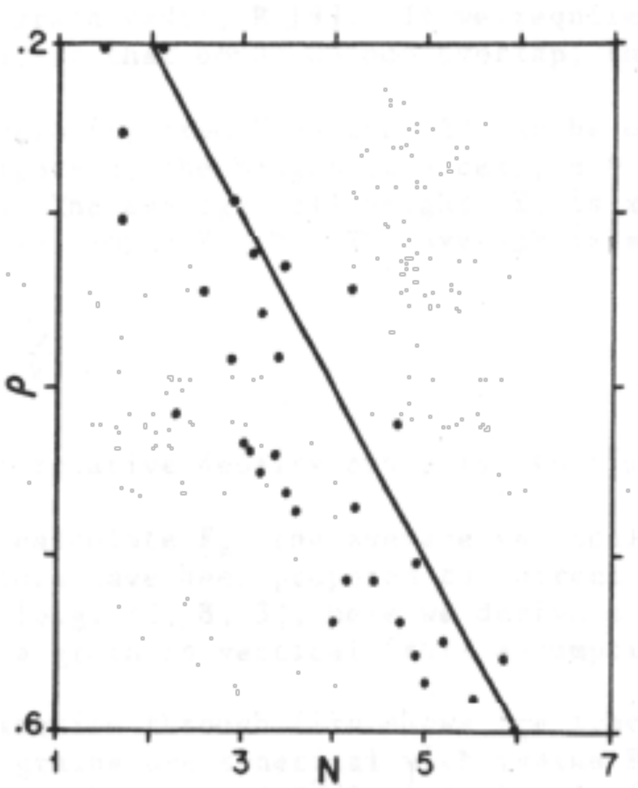
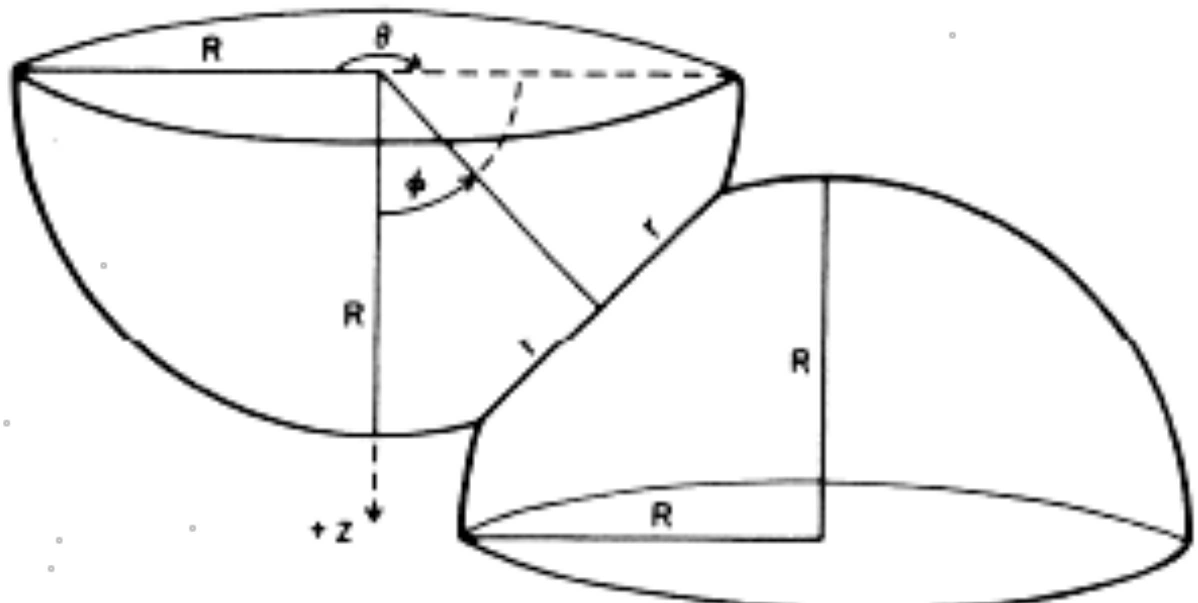


Fig. 1. Relative density (ρ) vs. coordination number (N) for firn from ridge BC and upstream B, West Antarctica, and from site A, Greenland. The approximation N = 10ρ also is shown. Use of an approximation that fits the data better would complicate the rate equations without changing them significantly.

Relative density: **ρ** is the volume fraction of ice

N = 10ρ
N is (?) determined by examining thin sections



α′ for N=2 and N=4

- For N=2, two grains are connected in 1D. Solvable with a single integral:

$$\bar{u}_z = \int_0^{\pi/2} u_z \sin\phi d\phi = \frac{\lambda}{\nu}\frac{F_z}{A}\int_0^{\pi/2} \sin^3\phi d\phi \equiv \frac{\lambda}{\nu}\frac{F_z}{A}\alpha'$$

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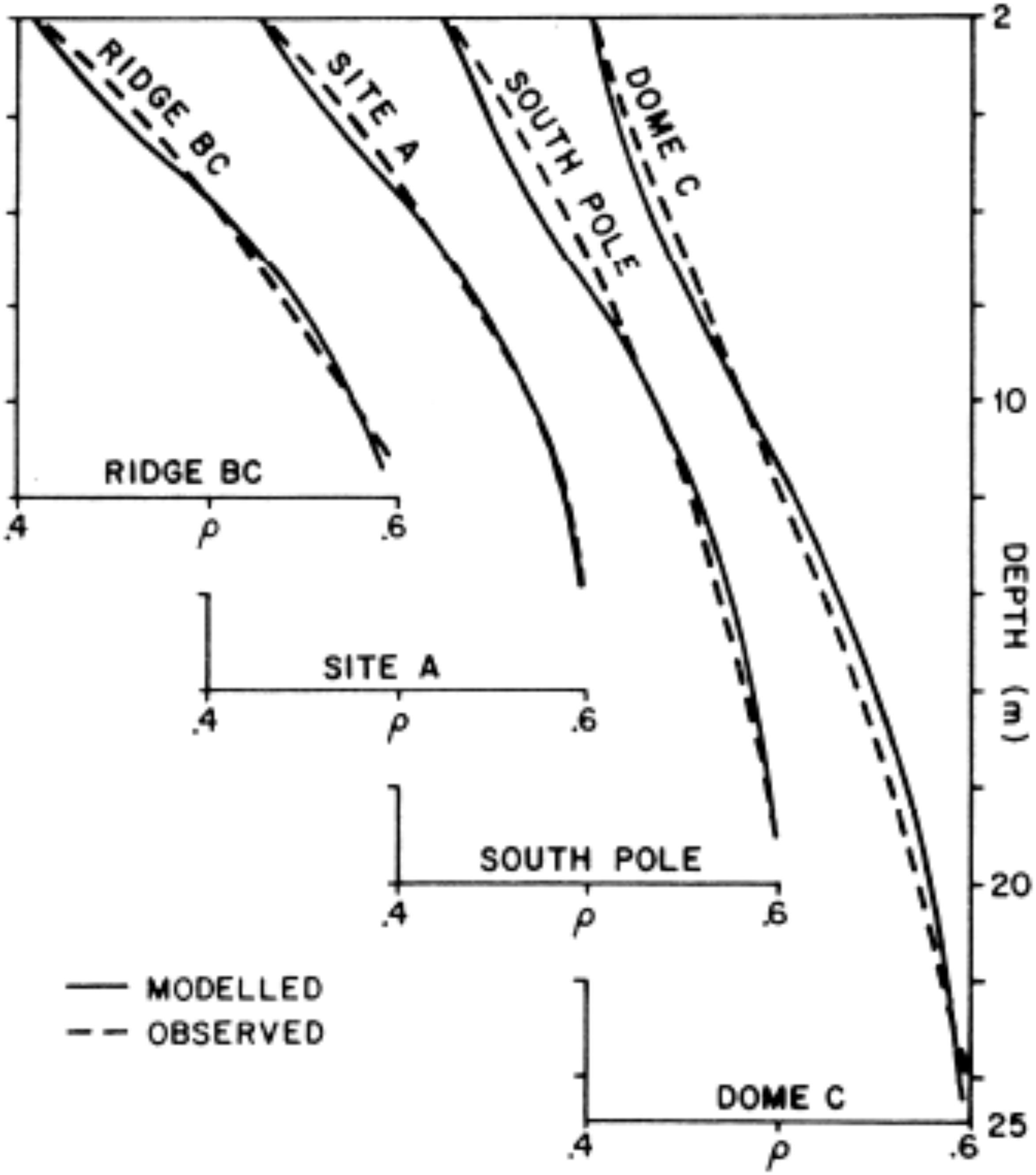
- For N=4, four grains are connected in 2D. This should(?) be solvable with a double integral, but they used Monte Carlo simulations. Why?



Activation energy for viscosity:
41 ± 2 kJ/mol

Compare to activation energy for creep in firn:
~60 kJ/mol

The activation of viscosity ~halfway down the firn column gives the model structure that the data doesn't have.

Can you tune the parameters so this extra structure doesn't appear?
Or is this not a good model?

Viscosity varies per site because of temperature dependence of viscosity

ν ~ 1/T

Activation energy for viscosity: 41 ± 2 kJ/mol

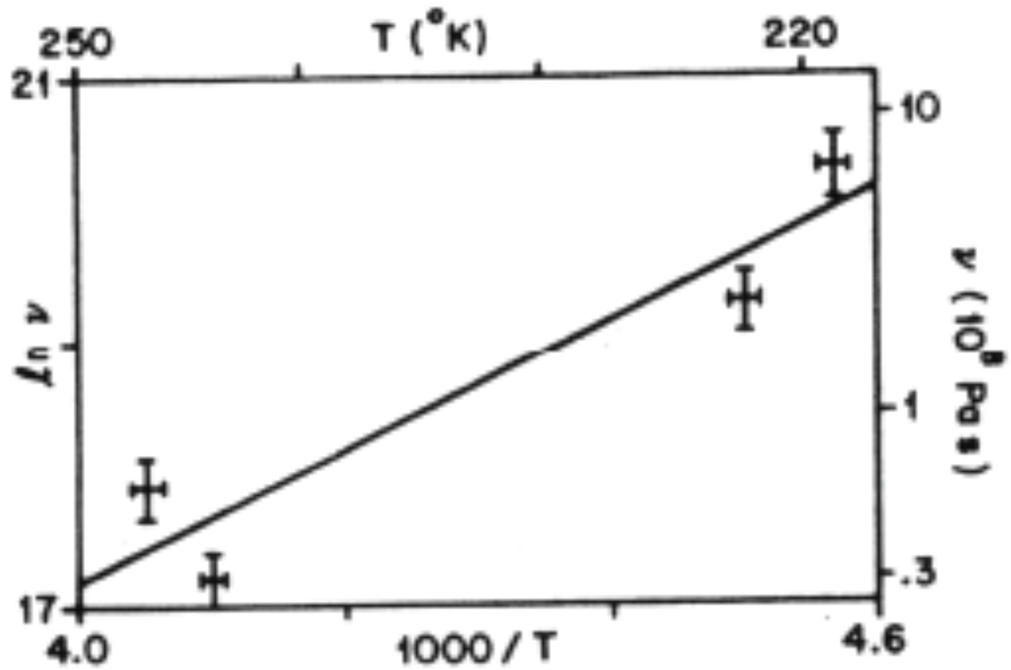


Fig. 4. Viscosity vs. temperature. The slope of the regression line gives the activation energy for viscosity.

Next week?

- More microstructure
  - Alley, Bolzan, and Whillans 1982: *Polar firn densification and grain growth*. (speculation about different mechanisms which control the densification processes in coarse and fine firn)
  - Gerland *et al.* 1999: *Firn density log from Berkner Island, Antarctica.* (switches in electrical conductivity of firn ➔ switches in density of firn)
- No more microstructure
  - I bet Jessica has ideas