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Interactive comment on "Impact of physical properties and accumulation rate on pore close-off in layered firn" *by* S. A. Gregory et al.

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The responses to all comments are directly below the original comment. The start of all author responses are also indicated with an asterisk (*).

Anonymous Referee #2

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Gregory et al. discuss an important topic of firnification, the pore close off at the transition of firn to ice. This is of general interest for glaciology and in particular for ice core scientists who work on gases in ice cores. Our confidence in the gas ages and conclusions drawn about the phasing between temperature and CO2 depends critically on our understanding of the air enclosure process. Gregory et al. present results

obtained by x-ray computed tomography (xCT) from WAIS Divide in West Antarctica and a Megadune site on the East-Antarctic plateau, two polar sites with different temperatures and accumulation rates. Focussing on permeability measurements they examine the nature of pore close off processes. They find that the open pore structure plays a more importantant role than density in predicting gas transport properties. In combination with permeability measurements the results are new and interesting, thus important to better chracterize pore close off and the air enclosure process in polar ice.

The presented study is highly relevant, however, we are concerned in several respects about the interpretation and conclusions drawn from the results:

1. The dimensions of the samples investigated are 8 mm by 8 mm by 15 mm. The authors do not discuss how representative a cube of typically 1 cm3 is to draw firm conclusions about the processes controlling pore close off on a much larger scale. For example, firn gas sampling is collecting air over cross sections of 10 cm at least.

*The small 8 mm by 8 mm by 10 mm samples were taken from larger samples, typically 5-10cm long, that were visually homogenous. In this way, the small sample should be representative of the larger homogenous firn layer that it was taken on which bulk density and permeability measurements were done. By avoiding layered samples, the use of the homogenous layers enables comparison between the microstructure of the sample and gas transport properties such as permeability. While the gas sampled during firn air campaigns involve sampling of air likely on the decimeter scale and larger, and so almost always will involve multiple layers of firn, for understanding what occurs as pores close off in firn, it is important to understand how microstructure (grain size, open porosity, closed porosity, and pore structure) evolve with depth in conjunction with the permeability of the firn. This gives a more detailed picture of the finer-scale processes involved in pore close-off. The aim of this paper is to show that grain size and the subsequent pore structure play an important role in controlling gas transport just above and through the lock-in zone as pore close-off occurs. The second aim of the paper is to show that a firn layer at a given density has a range of possible permeability values dependent upon the accumulation rate of the site and subsequent pore structure. We have added several sentences in the paper to make this point more clear.

2. Gregory et al. discuss pore close off on the micro-scale without taking into consideration its percolation nature.

*Including a discussion of the percolation modeling at pore close-off is beyond the scope of the paper. However, we did added reference to the work done by Freitag et al on percolation. While understanding pore close-off on both the macro and micro-scales is important for determining the LID and delta age, the purpose of this paper is to examine how microstructure impacts gas transport just above and through the lock-in zone. Our compilation of microstructural properties, density, and measured permeability for both WAIS Divide and Megadunes firn below 55m is a new contribution that will enable future additional work on constraining firn densification models and firn air models.

3. Gregory et al. are obviously not aware of the effect impurities have on densification in deep firn, see Hörhold et al., EPSL 2012, 325–326, p93–99.

*While we are well aware of the work done by Hörhold et al., we did not originally discuss it here because there are questions about those conclusions; a recent study by Capron et al., Clim. Past, 9, 983–999, 2013, call into question the effect of impurities on firn densification and LID at multiple Antarctic sites. In response to this comment, we have added reference to both the Horhold paper and the Capron paper, explaining that there is much to be learned and it is still an open question. The work we present in this paper on the propagation of fine grain and coarse grain firn from past accumulation sites and hiatus sites at the Megadunes location, from the surface through the lock-in zone, provides a direct link between accumulation rate and grain size the entire length of the firn column. In this way the physical structure of the firn lends support to an accumulation rate influence on microstructure from the surface through pore close-off

in polar firn.

4. Grain size an important parameter has not been determined quantitatively. It is only described qualitatively.

*This observation is correct. For the present study, determining which layers reach pore close-off first, coarse grain or fine grain, a qualitative analysis of grain sizes is adequate. Grain size is described qualitatively because we are using it as an indicator of layering relative to surrounding firn layers on the meter scale. The most coarse grained layers meter by meter are identified as coarse while the most fine grained layers are identified as fine grain. All other firn grain layers fall between these two identifiers. In this way, the quantitative measurements of a fine grain layer at the surface and a fine grain layer at depth will not be the same. Comparison between the WAIS site and the Megadunes site was also done visually with a back lit light table in which the coarse grain layers at WAIS Divide below 55m were smaller relative to the fine grain layers at Megadunes below 55m. We have added several sentences in the paper to clarify the use of grain size as a qualitative indicator.

5. Both sites are some sort of end member sites because in the Megadunes post depositional processes are important and at WAIS Divide surface density seems to be exceptionally high (above 400 kg/m3).

*This observation is correct and in fact is a motivator for selection of the cores used for the study. We have added a short paragraph to the paper to make this key point more clear. The two sites selected for the study were chosen due to their contrasting local climates. The WAIS Divide site was chosen as an equivalent to Summit, Greenland and has been sited by Battle et al., 2011 as an intermediate site as it is “neither very cold, nor is it warm enough to have melting episodes. The accumulation rate is comparable to Summit Greenland (âĹij 25 cm yr−1), higher than South Pole and Vostok (< 10 cm yr−1), but significantly lower than Law Dome (65 cm yr−1 at DSS and 1.19 myr−1 at DE08) (Etheridge et al., 1996).” In this way the WAIS Divide site was chosen for this study as a typical high accumulation polar firn location. The Megadunes site was chosen as a natural experiment where two different accumulation rates exist under the same temperature and other climatic conditions. The windward faces of the dunes experience accumulation while the leeward faces undergo zero accumulation or ablation. As the dunes migrate upwind, past dunes are slowly buried and the alternation between accumulation and hiatus firn layers persists down the firn column. While the post depositional processes may create the unique firn conditions at Megadunes, the presence of antidunes enables us to observe the influence of a small change in accumulation rate on the microstructure and gas transport properties of the firn.

All these aspects are not addressed adequately in the present manuscript. For example, Gregory et al. do not show a figure comparing the bulk densities of their large samples the cubes for xCT are taken from and the densities derived later from these little cubes. The scale problem becomes obvious in Figures 5 and Figure 9. See page 2545 lines 6 ff: ... "To understand the increase in closed porosity with no change seen in total porosity" applies only for Figure 5a and the small xCT samples while bulk density presented in Fugure 9a clearly shows that density and thus total porosity increase below the LID (lock in depth).

*We have revised the wording to address this point. The description in this portion of the paper should have referred to the rate of increase in closed porosity with no change seen in the rate of decrease in total porosity. This part of the paper has been re-written to clarify that there is no discrepancy between the bulk density increasing and bulk porosity decreasing below the LID and the xCT sample porosity decreasing while the rate in which closed porosity increases dramatically below the LID.

The scale problem is a fundamental problem, the percolation problem as well but which parameter control the percolation threshold? This does not become clearer from the paper in its present version. There is much work to be done on firn microstructure and it obviously cannot all be done in a single paper; these aspects will be topics of future work. It is important to investigate which processes control pore close off: density

and/or microstructure in the widest sense. The results as presented are important, however, as important is a critical discussion of the results and in particular because the xCT samples are so small. This part is missing in the present version of the paper.

*It is a good idea to make this distinction more clear. A short section has been added in the introduction to talk about this point so that readers do not get distracted from the main point of the paper.

Specific comments:

Important aspects have not been discussed. Therefore I do not make many specific comments.

Abstract

Line 14/15: Pore close off can not be defined by open porosity because such a definition is contradicting itself. How about "critical porosity of pore close off"?

*Using an open porosity related to the accumulation rate and subsequent firn grain size to define the point at which polar firn is no longer permeable may seem counter intuitive but the open porosity/grain size relationship takes into account the pore structure in a way that total porosity does not. The LID occurs in the first firn layer that is no longer permeable and the permeability of the sample relies on the open pore space not the total amount of pore space present. Defining the start of pore close-off as an open porosity threshold indicates the open porosity below which, firn will be impermeable despite having small amounts of interconnected pore space. Using just a simple total critical porosity does not have any information about the amount of open pore space versus closed pore space available for gas transport. We have added a sentence to clarify this.

Do we understand correctly that you conclude that pore close off depends on grain size in such way that fine grained firn closes off at a higher critical porosity (i.e. lower critical density) than coarse grains firn. Do you imply that fine-grained firn contains more air than coarse-grained firn under the same climatic conditions? Does this conclusion not contradict the "orange model" that the critical close off density/porosity is independent on the "orange/sphere" radius?

*Through this study we show that regardless of which layer is denser at depth (fine grain or coarse grain) the fine grain layers will undergo pore close-off shallower than the coarse grain layers. If a density inversion has occurred in which the fine grain layers are less dense at depth as is seen in many Antarctic cores they will contain more air than coarse grained firn at that site. If the inversion has not occurred such as at the Megadunes location, then the coarse grain layers will contain greater amounts of air. We are suggesting that the smaller the grains, the smaller the pore necks between the grains will be causing the layers to become impermeable before the coarse grain firn layers. This point has been made more clear in the conclusions of the paper.

Figures:

- Dealing with the low permeabilities at pore close off some results would better be presented on a logarithmic scale, e.g. Fig. 1f, 9b or 10a.

*The decision to not use a logarithmic scale was made based on the relatively small range of permeability values observed below 55m (0 to 1*10-3 m2) versus the range of permeability values seen over an entire firn core from the surface through the lock-in zone (0-500*10-3 m2). We plotted it on a logarithmic scale but that does not improve understanding, so we kept the original plot.

- The results are generally shown versus depth. Are not some results better plotted against density as the more "natural" parameter?

*In Fig. 1c,and Fig. 1f, permeability is plotted versus density. In Fig. 4d, surface to volume ratio is plotted versus density. The majority of the results are plotted with depth to see how they evolve down the firn column, since that is what is of interest to the firn air modeling community.

- It would be helpful to see how bulk density and xCT densities of the same sample compare. - some figures units are missing ËŸ

*We have clarified in the paper which density was used. For all figures the bulk density of the sample was plotted, since the xCT samples were only taken from homogenous larger samples. Other papers on firn microstructure in the literature do not plot both the bulk and micro-computed density and it does not add anything here either since there is a strong correlation between them.

Fig. 5: A graph showing open versus closed porosity is missing - to compare with the Schwander et al. closed porosity.

*A graph of open versus closed porosity was not included because the porosities covered in the paper, both open and closed, do not encompass the entire range of porosities in the Schwander et al. study. The utility of such a graph is unclear.

Fig. 6 Is this ïňĄgure needed in particular as the conclusion of Fig. 5 is valid only for the xCT samples but nut the bulk density/porosity?

*This has become clarified through revisions in the wording that we made in response to some of the comments above. The conclusion drawn from Fig. 5 should refer to the rate of increase in closed porosity with no change in the rate of decrease in total porosity (the total porosity continues to decrease below the LIZ but the percentage of closed pores dramatically increases). This is also addressed in the response to the general comments above. Fig. 6 is included to highlight the total number of pores increasing below the LID, while the size of the pores is decreasing to support the conclusions made from Fig. 5.

Fig. 7 "Closed pore fraction" is misleading. It is more interesting to see this parameter versus density or total porosity.

*The terminology of “closed pore fraction” was used to keep the same terminology of the study done by Lomanaco et al., 2011. We chose to be consistent in terminology.

Fig. 9 Where do we see the density cross-over? The three red dots at higher density abetween 50 and 60 m depth?

*Although the cross over is not extremely clear at the resolution of the bulk density measurements done on a 5-10cm scale on the WDC05C scale, we have included a reference to the work of Dan Breton in this section, since his high resolution measurements do show the crossover on the WDC06A firn core show the cross-over more clearly than our measurements show. Those measurements were done as part of Dan Breton's PhD thesis, Photonic non-destructive measurement methods for investigating the evolution of polar firn and ice, University of Maine, 2011.

Fig. 10 Probably better shown on a log-scale. Not clear, how the error is defined. What is it's meaning?

*The purpose of Fig. 10 is to illustrate the impact of pore structure on permeability. By confining the relationship to a simple metric of open porosity but not taking into account the pore structure the relationship by Freitag et al. does not describe the variability in permeability at a given open porosity of the firn due to layering. This difference is seen the most at low open porosities at the Megadunes location.

page 2541 l13,14 sentence seems not complete: Where the degree ...

*Good point. We changed the wording to "Using this definition, the degree of. . ."

Megadune firn Site conditions and postdepositional processes make the MD firn so special, no so much the climatic conditions in general.

*The purpose of using the Megadunes site in this study is to isolate the effects of accumulation rate when all other climatic conditions are the same and then compare the very low accumulation rate at Megadunes to the higher accumulation rate at WAIS Divide. The Megadunes is a natural laboratory for investigation accumulation rate effects, as described in Courville et al (2007). We have added this reference and made this critical point more clear in the revised language.

p2547/8 The cross-over in density is not clearly seen in the presented data (Fig. 9a). The WDC06A data were not accessible.

*See Daniel Breton's PhD Thesis, Photonic non-destructive measurement methods for investigating the evolution of polar firn and ice, University of Maine, 2011. We have added this to the paper, as described above.

For the discussion which layers first reach pore close off density see Hörhold et al.,2012. Hörhold et al.,2012 state that the layers with the largest amount of impurities will reach the critical close-off density first.

*As described above, this remains an open question and this study, along with the study of Capron et al., Clim. Past, 9, 983–999, 2013, which calls into question the effect of impurities on firn densification and LID. The present study makes the case for two critical close-off densities at a given site, one for the coarse grain firn and one for the fine grain firn. At WAIS Divide a density inversion occurs causing fine grain firn to reach pore close-off first at a lower density than coarse grain firn. At Megadunes the density inversion does not occur yet the fine grain firn reaches pore close-off shallower at a higher density than the coarse grain firn which closes off deeper. Essentially, fine grain firn appears to reach pore close-off at shallower depths than coarse grain firn regardless of which layer is more dense at the bottom of the firn column. Our revised language makes this point more clear.

Microstructure is often used synonymously for grain size but often also in a much wider context. This is confusing.

*We have clarified the language to be more specific in the places where grain size is being referred to versus microstructure in a wider sense.

Interactive comment on The Cryosphere Discuss., 7, 2533, 2013.