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Interactive comment on "Surface formation, preservation, and history of low-porosity crusts at the WAIS Divide site, West Antarctica" *by* John M. Fegyveresi et al.

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Interactive comment on "Surface formation, preservation, and history of low-porosity crusts at the WAIS Divide site, West Antarctica" by John M. Fegyveresi et al. M. Schneebeli (Referee) schneebeli@slf.ch Received and published: 29 July 2016

The paper by Fegyveresi et al presents glaciological and meteorological observations concerning the formation of a thin crust at the snow surface around the WAIS drill site. The existence of this glazed crust has been described for several decades, but detailed information about the formation is lacking. This paper contributes to the understanding of the formation of these specific layers.

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Discussion paper

The methodology to investigate the formation of these layers is rather old-fashioned, and is not taking into account developments in snow characterization. The paper is in most aspects descriptive, with little quantitative information especially about the microstructure of the snow.

The paper describes in much detail the observations, but little quantitative data analysis and no modelling at all. The authors formulate extensively a general hypothesis on the formation of these layers, but do not substantiate their claims. The recent developments in snow metamorphism are not considered, and essential aspects in the interpretation are missing, especially concerning the radiation balance and the thermal conditions of the snowpack in the topmost layers of the snowpack.

I suggest the following revisions: - The short and longwave radiation balance should be calculated and used in the interpretation of the formation of the crusts. - Ideally, the weather data should to model the thermal conditions of the snowpack in the top 30 cm, this should not be a major difficulty (there are several snowpack models easily available, as Crocus and SNOWPACK). - A statistical analysis of the processes is needed, it does not become clear in the paper if the same weather conditions occur without formation of a glazed surface. - The hypotheses concerning the formation should be reformulated and quantified based on the results above

Based on the old-fashioned methods, several questions will probable remain open concerning the microstructural properties of the snow. It is a pity that now snow samples were cast using Diethyl-phthalte, this technique was already used in 1957 in Antarctica. A general comment is also that the authors seem not to be aware of the difference between the terms "diagenesis" and "metamorphism". Diagenesis describes the densification by internal compaction or by a foreign sintering material. Metamorphism describes the recrystallization of minerals. Diagenetic processes in snow and firn occur in Antarctica below the isothermal zone (i.e. a few meters depth). Above, the dominant process is metamorphism. –

“Replaced terms to reflect metamorphism rather than diagenesis.”

“We did correct all noted issues and responded to reviewer comments, specifically with the inclusion of more on the crust extent and on related snow pit studies (that were previously left out), although we did not add either additional modeling or a full energy balance study. The paper is already quite long, and we have specific challenges with attempting to incorporate either of these additional and lengthy studies. We are aware of the additional papers cited by the referees, and note the large amount of careful work involved. We do also hope to be able investigate further the possible effects of solar heating on the specific type of PRT sensors. We have added relevant citations to our paper. With our manuscript being this long and the difficulties with adding such large/expansive analyses, we believe it is better to write a phenomenological paper first and then address modeling and a full energy balance in a separate/future study.”

Specific remarks: l 38 According to instruments, these are radiation sensors, not insulation sensors

“Reworded to "short and longwave radiation sensors"”

l 40 There is no detailed data later in the manuscript about the crack spacing, so delete in abstract

Deleted

l 42 If this theory is correct, then a very strong convective vapor transport would be necessary, and calculations (see e.g. Ebner et al, Calonne et al.)

“Don’t have a sufficient calculation here. We cannot partition accurately the relative contributions of vapor transport from below versus condensation of vapor in the atmosphere from other sources, but the wording ‘may have contributed’ should make this clear.”

l 48 Was this layering also found in the snowpit?

“It was and the detailed snow-pit investigation was added back to manuscript including text and 3 additional figures.”

l 54 Are there any measurements done on the spatial extent of these layers (e.g. in the snowpit)?

“We have semi-quantitative measures, but not accurate maps, and we have additional calculations from occurrence of partial crusts in the core, which are well-quantified; a reference to that latter calculation can be found in the later-referenced PhD (Fegyveresi, 2015).”

l 110 The radiation instruments are described here in detail, but the data not used, why? These data are essential for the interpretation of crust formation. Especially snow surface temperature can determined precisely from the pyrgeometers.

“They are used in the figures to show trends, but not used in more-detailed calculations. The final instrumentation was not the same from year-to-year; only in the final year was the full net radiometer installed. . .thus so a multi-year comparison of identical radiation data could not be performed.”

l 165 I miss in this description the following information, resolved with mm-vertical resolution: density and specific surface area, ideally also coordination number. This information is available by a number of techniques, even with simple thick-sectioning of cast samples.

“Edited for clarity using snowpit data (See other new figures).”

l 170 Is there any statistics on size? This is very descriptive.

“No additional measured field statistics exist, however we added more detail for clarity. Also, related thesis chapter does include field observation data table with some additional observation notes on surface glazes (See Fegyveresi, 2015)”

l 201 How are the PRD-strings influenced by solar heating? The 10 cm depths is clearly not sufficient to prevent solar heating.

"As originally designed (see Muto et al., 2011), the sensor itself is housed inside a small aluminum tube, encased in glue. . .which minimizes direct solar heating. Still, we recognize that the very top surface sensors in this study (S0) that's placed under just a very small layer of snow is likely to be influenced slightly by some fraction of solar heating. Specific calibrations for this effect were not carried out in the field, but we felt the influence was likely minimal due to the nature of the sensor design and the "surface sensors" not being directly exposed to solar radiation."

l 204 A 3 K over 40 cm results only in a temperature gradient of 7.5 K m-1, far too small to create a relevant mass flux (see e.g. Pinzer et al, 2012).

Gradients steepen towards surface (See Alley et al., 1990 ; eg. Their figure 2). A 3k over 40 cm gradient likely has much steeper gradient near the surface. . .sufficient to drive the relevant mass flux.

l 211 I would expect detailed drawings of the layer, how many snowpits measured, detailed statistics (spacing, size, ...) Added back in the detailed pit maps and associated figures.

l 217 How should I interpret "most commonly"? Any statistics here?

"As stated previously, 45% greater occurrence in Summers. Edited for clarity"

l 221 I think you have either to reduce the approximate sign (and the about 2 m snow pit, or with the over a depth of 2.000 m?). What was the number of pits?

Stated previously – one snowpit per year for a 5 year period (so 5 pits). . .but text has been added back in to clarify. Also, to clarify, all pits were measured to 2 meters, but due to sampling spacing and 5 cm thickness, the bottom sample was centered on 197.5 cm total depth (covering 195-200 cm).

l 240 "should be quite accurate", what do mean in numbers by this?

Reworded for clarity…“are well-constrained”

l 249 The upper 30 cm are definitively not firn but snow, see the great discussion in Anderson, D. L., and C. S. Benson (1963), The densification and diagenesis of snow, in Ice and Snow: Properties, Processes and Applications, edited by W. D. Kingery, pp. 391–411, MIT Press.

Reworded to indicate that the upper portion of firn is generally considered snow.

l 257 -274 The following descriptions are not a discussion, but a narrative of the observations

Relabled the section “Synopsis and Discussion”

l 275-282 I agree that surface hoar is an atmospheric deposition on the ground, but this paragraph disagrees with your hypothesis of vapor creeping out of cracks.

The paragraph states that there are two sources of hoar growth…from above and below. While some hoar growth was clearly related to high humidity fog episodes, the most dominant process related to hoar growth was sublimation related due to vapor transport.

l 283 Measured density data for crusts (for any snow layers) is not presented in this manuscript

Added in all snowpit density data and related figures. Also added text indicating all crusts densities measured and/or estimated over 400 kg m-3 .

l 301 I could not find any calculated temperature gradients in the result section Would have to be related to modeleling…need to calculate.

Referenced back to appropriate figures/data

Suggestions on recent papers on snow metamorphism Calonne, N., F. Flin, C. Geindreau, B. Lesaffre, and S. Rolland du Roscoat (2014), Study of a temperature gra-

dient metamorphism of snow from 3-D images: time evo- lution of microstructures, physical properties and their associated anisotropy, The Cryosphere, 8, 2255–2274, doi:10.5194/tc-8-2255-2014. Ebner, P. P., C. Andreoli, M. Schneebeli, and A. Steinfeld (2015), Tomography-based characterization of ice-air interface dynamics of temperature gradient snow metamor- phism under advective conditions, Journal of Geophysical Research: Earth Surface, 120(12), 2437–2451, doi:10.1002/2015JF003648. Pinzer, B. R., M. Schneebeli, and T. U. Kaempfer (2012), Vapor flux and recrystallization during dry snow metamorphism under a steady temperature gradient as observed by time-lapse micro-tomography, The Cryosphere, 6(5), 1141–1155, doi:10.5194/tc-6-1141-2012.

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