

point-by-point response

Please find the reviewers' comments below in blue font and our responses in black font.

The manuscript contains relevant revisions that have been marked in red.

The authors introduce a method to quantify the influence of temperature on firn creep. Through laboratory creep tests conducted at various temperatures and with different initial microstructures, they investigate how firn responds under these conditions. The microstructure of the samples is assessed before and after the tests using microtomography and thin-section analysis. Subsequently, the activation energy is determined and compared with the activation energy for grain-boundary sliding, which is estimated based on the observed grain growth rates.

This study represents a notable advancement in modelling the mechanical behaviour of firn, enhancing our understanding of ice material properties and informing the interpretation of ice-core data relevant to paleoclimatology.

However, the methodology used to determine the activation energies is not sufficiently detailed (lines 385–390). Specifically, the authors assume a fixed value for the stress exponent (without providing the actual value) and neglect to mention that the pre-factor A is considered constant across different microstructures and test temperatures. These omissions represent significant methodological shortcomings. I have serious concerns about the validity and applicability of the methodology, raising doubts about the reliability of the results. Therefore, I recommend major revisions.

Thank you for these comments, which we've used to improve the clarity of our manuscript. Please find our detailed explanations after each of your comments below.

General comments:

To determine the activation energy, the authors use the Glen-type power law (line 386). This equation introduces the activation energy (Q_c), the stress exponent (n), and the pre-factor (A). Thus, to identify the value of Q_c , assumptions about A and n must be made

Prefactor: The authors assume that the pre-factor in the power law remains constant across the different temperatures tested. However, the sample densities vary from 589 kg/m³ to 615 kg/m³ at 20 m depth. This approximation is not mentioned by the authors and must be acknowledged as a limitation of the method.

The pre-factor (A) in the Glen's flow law is typically regarded as a constant in studies of firn and ice mechanics to derive stress exponents and activation energy. Notably,

this assumption has often been omitted in the literature, e.g. Goldsby & Kohlstedt (1997; 2001). For completeness, we've included the following sentence in Section 3.5 to describe the role of A used in our calculations:

“From Glen-King’s results deriving the activation energy (Glen, 1955) $\dot{\epsilon}=A\exp(-Q_c/RT) = B\sigma^n \exp(-Q_c/RT)$, the pre-factor A , the material parameter B (Glen, 1955; Goldsby and Kohlstedt, 2001), and the stress exponent n (Li and Baker, 2022a) are assumed to be constant, as reported in the literature.”

Please see Lines 424-427.

In this research, samples with densities ranging from approximately 550 to 830 kg/m³ are utilized to investigate the deformation of firn plasticity, aligning with a widely accepted power law deformation mechanism (Li & Baker, 2022a). A significant challenge in experimental science arises from discrepancies between theoretical predictions and laboratory results, particularly when using natural samples from Greenland and Antarctica. However, the observed density variation between 589 and 615 kg/m³ at a depth of 20 m is deemed acceptable for mechanical experiments involving natural porous samples. These variations stem from multiple factors, including the intrinsic properties of the samples, e.g. inclusions (impurities, dust, bubbles, clathrate hydrates), the effects of deformation and partial annealing of firn due to stress distribution and temperature changes during drilling, extraction, transportation, or storage, and also the fact that the samples are taken from adjacent parts of the core, and might sample heterogeneous density layers, as well as potential measurement errors associated with the equipment used. To clarify this point, we've add the following sentence to Section 3.5:

“The variability in density for the samples from 20-m depth on the mechanical behavior are negligible due to a small difference (up to ~4%), between samples, which falls within an acceptable error range in previous studies. This is likely related to multiple factors, including the intrinsic properties of the samples, e.g. inclusions (impurities, dust, bubbles, clathrate hydrates), the effects of deformation and partial annealing of firn due to stress distribution and temperature changes during drilling, extraction, transportation, or storage, and the fact that the samples are taken from adjacent parts of the core, and might capture heterogeneous density layers, as well as potential measurement errors associated with the equipment used.”

Please see Lines 427-434.

Stress exponent: The stress exponent is only mentioned toward the end of the section (lines 462-470), where the values 0.1 and -1.2 are considered. However, the method for determining these values is not explained. Moreover, these exponents are inconsistent with those reported in the literature and in Li and Baker (2022), and they do not align with any known physical behaviour of materials.

We agree with you that the stress exponent values of $n = 0.1$ and $n = -1.2$ are inconsistent with the literature, and we tried to highlight that point in Lines 463–464: *This is in disagreement with the reported $n = \sim 4.3$ by Li and Baker (2022a).* To make this point clearer, we modified the text to:

“We found n to be ~ 0.1 and ~ -1.2 for the -5°C and -18°C samples, respectively, which contradicts the reported $n = \sim 4.3$ by Li and Baker (2022a) and other values around 3 (Glen, 1955; Kamb, 1961; Raymond, 1973; Thomas et al., 1980; Weertman, 1985; Goldsby and Kohlstedt, 2001; Cuffey, 2006). This significant discrepancy implies that the uncalibrated SRMin value from all of the samples is not appropriate for estimating the stress exponent, and hence the activation energy during their deformation.”

Please see Lines 514-519.

To clarify our methods in this section, we added the following text to describe our method of obtaining the stress exponent:

*“The value of the stress exponent n is determined by plotting the line fit the logarithm relation of the steady-state strain rate, $\dot{\epsilon}$, versus the effective stress, σ , and is, thus, the slope of this line from the measured SRmins (**Table 2**).”*

Please see Lines 512-514.

A “post-calibration” method is then introduced, which imposes a fixed stress exponent but fails to account for density dependence. This approach leads to variable results, depending on the chosen reference sample. These inconsistencies arise from the identification of the power law using data in which both stress and density vary simultaneously. As demonstrated in Li and Baker (2022a), the strain-rate minimum (SRMin) is dependent on density, with the strain rate decreasing by a factor of 12 when the density increases from 756 to 861 kg/m³. However, the effect of microstructure is overlooked in this study, as it treats samples with densities ranging from 589 to 790 kg/m³ as identical.

Stress exponents reported during the creep of polar firn range from 4.1 ± 0.37 to 4.6 ± 0.16 (Li and Baker, 2022a). It is crucial to emphasize that the stress exponent does not depend on the density of the tested samples, thereby negating any basis for discussing a relationship between the stress exponent and sample density. Instead, variations in stress corresponding to density will manifest in the strain rate, ensuring that the derivation of the stress exponent and activation energy remains consistent, as noted by the reviewer. Further, the minimum strain rate is indeed influenced by density (Li and Baker, 2022a), which is typically utilized to derive the stress exponent in accordance with Glen’s law, considering the effective stress’s impact on porous firn reflected in strain rates. Consequently, the stress exponents are expected to be similar across samples of varying densities. To highlight this distinction in the manuscript, we added

the following text:

“It is important to note that the stress exponent does not depend on the density of the tested samples, thereby negating any basis for discussing a relationship between the stress exponent and sample density. Instead, variations in stress corresponding to density variations are manifested in the strain rate, ensuring that the derivation of the stress exponent and activation energy remains consistent.”

Please see Lines 521-525.

The authors need to improve the methodology and clearly outline the assumptions made, particularly regarding the density dependence of viscoplastic behaviour. This could be based on their previous work (Li and Baker, 2022) or by considering other models from the literature. Finally, the discussion in the “activation energy” section should be revisited in light of these methodological assumptions.

Thank you for pointing out our omissions in the methodological steps described above. In addition to the relevant methodological assumptions we’ve added above, we also included the following description of the method to calculate Q_c :

“The value of the apparent activation energy of creep, Q_c (kJ mol^{-1}), is equal to the slope of a line fitted $\ln \dot{\epsilon}$ versus $1/T$ as did in Goldsby & Kohlstedt (1997; 2001), using the Arrhenius relation $\dot{\epsilon} = B\sigma^n \exp(-\frac{Q_c}{RT})$, where $\dot{\epsilon}$ (s^{-1}) is the strain rate, B ($\text{s}^{-1} \text{Pa}^{-n}$) is the material parameter; σ (MPa) is the applied stress, n is the creep (stress) exponent, R ($8.314 \text{ J mol}^{-1} \text{ K}^{-1}$) is the gas constant, and T (K) is Kelvin temperature.”

Please see Lines 418-422.

Specific Comments:

Lines 43-48: What about the study of Burr et al., (2019) for the in-situ compression test? Does it relate or include relevant data to evaluate the results of this study?

We chose to not include this reference in our introduction. Burr et al. (2019) extensively examined the influence of pore closure and ice crystal grain growth on the densification of polar firn, utilizing *in situ* micro-computed tomography imaging while neglecting airflow effects. Although their study addressed thermal treatments of samples 801, 806, and 901, the effects were predominantly attributed to pressureless sintering, as these samples underwent strain without an applied load. Sample 806 was initially compressed at -10°C before being thermally treated at -2°C . In contrast, our research focuses on the deformation of firn samples subjected to constant stress across

varying temperatures.

Lines 57-59: Using homogenization approaches, considering the behaviour of ice, is common for studying the physical properties of firn and snow.

Yes, porous snow and firn primarily consist of an ice matrix interspersed with air. Hence, research on their mechanical properties often centers on the solid ice component, while also considering the influence of airflow.

Lines 233-235: Please provide more details on how the thermal gradient was evaluated during your experiments.

We've added the following text to address how the thermal gradient was generated:

“The thermal gradient appears to be associated with a fluctuation of 0.2°C around the test temperature, similar to temperature cycling occurred within firn (Mellor and Testa, 1969; Weertman, 1985), which stems from the thermometer's inherent accuracy as noted in Section 2.2 ($-5 \pm 0.2^\circ\text{C}$, $-18 \pm 0.2^\circ\text{C}$ and $-30 \pm 0.2^\circ\text{C}$).”

Please see Lines 255-259.

Lines 285-289: As deformation mechanisms are not directly measured in this study, please add references to the literature in this discussion.

We added the following relevant references to the text:

“The transient creep stage may be caused by strain hardening that occurs from the yield point to the ultimate strength (Glen, 1955; Jacka, 1984). The plastic deformation is accommodated by an increase in dislocation density through dislocation multiplication or the formation of new dislocations (Frost and Ashby, 1982; Duval et al., 1983; Ashby and Duval, 1985), which leads to an increase of the firn strength as the dislocations become pinned or tangled, and thus more difficult to move.”

Please see Lines 312-317.

Line 336: Unclear, it is the temperature which is a state variable of the strain-rate.

In these experiments, strain rate is considered a state variable of temperature. Under optimal conditions, the strain rate of a creep sample subjected to a specific stress to achieve a certain strain can be exclusively determined by the temperature.

Lines 410-411: The word “methods” can be misleading. Using 2 or 3 data points to

identify a parameter is not a separate method. Either remove the word “method” or include the data point at -10 °C in the overall dataset.

We replaced “methods” with “avenues”.

Lines 453-455: The statement about the activation energy of firn should be nuanced. While older studies show lower values than those of ice, you have already discussed that values of Q_c are highly scattered and debated (as mentioned in lines 416-426 of your manuscript).

Indeed, the activation energies derived in this work exhibit a wide range, which are consistent with a broad spread of 58.6–113 kJ/mol estimated by Landauer (1958). We’ve highlighted the factors that likely contribute to differences in Q_c values from the older literature in Table 3, e.g. the sample density, temperature inaccuracies during testing, and differences in the methodologies used for derivation. For further clarification, we explained this in the text:

“Alternatively, firn creep is easier than that of polycrystalline ice due to either the easier sliding of grains in firn along more directions in the more porous and heterogeneous structure (Section 3.3), or the decrease of viscosity associated with inclusions (e.g. Baker and Gerberich, 1979; Goodman et al., 1981) that facilitate the intra- and inter-grain sliding (Salamatin et al., 2009).”

Please see Lines 477-479, and Lines 502-503.

Lines 475-480: It's not clear that each brace corresponds to a depth. Please clarify it.

To further indicate what each bracket refers to, we added “20-m samples; 40-m samples; 60-m samples” above their respective bracket.

Technicals Comments:

Figure 6: Please specify in the title of the y-axis in Figure 6 that this is the logarithm of SRmin, to ensure consistency in the names used.

Corrected.

Figure 6: The text and colours in the caption do not appear to correspond to the figure. Please check.

Corrected.

General comments

This manuscript investigates the metamorphism and deformation mechanism using natural firn samples recovered at Greenland summit by mechanical tests and microstructure observations. Based on the experimental results, activation energy for creep deformation and grain boundary diffusion is estimated. The authors compare the results with previous studies on activation energy and discuss the firn deformation, and differences between firn and solid ice, and argued that the minimum strain rate is determined by temperature. Microstructures of firn samples before and after creep experiments are analyzed by X-ray micro computed tomography. Changes in geometric structure during creep deformation are investigated in detail.

This manuscript provides interesting results in mechanical behavior of firn samples (strain rate vs strain) and extensive 3D data on geometric structures before and after creep experiments. They are important data for discussion the deformation mechanisms and microstructural evolution of firn.

However, I have some significant concerns in the methodology, interpretation and references. In particular, experimental samples and conditions should be verified. Cited references are biased toward the author's paper. Please cite the references widely. Reconstruction of the manuscript is required. Therefore, I recommend major revisions.

Thank you for your thoughtful comments, which greatly improved our manuscript. Please find our detailed responses to the general comments you raised above in our responses to your specific comments below. As noted below in response to multiple comments, we added other references throughout the manuscript wherever possible.

Specific comments:

Abstract and Introduction:

It is difficult to understand the new findings of this study. In the field of ice and snow deformation, it is widely recognized that temperature is an important factor, and that tertiary creep is driven by recrystallization (Cuffey and Paterson, 2010; Faria et al., 2014). Compression deformation of firn, accompanied by an increase in density, differs from that of ice. Different creep behaviors between firn and ice could be expected.

This study presents novel firn creep data for three different depths of the Summit 2017 core at three different temperatures. As firn deformation studies are scarce, these data provide important empirical data that are useful for improving firn flow laws and models as well as our understanding of the mechanisms driving firn creep. While we

expect firn and ice to display different creep behavior, it is still informative to compare them, especially because firn contains an ice-matrix. To emphasize the novelty of this data set, we added the following text to the abstract:

“The results of these experiments comprise a novel data set on the creep of firn at three depths of a firn column at three different temperatures, providing useful calibration data for firn model development.”

Please see Lines 17-19.

The Introduction Section includes few references to previous research on firn deformation and metamorphism, making it unclear how this study fits within the context of current research and its problems. In addition to prior studies on ice deformation experiments, please also cite prior studies on firn deformation experiments.

We added a more thorough description of prior deformation studies with the following text:

“Numerous studies of firn and ice deformation have been conducted (e.g. Steinemann, 1954; Glen, 1955; Landauer, 1958; Mellor, 1975; Salm, 1982; Maeno and Ebinuma, 1983; Jacka, 1984; Ambach and Eisner, 1985; Budd and Jacka, 1989; Li et al., 1996; Meussen et al., 1999; Petrenko and Whitworth, 1999; Bartelt and von Moos, 2000; Jacka and Li, 2000; Durham et al., 2001; Goldsby and Kohlstedt, 2001; Hooke, 2005; Song et al., 2006a, 2006b, 2008; Theile et al., 2011; Treverrow et al., 2012; Hammonds and Baker, 2016, 2018; Li and Baker, 2021, 2022a), but there are few reports about their mechanical behaviors at different temperatures. Temperature is a key component of firn and ice-flow models, as the deformation of firn, polythermal glaciers, and temperate glaciers is significantly influenced by the temperature.”

Please see Lines 43-51.

In the Discussion section, there are many comparisons with the authors' own related papers, and the discussion with other studies is not sufficient. Please specify how the findings of this study advance our current understanding of firn deformation.

We've added additional discussions from various sources to Section 3.4:

In Section 3.3, significant references are cited from Li and Baker (2022a), including works by Glen (1955), Landauer (1958), Glen and Jones (1967), Jones and Glen (1968), Barnes et al. (1971), Homer and Glen (1978), Meussen et al. (1999), Freitag et al. (2002), and Theile et al. (2011). To avoid unnecessary repetition, these references are not elaborated upon in this study.

“These values of strain at different SRmin values are different from those usually observed at strains of 0.5–3% for fully-dense ice (Cuffey and Paterson, 2010, and references therein), implying different mechanical behavior between firn and pure ice (Duval, 1981; Mellor and Cole, 1983; Jacka, 1984; Li et al., 1996; Jacka and Li, 2000; Song et al., 2005, 2008; Cuffey and Paterson, 2010). Overall, the strain at the SRmin is greater with lower density and higher temperature, e.g. 11.8% strain from the –5°C specimens at 20 m, and 4.1% strain from the –18°C specimens at 40 m. This is likely due to the effect of strain hardening on density and temperature (Li, 2023b). Additionally, tertiary creep occurs both during quasi-steady state deformation (from the –5°C specimens at 40 m and 60 m) and in the ascending stage (from the –5°C and –18°C specimens at 20 m and the –18°C specimen at 40 m) more easily with lower firn density, greater effective stress, and higher creep temperature, e.g. from the –5°C specimens at 20 m, where the strain softening is primarily due to recrystallization (Duval, 1981; Jacka, 1984; Jacka and Li, 2000; Song et al., 2005; Faria et al., 2014) or the activated easy slip systems (Jonas and Muller, 1969; Duval and Montagnat, 2002; Alley et al., 2005; Horhold et al., 2012; Fujita et al., 2014; Eichler et al., 2017).”

Please see Lines 397-411.

The work presented in this manuscript builds upon Li & Baker (2022a) by investigating the impact of temperature on firn creep by conducting deformation experiments on samples from three depths of the Summit 2017 core at three different temperatures. Prior work only investigated the creep of the Summit 2017 firn at different depths, holding all other experimental variables constant. Thus, we believe the thermal focus of this work differentiates it from the prior study.

2. Sample and measurements

Please provide a schematic diagram of experimental setup even if it is shown in supporting paper (Li and Baker, 2022a).

As suggested, we now include Figure 1 from Li and Baker (2022a) to show the experimental setup.

Differences in initial conditions of each sample may significantly impact the results. For example, factors like fabric and impurity concentration may vary with depth. In the case of EastGRIP, it has been reported that fabric develops even in near-surface snow (Montagnat et al., 2022). Although geometric structure is discussed in the text and Table 1, it is also necessary to examine other elements of the initial samples, such as fabric, impurity concentration, and grain size. Not only is there a difference in the initial microstructure depending on the depth, but there is also a heterogeneity unique to the natural sample at the same depth. Otherwise, direct comparisons between

different samples may not be valid. I have question about the reproducibility of the experiment, in particular, strain rate vs strain.

Indeed, any underlying differences in fabric, grain size, and impurity content in firn samples may significantly impact results, highlighting a significant challenge in conducting creep experiments on natural firn. To limit the possibility of significant differences in those variables, care was taken to extract the three replicate samples from each depth as closely as possible to each other. With the limited amount of ice available at each depth in any given core, it is challenging to generate more creep experiment samples and more strain rate vs. strain data. To highlight these points, we've added the following text to Section 2:

“It’s also important to note that firn is a heterogeneous material that can have variations in layering, fabric, grain size, and impurity concentration across short distances. Thus, care was taken to extract the three replicate samples from the core at each depth as closely as possible to reduce the variability in their initial conditions.”

Please see Lines 123-127.

3.4 Relationship of strain rate to strain and 3.5 Apparent activation energy for creep:

I have questions about the calibration of experimental data. If the number of experiments is increased or experimental conditions are changed, then no calibration would be necessary. Or is it common practice to make calibration in firn deformation experiments? Looking at Table 2 and Figure 6, 7, it appears that the results vary greatly depending on the type of calibration. The discussion of strain rate (creep curve) and activation energy does not seem robust because of the large influence of the calibration. Please explain clarify, as it is difficult to understand the necessity and appropriateness of the calibration.

The increasing number of experiments cannot guarantee that the results used for deriving the apparent activation energy for creep are not calibrated, as performed by Glen (1955) for developing the Glen flow law. The necessity of calibration in this study will be detailed for your following concern about this sample question.

The variability in the activation energy for firn creep in Figure 6 is consistent with those reported in the literature, thereby ensuring the projected relationship between the strain rate minimum and temperature in Figure 7. Thus, this calibration is necessary, and the calibration method used is appropriate.

Appendix A:

The authors determine the loading stress during deformation experiments from the hydrostatic pressure at the point where the sample was taken, but is this reasonable? Hydrostatic pressure is considered to have no effect on strain rate in ice (Rigsby, 1958;

Cuffey and Paterson, 2010), and in ice it is the deviatoric stress that determines strain rate.

Hydrostatic pressures resulting from the overburden of overlying strata are frequently estimated through the integration of depth-density profiles. This pressure is crucial for determining the depth at which the stress applied to a single sample in laboratory tests corresponds to the conditions within the firn or ice core. The deviatoric normal stress is roughly equal to the difference between the principal stress at a given depth along the ice sheet's surface-base and its hydrostatic pressure, influencing the strain and strain rate during the deformation of snow, firn, and glacier ice. In contrast, the deviatoric shear stress is the same as the non-deviatoric component (Hook, 2005). Consequently, in many regions of polar ice sheets, a low deviatoric stress, typically around 0.1 MPa or less, prevails (e.g. Montagnat et al., 2015). However, the samples used in this study originate from the horizontal surface of the Greenland Summit, where the deviatoric stress approaches zero, indicating that the principal stress is nearly equal to the hydrostatic pressure at the corresponding depth.

It is understandable that a high stress is necessary to make the experiment (deformation) proceed quickly and that the ratio of effective stress to hydrostatic pressure should be considered to approximate actual ice sheet conditions (set so that the effective stress becomes smaller as the depth increases). However, the strain rates obtained in this experiment are on the order of 10^{-5} to 10^{-6} s⁻¹, which is several orders of magnitude larger than actual ice sheet firn. As an example, Faria et al. (2014) estimated the vertical strain rate of EDML firn at 50 m depth as order of 10^{-11} - 10^{-12} s⁻¹. Furthermore, they concluded that EDML firn at 50-m depth is determining in the tertiary creep with dynamic recrystallization.

The high stresses (or high strain rate) will also cause dislocation accumulation and tangle, and recrystallization to be more active than it actually is.

Yes, you are correct. You are highlighting another challenge in conducting laboratory creep experiments on natural firn (and ice). Unfortunately, natural deformation in ice sheets occurs at rates that are orders of magnitude slower than what is possible to achieve in the laboratory setting. These issues are present in all laboratory-based creep studies and must be considered when discussing their results. Thus, we put the following text in Appendix A to remind readers of this caveat:

“Also, it’s important to note that the strain rates achieved during creep experiments in laboratory settings are 6 to 7 times faster than on ice sheets due to the constraints of conducting experiment in reasonable times, which requires higher loads.”

Please see Lines 661-663.

Others

L233-235: Could a decrease in density associated with deformational compression occur in a real ice sheet firm?

No. To highlight this point, we've added the following description in the text:

“In the relatively simple deformation found at ice-sheet dome sites, such as Summit, there is no mechanism to decrease density during compression. At sites closer to the ice sheet margins, cracking due to extension of the ice may cause a localized decrease in density.”

Please see Lines 259-261.

L239-241: Does the fact that the ratio of effective stress to hydrostatic pressure in the experiments (discussed in Appendix A) varies from sample to sample (depth to depth) not affect the differences in density increase?

No. Both the effective stress and the hydrostatic pressure take density, and therefore the porosity/ice-matrix, into account. Thus, the values of effective stress and hydrostatic pressure are proportional to the sample densities at each depth.

L250-255: Only one example of grain size change before and after creep experiment is shown (40-m sample at -5°C). In the manuscript, it just says, refer to Li and Fu (2024) (L401) for other samples, but it needs to mention in the present paper. Please provide other measurement results in grain size changes before and after deformation.

The 40-m sample at -5°C is to show the occurrence of recrystallization during firm deformation, not for all samples. Thus, it is taken as an example. Additionally, we've added the relevant grain size data in Table 3.

Table 3. Grain area (mm^2) measured from optical thin sections for samples at -5°C , -18°C , and -30°C from depths of 20 m, 40 m, and 60 m before and after creep.

Depth	20 m		40 m		60 m	
$T/^{\circ}\text{C}$	Before	After	Before	After	Before	After
-5	0.29 ± 0.25	0.42 ± 0.28	0.53 ± 0.32	0.79 ± 0.67	0.78 ± 0.67	0.97 ± 0.8
-18	0.29 ± 0.25	0.34 ± 0.2	0.53 ± 0.32	0.7 ± 0.42	0.78 ± 0.67	0.9 ± 0.59
-30	0.29 ± 0.25	0.31 ± 0.17	0.53 ± 0.32	0.57 ± 0.34	0.78 ± 0.67	0.81 ± 0.56

L285-294: The strain rate transition (creep curve) in deformation and recrystallization have been described by numerous papers and textbooks (e.g., Budd and Jacka, 1989; Cuffey and Paterson, 2010; Faria et al. 2014). Please cite references widely as well as the authors' papers.

We modified as below:

“The transient creep stage may be caused by strain hardening that occurs from the yield point to the ultimate strength (Glen, 1955; Jacka, 1984). The plastic deformation is accommodated by an increase in dislocation density through dislocation multiplication or the formation of new dislocations (Frost and Ashby, 1982; Duval et al., 1983; Ashby and Duval, 1985), which leads to an increase of the firn strength as the dislocations become pinned or tangled, and thus more difficult to move. The initial decrease of creep rate may also be related to the rearrangement of dislocations into a more stable pattern through a dragging mechanism (Weertman, 1983) for the -5°C specimens. The tertiary creep stage may be associated with strain softening deriving either from the thermally-activated processes at the high homologous temperature approaching the melting point of ice, or from recrystallization (Li and Baker, 2022a).”
Please see Lines 312-322.

L306-309: What is the reason why the 20m and 60m samples with large density differences are close to each other and the 40m sample is greater than that?

To make further clarification, we’ve modified the following description in the text:

“Interestingly, an evident relationship between the density of firn and the k values, regardless of the effect of stress (Li and Baker, 2022a) and temperature, remains unknown.”

Please see Lines 347-349.

L309-310: I did not understand this logic (These k values imply that the more the constraints from the grain-boundaries, the slower the deformation rate will be,..). Please explain in detail.

To make further clarification, we’ve modified the following description in the text:

“A greater k value signifies faster deformation. The k values derived for firn are generally higher than those for polycrystalline ice, implying that the higher firn deformation rates compared to those of ice are likely related to the fewer grain-boundary constraints with more void space in firn (Li and Baker, 2022a; Li, 2023b).”

Please see Lines 349-352.

L327-329: I did not understand this logic (likely suggesting that the effect of temperature overwhelmed the effect of impurities during creep of polar firn.). Please explain in detail.

To make further clarification, we've modified the following description in the text:

“k values lower than 0.33 observed under constant load and temperature occurred at relatively low effective stresses (Li and Baker, 2022a). However, the steady decrease of k values from -5°C to -18°C remains further investigation.”

Please see Lines 356-359.

L369-370: Why does the strain at which the minimum strain rate is achieved vary with density and temperature?

We tried to highlight a reason behind this phenomenon in Lines 371–372:

“Overall, the strain at the SRMin is greater with lower density and higher temperature, e.g. 11.8% strain from the -5°C specimens at 20 m, 4.1% strain from the -18°C specimens at 40 m, where a larger strain was caused by the longer-lasting strain hardening (Li, 2023b).”

To make this point clearer, we modified the text to:

“Overall, the strain at the SRmin is greater with lower density and higher temperature, e.g. 11.8% strain from the -5°C specimens at 20 m, and 4.1% strain from the -18°C specimens at 40 m. This is likely due to the effect of strain hardening on density and temperature (Li, 2023b).”

Please see Lines 401-404.

L462-464: Why does the stress exponent obtained in this experiment differ from previous studies? The value of 0.1 obtained in this study seems quite low. The difference may be too large to address with calibration alone. Please also cite previous studies other than Li and Baker (2022a) that estimated the stress exponent.

This is due to the inappropriate use of the strain rate minimum for the -30°C specimens, which is difficult to observe a steady-state secondary creep at such low temperature, thereby leading to the different values of the stress exponent from those in Li and Baker (2022a), which exhibits similar flow law from a same core.

We tried to highlight that point in Lines 463–464:

This is in disagreement with the reported $n = \sim 4.3$ by Li and Baker (2022a). To make this point clearer, with additional reports regarding the stress exponent, we modified the text to:

“We found n to be ~ 0.1 and ~ -1.2 for the -5°C and -18°C samples, respectively, which contradicts the reported $n = \sim 4.3$ by Li and Baker (2022a) and other values

around 3 (Glen, 1955; Kamb, 1961; Raymond, 1973; Thomas et al., 1980; Weertman, 1985; Goldsby and Kohlstedt, 2001; Cuffey, 2006). This significant discrepancy implies that the uncalibrated SRMin value from all of the samples is not appropriate for estimating the stress exponent, and hence the activation energy during their deformation.”

Please see Lines 514-519.

Also, is it possible for the stress exponent to be negative? There may be large fluctuations in the strain rate obtained in the deformation experiments, which could hinder accurate estimation. If these values are correct, what deformation mechanism do they correspond to?

No. See response above.

I question the practice of determining the stress exponent from experimental results of different samples. If the initial conditions of the samples differ, the deformation characteristics will also change, making it impossible to accurately determine the stress exponent.

Natural firn and ice samples provide a more accurate representation of the ice flow law governing glaciers and ice sheets. According to Glen’s flow law, numerous laboratory experiments have consistently yielded a stress exponent value around 3, based on tests utilizing laboratory-generated snow and ice samples with varying initial grain sizes, crystallization preferred orientations, densities, or impurity levels (Cuffey and Paterson, 2010 and references therein). Therefore, selecting initial samples with diverse microstructural parameters is essential for a deeper understanding of flow rates during firn and ice deformation, accompanied by the associated microstructural evolution.

Table 1: Please provide the explanation of each parameter (e.g., S.Th, TP...) in the caption.

We added this note below the table :

“Note: SSA is the specific surface area, S.Th is the structure thickness, TP is the total porosity, CP is the closed porosity, SMI is the structure model index, and ECDA is the area-equivalent circle diameter”.

Please see Lines 220-222.

Figure 4 (L317-318): “-30°C (blue lines)” is correct?

We corrected the caption:

“Figure 5: Strain vs. time for firn specimens at -5°C (yellow lines), -18°C (blue lines), and -30°C (brown lines), from depths of 20 m (applied stress 0.21 MPa), 40 m (0.32MPa) and 60 m (0.43MPa).”

Please see Lines 339-341.

Sincerely,

Yuan Li, Kaitlin Keegan, Ian Baker

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