Dear Reviewer,

We thank you very much for your comments to improve the manuscript.
Please find our responses below in black font, and your comments in blue font.

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 of firn creep at three depths of a firn column under three different temperatures, providing useful calibration data for firn model development."

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 the mechanical behavior 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."

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 that 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)….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 either 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).*"

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 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."

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 determing 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 orders of magnitude faster than on sheets due to the constraints of running a reasonable experiment."

Others

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

No. To highlight this point, we've added the following description in the text:
"In the relatively simple deformation system found at ice-sheet dome sites, such as Summit, there is no mechanism to decrease density during deformational compression. At sites closer to the ice sheet margins, cracking due to extension of the ice may cause a localized decrease in density due to deformation."

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 ^{o}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 ^{o}C is to show the occurrence of recrystallization during firn 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^{o}C, –18^{o}C, and –30^{o}C from depths of 20 m, 40 m, and 60 m before and after creep.

Depth	*20 m*		*40 m*		*60 m*	
T/^{o}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 and others, 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)".

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.*"

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 swifter deformation. These k values derived for firn are generally higher than those for polycrystalline ice, implying that higher firn deformation rate than ice is related likely to its less grain-boundary constraints with more free void space (Li and Baker, 2022a; Li, 2023b)."

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 the relatively low effective stresses (Li and Baker, 2022a). In contrast, this is seemingly to occur at the relatively low temperatures due to the steady decrease of k values from –5°C to –18°C, thereby remaining further investigation.*"

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, 4.1% strain from the –18°C specimens at 40 m. This is related to the effect of strain hardening on density and temperature (Li, 2023b).*"

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 = ~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 = ~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 the samples is not appropriate for estimating the stress exponent, and hence the activation energy during their deformation."

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*".

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

We corrected the caption:
"***Figure 4:*** *Strain vs. time for firn specimens at –5 ℃ (yellow lines), –18 ℃ (blue lines), and –30 ℃ (brown lines), from depths of 20 m (applied stress 0.21 MPa), 40 m (0.32MPa) and 60 m (0.43MPa)*".

Sincerely,
Yuan Li, Kaitlin Keegan, Ian Baker

References:
Cuffey, K.M., Paterson, W.S.B., 2010. The Physics of Glaciers, 4th edited. Elsevier Inc.
Faria, S.H., et al. 2014. The Mcrostructure of Par Ie. Part II: State of the Art. J. Struct. Geol. 61: 21-49.
Hooke, R.L. 2005. Principles of Glacier Mechanics. Cambridge: Cambridge University. Press.
Montagnat, M., Chauve, T., Barou, F., Tommasi, A., Beausir, B., Fressengeas, C. 2015. Analysis of Dynamic Recrystallization of Ice from EBSD Orientation Mapping. Front. Earth Sci. 3:81.