https://doi.org/10.5194/egusphere-2024-2337
Preprint. Discussion started: 27 September 2024

Observations of creep of polar firn at different temperatures

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https://doi.org/10.5194/egusphere-2024-2337
Preprint. Discussion started: 27 September 2024

Abstract

To improve our understanding of firn compaction and deformation processes, constant-load compressive creep tests were performed on specimens from a Summit, Greenland (72°35' N, 38°25' W) firn core that was extracted in June, 2017. Cylindrical specimens were tested at temperatures of –5ºC, –18ºC and –30ºC from depths of 20 m, 40 m and 60 m at stresses of 0.21 MPa, 0.32 MPa and 0.43MPa, respectively. The microstructures were characterized before and after creep using both X-ray micro-computed tomography (micro-CT) and thin sections viewed between optical crossed polarizers. Examining the resulting strain vs. time and strain vs. strain rate curves from the creep tests revealed the following notable features. First, the time exponent k was found to be 0.34–0.69 during transient creep, which is greater than the 0.33 usually observed in fully-dense ice. Second, the strain rate minimum (SRMin) in secondary creep occurred at a greater strain from specimens with lower density and at higher temperature. Third, tertiary creep occurred more easily for the lower-density specimens at greater effective stresses and higher temperatures, where strain softening is primarily due to recrystallization. Fourth, the SRMin is a function of the temperature for a given firn density. Lastly, we developed empirical equations for inferring the SRMin, as it is difficult to measure during creep at low temperatures. The creep behaviors of polar firn, being essentially different from full-density ice, imply that firn densification is an indispensable process within the snow-to-ice transition, particularly firn deformation at different temperatures connected to a changing climate.

Keywords: Firn; Creep; Activation energy; Microstructure; Temperature

https://doi.org/10.5194/egusphere-2024-2337
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1. Introduction

Understanding firn compaction and densification experimentally is critical for developing physics-based firn models that are necessary for many glaciological applications, e.g. in developing clean hydrogen storage technology (Li, 2023a; 2024), and on the effect related to snowstorm and thunderstorm electrification (Li, et al., 2023). This motivation is thoroughly described in the companion paper to this work (Li and Baker, 2022a), where the creep of firn at different constant stresses at a single temperature (–10ºC) was studied. The work presented, here, focuses on the creep of firn at constant stress but at different temperatures. Both papers use the same measurement methods and similar analysis methodologies. To avoid redundancy, we only discuss the deformation of ice and firn related to the effects of temperature. It must be noted that the study of the transition from firn (density > ~550 kg m^{-3}, and porosity < ~40%) to bubbly ice (< ~820–840 kg m^{-3}, and > ~11–8%) is indispensable for gaining insight into how snow transforms to ice. Surprisingly, the mechanical behavior of two-phase flow coupling the air flow with the ice matrix deformation has not yet been performed experimentally hitherto, even though the role of the microstructures of firn on air flow has been studied (Albert et al., 2000; Courville et al., 2010; Adolph and Albert, 2014). This difficulty is largely due to the limitations of the observation techniques of nondestructive visualization of the microstructures during snow and firn deformation. Thus, caution should be taken with extending the conclusions to ice-sheet and glacier-scales from sample laboratory experiments. Macroscopically, the creep of firn obeys a power-law dependence of the strain rate on the stress at constant stresses and temperature, similar to that of full-density ice (Li and Baker, 2022a). Note that both the diffusivity and permeability of the air in the pores (Albert et al., 2000; Courville et al., 2010; Adolph and Albert, 2014) impact

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heat conduction of the ice matrix, and hence the grain growth. This is tightly tied to the micro-mechanisms, e.g. grain-boundary and lattice diffusion of the ice crystals (Li and Baker, 2021), superplastic deformation and inter-particle sliding from dislocation motion in the ice necks (Bartelt and Von Moos, 2000), and likely rearrangement of the ice particles (Perutz and Seligman, 1939; Anderson and Benson, 1963; Ebinuma and Maeno, 1987). To some degree, it is not useful to discuss only the deformation of snow and firn without discussing the mechanical behavior of ice.

Through experiments on isotropic ice samples subjected to uni-axial compaction at octahedral stresses of 0.1–0.8 MPa and temperatures from –45ºC to –5ºC, Jacka and Li (2000) determined the mechanisms involved in the empirical *power-law flow*, which was derived by Glen (1955) for stresses ranging from 0.1–1 MPa at temperatures spanning from –13ºC to the melting-point. They found that dynamic recrystallization predominated at higher temperatures and stresses, whereas crystal rotation governed at lower temperatures and stresses. Later, Goldsby and Kohstedt (2001) found that ice could exhibit *superplastic flow*, which depends inversely on the grain size, particularly for fine-grained ice, while both dislocation creep and basal slip-limited creep were unrelated to the grain size at stresses of 0.1 MPa or less over a wide range of temperatures. Moreover, Baker and Gerberich (1979) reported that the apparent activation energy for creep for polycrystalline ice, which was derived from tests at constant stress and temperatures ranging from –40ºC to –5ºC, increased with increasing volume fraction of inclusions (bubbles, impurities, dust, and the air clathrate hydrates). Such inclusions governed the evolution of grain size related to thermal activations. The activation energies for the creep of snow and ice have been determined

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by a number of authors: values ranging from 58.6–113 kJ mol^{-1} were obtained under both uniaxial and hydrostatic experiments for snow with a density of ~400 kg m^{-3} at –13.6 to –3.6°C (Landauer, 1958); 44.8–74.5 kJ mol^{-1} from snow with densities of 440–830 kg m^{-3} at –34.5 to –0.5°C (Mellor and Smith, 1966); ~72.9 kJ mol^{-1} for firn with a density of 320–650 kg m^{-3} at the South Pole (Gow, 1969); 69 ± 5 kJ mol^{-1} for a mean snow density of 423 ± 8 kg m^{-3} at –19 to –11°C (Scapozza and Bartelt, 2003); the 78 kJ mol^{-1} from polycrystalline ice compression deformation at a temperature of –10°C (Duval and Ashby, 1983); ~60 kJ mol^{-1} for artificial and natural ice at the South Pole (Pimienta and Duval, 1987); and 78 ± 4 kJ mol^{-1} for monocrystal ice at –20 to –4.5°C and 75 ± 2 kJ mol^{-1} for bicrystal ice at –15 to –4.5°C (Homer and Glen, 1978). In summary, the flow law of polycrystalline ice and firn depends on the effects of recrystallization, grain size, inclusions (Mellor and Testa, 1969; Vickers and Greenfield, 1968; Barnes et al., 1971; Baker and Gerberich, 1979; Goodman et al., 1981), and the temperature.

With advanced observation techniques, the relevant microstructural parameters of snow and firn have been characterized by a number of scientists (Arnaud et al., 1998; Coleou et al., 2001; Flin et al., 2004; Wang and Baker, 2013; Wiese and Schneebeli, 2017; Li, 2022). Using X-ray micro-computed tomography (micro-CT), Li and Baker (2022b) characterized metamorphism from snow to depth hoar under opposing temperature gradients. Only rarely has work been performed on the co-effects of temperature-stress on the densification of firn while simultaneously visualizing the microstructural changes using a micro-CT. For example, Schleef et al. (2014) reported that densification under varying conditions of overburden stress and temperature from natural and laboratory-grown new snow showed a linear relationship between

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density and the specific surface area (SSA). To this end, the aim of our present work is to investigate the temperature dependence of the creep of polar firn, and relate this to the change of microstructure determined using micro-CT studies on firn obtained from Summit, Greenland in 2017. As is well known, temperature is a key parameter affecting the flow of firn and ice, and plays a determined role in their deformation, especially for polythermal and temperate glaciers. Due to the great difficulty of analyzing firn and ice deformation with the presence of liquid water, this work focuses on the firn creep from the dry snow zone, i.e., areas without meltwater, at different temperatures.

2. Samples and measurements

2.1 *Samples*

Three cylindrical samples (22 ± 0.5 mm diameter; 50 ± 0.5 mm high) were produced at each of three depths of 20 m, 40 m and 60 m from the same 2017 Summit, Greenland firn core that was studied in Li and Baker (2022a). Incidentally, both the densities and porosities of these above samples are typical of values in the snow-to-ice transition zone as introduced in Sect. 1. More importantly, samples from three depths meet the experimental requirement designed as the decrease of the effective stress with increasing depth (**Appendix A**). Before creep testing, one cylindrical firn samples from each depth was stored at a temperature of –5 ± 0.5ºC, –18 ± 0.5ºC, and –30 ± 0.5ºC for two days to achieve thermal equilibrium (Li and Baker, 2022a).

2.2 Creep measurements

Three home-built creep jigs were placed in individual Styrofoam boxes in three different cold

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rooms that were held at temperatures of –5 ± 0.5ºC, –18 ± 0.5ºC and –30 ± 0.5ºC. Each creep jig consists of an aluminum base plate and three polished aluminum-guide rails passing through linear bearings that hold the upper aluminum loading plate (Fig. 1 in Li and Baker (2022a)). A linear voltage differential transducer (LVDT-Omega LD-320: resolution of 0.025%; linearity error of ± 0.15% of full scale output), parallel to the three aluminum-guide rails, was located adjacent to the center of the upper plate, and fixed firmly using a screw through the plate (Fig. 1 in Li and Baker (2022a)) for measuring the displacement during a test. The displacement was logged every 5 seconds using a Grant SQ2010 datalogger (accuracy of 0.1%). Temperatures were logged at 300-second time intervals over the entire test period, using a k-type thermocouple (Omega RDXL4SD thermistor: resolution of 0.1ºC) that was mounted inside each box. In this work, specimens were tested at temperatures of –5 ± 0.2ºC, –18 ± 0.2ºC and –30 ± 0.2ºC-the smaller error bars for the temperature of the specimens than the room temperature deviation is because the creep jigs were in insulated Styrofoam boxes-from depths of 20 m (applied stress 0.21 MPa), 40 m (0.32 MPa) and 60 m (0.43 MPa). These stresses were chosen based on experience from previous tests (Li and Baker, 2022a) in order to give measurable creep rates in a reasonable time.

2.3 *X-ray micro computed tomography (micro-CT)*

Each specimen at each depth and temperature combination was scanned using a Skyscan 1172 micro-CT, before and after creep testing. Each micro-CT scan lasted ~2 hours. The cubic Volume of Interest (VOI, a side length of 8 mm) was taken from near the center of the firn specimen as conducted in Li and Baker (2022a). The microstructural parameters obtained from the micro-CT

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data are the SSA, the mean structure thickness of the ice matrix (S.Th), the area-equivalent circle diameter of the pores (ECDa), the total porosity (TP), the closed porosity (CP), and the structure model index (SMI). The SSA (mm^{-1}) is the ratio of the ice surface area to total firn volume (ice plus air) in a VOI analytical element, and is calculated using the hexahedral marching cubes algorithm via CTAn software (Wang and Baker, 2013). It characterizes the thickness and complexity of the firn microstructure. Changes in SSA indicate a change in free energy of the ice surfaces, the decrease of which represents the occurrence of sintering-pressure. The S.Th (mm) is the mean structure thickness of an ice matrix (Hildebrand and Ruegsegger, 1997), which represents the characteristic size of an ice particle in the firn, where the ice particle consists of one or many crystals or grains. It is measured based on the largest sphere diameter that encloses a point in the ice matrix and is completely bounded within solid surfaces. The ECDa (mm) is the diameter of a circle having the same area as the measured on average from 2-D binary images for all pores involved in a computed VOI, indicative of the characteristic size for the void space (Adolph and Albert, 2014). The TP (%) is the ratio of the pore volume, including both open and closed pores, to the total VOI. The CP (%) is the ratio of the volume of the closed pores to the total volume of solid plus closed pores volume in a VOI, while the open porosity (%) is the ratio of the volume of the open pores to the total VOI. The SMI is calculated based on the dilation of a 3-D voxel model (Hildebrand and Ruegsegger, 1997) as $\mathrm{SMI} = 6\left(S' \times V\right)/S^2$, where S' is the change in the surface area due to dilation, and V and S are the object volume and surface area, respectively. It indicates the prevalent ice curvature, negative values of which represent a concave surface, e.g. the hollow air structure surrounded by an ice matrix. The more negative the SMI value, the more spherical the pore. Notably, the micro-CT-derived density of each specimen

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agrees well with the bulk density measured using the mass-volume approach (Li and Baker, 2021).

2.4 Thin section preparation and imaging

Thin sections for optical photographs before and after creep testing were cut from bulk specimens, one side of which was first smoothed with a microtome. This side was then frozen onto a glass plate (100 × 60 × 2 mm) by dropping supercooled gas-free water along its edges. Its thickness was reduced to ~2 mm by a band saw, and finally thinned further to a uniform thickness of ~0.5 mm using a microtome. Images were captured using a digital camera after each thin section was placed on a light table between a pair of crossed polarizing sheets.

3 Results and discussion

3.1 *Microstructures before creep*

Increasing firn density with increasing depth from either of the –5°C, –18°C, and –30°C specimens can be readily recognized by visual inspection of the micro-CT 3-D reconstructions of the firn microstructure (**Figure 1**). Correspondingly, the microstructural parameters, with the exception of the CP, changed monotonically with increasing depth at each temperature, e.g. the –30ºC samples increased in density from 591 ± 1.4 kg m^{-3}, to 683 ± 4.2 kg m^{-3}, to 782 ± 1.5 kg m^{-3}, decreased in SSA from 4.64 ± 0.04 mm^{-1}, to 3.3 ± 0.06 mm^{-1}, to 2.39 ± 0.01 mm^{-1}, and decreased

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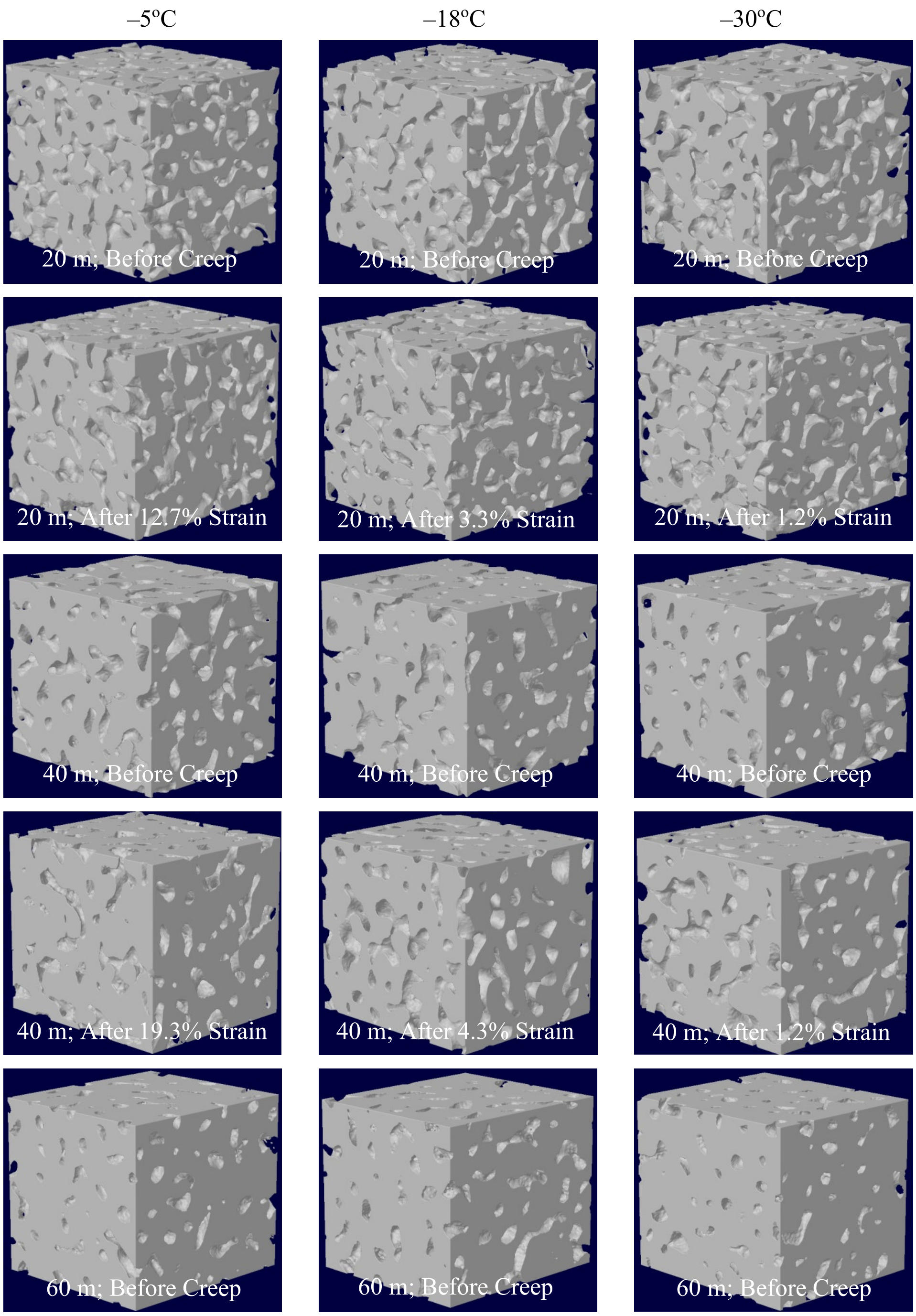

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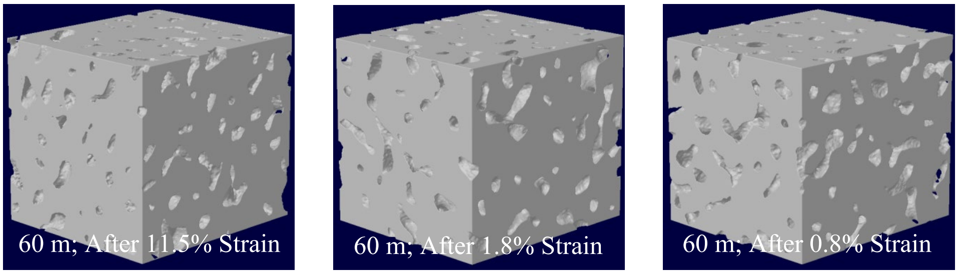

Figure 1: Micro-CT 3-D reconstructions (the side length of each cubic volume of interest is 8 mm) of specimens before and after creep testing at the depths and temperatures shown. Grey voxels represent ice in the firn structure.

Table 1. Microstructural parameters derived from Micro-CT for samples at –5ºC, –18ºC, and –30ºC from depths of 20 m, 40 m, and 60 m before creep.

20m							
T ºC	Density kg m^{-3}	SSA mm^{-1}	S.Th mm	TP %	CP %	SMI	ECDa mm
–5	589±1.3	4.74±0.03	0.732±0.001	35.9±0.08	0.03±0.002	-0.31±0.04	1.07±0.005
–18	615±2.5	4.51±0.04	0.758±0.001	33.1±0.2	0.01±0.001	-0.57±0.01	0.995±0.013
–30	591±1.4	4.64±0.04	0.747±0.004	35.6±0.05	0.02±0.001	-0.27±0.05	1.09±0.004

40m							
T ºC	Density kg m^{-3}	SSA mm^{-1}	S.Th mm	TP %	CP %	SMI	ECDa mm
–5	685±1.4	3.26±0.04	0.95±0.004	25.5±0.1	0.015±0.001	-1.85±0.11	0.857 ±0.005
–18	669±0.6	3.41±0.04	0.914±0.003	27.1±0.03	0.01±0.001	-1.69±0.09	0.892±0.002
–30	683±4.2	3.30±0.06	0.94±0.01	25.6±0.4	0.021±0.005	-1.87±0.13	0.86±0.01

60m							
T ºC	Density kg m^{-3}	SSA mm^{-1}	S.Th mm	TP %	CP %	SMI	ECDa mm
–5	790±1.0	2.34±0.03	1.1±0.003	14.0±0.1	0.11±0.01	-4.81±0.22	0.594±0.003
–18	780±0.5	2.37±0.03	1.08±0.01	15.2±0.06	0.014±0.007	-4.8±0.2	0.632±0.001
–30	782±1.5	2.39±0.01	1.076±0.0003	14.8±0.2	0.02±0.001	-4.92±0.14	0.639±0.002

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in TP from 35.6 ± 0.05%, 25.6 ± 0.4%, to 14.8 ± 0.2% at 20, 40, and 60 m, respectively (**Table 1)**. These above changes are similar to those previously observed in this firn core (Li and Baker, 2022a), implying that the sintering-pressure mechanism plays a crucial role in the densification of polar firn due to the increasing overburden of snow and firn with increasing depth. However, the microstructures of the samples from the three temperatures at each depth shows little variability and does not monotonically change with temperature, e.g. at 20 m depth the –5ºC, –18ºC, and –30ºC samples having densities of 589 ± 1.3 kg m^{-3}, 615 ± 2.5 kg m^{-3}, and 591 ± 1.4 kg m^{-3}, and SSAs of 4.74 ± 0.03 mm^{-1}, 4.51 ± 0.04 mm^{-1}, and 4.64 ± 0.04 mm^{-1}, respectively (**Figures 1**–**2**; **Table 1)**. Here, the –18ºC specimen being denser than the two others at –5ºC and –30ºC is not able to be concluded that the sintering of firn is not directly related to the temperature. This is likely because the duration of two days during thermal equilibration in the absence of compression is too short to sufficiently exert the influence of temperature on firn sintering. The microstructural differences seen in these specimens more likely arose from the initial samples themselves, which were anisotropic and heterogeneous even if taken from the same depth, attributed to firn pre-deformation and partial anneal before experiments (Li and Baker, 2022a).

3.2 *Microstructures after creep*

The microstructural evolution can be characterized well by the microstructural parameters in **Figure 2**. The largest changes occur in the –5ºC specimens due to the higher temperature, i.e., the density, S.Th, and CP increased, while the ECDa, TP, SSA and SMI decreased, indicative of consolidation of the firn after creep. It is important to note that for the 60 m sample tested at –5ºC there was no change in density, i.e. 790.2 ± 1 kg m^{-3} before creep vs. 790.7 ± 0.9 kg m^{-3} after

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creep, or TP, i.e. 14.0 ± 0.1% before creep vs. 13.9 ± 0.1% after creep. These lack of microstructural change is due to the high initial density, which was close to the firn pore close-off density of ~830 kg m^{-3}. Thus, the creep of this sample may involve a transition from firn to bubbly ice, as also indicated with the increase in CP, which would have made it difficult to compress further. Intriguingly, some of the changes in microstructure observed in the micro-CT 3-D reconstructions from the specimens before and after creep, e.g. the distribution of ice-space, are indistinguishable in **Figure 1**. This is presumably due to the relatively large initial particle size, or from radial dilation exceeding the axial compression because of the small strains that occurred at the relatively low temperatures.

One exception to the expected microstructural change after creep was the decrease of CP, which was likely due to the measurement uncertainty of the micro-CT (Burr et al., 2018), or the radial dilation of the specimen during creep. Another exception was the decrease in density after creep for the –18ºC specimen at 20 m and the –30ºC specimen at 60 m, which was due to temperature gradient metamorphism, as confirmed by the increase of both TP and S.Th (Li and Baker, 2022b). The rate of firn densification should decrease with increasing depth at a given temperature, due to the decrease of effective stress with increasing depth (**Appendix A**). As a matter of fact, the density of the –5ºC samples after creep increased by 32 kg m^{-3}, 44 kg m^{-3}, and 0.5 kg m^{-3} for the 20 m, 40 m, and 60 m samples, respectively. The 44 kg m^{-3} unexpectedly outnumbers the 32 kg m^{-3}, implying that the densification of firn is also affected by other undetermined factors, e.g. the effect of inclusions, in addition to the stress and temperature.

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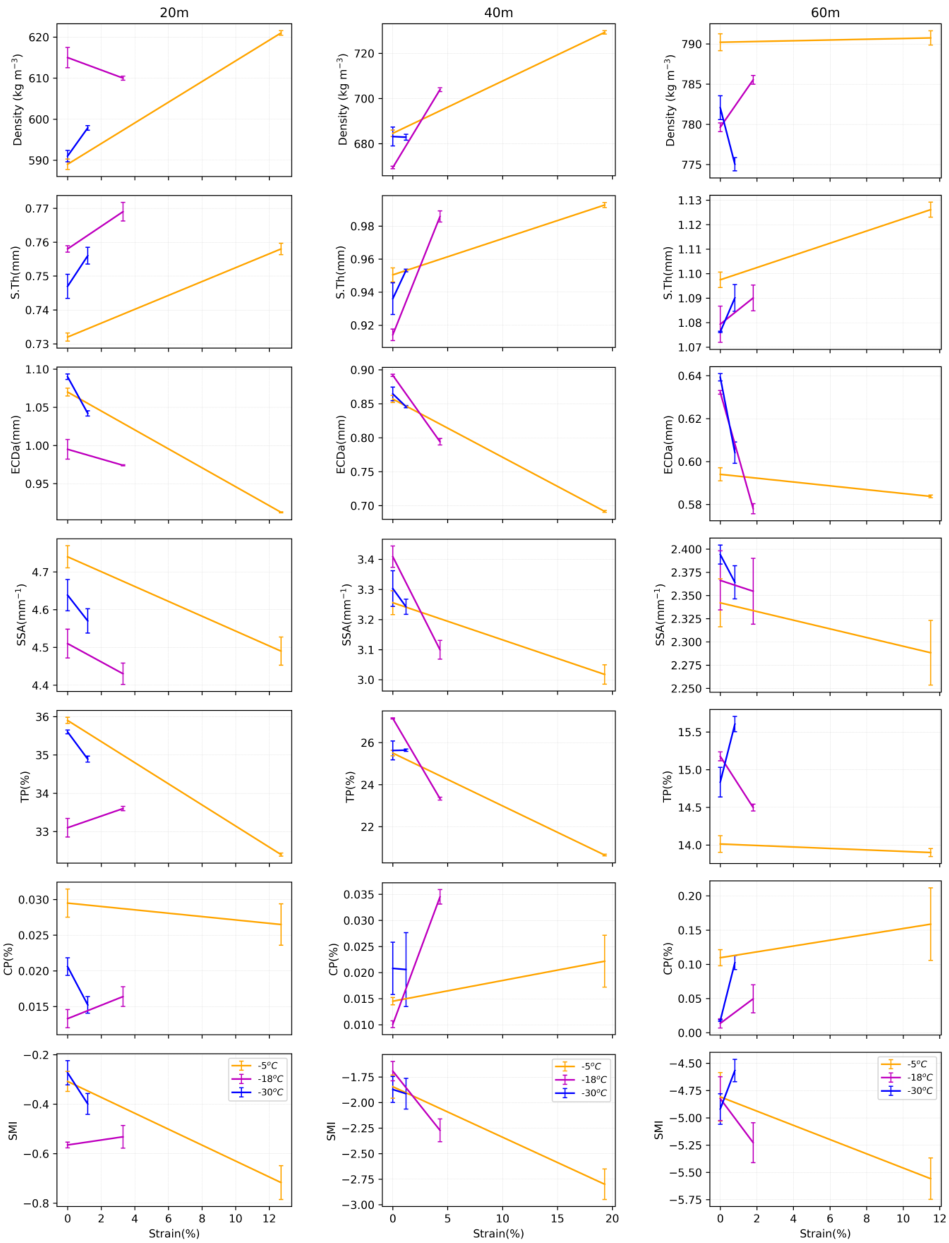

Figure 2: Density, structure thickness (S.Th), area-equivalent circle diameter (ECDa), specific surface area (SSA), total porosity (TP), closed porosity (CP), and structure model index (SMI) of the firn samples before and after creep at three temperatures (orange, magenta, and blue lines)

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from depths of 20 m, 40 m and 60 m. Error bars indicate the variation of each microstructural parameter as derived from three different VOIs of the same sample.

Another way to investigate microstructure changes before and after creep tests is to compare their grain sizes using thin sections. As an example, **Figure 3** shows optical micrographs of thin sections made from the –5ºC sample at 40 m before and after creep to a strain of 19.3%, where the significant reduction in grain size from 0.8 ± 0.17 mm to 0.53 ± 0.18 mm implies the occurrence of recrystallization during testing. However, it is also unclear at what strain recrystallization

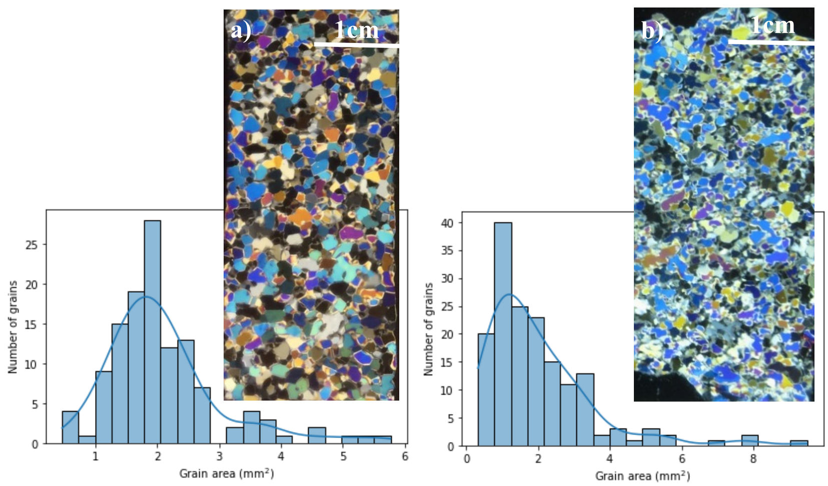

Figure 3: Optical micrographs of thin sections, and the distribution of grain sizes for the 40 m sample at –5ºC (a) before and (b) after creep (19.3% strain).

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was initiated in each test, as noted in Li and Baker (2022a). Recrystallization occurs frequently at a temperature higher than the homologous temperatures of 0.9 T_m, however no evidence was found for recrystallization after testing at the relatively cold –18ºC and –30ºC conditions, probably due to the small creep strains at these relatively low temperatures. The creep mechanisms for these samples, and whether the mechanisms were different at different temperatures, could not be determined from the micro-CT-derived microstructural observations alone. This is because the micro-CT can only capture the microstructure before and after creep. Instead, plots of both strain vs. time and strain rate vs. strain can be used to elucidate the onset of recrystallization during creep (Sects. 3.3 and 3.4; Ogunmolasuyi, et al., 2023).

3.3 *Relationship between strain and time*

Figure 4 shows the strain vs. time creep curves. The specimens at –5ºC at 20 m, and at –18ºC at 20 m, 40 m and 60 m, show decelerating transient creep and quasi-viscous steady-state creep, while the specimens at –5ºC at 40 m and 60 m show transient, secondary, and accelerating tertiary creep. Note that the curves from the –30ºC specimens are not easily interpreted, due to a large amount of noise arising from both the insufficient resolution of a linear voltage differential transducer (Li and Baker, 2022a) and the very small strains. The transient creep stage may be caused by strain hardening that occurs from the yield point to the ultimate strength. The plastic deformation is accommodated by an increase in dislocation density through dislocation multiplication or the formation of new dislocations, 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 –5ºC 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). Clearly, the creep rate of firn is sensitive to temperature under a constant stress at a given depth, *viz.*, the creep rate increases with increasing temperature (**Figure 4**). Incidentally, there is no evidence of the onset of recrystallization in the creep curves themselves despite the thin-section observation that –5ºC specimens clearly underwent recrystallization during creep (Sects. 3.2).

A modified Andrade-like equation $\varepsilon = \beta t^k + \varepsilon_0$ in Li and Baker (2022a) was used to describe the transient creep behavior of the firn, in which the primary creep was well represented in black dashed lines on the creep curves in **Figure 4**. The time exponent *k*, derived from the above equation, ranges from 0.34–0.69: the data for the –30ºC specimens are excluded since the noise in the results makes them uninterpretable. These *k* values are also smaller than those from monocrystalline and bicrystalline ice: 1.9 ± 0.5, 1.5 ± 0.2, and 1.3 ± 0.4 (Li and Baker, 2022a and references therein). We also note that the *k* values from the specimens at –5ºC from 20–60 m (0.68, 0.61, and 0.69), and at –18ºC from 40 m (0.49) are greater than 0.33, while the *k* value from the –18ºC specimens at 20 m (0.34) and 60 m (0.34) are close to 0.33 that is usually obtained for full-density polycrystal ice. These *k* values imply that the more the constraints from the grain-boundaries, the slower the deformation rate will be, and that the grains in firn deform with less grain-boundary constraints than in a full-density polycrystalline ice because of the presence of void space in firn (Li and Baker, 2022a; Li, 2023b). Clearly, the above *k* values,

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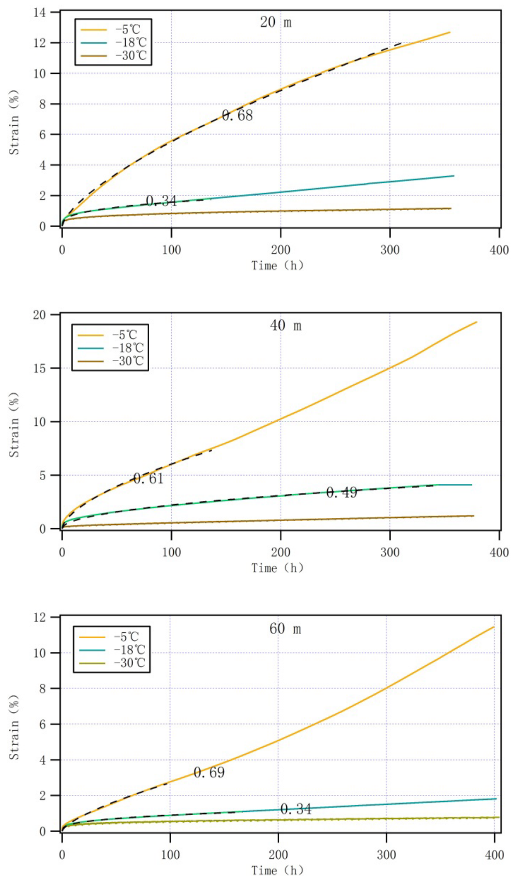

Figure 4: Strain vs. time for firn specimens at –5°C (red lines), –18°C (green lines), and –30°C (blue lines), from depths of 20 m (applied stress 0.21 MPa), 40 m (0.32MPa) and 60 m (0.43MPa). The black dashed curves represent fits to a modified Andrade-like equation with the time exponents indicated on the curves, if any.

which increased with increasing temperature (**Figure 4**), indicate that deformation is easier because of the lower viscosity at the higher temperature. Thus, *k* seems to be a state variable with

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respect to temperature. In addition, *k* values greater than 0.33 may be related to the decrease of viscosity of the firn specimens (Freitag et al., 2002; Fujita et al., 2014). These features seem to be simpler than those in Li and Baker (2022a), where some *k* values were lower than 0.33, likely suggesting that the effect of temperature overwhelmed the effect of impurities during creep of polar firn. Alternatively, the enhanced cohesion strength in the firn, which resulted from both the ice matrix with higher purity and the stronger bond connection of inter-grains, increases the viscosity of test samples and lowers the *k* value to less than 0.33.

3.4 *Relationship of strain rate to strain*

Figure 5 shows log strain rate vs. strain plots from all the –5ºC and –18ºC specimens; the –30ºC samples are excluded due to noise. The evolution of the strain rate is characterized more clearly in **Figure 5** than in **Figure 4**. Clearly, the strain rate is also a state variable of temperature, where the strain rate increases with increasing temperature for a given strain at a given depth (**Figure 5**; **Table 2**). The strain rate minimum at the secondary creep stage (SRMin) and the strain at the SRMin for all the –5ºC and –18ºC specimens are shown in **Figure 5** and **Table 2**. The SRMin was reached at a strain of 11.8%, 7.5% and 2.7% for the –5ºC specimens from depths of 20 m, 40 m, and 60 m, respectively, consistent with strains at the SRMin decreasing with increasing depth at a given temperature in **Figure 7** and **Table 3** in Li and Baker (2022a). For the –18ºC specimens, the SRMin occurred over a range of strains from 1.81–2.9% at 20 m, at a fixed strain of 4.1% at 40 m, and at a strain oscillating between 1.1 and 1.8% at 60 m. These values of strain at different SRMin values are different from those usually observed at strains of 0.5–3% for fully-dense ice (e.g. Cuffey and Paterson, 2010), implying that different mechanical behavior between firn and

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Table 2. Observed and inferred strain rate minima and strains observed at the strain rate minima.

20 m	SRMin s^{-1}	PC1-SRMin s^{-1}	PC2-SRMin s^{-1}	PC3-SRMin s^{-1}	Strain %
–5ºC	5.53×10^{-6}	5.53×10^{-6}	1.68×10^{-6}	2.56×10^{-7}	11.8
–18ºC	1.36×10^{-6}	1.36×10^{-6}	2.29×10^{-7}	2.45×10^{-8}	1.81–2.9
–30ºC(U)	–	7.14×10^{-7}	2.17×10^{-7}	3.3×10^{-8}	–
–30ºC(L)	–	3.16×10^{-8}	9.6×10^{-9}	1.46×10^{-9}	–

40 m	SRMin s^{-1}	PC1-SRMin s^{-1}	PC2-SRMin s^{-1}	PC3-SRMin s^{-1}	Strain %
–5ºC	1.03×10^{-5}	3.39×10^{-5}	1.03×10^{-5}	1.57×10^{-6}	7.5
–18ºC	1.4×10^{-6}	8.32×10^{-6}	1.40×10^{-6}	1.5×10^{-7}	4.1
–30ºC(U)	–	4.37×10^{-6}	1.33×10^{-6}	2.03×10^{-7}	–
–30ºC(L)	–	1.94×10^{-7}	5.88×10^{-8}	8.97×10^{-9}	–

60 m	SRMin s^{-1}	PC1-SRMin s^{-1}	PC2-SRMin s^{-1}	PC3-SRMin s^{-1}	Strain %
–5ºC	5.59×10^{-6}	1.21×10^{-4}	3.67×10^{-5}	5.59×10^{-6}	2.7
–18ºC	5.33×10^{-7}	2.96×10^{-5}	4.99×10^{-6}	5.33×10^{-7}	1.1–1.8
–30ºC(U)	–	1.56×10^{-5}	4.74×10^{-6}	7.21×10^{-7}	–
–30ºC(L)	–	6.91×10^{-7}	2.1×10^{-7}	3.19×10^{-8}	–

The SRMin without the prefix is the observed values during creep, while the SRMin with a prefix is the inferred values. Note that PC-SRMin is the abbreviation of the post-calibration SRMin, and that –30ºC(U) and –30ºC(L) indicate the upper and lower bound from the –30ºC samples from 44.8 kJ mol^{-1} and 113 kJ mol^{-1}, respectively. PC1-SRMin, PC2-SRMin, and PC3-SRMin are described in **Appendix B**. The symbol – indicates the unavailable values of SRMin and the strain value at the SRMin observed during creep. The color fonts and backgrounds are described in **Appendix B**.

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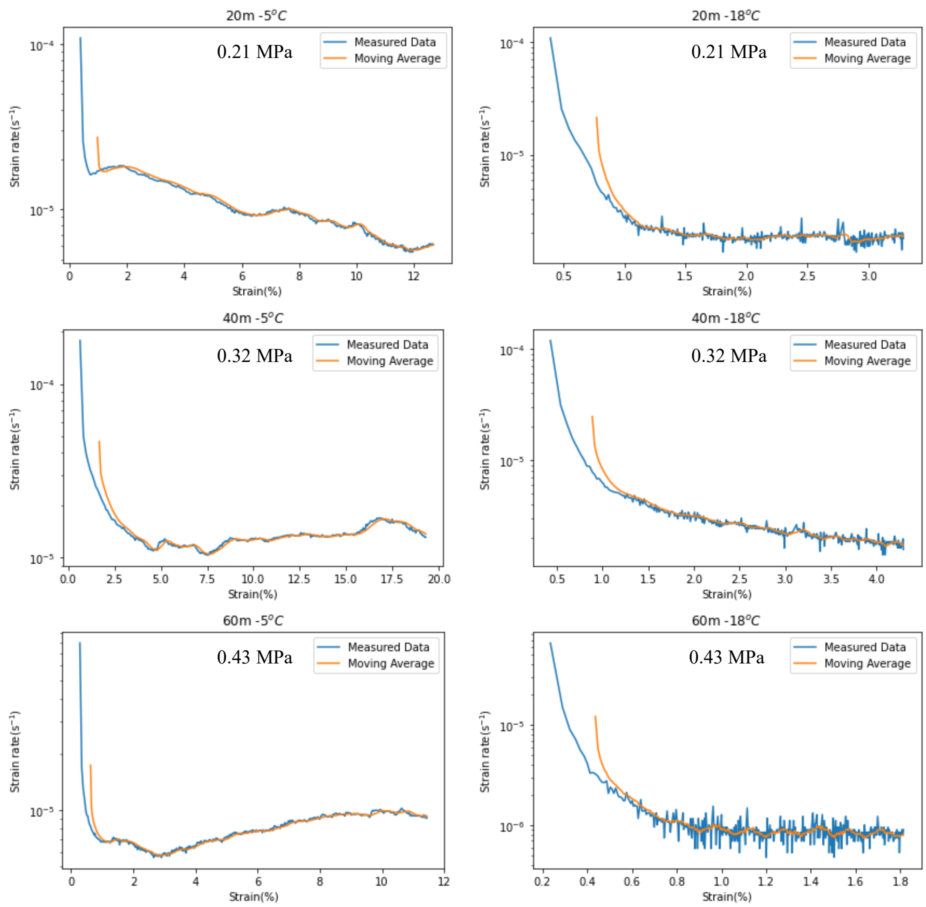

Figure 5: Log strain rate vs. strain from the firn specimens at temperatures of -5°C and -18°C from depths of 20 m (applied stress 0.21 MPa), 40 m (0.32MPa) and 60 m (0.43MPa). Samples from -30°C are not shown due to the very large noise. The blue lines represent discrete strain rates, which are calculated by extracting the strain data hourly, while the orange lines represent a moving average of 15 moving windows with respect to the strain.

pure ice (Li and Baker, 2022a). 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 –

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18ºC specimens at 40 m, where a larger strain was caused by the longer-lasting strain hardening (Li, 2023b). Additionally, tertiary creep occurs both during quasi-steady state deformation (from the –5ºC specimens at 40 m and 60 m) and in the ascending stage (from the –5ºC and –18ºC specimens at 20 m and the –18ºC specimen at 40 m) more easily with lower firn density, greater effective stress, and higher creep temperature, e.g. from the –5ºC specimens at 20 m, where the strain softening is primarily due to recrystallization.

3.5 *Apparent activation energy for creep*

Experimental observations of the SRMin are sparse and limited, as they only occurred for the –5ºC and at –18ºC specimens at each depth (**Table 2**). It is hard to achieve the SRMin for all firn specimens in laboratory environments (Landauer, 1958), especially under low temperatures and stresses such as those from the –30ºC specimens in this work. To this end, we offer the various possibilities of the SRMin using the evidence we have.

First, we attempted to estimate the apparent activation energy of creep, Q_c (kJ mol^{-1}), by rearranging the Arrhenius relation $\dot{\varepsilon}=A\sigma^{n}\exp(-Q_c/RT)$ to $Q_c = -R\left[\partial \ln\left(\dot{\varepsilon}/\sigma^{n}\right)/\partial\left(1/T\right)\right]$, where $\dot{\varepsilon}$ (s^{-1}) is the strain rate, A (s^{-1} Pa^{-n}) is the creep exponent factor, σ (MPa) is the applied stress, n is the creep (stress) exponent, R (8.314 J mol^{-1} K^{-1}) is the gas constant, and T (K) is Kelvin temperature, on the basis of *only* two SRMins from the –5ºC and –18ºC samples at each depth (**Table 2**). The Q_c values from the 20 m, 40 m, and 60 m specimens were calculated to be 61.4 kJ mol^{-1}, 87.3 kJ mol^{-1}, and 102.8 kJ mol^{-1}, respectively (**Figure 6**). Based on the three SRMins from the –5ºC and –18ºC samples at 60 m in this work, and from –10ºC samples at 60 m

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in Li and Baker (2022a), a Q_c value for the 60 m specimen was calculated to be 100.7 kJ mol^{-1}. To see whether or not these above Q_c values are reliable, we estimated the activation energy of grain-boundary diffusion/viscosity, Q_{gbd} (kJ mol^{-1}), using the relation $K = \left(D_t^2 - D_0^2\right)/t = k\exp(-Q_{gbd}/RT)$, in an alternative form of $Q_{gbd} = -R\left[\partial \ln K/\partial\left(1/T\right)\right]$, where K is the observed rate of grain growth (mm^2 a^{-1}), D_0^2 and D_t^2 are the measured mean grain area (mm^2) in a firn sample at the onset of the creep (t = 0), and at the end time of the creep (t-year), and k is a constant grain growth factor. The grain growth rates are plotted on a logarithmic scale against the reciprocal of T (**Figure 6**). For changes in grain size from the related specimens before and after creep see Li and Fu (2024). Correspondingly, the Q_{gbd} values calculated were 41.4 kJ mol^{-1}, 40.8 kJ mol^{-1}, and 40.9 kJ mol^{-1} for the specimens at 20 m, 40 m, and 60 m, respectively. These Q_{gbd} values are comparable to the values of 40.6 kJ mol^{-1} obtained in laboratory experiments on polycrystalline ice (Jumawan, 1972), and 42.4 kJ mol^{-1} from 13 polar firn cores (Cuffey and Paterson, 2010) for grain-boundary self-diffusion of polycrystalline ice. Further, the ratio of Q_{gbd}/Q_c is 0.67, 0.47, and 0.4 for the 20 m, 40 m, and 60 m specimens, respectively. We noted that the ratio of 0.67 for Q_{gbd}/Q_c was recommended by Hobbs (1974) and Cuffey and Paterson (2010). The Q_c values calculated using the Arrhenius relation for the 40 m and 60 m specimens are likely greater than the actual values, and hence are seemingly less reliable. There is little difference between the two-SRMin-derived Q_c value (102.8 kJ mol^{-1}) and the three-SRMin-derived Q_c value (100.7 kJ mol^{-1}), implying that these two methods for calculating Q_c have equal utility. Moreover, the above Q_{gbd} values are lower than the 48.6 kJ mol^{-1} that was inferred by the grain growth rate for firn samples with densities ranging from 320–650 kg m^{-3} from cores drilled at South Pole, Antarctic (Gow, 1969), which makes a ratio of 0.67

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for Q_{gbd}/Q_c an unreliable sole-criterion. In short, it is difficult to assess the reliability of both Q_c and Q_{gbd}, as discussed above due to their scatter and debates in the current literature. Thus, these Q_c values estimated in this work ranging from 61.4–102.8 kJ mol^{-1} are reasonable, falling within the range of 44.8–113 kJ mol^{-1} reported in the literature (**Table 3**).

A great challenge is the estimation of the Q_c using the SRMins including the –30ºC specimens, whose SRMin shows high variability due to the extraordinarily slow strain rate at low temperatures. This difficulty cannot be resolved by extrapolating experimental data (Sinha, 1978; Hooke et al., 1980), e.g. the use of Andrade's law (Glen, 1955). Instead, we turned our focus to studying the relationship between the SRMin and temperature by constraining our data in a wide range of Q_c values reported in the literature presented in Table 3. Clearly, there is a larger scatter of Q_c values for firn than for ice. The increase of Q_c from mono-crystalline and bi-crystalline to polycrystalline ice implies that the fewer the constraint of grain-boundaries, the greater is Q_c. 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 (Sect. 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).

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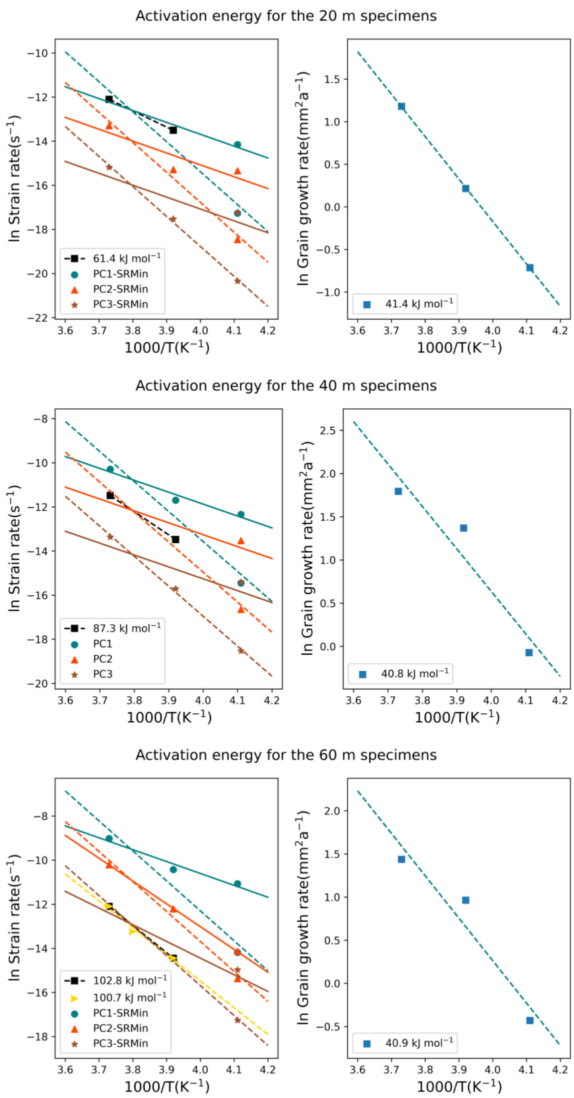

Figure 6: Arrhenius plots to estimate the apparent activation energy of creep (Q_c; left panel) and the apparent activation energy of grain-boundary diffusion (Q_{gbd}; right panel) from the firn specimens noted. The blue, magenta, and red solid lines are the upper bound (44.8 kJ mol^{-1}) of PC1-SRMin, PC2-SRMin, and PC3-SRMin, respectively, while the blue, magenta, and red dashed lines are the lower bound (113 kJ mol^{-1}) of PC1-SRMin, PC2-SRMin, and PC3-SRMin,

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respectively (Table 2). The blue circles, the magenta triangles, and the red stars are the data in Table 2. The black dashed lines are from *only* two SRMins at –5ºC and –18ºC (the black squares are the data measured), whose Q_c is indicated in each subfigure. The green dashed line is from the three SRMins at –5ºC, –18ºC in this work, and –10ºC from Li and Baker (2022a) (the green triangles are the measured data), whose Q_c is 110.7 kJ mol^{-1}. The blue dashed lines (right panel) are from grain growth rate at three temperatures (the blue squares are the observed data), whose Q_{gbd} is indicated in each subfigure.

Table 3. Apparent activation energy for the creep of firn and ice, Q_c, reported in literature.

Q_c kJ mol^{-1}	Sample	Density kg m^{-3}	Temperature ºC	Methods	Source
58.6–113	Firn	~400	[–13.6, –3.6]	Uniaxial/Hydrostatic Compression	Landauer (1958)
44.8–74.5	Firn/Bubbly Ice	440–830	[–34.5, –0.5]	Uniaxial Unconfined Compression	Mellor & Smith (1966)
54	Firn/Bubbly Ice	Undetailed	[−28, −16]	Shear Deformation of Boreholes	Paterson (1977)
~72.9	Firn	320–650	Unnecessary	Grain Growth Rate	Gow (1969)
69 ± 5	Firn	423 ± 8	[–19, –11]	Triaxial Compression	Scapozza & Bartelt (2003)
~60	Artificial/Natural Ice (South Pole)	~917	–15	Torsion Creep Test	Pimienta & Duval (1987)
61	Polycrystalline Ice	~917	–9.6	Hydrostatic Pressure	Duval et al. (1983)
78	Monocrystalline Ice	~917	[–30, –4]	Derived from Bicrystal Ice	Homer & Glen (1978)
75	Ice Bicrystal	~917	[–30, –4]	Tensile Test Parallel to Grain-boundary	Homer & Glen (1978)

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In principle, Q_c of firn should exceed that for polycrystalline ice. Intriguingly, some reported Q_c values from firn are less than that for ice, meaning the degree of spatial freedom in the ice-matrix is limited by the topological structure of the firn (Liu et al., 2022). Incidentally, the effective stress of porous materials is determined by not only its porosity, but also other factors, e.g. the microstructural topology (Liu et al., 2022) and the impurity types and concentrations in the firn. However, this issue is beyond the scope of this work. In summary, a Q_c for firn, which ranges from 44.8–113 kJ mol^{-1}, is plausible due to the intrinsic nature of natural firn that has a far more complicated and changeable microstructure than ice.

The stress exponent n is calculated from the measured SRMins (**Table 2**) to be ~0.1 and ~ –1.2 from the –5ºC and –18ºC samples, respectively, using Glen's law $\dot{\varepsilon} = A\sigma^n$. This is in disagreement with the reported n = ~4.3 by Li and Baker (2022a). Thus, the SRMin value from all the samples must be calibrated via a constraint from the n values. To proceed, the post-calibration SRMins for the –5ºC and –18ºC samples are highlighted in Table 2 (see **Appendix B** in detail). From here on we only discuss the applied stress since there is little difference between the effective stress and applied stress for calculating the stress exponent (Li and Baker, 2022a). Based on both the reported range of Q_c and the two observed SRMins at −5°C and −18°C, the SRMins for the −30°C samples are inferred (**Table 2**), using the Arrhenius relation.

Also, based on both the observed and inferred SRMins with the upper and lower bounds (**Table 2**), a series of fitted functions are then found between the SRMin and the reciprocal of the temperature (°C), $1/T_c$:

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$$\begin{cases} \mathrm{SRMin} = -3\times10^{-5}/T_c - 7\times10^{-7}[R^2 = 0.988; \mathrm{PC1(L20)}] \\ \mathrm{SRMin} = -3\times10^{-5}/T_c - 2\times10^{-7}[R^2 = 1; \mathrm{PC1(U20)}] \\ \mathrm{SRMin} = -1\times10^{-5}/T_c - 3\times10^{-7}[R^2 = 1; \mathrm{PC2(L20)}] \\ \mathrm{SRMin} = -9\times10^{-6}/T_c - 2\times10^{-7}[R^2 = 0.987; \mathrm{PC2(U20)}] \\ \mathrm{SRMin} = -2\times10^{-6}/T_c - 6\times10^{-8}[R^2 = 0.998; \mathrm{PC3(L20)}] \\ \mathrm{SRMin} = -1\times10^{-6}/T_c - 3\times10^{-8}[R^2 = 0.976; \mathrm{PC3(U20)}] \end{cases},$$

$$\begin{cases} \mathrm{SRMin} = -2\times10^{-4}/T_c - 4\times10^{-6}[R^2 = 0.988; \mathrm{PC1(L40)}] \\ \mathrm{SRMin} = -2\times10^{-4}/T_c - 2\times10^{-6}[R^2 = 1; \mathrm{PC1(U40)}] \\ \mathrm{SRMin} = -6\times10^{-5}/T_c - 2\times10^{-6}[R^2 = 1; \mathrm{PC2(L40)}] \\ \mathrm{SRMin} = -6\times10^{-5}/T_c - 1\times10^{-6}[R^2 = 0.987; \mathrm{PC2(U40)}] \\ \mathrm{SRMin} = -1\times10^{-5}/T_c - 3\times10^{-7}[R^2 = 0.998; \mathrm{PC3(L40)}] \\ \mathrm{SRMin} = -9\times10^{-6}/T_c - 2\times10^{-7}[R^2 = 0.976; \mathrm{PC3(U40)}] \end{cases},$$

$$\begin{cases} \mathrm{SRMin} = -7\times10^{-4}/T_c - 2\times10^{-5}[R^2 = 0.988; \mathrm{PC1(L60)}] \\ \mathrm{SRMin} = -6\times10^{-4}/T_c - 6\times10^{-6}[R^2 = 1; \mathrm{PC1(U60)}] \\ \mathrm{SRMin} = -2\times10^{-4}/T_c - 7\times10^{-6}[R^2 = 1; \mathrm{PC2(L60)}] \\ \mathrm{SRMin} = -2\times10^{-4}/T_c - 4\times10^{-6}[R^2 = 0.987; \mathrm{PC2(U60)}] \\ \mathrm{SRMin} = -3\times10^{-5}/T_c - 1\times10^{-6}[R^2 = 0.998; \mathrm{PC3(L60)}] \\ \mathrm{SRMin} = -3\times10^{-5}/T_c - 7\times10^{-7}[R^2 = 0.976; \mathrm{PC3(U60)}] \end{cases},$$

where PC1(L20) and PC1(U20) indicate the lower and upper bound values of the post-calibration SRMins from the 20 m samples (**Table 1**), and other symbols are similarly formatted, e.g. PC1(L40), PC1(U40), PC1(L60), PC1(U60), and so on. These relationships are plotted in **Figure 7**, where the SRMin vs. $1/T_c$ plots from the three depths are almost the same shape, implying that the SRMin is dependent on the temperature at a constant stress. It is important to note that the average (minimum) strain rate for the secondary creep stage for a given temperature increases

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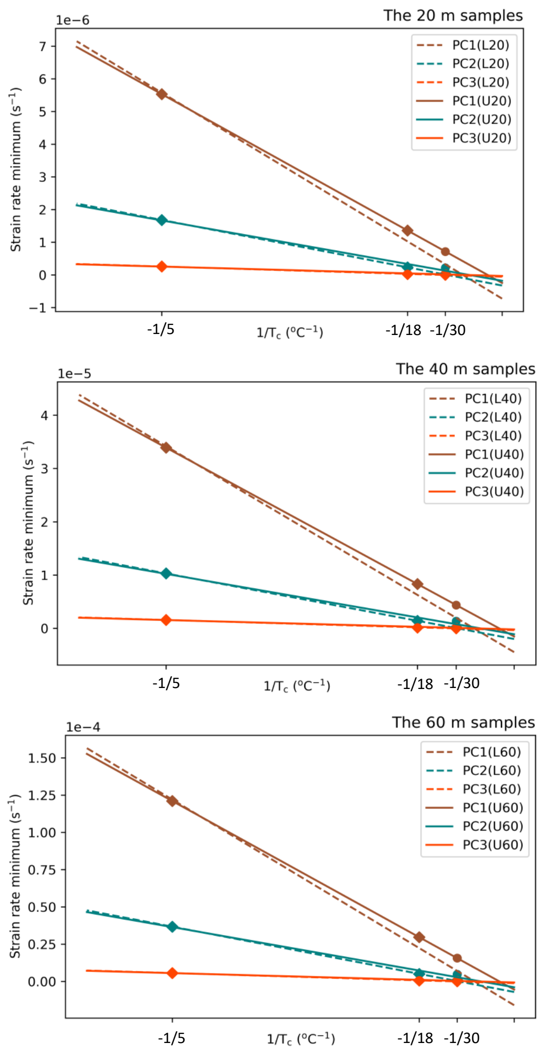

Figure 7: Plots of the strain rate minimum versus the reciprocal of temperature. PC1(L20) and PC1(U20) indicates the lower and upper bound, respectively, from the 20 m samples via PC1 as noted in Table 2, and so on. The circles indicate the upper bound data measured and inferred, while the squares indicate the lower bound data. The dashed line is the fit from the lower bound, while the solid line is the fit from the upper bound.

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with increasing depth/density of the samples (**Figure 7**; **Table 2**). This is opposite to a decrease of the SRMin at a fixed stress and temperature in **Figure 7** and **Table 3** in Li and Baker (2022a). These changes in SRMin are irrespective of the stress (**Appendix A**). The temperature plays a predominant role during firn creep for a given density of sample at a constant stress. An interesting question on firn creep at a specific temperature is whether the SRMin slows down or speeds up with decreasing density of firn. Certainly, natural firn samples raise the complexity in interpreting the firn creep due to the influences both from inclusions (Li and Baker, 2022a and references therein; Li, 2024), and from the topology of the microstructures (Liu et al., 2022). In addition, there is a broad spread of the SRMin at each depth, in which the SRMin varies by several times, even one order of magnitude or more between the different possibilities of post-calibration SRMins (**Figure 7**), implying that the microstructure of the sample significantly influences the process of the creep of firn. Moreover, it is hard to generalize a universal formula for predicting the SRMin at temperatures below −30°C, where the SRMins becomes negative (**Figure 7**). Thus, there is a need for an in-depth understanding of the polar firn creep behavior in secondary creep stage.

To illustrate the differences between the Q_c values calculated from PC1-SRMin, PC2-SRMin, and PC3-SRMin, we have plotted them in **Figure 6**. Interestingly, the Arrhenius plots of the natural logarithm of strain rate with 1000/T (**Figure 6**) are similar to those observed by Glen (1955) and Homer and Glen (1978), implying that there is no significant difference in the creep mechanism for a temperature range of –30°C to –5°C (Glen, 1955; Homer and Glen, 1978), where both diffusion via grain-boundary, vacancy or interstitial defects (Barnes et al., 1971; Brown and

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George, 1996; Nasello et al., 2005; Li and Baker, 2022b) and dislocations contribute to the creep of polar firn.

4. Conclusions

Constant-load creep tests were performed on three cylindrical specimens tested from depths of 20 m (applied stress 0.21 MPa), 40 m (0.32MPa) and 60 m (0.43MPa) at temperatures of –5 ± 0.2ºC, –18 ± 0.2ºC, and –30 ± 0.2ºC from a firn core extracted at Summit, Greenland in June, 2017. The microstructures were characterized before and after creep testing using the micro-CT and thin sections viewed between optical crossed polarizers. It was found that:

1. Microstructural parameters measured using the micro-CT show that the polar firn densified during the creep compression (e.g. from 685 to 729 kg m^{-3} for the 40 m specimen at –5ºC), *viz.*, the TP (from 25.5 to 20.7%), the ECDa (from 0.86 to 0.69 mm), the SSA (from 3.26 to 3.02 mm^{-1}), and the SMI (from –1.85 to –2.8) decreased, while the S.Th (from 0.95 to 0.99 mm) and the CP (from 0.01 to 0.02%) increased. Anomalies in the microstructures, especially at low temperatures of –18ºC and –30ºC, are likely due to metamorphism under temperature gradients, the radial dilation effect during firn deformation, the measurement uncertainty of the micro-CT, or the anisotropy and the heterogeneity of natural firn.
2. The transient creep behavior of firn at constant stress and different temperatures obeys an Andrade-like law, but, the time exponent *k* of 0.34–0.69 is greater than the 0.33 found for ice. This is due to fewer grain-boundary constraints in porous firn than in ice.
3. The secondary creep behavior of firn at constant stress and different temperatures presented

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here shows that the strain at the SRMin increases with decreasing firn density and increasing creep temperature. In particular, low-density firn during creep at high temperatures shows that the strain at the SRMin, e.g. 11.8% and 7.5% respectively from the 20 m and 40 m specimens at –5°C, is greater than the strain of 3% that is the maximum found at the SRMin of ice.

4. The tertiary creep behavior of firn at constant stress and different temperatures is more easily observed from lower-density specimens at greater effective stresses and higher creep temperatures. The strain softening in tertiary creep is primarily due to recrystallization.
5. The apparent activation energy for the firn creep has a wide range of 61.4–102.8 kJ mol^{-1} because the grains in firn slide more easily along more directions in the more porous and heterogeneous structure, the enhanced fluidity from inclusions, and the topological structure of the firn. In addition, the SRMin is a function of the temperature, depending on the microstructure of firn and the inclusion content. The predicted SRMin increases with increasing firn density at a given temperature, and is independent on the effective stress. Lastly, there is no significant difference in creep mechanism at temperatures ranging from –30°C to –5°C.

The creep of polar firn behaves differently from full-density ice, implying that firn densification is an indispensable process in fully understanding the transformation of ice from snowfall in the polar areas. Observed firn deformation indicates that temperature plays a determined role in firn densification. Thereby, it will be helpful to bridge a gap between the firn temperature and climate of the past for reconstructing paleoclimate. Also, it will be helpful to apply a confining load to investigate the microstructure of the creep of polar firn with smaller initial particle sizes at low

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temperatures using the micro-CT. Further studies of interest are to investigate the quantitative relationship between the microstructural parameters and the mechanical behavior of polar firn, and when the onset of recrystallization occurs during creep, as well as verify the SRMin predicted by the relationship of SRMin vs. temperature from the firn specimens at more extensive ranges of stresses and temperatures.

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Appendix A: Hydrostatic pressure, the applied stress, and the effective stress

The hydrostatic pressure, p, was calculated from the overburden of snow, using $p=\bar{\rho}_f gh$, where $\bar{\rho}_f$ is the average firn density above the depth of interest, h, and g is the acceleration of gravity. At Summit, p at the depths of 20 m, 40 m, and 60 m was estimated to be ~0.1 MPa, ~0.22 MPa, and ~0.38 MPa, respectively. Note that the slope of the surface of ice sheets and glaciers at Summit is idealized to be zero, i.e. their surfaces are horizontal. The applied stress, σ, is the applied load divided by the cross-sectional area of a sample. The σ at the depths of 20 m, 40 m, and 60 m were 0.21 MPa, 0.32 MPa, and 0.43 MPa, respectively. The effective stress, $\tilde{\sigma}$, is defined as σ divided by the fraction of ice matrix in firn, see in detail from Li and Baker (2022a). Thereby, $\tilde{\sigma}$ is 0.32 MPa (the mean porosity of 34.9%), 0.43 MPa (24.8%), and 0.5 MPa (14.4%) from the 20–60 m samples, respectively. Note that the stresses were vertically loaded on the sample (parallel to the direction of core axis of the sample) in laboratory tests. Ideally, in order to be analogous to the densification of firn in nature, $\tilde{\sigma}$ for laboratory samples from a given depth should be equal to the p of firn *in situ* at an equivalently same depth at Summit, namely $\tilde{\sigma}$/p = 1. However, in consideration of the laboratory timeframe for experiments (Pimienta and Duval, 1987), the stresses applied in laboratory tests are usually higher with a resulting higher rate of deformation than those *in situ*. Thus, to observe the effect of the stress on the creep of firn with different densities at different depths, we designed the following configuration of the $\tilde{\sigma}$/p with depth, *viz.*, 0.32 MPa/~0.1 MPa = ~3.2, 0.43 MPa/~0.22 MPa = ~1.95, and 0.5 MPa/~0.38 MPa = ~1.32 for the samples from the depths of 20 m, 40 m, and 60 m, respectively. In this manner, the decrement of $\tilde{\sigma}$/p with increasing depth represents the decrease of the effective stress with increasing depth.

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Appendix B: Strain rate minimum inferred via two kinds of constraints

To improve the reliability of inferred SRMins, two kinds of constraints were applied. First, the SRMins from the –5ºC and –18ºC samples are calibrated using Glen' law $\dot{\varepsilon}=A\sigma^{n}$ with n = 4.3 (Li and Baker, 2022a). PC1-SRMin, PC2-SRMin, and PC3-SRMin indicate three possibilities of the SRMins that are calculated in turn from the 20 m, 40 m, and 60 m samples via the *only* SRMin observed at a given temperature (Table 2). As an example, for the –5ºC samples there exist three possibilities from three depths. 1) The SRMin observed from the 20 m sample in the orange font with grey background is used to respectively calculate two other SRMins for the 40 m and 60 m samples in the dark red font in the column of PC1-SRMin. 2) In the same manner as in scenario 1), the SRMin observed from the 40 m sample is calculated in the column of PC2-SRMin, and the SRMin observed from the 60 m sample is calculated in the column of PC3-SRMin. 3) In the same manner as in scenarios 1) and 2), the SRMin is calculated for the –18ºC samples in the blue font with grey background in turn from three depths. Second, the SRMin of the –30ºC samples is inferred on the basis of the range of Q_c, i.e. from 44.8 kJ mol^{-1} (upper bound) to 113 kJ mol^{-1} (lower bound), using the Arrhenius relation.

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Data availability

The data supporting the conclusions in this study are available at https://arcticdata.io/catalog.

Author contribution

YL and IB designed the experiments and YL carried them out. YL analyzed the data and visualized the relevant results. YL prepared the manuscript with contributions from all co-authors.

Competing interests

At least one of the (co-)authors is a member of the editorial board of The Cryosphere.

Acknowledgements

This work was sponsored by the National Science Foundation Arctic Natural Science grant 1743106. Y. L. is grateful to Ciao Fu for the great support and help in COVID-19. The authors wish to thank Chris Polashenski, Zoe Courville and Lauren B. Farnsworth at USA-CRREL for their help with storage of the firn cores. The authors acknowledge the use of the Ice Research Laboratory (Director-Erland Schulson) at Dartmouth College.

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