

Temperature Dependence of Ice Crystal Size in Tibetan Ice Core

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Abstract. Ice crystal sizes in ice cores can not only reflect the glacial strain processes but also be linked to climate change. However, the variation of ice crystal sizes along ice cores in mountain glaciers remain largely unexplored. Here, we continuously measured the ice grain areas along two deep ice cores drilled from the Tibetan Plateau, and found that the two
10 ice cores exhibit vertical grain area differentiation at the hundred-meter scale, analogous to polar ice-core profiles. Relatively higher temperatures significantly accelerate grain growth and result in larger grain areas. Refreezing under warm conditions gives rise to abrupt increases in grain area within melt-refrozen layers, whereas impurities result in abrupt decreases in grain area within impurity layers. Together, these two factors drive centimeter-scale fluctuations in grain area. Even so, we also found that grain area exhibits a significant correlation with $\delta^{18}\text{O}$ in ice layers where Rotation Recrystallization
15 (RRX)-induced refinement is negligible, indicating that the ice crystal size of mountain glacier ice cores can retain temperature signals.

1 Introduction

As a critical component of the Earth's climate system, glaciers not only dynamically feedback to global climate patterns but also enable systematic reconstruction of past glacial evolution and climatic history through the physical and chemical records
20 in ice cores. Ice microstructure represents a key physical property widely studied in ice core research. Pioneering work on ice microstructure was first carried out by Perutz & Seligman (1939) on the Great Aletsch Glacier. Since then, systematic studies have been conducted on mountain glacier surface ice and deep polar ice cores (Rigsby, 1951, 1960; Kamb, 1959; Gow, 1969; Gow et al., 1997; Faria et al., 2014a). These studies show that ice crystal size can reflect glacial strain processes (Gow and Williamson, 1976; Alley et al., 1986a, b; Hellmann et al., 2021) and retain signals of climate change. Specifically,
25 ice crystal size is smaller in ice layers dating to cold periods and larger in those from warm periods (Svensson et al., 2003; Durand et al., 2007; Fitzpatrick et al., 2014).

After decades of research, the polar ice core “three-stage model” has been widely adopted to describe ice crystal size variation profiles and to clarify grain growth/recrystallization mechanisms (Alley et al., 1986a, b; Faria et al., 2014a). However, high-resolution studies have revealed limitations in this classic model, especially for short-scale ice crystal

30 variations and multi-factor interactions, stimulating ongoing refinements and scientific debates (Kipfstuhl et al., 2006, 2009; Weikusat et al., 2009; Faria et al., 2014b; Kerch, 2016).

Compared with polar glaciers, ice crystal evolution is far more complex in mountain glaciers, which typically feature higher temperatures, greater accumulation rates, and faster flow velocities (Clavette, 2020; Hellmann et al., 2021; Jennings & Hambrey, 2021; Li et al., 2026). These characteristics drive rapid changes in crystal size and fabric, and even induce
35 significant centimeter-scale fluctuations in ice microstructures (Tison & Hubbard, 2000; Kerch, 2016; Hellmann et al., 2021; Hruby et al., 2020; Monz et al., 2021; González-Santacruz et al., 2023).

The Tibetan Plateau constitutes the core of High Mountain Asia (HMA), widely recognized as the Third Pole, and hosts numerous typical mountain glaciers. These glaciers are particularly sensitive to climate change (Bolch et al., 2012; Yao et al., 2012; Sakai & Fujita, 2017). Diverse climatic and topographic conditions across the plateau (Nie et al., 2021) lead to distinct
40 ice formation processes and different microstructural characteristics (Zhang et al., 1993; Li et al., 2017, 2026). However, systematic investigations of ice crystal evolution, recrystallization, and their responses to thermal conditions remain very limited in this region.

This study is thus based on two ice cores recovered using an electromechanical drill from the accumulation zones of mountain glaciers on the Tibetan Plateau: Animaqing (ANMQ) and Bugyai Kangri (BJGR) (Fig. 1a). Using a Microstructure
45 Mapping system following established protocols (Kipfstuhl et al., 2006; Fegyveresi, 2015; Kerch, 2016), we successfully obtained continuous longitudinal microstructure images spanning from the firn to the base of both ice cores. We present the first continuous ice grain area profiles for mountain glacier ice cores. This dataset compensates for the centimeter-scale microstructural variations missed by traditional discrete sampling.

This study aims to address three key questions: (1) What are the vertical variations in ice crystal size and recrystallization
50 mechanisms in mountain glacier ice cores under high-temperature conditions? (2) How do impurities and refreezing processes affect centimeter-scale fluctuations? (3) Can ice crystal size in mountain ice cores retain information about climate change? By providing new microscopic evidence, this study advances the fundamental understanding of ice crystal size variation and recrystallization mechanisms in mountain glacier ice cores and offers a new perspective for exploring the responses of Tibetan Plateau mountain glaciers to climate change.

55 **2 Samples and methods**

In November 2020, a full-depth ice core was drilled from the summit accumulation zone of the Weigeledangxiong Glacier, Mount Animaqing, eastern Kunlun Mountains (ANMQ: 169.45 m length, 9.4 cm diameter, 99.45° E, 34.81° N, 5750 m a.s.l.). This glacier has a total length of ~10 km and an area of 12.53 km², making it one of only three glaciers exceeding 10 km² in the region (Liu et al., 2015). In November 2022, another full-depth ice core was drilled from the summit
60 accumulation zone on the southern slope of Mount Bugyai Kangri, eastern Tanggula Mountains (BJGR: 77.6 m length, 8.2 cm diameter, 94.7094° E, 31.8118° N, 6180 m a.s.l.). This glacier stretches 10.6 km with an area of 22.27 km². Climate in

both regions is dominated by the Asian monsoon. The annual precipitation and average temperature near the ELA (BJGR: 5300–5400 m a.s.l., ANMQ: 4900–5190 m a.s.l.) are 600–700 mm and -6°C for the BJGR region, and 700–900 mm and -9.4°C for the ANMQ region (Liu et al., 2016; Jiang et al., 2018). Over recent decades, these two regions have experienced a significant warming trend, with precipitation showing a fluctuating increase and concentrated in summer. Both glaciers have been retreating in recent decades.

Ice core drilling was initiated from excavated snow pits at depths of 1.5 m (ANMQ) and 1.4 m (BJGR) using an electromechanical drill. The recovered ice cores were sealed in clean polyethylene bags, placed in insulated hard-core barrels, transported by refrigerated truck, and stored in the -20°C ice core laboratory at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (ITPCAS). The density of each ice core section was calculated from its measured length, diameter, and mass in this laboratory. While the density of each ice slice was deduced using the formula: slice density = $(1 - \text{porosity}) \times 0.917 \text{ g/cm}^3$ (Kerch, 2016). In Figure A2b, we present the slice density profiles. The borehole temperatures were measured with a 152 m-long cable (Cable No. 16BX-XBQ-1A) equipped with 15 platinum RTD sensors at 1 m intervals, with a measurement accuracy of $\pm 0.02^{\circ}\text{C}$. At each depth, sensors were stabilized for at least 30 minutes to ensure thermal equilibrium between borehole air and the surrounding ice. Temperatures below 150 m were not measured in the ANMQ ice core. Based on the positive linear temperature trend from 130 m (-6.56°C) to 152 m (-6.23°C) ($R^2 = 0.93$), the basal temperature at 170 m depth is estimated to be approximately -5.94°C .

We prepared vertical ice slices following standard microtoming procedures (Fig. 2a; Kipfstuhl et al., 2006; Fegyveresi, 2015; Kerch, 2016). First, continuous ice slabs were cut longitudinally along the ice core using a band saw. These slabs were then cut into smaller pieces 6–10 cm in length, ~ 4.5 cm in width, and ~ 7 mm in thickness. For the BJGR ice core, sampling started at 22.30 m and continued downward to the base, yielding a total of 560 slices (covering 71% of the total length). For the ANMQ ice core, sampling started at 14.94 m and continued downward to the base, yielding 1890 slices (covering 91% of the total length). The upper firn section of both ice cores was not sampled, as they were too porous and unconsolidated to prepare thin sections. The slices were then frozen onto microtome glass plates using a $\sim 1\%$ ethanol solution, and were microtomed to a flat surface with a Leica SM2000R microtome (Fig. A5). Finally, the slices were placed in a lidded foam box and sublimated at -20°C for approximately 15 hours until their surfaces were smooth and grain boundaries were clearly visible.

We used a Microstructure Mapping system to acquire microstructural images, following protocols described in previous studies (Fig. 2b; Kipfstuhl et al., 2006; Fegyveresi, 2015; Kerch, 2016). The system comprises an imaging module (a Canon EOS 5D Mark IV camera with an 180 mm macro lens), an illumination module (a vertical coaxial light and controller), and a manual X-axis translation stage. Photographic parameters, autofocus, and image capture were controlled using Canon Camera Connect software.

Each ice slice was placed on a black sponge background and illuminated under vertical coaxial light. Under this lighting, air bubbles and grain boundaries appear dark, while subgrain boundaries appear gray. Each panoramic slice image, with a resolution of $\sim 8 \mu\text{m}$ per pixel, was automatically and seamlessly stitched from 5 consecutive photographs using the

Photomerge function in Adobe Photoshop (Fig. 2c). The irregular edges of each panoramic slice image were cropped, and interfering features (e.g., scratches and cracks) were manually removed. Binary segmentation was performed using the U-Net neural network (Ronneberger et al., 2015), and grain boundary maps were generated using ImageJ software with its MorphoLibJ plugin (Fig. 2a–2c; Legland et al., 2016). After scale calibration, grain and bubble areas, positions, and shapes were automatically extracted into a .CSV file using the Particle Analysis function in ImageJ. These results were then combined with depth data for statistical analysis. Grains with an area smaller than 0.01 mm² and bubbles with an area smaller than 0.006 mm² were excluded from the analysis (Fegyveresi, 2015; Kerch, 2016).

3 Results and discussion

3.1 Grain area profile and recrystallization mechanism

Fresh snow crystals (~1 mm²) evolve continuously with increasing depth and time, adapting to temperature and stress conditions via deformation and recrystallization (Gow, 1969). This evolutionary process can be characterized by microstructural images and ice crystal size statistical data. In this study, we observed that the vertical profiles of grain area, porosity, and density in the ANMQ and BJGR ice cores exhibit hundred-meter-scale differentiation patterns analogous to polar ice cores profiles (Fig. 4, and A1; Faria et al., 2014a). Based on this observation, we classified their grain area profiles into distinct layers and analyzed the dominant recrystallization mechanisms. These efforts aim to establish a foundational understanding of ice crystal size variation in Tibetan Plateau mountain glacier ice cores.

3.1.1 Firn layer (ANMQ: 0–35 m; BJGR: 0–35 m)

In this layer, as depth increases, numerous irregularly shaped unclosed pores are progressively compressed, leading to an increase in density. Both ice cores reached the critical density of 0.830 g/cm³ for pore closure at ~35 m depth (Fig. A2b; Dadic et al., 2019). The average grain area of both ice cores is less than 2 mm² and increases slowly with depth (ANMQ: 2–5 mm²; BJGR: 1–3 mm²). Grains > 1 mm² and those ≤ 1 mm² each account for approximately 50% of the total, while grains > 5 mm² account for ~10% (Fig. 4) of both ice cores.

3.1.2 Firn-ice transition layer (ANMQ: 35–45 m; BJGR: 35–45 m)

In this layer, pores become isolated from the free atmosphere, with ~10% of the original air volume eventually trapped as enclosed bubbles and gradually compressed into ellipsoidal shapes (Schaller et al., 2017). The firn transforms into ice, and the average grain area of both ice cores increases rapidly with fluctuations (ANMQ: 10–20 mm²; BJGR: 5–10 mm²). The ice crystal size becomes heterogeneous, and grain boundaries begin to curve.

Notably, the firn layer and Firn-ice transition layer exhibit consistent evolutionary trends (these two layers are often classified as a single unit in polar ice core studies). The average grain area increases while the grain number decreases. The average grain area and proportion of grains > 5 mm² increase, whereas the small-grain average grain area decreases and their

proportion increases slightly (Fig. 4). Additionally, typical "foam" textures formed by Normal Grain Growth (NGG) are observable in microstructure images (Fig. 3d) (Svensson et al., 2005; Kipfstuhl et al., 2009). This indicates that grain growth primarily results from larger grains consuming smaller ones.

130 These observations indicate that ice crystal size in these two layers is significantly influenced by NGG, which is primarily regulated by temperature (Gow, 1969). Generally, higher temperatures tend to promote the formation of larger ice crystals (Cuffey & Paterson, 2010), such that the grain area of the ANMQ ice core with higher temperature (Fig. 1b) is larger than that of the BJGR.

3.1.3 RRX layer (ANMQ: 45–140 m; BJGR: 45–73 m)

135 In this layer, the average grain area stabilizes and declines to $\sim 5 \text{ mm}^2$. Both the average grain area and proportions of grains $> 5 \text{ mm}^2$ gradually decrease, while the small-grain proportions and total grain number increase (Fig. 4, and A2a). In microstructure images, abundant subgrain boundaries are observed (Fig. 3e). This indicates that the average grain area decline primarily results from large grains splitting into smaller ones.

140 These observations indicate that this layer is mainly influenced by RRX. Under stress conditions, subgrain boundaries form inside grains and gradually develop into grain boundaries, splitting large grains into smaller ones (Kipfstuhl et al., 2009; Weikusat et al., 2009; 2017). This stress-induced grain refinement restricts the growth of large grains (Duval and Castelnau, 1995). However, the average grain area in deeper, warmer section of ANMQ remains larger than that in the shallower, colder section of BJGR, even though ANMQ experiences higher vertical stress. This confirms that higher temperatures enhance grain growth, resulting in a larger equilibrium grain area (Gow, 1969; Cuffey and Paterson, 2010; Montagnat et al., 2014). Grain size in the RRX layer thus represents a balance between stress-driven refinement and temperature-driven growth, 145 consistent with polar ice core studies (Alley et al., 1986a, b; Faria et al., 2014a, b; Weikusat et al., 2017).

3.1.4 SIBM layer (ANMQ: 140–169.5 m; BJGR: 73–77.6 m)

150 This layer is located at the bottom of the ice core. The average grain area increases rapidly with drastic fluctuations. The growth rate of grains $> 5 \text{ mm}^2$ is approximately 10 times higher than that in the Firn-ice transition layer (Fig. A3), with their proportion rising rapidly (Fig. 4). In microstructure images, large grains exhibit interlocked structures, accompanied by the connection between subgrain boundaries and highly curved grain boundaries (Fig. 3f).

These observations are consistent with rapid grain boundary migration dominated by Strain-Induced Boundary Migration (SIBM), which tends to occur when ice temperatures are above $-10 \text{ }^{\circ}\text{C}$ (Duval and Castelnau, 1995; Faria et al., 2014b). The basal temperatures of both ice cores satisfy this criterion (BJGR: -8.31 – $-8.17 \text{ }^{\circ}\text{C}$, ANMQ $> -6.38 \text{ }^{\circ}\text{C}$). Notably, in the ANMQ ice core, ice temperature reaches its minimum of $-6.84 \text{ }^{\circ}\text{C}$ at 126 m depth, where grain area is also minimized at 155 $\sim 5 \text{ mm}^2$. Below 126 m, the temperature trend reverses from decreasing with depth to increasing, and grain size increases accordingly. Below 150 m ($> -6.27 \text{ }^{\circ}\text{C}$), grains grow rapidly, accompanied by abnormally large grains ($> 400 \text{ mm}^2$) and a 5

m thick basal bubble-free ice layer. These observations indicate that basal temperature also influences ice crystal size in this SIBM layer.

3.2 Temperature, melt-refreezing, and impurity effects on ice crystal size

160 The above results indicate that temperature influences ice crystal size by regulating recrystallization across all layers. Furthermore, temperature differences have also contributed to variations in ice formation processes between the two ice cores.

The BJGR ice core, with relatively lower temperatures, exhibits lower firn density and smaller ice crystal sizes. Firn density and grain area increase gradually and steadily with minimal fluctuations, and melt-refrozen ice are rarely observed,
165 consistent with the typical Cold-type Ice Genesis (i.e., ice formation without meltwater involvement; Gow, 1969; Cuffey and Paterson, 2010; Kerch, 2016). Before pore closure, the higher surface energy of smaller grains tends to drive sublimation, some water molecules condense on larger grains with lower surface energy, while others diffuse into the free atmosphere. After pore closure, large grains grow rapidly by consuming smaller ones.

The ANMQ ice core, with relatively higher temperatures and surface temperature approaching 0 °C, contains numerous
170 centimeter-scale melt-refrozen ice layers in its firn layer (Fig. 5a). Firn density and grain area exhibit substantial fluctuations, consistent with typical Warm-type Ice Genesis (i.e., ice formation involving meltwater percolation; Gow, 1969; Cuffey and Paterson, 2010; Kerch, 2016). Meltwater percolation and liquid-mediated recrystallization drive accelerated densification and larger ice crystal sizes (Wilson et al., 2023), with both the average grain area and growth rate exceeding those of BJGR. Additionally, these high-temperature-induced melt-refrozen ice layers lead to abrupt increases in average grain area and
175 serve as a critical factor driving centimeter-scale average grain area fluctuations.

We compared the two ice cores with four additional ice cores from mountain glaciers in the eastern Tibetan Plateau, Tianshan Mountains, and European Alps (Table A1; Zhang et al., 1993; Tison & Hubbard, 2000; Kerch, 2016; Li et al., 2017). At a depth of ~35 m, we observed the following ice temperature ranking: Tsanfleuron > Urumqi Glacier No. 1 > ANMQ > BJGR > KCC > Guliya. This ranking is broadly consistent with the grain area ranking at the same depth: Urumqi
180 Glacier No. 1 > ANMQ > BJGR > KCC. These comparisons further confirm that temperature is the dominant factor controlling grain growth in these mountain glaciers. Note that the grain areas of the Tsanfleuron and Guliya ice cores were measured using the linear intercept method (Pickering, 1976), which tends to overestimate the average grain area.

We also observed numerous impurity layers (mm to cm scale) in both ice cores (Fig. 5b). Within these layers, abundant small grains (typically < 2 mm²) form multiple small-grain walls, leading to abrupt decreases in average grain area.
185 Generally, the cumulative thickness of all impurity layers within one meter of ice is < 20 cm (Fig. A4). However, in the ANMQ ice core, a dense zone of impurity layers occurs at 120–140 m depth, where the cumulative thickness of impurity layers within one meter reaches up to 90 cm. This thickness shows a strong negative correlation with average grain area ($r = -0.715$, $p < 0.01$; Fig. A4). A less prominent dense zone of impurity layers is also observed in the BJGR ice core at 66–75 m depth, which also shows an inverse correspondence between impurity layer thickness and grain size. This indicates that, in

190 these two ice cores, impurity-induced grain growth restriction is another critical factor driving centimeter-scale average grain area fluctuations.

A similar inverse relationship between impurity content and grain size has also been documented in a study of the Monte Perdido Glacier in the Pyrenees (González-Santacruz et al., 2023). Polar ice core research also shows ice crystal sizes in impurity layers are typically smaller and negatively correlated with impurity concentration (Alley and Woods 1996; 195 Svensson et al., 2005). This is generally interpreted as impurities inhibiting grain boundary migration by reducing migration rates and "pinning" grain boundaries, thereby restricting grain growth (Weiss et al., 2002; Durand et al., 2006; Faria et al., 2010; González-Santacruz et al., 2023). In our samples, grain boundary pinning features are visible in the micrographs from both ice cores. But the exact nature of the pinning particles cannot be fully resolved owing to resolution limits. Notably, some studies have suggested that impurities will change ice properties by influencing grain internal strain (Eichler et al., 200 2017, 2019; Stoll et al., 2021). However, the deep discussion of these mechanisms is beyond the scope of the present work and may be addressed in future research.

3.3 The link between ice crystal size and climate change

Ice crystal size is significantly influenced by ice temperature, which is modulated by air temperature. Theoretically, ice crystal size can preserve climate change information. Studies on polar ice cores (e.g., NGRIP, EDC, WAIS) indicate that ice 205 crystal size is typically linked to climate history: average grain area usually correlates with other climate proxies (e.g., $\delta^{18}\text{O}$), and its abrupt changes often correspond to cold-warm transitions or paleoclimatic cold/hot events (Svensson et al., 2003; Durand et al., 2007; Fitzpatrick et al., 2014). However, the ice crystal size of these two ice cores is influenced by high temperatures, melt-refrozen ice layers, and impurities—can it still retain climate information amid these multiple influences? In studies of Tibetan Plateau ice cores, $\delta^{18}\text{O}$ have been widely used to reconstruct climate change history (Thompson et al., 210 1997). We compared the average grain area with $\delta^{18}\text{O}$ of these two ice cores and found that, at 45–51 m depth in both ice cores, their average grain area and $\delta^{18}\text{O}$ show comparable fluctuation: the BJGR ice core show a significant negative correlation ($r = -0.286$, $p < 0.01$; Fig. 6a, 6b), while the correlation is insignificant in the ANMQ due to strong refreezing interference. According to the dating results, the age ranges corresponding to this depth interval are 1975–1985 for BJGR and 1957–1969 for ANMQ, respectively. This suggests that grain area may retain the signal of seasonal climate variations. 215 Additionally, average grain area and $\delta^{18}\text{O}$ also show comparable fluctuation in the dense zone of impurity layers: the ANMQ ice core shows a significant correlation ($r = 0.205$, $p < 0.01$; Fig. 6c, 6d), while the correlation is insignificant in the BJGR due to lower impurity layers density. The low $\delta^{18}\text{O}$ values in the dense zone of impurity layers indicate cold climatic periods (No definitive age constraints are available for this depth interval; however, it is inferred to be on the centennial scale), which aligns with previous studies demonstrating that densified impurity layers and elevated dust concentrations 220 typically occur during cold periods (Ram et al., 1997; Mahowald et al., 1999; Overpeck et al., 1996).

At 45–51 m depth, RRX-induced grain refinement is minimal since low vertical pressures, and grain growth dominated by temperature-dependent NGG. In the dense zone of impurity layers, low temperatures and impurity-induced restriction result

in smaller ice crystal sizes and limited strain accumulation, thereby inhibiting RRX-induced grain refinement. This allows ice crystal sizes to retain temperature-sensitive signals in both intervals. This lays the groundwork for further exploring the connections between the physical characteristics—such as bubble number density—of mountain glacier ice cores and climate change (Spencer et al., 2006; Fegyveresi et al., 2016; Lipenkov, 2018).

4 Conclusions

This study presents the first continuous profiles of ice grain area spanning from the firn to the base of two deep mountain glacier ice cores from the Tibetan Plateau, revealing vertical differentiation in grain area at the hundred-meter scale, analogous to polar ice core profiles. Temperature is the key factor influencing ice crystal evolution across all depth intervals. Relatively higher temperatures significantly enhance grain growth, thus resulting in a larger equilibrium grain area. Refreezing under warm conditions gives rise to abrupt increases in grain area within melt-refrozen layers, whereas impurities result in abrupt decreases in grain area within impurity layers. Together, these two factors drive centimeter-scale fluctuations in grain area. Notably, in layers where RRX-induced refinement is negligible, grain area exhibits a significant correlation with $\delta^{18}\text{O}$, indicating that ice crystal size in mountain glacier ice cores can still retain temperature signals despite multiple influencing factors.

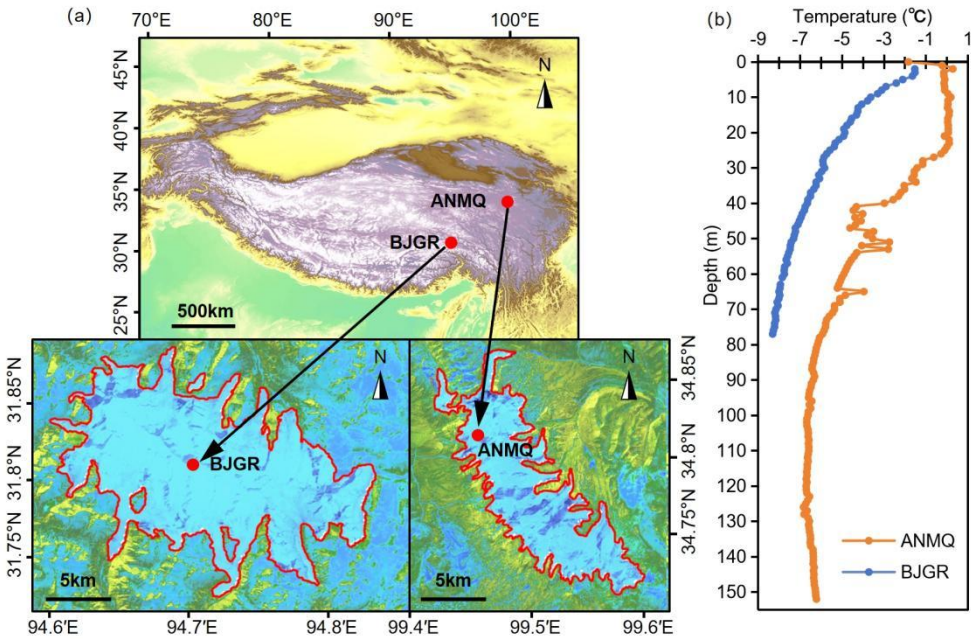


Figure 1. (a) Drilling sites of the ANMQ and BJGR ice cores; (b) Borehole temperatures, measured using a 150 m resistance temperature sensor cable with an accuracy of ± 0.02 °C. Temperatures below 150 m in the ANMQ ice core were not measured.

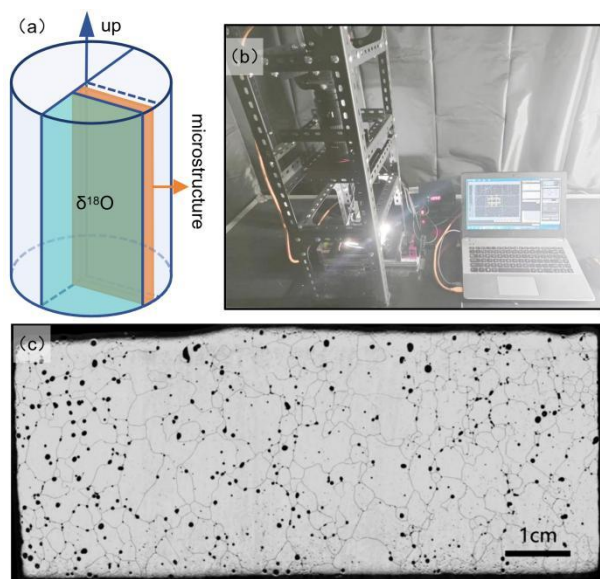


Figure 2. (a) Schematic diagram of ice slice cutting; the orange section represents a slice with approximate dimensions: $10 \times 4.5 \times 0.7$ cm; (b) Photograph of the microstructure mapping system; (c) Seamlessly stitched panoramic image of a slice, generated from 5 consecutive photos.

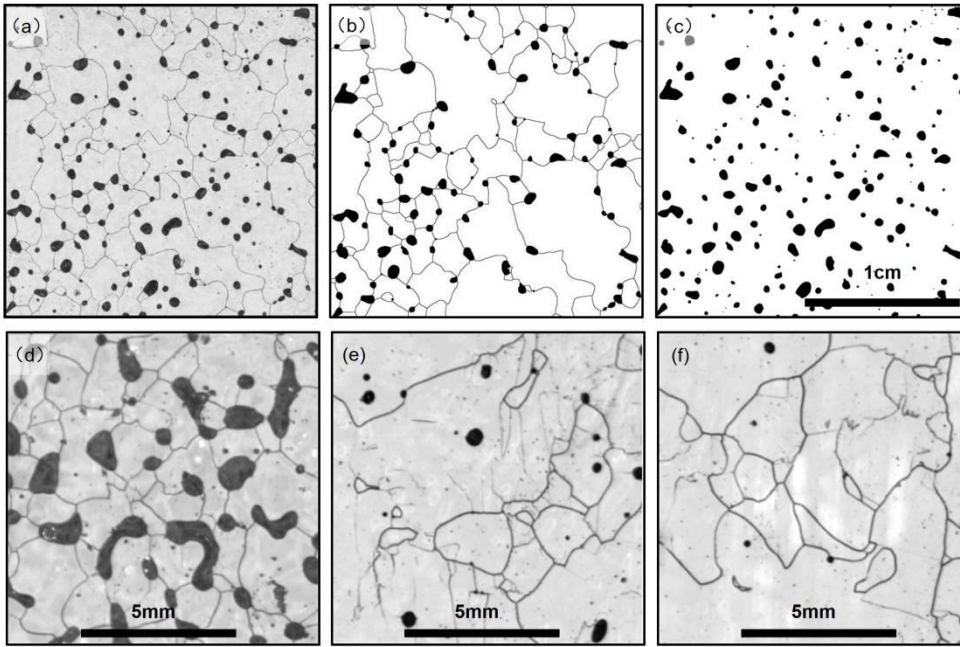


Figure 3. Microstructure images and image processing procedures: (a) Original microstructural image (ANMQ: T49B15); (b) Grain boundary map; (c) Pore/bubble map; (d)–(f) Microstructural images of the BJGR ice core: straight grain boundaries and triple junctions in the firn layer; abundant subgrain boundaries in the RRX layer; subgrain boundaries and highly curved grain boundaries in the SIBM layer.

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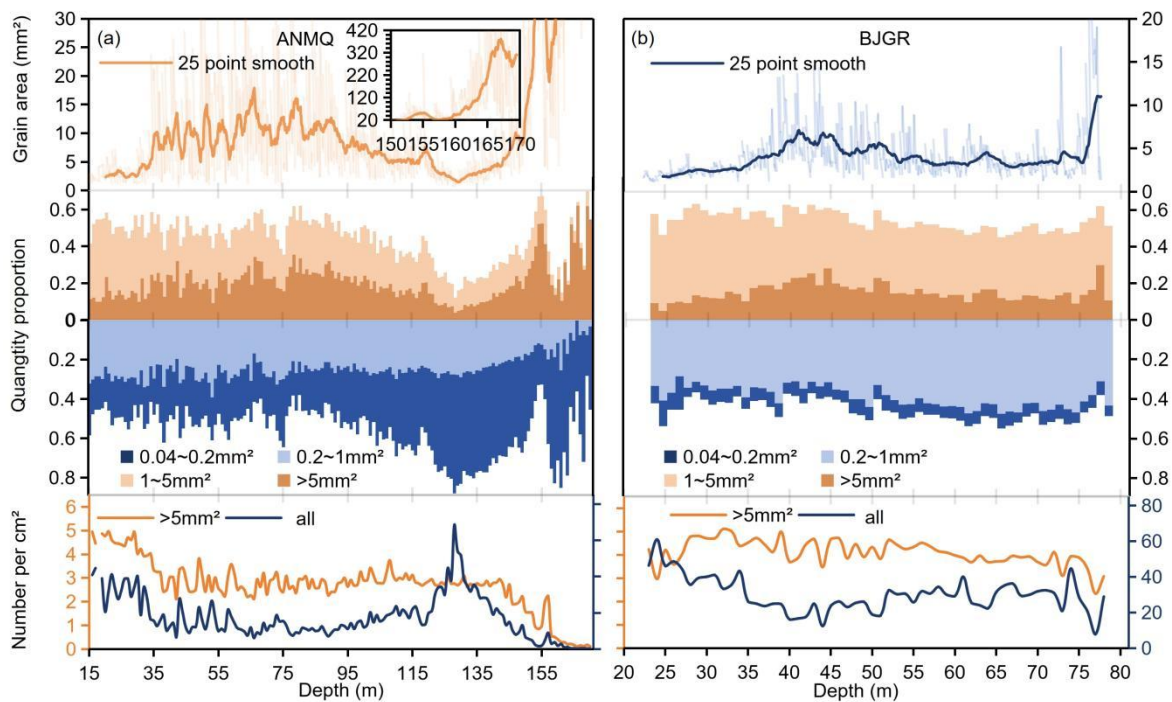


Figure 4. Profiles of average grain area and proportion of grain quantities across different size ranges: (a) For the ANMQ ice core; the inset depicts rapid grain growth, with the grain area reaching $\sim 400 \text{ mm}^2$ near the base of the core; (b) For the BJGR ice core. Thin lines represent 2 cm resolution data, while bold lines represent 25 point smoothed data. The number of grains in different size grades was statistically analyzed on a per meter basis.

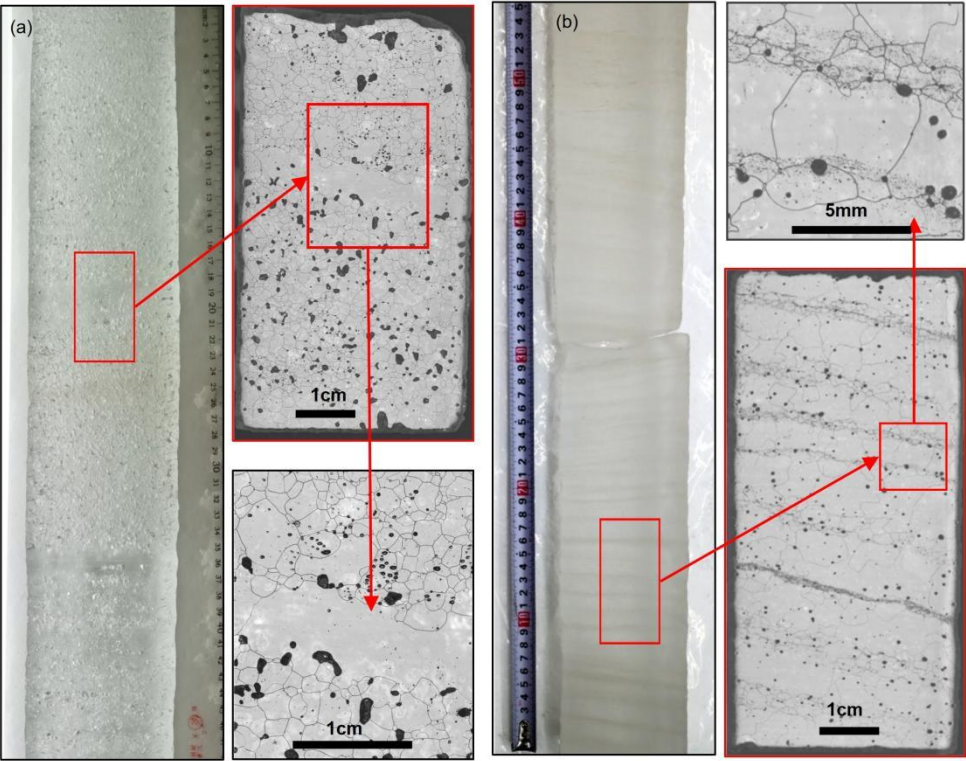


Figure 5. Illustrations of centimeter-scale fluctuations in the ANMQ ice core: (a) Photograph of a melt-refrozen layer in the firn layer, with a magnified inset showing abrupt enlargement of grain area; (b) Photograph of a dense zone of impurity layers, with a magnified inset displaying clustering of small grains.

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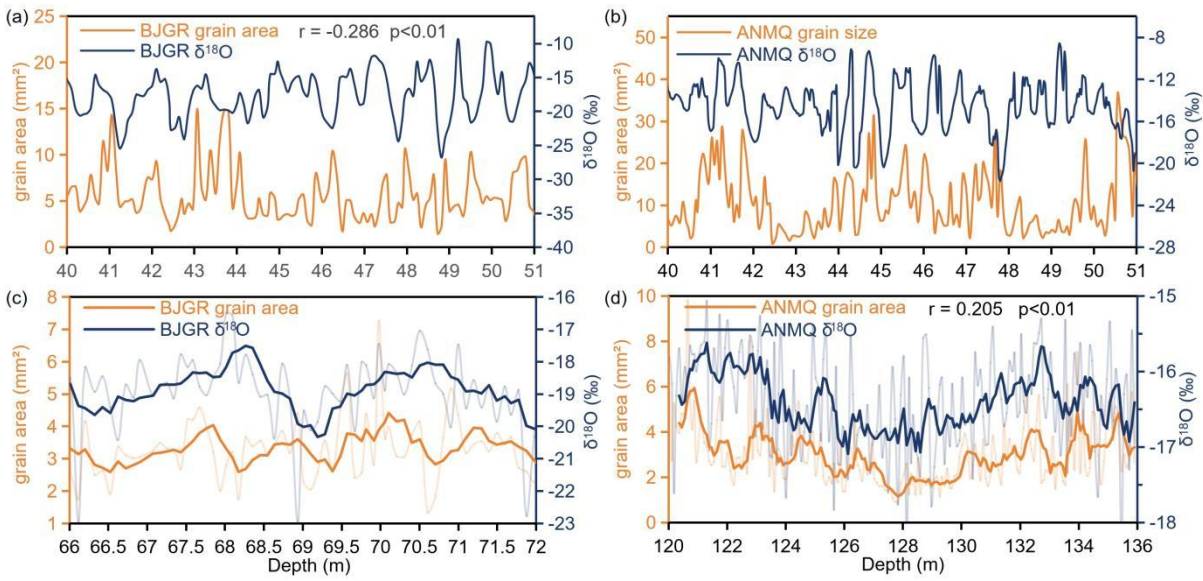
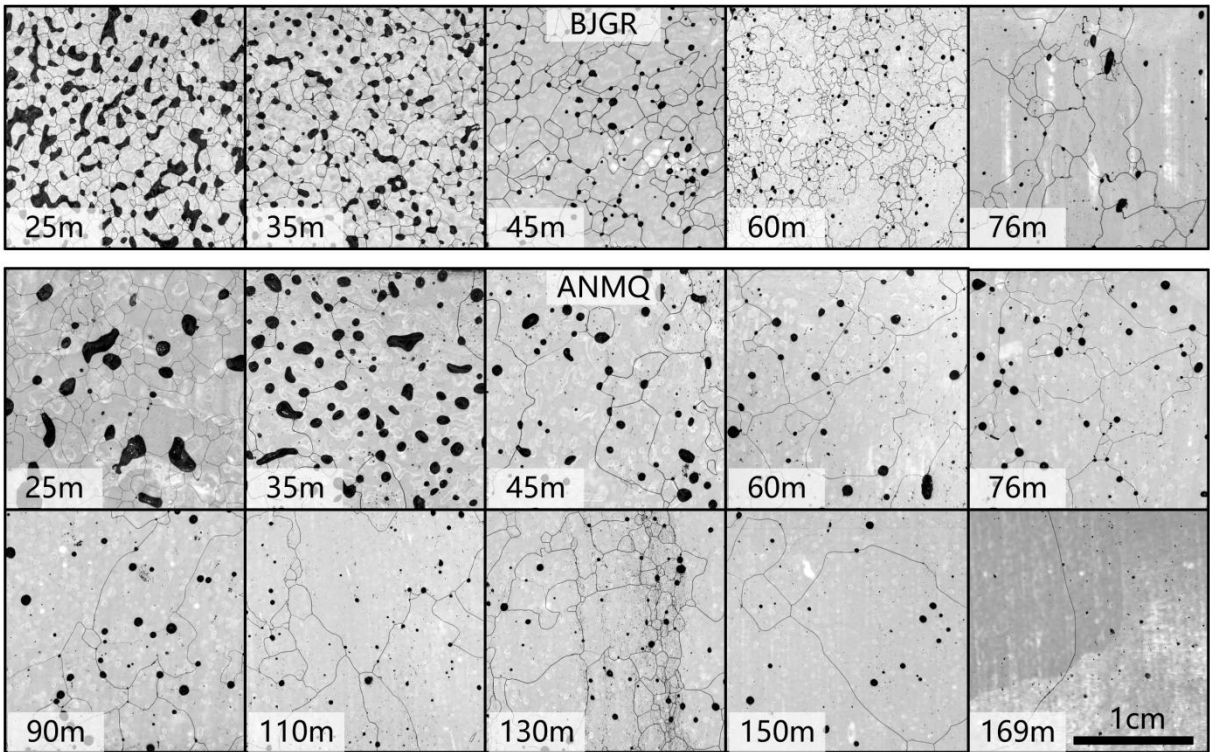
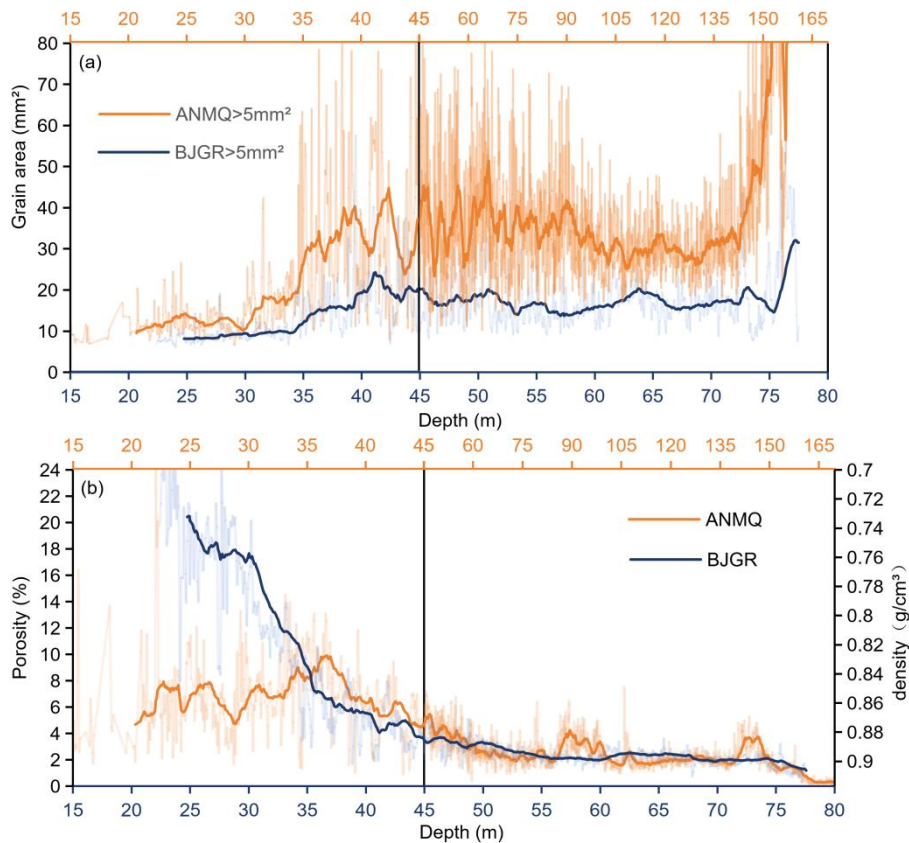


Figure 6. Comparison between average grain area and $\delta^{18}\text{O}$ values: (a) and (b) in the 40–51 m interval show inverse fluctuations because the "amount effect" results in lower $\delta^{18}\text{O}$ values in summer and higher values in winter (Yang, 2024, Unpublished doctoral dissertation). (c) and (d) show similar fluctuations in the dense zones of impurity layers. The thin lines represent 2 cm resolution data, and the bold lines represent 5 point smoothed data.

Appendix A



270 **Figure A1. Exemplary microstructure images of BJGR and ANMQ ice cores; Microstructure images at different depths are selected, showing significant variations in grain area and bubbles.**



275 **Figure A2. (a) Average area of grains > 5 mm² profiles of ANMQ and BJGR ice cores. The average area of all grains is significantly correlated with the average area of grains > 5 mm² (ANMQ: $r = 0.847$, $p < 0.01$; BJGR: $r = 0.909$, $p < 0.01$); (b) The porosity and slice density profiles of ANMQ and BJGR ice cores; The thin lines represent original data, the bold lines represent the 25 point smooth.**

The ice core slice density was deduced using the formula: slice density = $(1 - \text{porosity}) \times 0.917 \text{ g/cm}^3$ (Kerch, 2016). Due to the fragility of loose firn slice samples in the upper part of the ANMQ ice core, combined with the retention of many melt-refrozen ice layer samples, this sampling error caused abnormally high density values and a downward trend above 35 m in the ANMQ ice core. The section below 45 m of the ANMQ core is compressed onto a reduced scale.

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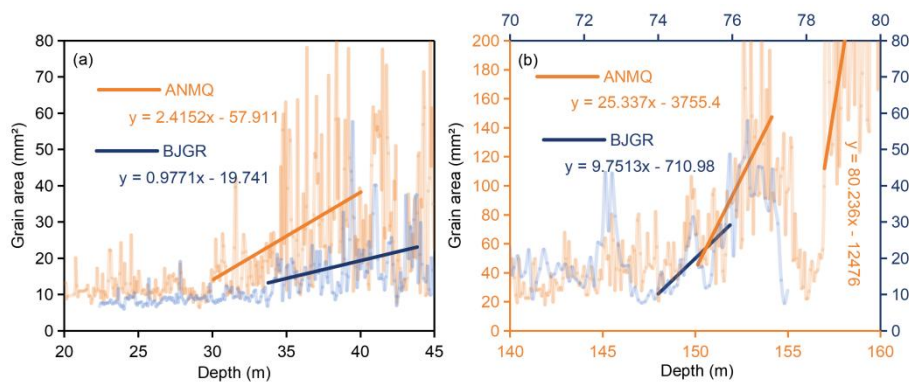


Figure A3. Growth rate of grains > 5 mm²: (a) Firn-ice transition layer; (b) SIBM layer; The thin lines represent 2 cm resolution data, the bold lines represent linear fitting results.

285 Below 156 m depth in the ANMQ ice core, the growth rate of grains > 5 mm² reaches up to 80 mm²/m. At the base, grain areas exceed 3000 mm², with grain boundaries extending beyond ice slice edges. Concurrently, impurity layers vanish, and the ice core approximates transparent pure ice. We infer that the grains at this depth underwent intense refreezing: excessive temperatures caused extensive melting, and prolonged high temperatures induced repeated freeze-thaw cycles, ultimately generating exceptionally large grains. High-temperature-induced melt-refrozen ice layers are a primary driver of the abrupt

290 grain area increase at the ANMQ core base.

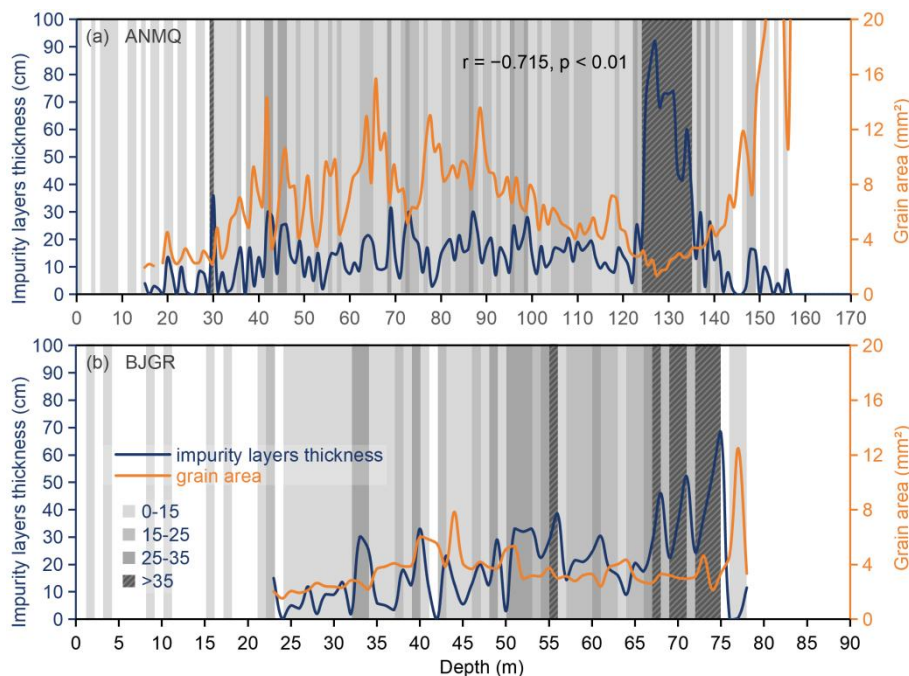
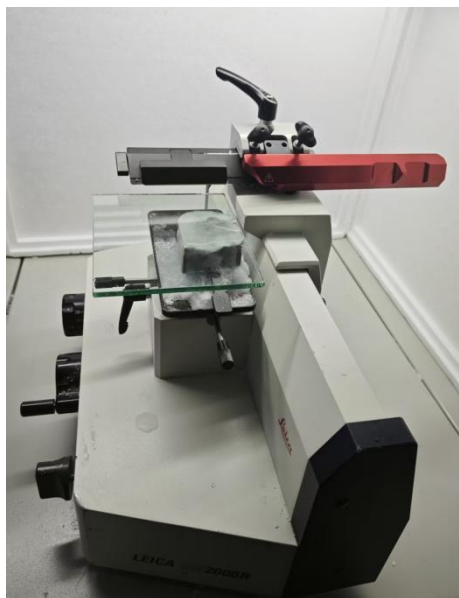


Figure A4. Variation sequences of impurity layers thickness and average grain area: (a) ANMQ; (b) BJGR; Background colors also indicate the thickness of impurity layers.



295 **Figure A5. The Leica SM2000R microtome with a modified glass platform used in this study.**

Table A1. Ice temperature and grain size at ~35 m depth in different mountain glaciers

Ice Core	Location	Elevation (m a.s.l.)	Length (m)	Firn Thickness (m)	Temperature (°C)	Grain Area (mm ²) (Diameter (mm))
Tsanfleuron	Western Alps	2800	39.86	36	~0	> 78 (> 10)
Urumqi Glacier No. 1	Middle Tianshan Mountains	4050	90.24	3	-1	7-12 (1.5-2)
ANMQ	Eastern Tibetan Plateau	5750	169.45	35	-2	5-10
BJGR	Eastern Tibetan Plateau	6180	77.6	35	-6.2	3-5
KCC(Colle Gnifetti)	Western Alps	4484	72	36	-13	2-4
Guliya	Western Tibetan Plateau	6200	308.6	1	-14.8	> 50 (> 8)

Data availability. Microstructure images and raw grain parameter data are available upon request.

300 *Author contributions.* HZQ designed the study, conducted field sampling and laboratory experiments, analyzed the data, and drafted the manuscript; XBQ supervised the research, revised the manuscript critically, and secured funding.

Competing interests. The contact author has declared that neither they nor their co-authors have any competing interests.

Acknowledgments. We thank all personnel involved in the drilling of the ANMQ and BJGR ice cores and the associated experiments. Special appreciation is extended to Bo Fang, Siyv Lu, Xiaoxi Zhu, and Jiajia Wang for their valuable assistance and insightful suggestions.

305 *Financial support.* This research was supported by Excellent Research Group Program for Tibetan Plateau Earth System (No. 42588201).

References

- Alley, R. B., Perepezko, J. H., and Bentley, C. R.: Grain growth in polar ice: I. Theory, *Journal of Glaciology*, 32(112), 415–424, <https://doi.org/10.3189/S0022143000012120>, 1986a.
- 310 Alley, R. B., Perepezko, J. H., and Bentley, C. R.: Grain growth in polar ice: II. Application, *Journal of Glaciology*, 32(112), 425–433, <https://doi.org/10.3189/S0022143000012132>, 1986b.
- Alley, R. B. and Woods, G. A.: Impurity influence on normal grain growth in the GISP2 ice core, Greenland, *Journal of Glaciology*, 42(141), 255–260, <https://doi.org/10.3189/S0022143000004111>, 1996.
- Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., ... and Stoffel, M.: The state and fate of Himalayan
315 glaciers, *Science*, 336(6079), 310–314, <https://doi.org/10.1126/science.1215828>, 2012.
- Clavette, R.: The Microstructural Heterogeneity of Ice in Jarvis Glacier, Alaska, Honors College Dissertation, University of Maine, 2020.
- Cuffey, K. M. and Paterson, W. S. B.: The physics of glaciers, 4th edn., Academic Press, 2010.
- Dadic, R., Schneebeli, M., Wiese, M., Bertler, N. A. N., Salamin, A. N., Theile, T. C., ... and Lipenkov, V. Y.:
320 Temperature-driven bubble migration as proxy for internal bubble pressures and bubble trapping function in ice cores, *Journal of Geophysical Research: Atmospheres*, 124(17-18), 10264–10282, <https://doi.org/10.1029/2019JD030891>, 2019.
- Durand, G., Gillet-Chaulet, F., Svensson, A., Gagliardini, O., Kipfstuhl, S., Meyssonier, J., ... and Dahl-Jensen, D.: Change in ice rheology during climate variations—implications for ice flow modelling and dating of the EPICA Dome C core, *Climate of the Past*, 3(1), 155–167, <https://doi.org/10.5194/cp-3-155-2007>, 2007.
- 325 Durand, G., Weiss, J., Lipenkov, V., Barnola, J. M., Krinner, G., Parrenin, F., ... and Bigler, M.: Effect of impurities on grain growth in cold ice sheets, *Journal of Geophysical Research: Earth Surface*, 111(F1), <https://doi.org/10.1029/2005JF000320>, 2006.
- Duval, P. and Castelnau, O.: Dynamic recrystallization of ice in polar ice sheets, *Le Journal de Physique IV*, 5(C3), C3-197, <https://doi.org/10.1051/jp4:1995317>, 1995.
- 330 Eichler, J., Kleitz, I., Bayer-Giraldi, M., Jansen, D., Kipfstuhl, S., Shigeyama, W., Weikusat, C., and Weikusat, I.: Location and distribution of micro-inclusions in the EDML and NEEM ice cores using optical microscopy and in situ Raman spectroscopy, *The Cryosphere*, 11, 1075–1090, <https://doi.org/10.5194/tc-11-1075-2017>, 2017.
- Eichler, J., Weikusat, C., Wegner, A., Twarloh, B., Behrens, M., Fischer, H., ... and Weikusat, I.: Impurity analysis and microstructure along the climatic transition from MIS 6 into 5e in the EDML ice core using cryo-Raman microscopy,
335 *Frontiers in Earth Science*, 7, 20, <https://doi.org/10.3389/feart.2019.00020>, 2019.
- Faria, S. H., Freitag, J., and Kipfstuhl, S.: Polar ice structure and the integrity of ice-core paleoclimate records, *Quaternary Science Reviews*, 29(1-2), 338–351, <https://doi.org/10.1016/j.quascirev.2009.10.016>, 2010.
- Faria, S. H., Weikusat, I., and Azuma, N.: The microstructure of polar ice. Part I: Highlights from ice core research, *Journal of Structural Geology*, 61, 2–20, <https://doi.org/10.1016/j.jsg.2013.09.010>, 2014a.

- 340 Faria, S. H., Weikusat, I., and Azuma, N.: The microstructure of polar ice. Part II: State of the art, *Journal of Structural Geology*, 61, 21–49, <https://doi.org/10.1016/j.jsg.2013.11.003>, 2014b.
- Fegyveresi, J. M.: Physical properties of the West Antarctic Ice Sheet (WAIS) Divide deep core: Development, evolution, and interpretation, Doctoral dissertation, The Pennsylvania State University, 2015.
- Fegyveresi, J. M., Alley, R. B., Fitzpatrick, J. J., Cuffey, K. M., McConnell, J. R., Voigt, D. E., ... and Stevens, N. T.: Five
345 millennia of surface temperatures and ice core bubble characteristics from the WAIS Divide deep core, West Antarctica, *Paleoceanography*, 31(3), 416–433, <https://doi.org/10.1002/2015PA002851>, 2016.
- Fitzpatrick, J. J., Voigt, D. E., Fegyveresi, J. M., Stevens, N. T., Spencer, M. K., Cole-Dai, J., and McConnell, J. R.: Physical properties of the WAIS Divide ice core, *Journal of Glaciology*, 60(224), 1181–1198, <https://doi.org/10.3189/2014JoG14J100>, 2014.
- 350 González-Santacruz, N., Muñoz-Marzagon, P., Bartolomé, M., Moreno, A., Huidobro, J., and Faria, S. H.: Effects of impurities on the ice microstructure of Monte Perdido Glacier, Central Pyrenees, NE Spain, *Annals of Glaciology*, 64(91), 107–120, <https://doi.org/10.1017/aog.2023.66>, 2023.
- Gow, A. J.: On the rates of growth of grains and crystals in South Polar firn, *Journal of Glaciology*, 8(53), 241–252, <https://doi.org/10.3189/S0022143000031233>, 1969.
- 355 Gow, A. J. and Williamson, T.: Rheological implications of the internal structure and crystal fabrics of the West Antarctic ice sheet as revealed by deep core drilling at Byrd Station, *Geological Society of America Bulletin*, 87(12), 1665–1677, [https://doi.org/10.1130/0016-7606\(1976\)87<1665:RIOTIS>2.0.CO;2](https://doi.org/10.1130/0016-7606(1976)87<1665:RIOTIS>2.0.CO;2), 1976.
- Hellmann, S., Kerch, J., Weikusat, I., Bauder, A., Grab, M., Juvet, G., ... and Maurer, H.: Crystallographic analysis of temperate ice on Rhonegletscher, Swiss Alps, *The Cryosphere*, 15(2), 677–694, <https://doi.org/10.5194/tc-15-677-2021>,
360 2021.
- Hörhold, M. W., Laepple, T., Freitag, J., Bigler, M., Fischer, H., and Kipfstuhl, S.: On the impact of impurities on the densification of polar firn, *Earth and Planetary Science Letters*, 325, 93–99, <https://doi.org/10.1016/j.epsl.2011.12.022>, 2012.
- Hruby, K., Gerbi, C., Koons, P., Campbell, S., Martín, C., and Hawley, R.: The impact of temperature and crystal orientation fabric on the dynamics of mountain glaciers and ice streams, *Journal of Glaciology*, 66(259), 755–765,
365 <https://doi.org/10.1017/jog.2020.44>, 2020.
- Jiang, Z. L., Liu, S. Y., Guo, W. Q., Li, J., Long, S. C., Wang, X., and Wu, K. P.: Recent changes in the surface elevation of typical glaciers in the Animaqing Mountains in the Yellow River source area, *Journal of Glaciology and Geocryology*, 40(2), 231–237, <https://doi.org/10.7522/j.issn.1000-0240.2018.0027>, 2018.
- Jennings, S. J. A. and Hambrey, M. J.: Structures and deformation in glaciers and ice sheets, *Reviews of Geophysics*, 59,
370 e2021RG000743, <https://doi.org/10.1029/2021RG000743>, 2021.
- Kerch, J. K.: Crystal-orientation fabric variations on the cm-scale in cold Alpine ice: Interaction with paleo-climate proxies under deformation and implications for the interpretation of seismic velocities, Doctoral dissertation, Universität Heidelberg, 2016.

- Kipfstuhl, S., Hamann, I., Lambrecht, A., Freitag, J., Faria, S. H., Grigoriev, D., and Azuma, N.: Microstructure mapping: a new method for imaging deformation-induced microstructural features of ice on the grain scale, *Journal of Glaciology*, 52(178), 398–406, <https://doi.org/10.3189/172756506781828647>, 2006.
- Kipfstuhl, S., Faria, S. H., Azuma, N., Freitag, J., Hamann, I., Kaufmann, P., ... and Wilhelms, F.: Evidence of dynamic recrystallization in polar firn, *Journal of Geophysical Research: Solid Earth*, 114(B5), B05204, <https://doi.org/10.1029/2008JB005583>, 2009.
- Legland, D., Arganda-Carreras, I., and Andrey, P.: MorphoLibJ: integrated library and plugins for mathematical morphology with ImageJ, *Bioinformatics*, 32(22), 3532–3534, <https://doi.org/10.1093/bioinformatics/btw413>, 2016.
- Li, Y., Kipfstuhl, S., and Huang, M.: Ice microstructure and fabric of Guliya ice cap in Tibetan plateau, and comparisons with Vostok 3G-1, EPICA DML, and North GRIP, *Crystals*, 7(4), 97, <https://doi.org/10.3390/cryst7040097>, 2017.
- Li, Y. and Fu, C.: Meltwater and cold pump effects override climate control of grain size in polythermal glacier ice, *Scientific Reports*, 16, 5692, <https://doi.org/10.1038/s41598-026-35538-x>, 2026.
- Lipenkov, V. Y.: How air bubbles form in polar ice, *Earth's Cryosphere*, 22(2), 16–28, [https://doi.org/10.21782/EC2541-9994-2018-2\(14-25\)](https://doi.org/10.21782/EC2541-9994-2018-2(14-25)), 2018.
- Liu, Q., Guo, W. Q., Nie, Y., Liu, S. Y., and Xu, J. L.: Recent glacier and glacial lake changes and their interactions in the Bugyai Kangri, southeast Tibet, *Annals of Glaciology*, 57(71), 61–69, <https://doi.org/10.3189/2016AoG71A415>, 2016.
- Liu, S., Yao, X., Guo, W., Xu, J., Shangguan, D., Wei, J., Bao, W., and Wu, L.: The contemporary glaciers in China based on the Second Chinese Glacier Inventory, *Acta Geographica Sinica*, 70(1), 3–16, <https://doi.org/10.11821/dlxb201501001>, 2015.
- Llorens, M. G., Grier, A., Steinbach, F., Bons, P. D., Gomez-Rivas, E., Jansen, D., ... and Weikusat, I.: Dynamic recrystallization during deformation of polycrystalline ice: insights from numerical simulations, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 375(2086), 20150346, <https://doi.org/10.1098/rsta.2015.0346>, 2017.
- Mahowald, N., Kohfeld, K., Hansson, M., Balkanski, Y., Harrison, S. P., Prentice, I. C., ... and Rodhe, H.: Dust sources and deposition during the last glacial maximum and current climate: A comparison of model results with paleodata from ice cores and marine sediments, *Journal of Geophysical Research: Atmospheres*, 104(D13), 15895–15916, <https://doi.org/10.1029/1999JD900084>, 1999.
- Montagnat, M., Castelnau, O., Bons, P. D., Faria, S. H., Gagliardini, O., Gillet-Chaulet, F., ... and Suquet, P.: Multiscale modeling of ice deformation behavior, *Journal of Structural Geology*, 61, 78–108, <https://doi.org/10.1016/j.jsg.2013.05.002>, 2014.
- Monz, M. E., Hudleston, P. J., Prior, D. J., Michels, Z., Fan, S., Negrini, M., ... and Qi, C.: Full crystallographic orientation (c and a axes) of warm, coarse-grained ice in a shear-dominated setting: a case study, Storglaciären, Sweden, *The Cryosphere*, 15(1), 303–324, <https://doi.org/10.5194/tc-15-303-2021>, 2021.

- Nie, Y., Pritchard, H. D., Liu, Q., Hennig, T., Wang, W., Wang, X., ... and Chen, X.: Glacial change and hydrological implications in the Himalaya and Karakoram, *Nature Reviews Earth & Environment*, 2(2), 91–106, <https://doi.org/10.1038/s43017-020-00124-w>, 2021.
- 410 Overpeck, J., Rind, D., Lacis, A., and Healy, R.: Possible role of dust-induced regional warming in abrupt climate change during the last glacial period, *Nature*, 384(6608), 447–449, <https://doi.org/10.1038/384447a0>, 1996.
- Perutz, M. F. and Seligman, G.: A crystallographic investigation of glacier structure and the mechanism of glacier flow, *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, 172(950), 335–360, <https://doi.org/10.1098/rspa.1939.0108>, 1939.
- 415 Pickering, F. B.: *The Basis of Quantitative Metallography*, Metals and Metallurgy Trust for the Institute of Metallurgical Technicians, Whetstone, UK, 1976.
- Ram, M., Stolz, M., and Koenig, G.: Eleven year cycle of dust concentration variability observed in the dust profile of the GISP2 ice core from Central Greenland: Possible solar cycle connection, *Geophysical Research Letters*, 24(19), 2359–2362, <https://doi.org/10.1029/97GL02521>, 1997.
- 420 Rigsby, G. P.: Crystal fabric studies on Emmons Glacier, Mount Rainier, Washington, *The Journal of Geology*, 59(6), 590–598, <https://doi.org/10.1086/625914>, 1951.
- Rigsby, G. P.: Crystal orientation in glacier and in experimentally deformed ice, *Journal of Glaciology*, 3(27), 589–606, <https://doi.org/10.3189/S0022143000023716>, 1960.
- Ronneberger, O., Fischer, P., and Brox, T.: U-Net: Convolutional Networks for Biomedical Image Segmentation, in: 425 *Medical Image Computing and Computer-Assisted Intervention – MICCAI 2015*, edited by: Navab, N., Hornegger, J., Wells, W., and Frangi, A., Springer, Cham, 9351, 234–241, https://doi.org/10.1007/978-3-319-24574-4_28, 2015.
- Sakai, A. and Fujita, K.: Contrasting glacier responses to recent climate change in high-mountain Asia, *Scientific Reports*, 7(1), 13717, <https://doi.org/10.1038/s41598-017-14256-5>, 2017.
- Schaller, C. F., Freitag, J., and Eisen, O.: Critical porosity of gas enclosure in polar firn independent of climate, *Climate of* 430 *the Past*, 13(11), 1685–1693, <https://doi.org/10.5194/cp-13-1685-2017>, 2017.
- Spencer, M. K., Alley, R. B., and Fitzpatrick, J. J.: Developing a bubble number-density paleoclimatic indicator for glacier ice, *Journal of Glaciology*, 52(178), 358–364, <https://doi.org/10.3189/172756506781828638>, 2006.
- Stoll, N., Eichler, J., Hörhold, M., Shigeyama, W., and Weikusat, I.: A review of the microstructural location of impurities in polar ice and their impacts on deformation, *Frontiers in Earth Science*, 8, 615613, <https://doi.org/10.3389/feart.2020.615613>, 435 2021.
- Svensson, A., Baadsager, P., Persson, A., Hvidberg, C. S., and Siggaard-Andersen, M. L.: Seasonal variability in ice crystal properties at NorthGRIP: a case study around 301 m depth, *Annals of Glaciology*, 37, 119–122, <https://doi.org/10.3189/172756403781815582>, 2003.

- Svensson, A., Nielsen, S. W., Kipfstuhl, S., Johnsen, S. J., Steffensen, J. P., Bigler, M., ... and R  thlisberger, R.: Visual stratigraphy of the North Greenland Ice Core Project (NorthGRIP) ice core during the last glacial period, *Journal of Geophysical Research: Atmospheres*, 110(D2), D02107, <https://doi.org/10.1029/2004JD005134>, 2005.
- Thompson, L. G., Yao, T., Davis, M. E., Henderson, K. A., Mosley-Thompson, E., Lin, P.-N., Beer, J., Synal, H.-A., Cole-Dai, J., and Bolzan, J. F.: Tropical climate instability: The last glacial cycle from a Qinghai-Tibetan ice core, *Science*, 276(5320), 1821–1825, <https://doi.org/10.1126/science.276.5320.1821>, 1997.
- Tison, J. L. and Hubbard, B.: Ice crystallographic evolution at a temperate glacier: Glacier de Tsanfleuron, Switzerland, *Geological Society, London, Special Publications*, 176(1), 23–38, <https://doi.org/10.1144/GSL.SP.2000.176.01.03>, 2000.
- Weikusat, I., Kipfstuhl, S., Faria, S. H., Azuma, N., and Miyamoto, A.: Subgrain boundaries and related microstructural features in EDML (Antarctica) deep ice core, *Journal of Glaciology*, 55(191), 461–472, <https://doi.org/10.3189/002214309788816614>, 2009.
- Weikusat, I., Kuiper, E. J. N., Pennock, G. M., Kipfstuhl, S., and Drury, M. R.: EBSD analysis of subgrain boundaries and dislocation slip systems in Antarctic and Greenland ice, *Solid Earth*, 8(5), 883–898, <https://doi.org/10.5194/se-8-883-2017>, 2017.
- Weiss, J., Vidot, J., Gay, M., Arnaud, L., Duval, P., and Petit, J. R.: Dome Concordia ice microstructure: impurities effect on grain growth, *Annals of Glaciology*, 35, 552–558, <https://doi.org/10.3189/172756402781816573>, 2002.
- Wilson, N. J., Vreugdenhil, C. A., Gayen, B., and Hester, E. W.: Double-diffusive layer and meltwater plume effects on ice face scalloping in phase-change simulations, *Geophysical Research Letters*, 50(17), e2023GL104396, <https://doi.org/10.1029/2023GL104396>, 2023.
- Wu, R. Z., Huang, X. R., Li, Y., Li, M. Y., Sun, T., Wang, X. W., and Liu, G. X.: Analysis of Snowline Altitude Variation and Its Influencing Factors in the Bujagangri Region from 1994 to 2016, *Journal of Geomatics*, 48(6), 78–82, <https://doi.org/10.14188/j.2095-6045.2020075>, 2023.
- Yao, T., Thompson, L., and Yang, W.: Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings, *Nature Climate Change*, 2, 663–667, <https://doi.org/10.1038/nclimate1580>, 2012.
- Zhang, W., Han, J., Xie, Z., Wang, X., Lluberas, A., and Goto-Azuma, K.: A preliminary study of ice texture and fabric on an ice core to the bedrock extracted from Glacier No.1 at the headwater of Urumqi River, Tianshan, China, *Bulletin of Glacier Research*, (11), 9–15, 1993.