

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 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 (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 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, 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

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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 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 Mapping system ~~following established protocols (Kipfstuhl et al., 2006; Fegyveresi, 2015; Kerch, 2016)~~, we successfully obtained continuous longitudinal microstructure images spanning from the firm 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 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~~

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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: $\text{slice density} = (1 - \text{porosity}) \times 0.917 \text{ g/cm}^3$ (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

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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

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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.

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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.

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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.

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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

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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.

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)

In this layer, the average grain area stabilizes and declines to ~5 mm². Both the average grain area and proportions of grains > 5 mm² 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.

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, 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)

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 mm² 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 °C (Duval and Castelnau, 1995; Faria et al., 2014b).

The basal temperatures of both ice cores satisfy this criterion (BJGR: -8.31–-8.17 °C, ANMQ > -6.38 °C). Notably, in the ANMQ ice core, ice temperature reaches its minimum of -6.84 °C at 126 m depth, where grain area is also minimized at ~5 mm². Below 126 m, the temperature trend reverses from decreasing with depth to increasing, and grain size increases accordingly. Below 150 m (> -6.27 °C), grains grow rapidly, accompanied by abnormally large grains (> 400 mm²) and a 5,

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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**

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, 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 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 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 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.

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

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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; 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., 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 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., 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 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

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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).

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4 Conclusions

This study presents the first continuous profiles of ice grain area spanning from the firm 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.

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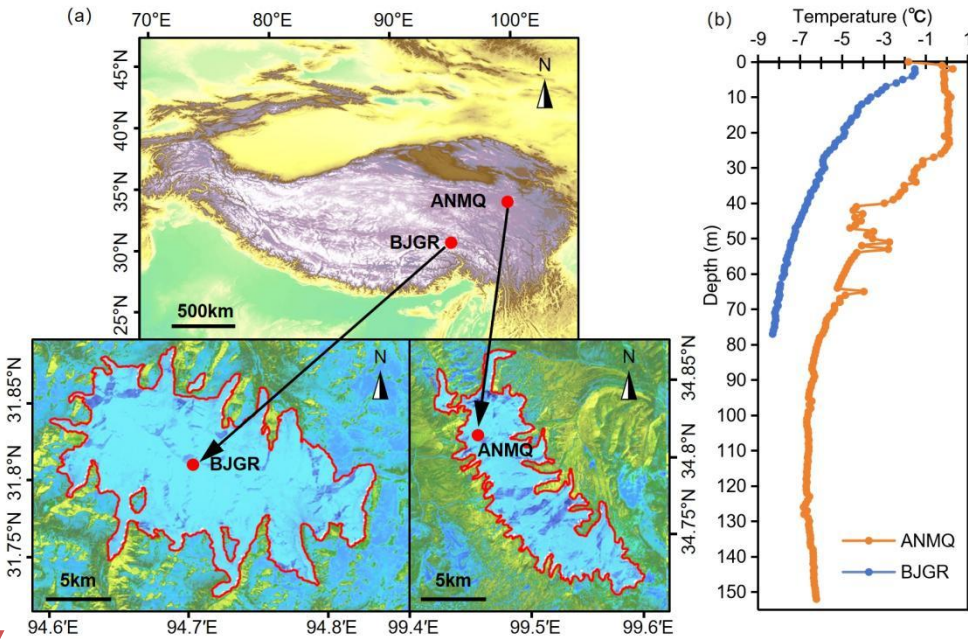


Figure 1. (a) Drilling sites of the ANMQ and BJGR ice cores; (b) Borehole temperatures, measured using a 150 m resistance temperature sensor cable with an accuracy of $\pm 0.02\text{ }^{\circ}\text{C}$. Temperatures below 150 m in the ANMQ ice core were not measured.

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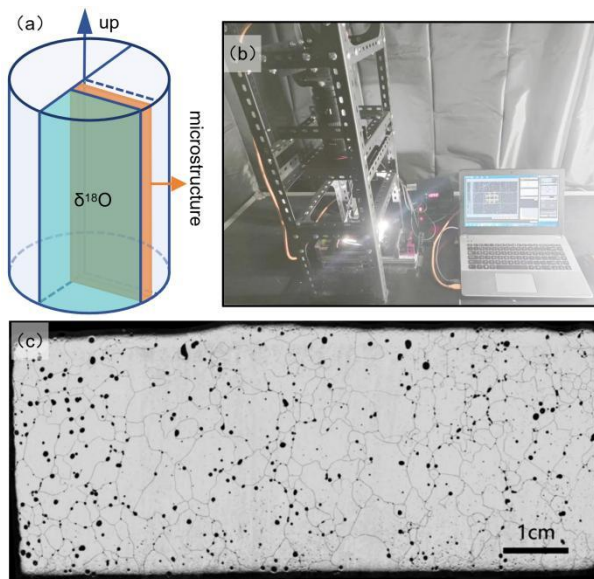


Figure 2. (a) Schematic diagram of ice slice cutting; the orange section represents a slice with approximate dimensions: $10 \times 4.5 \times 0.7$ cm; (b) Photograph of the microstructure mapping system; (c) Seamlessly stitched panoramic image of a slice, generated from 5 consecutive photos.

删除[Hezq]: . The system comprises an imaging module (equipped with a Canon EOS 5D Mark IV camera and an 180 mm macro lens), an illumination module (including a vertical coaxial light source and a light controller), and a manual X-axis translation stage. Photo-shooting parameters, focusing, and image capture were controlled via Canon Camera Connect software

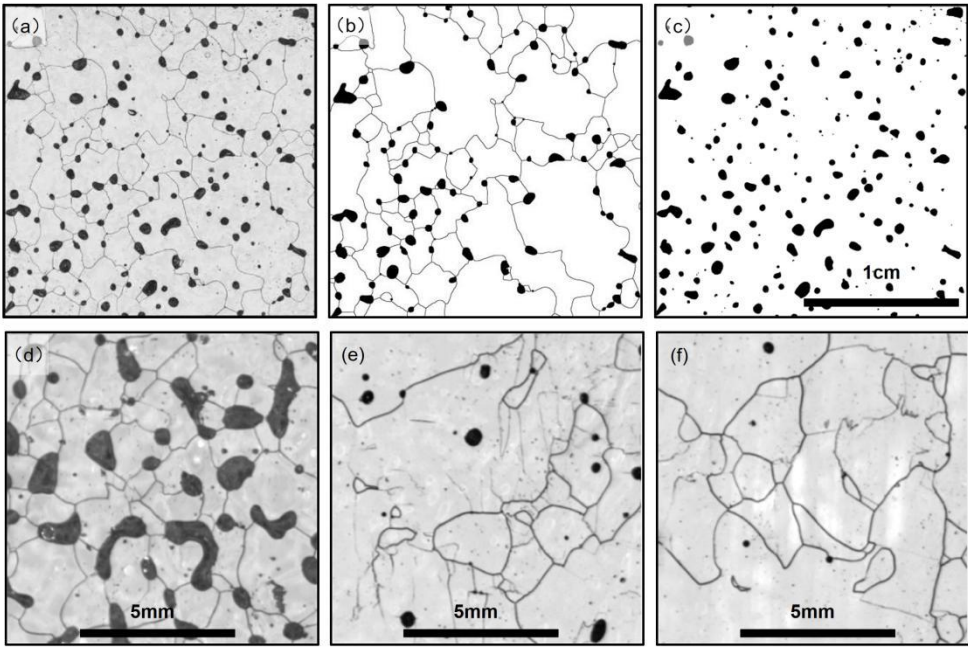


Figure 3. Microstructure images and image processing procedures: (a) Original microstructural image (ANMQ: T49B15); (b) Grain boundary map; (c) Pore/bubble map; (d)–(f) Microstructural images of the BJGR ice core: straight grain boundaries and triple junctions in the firn layer; abundant subgrain boundaries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

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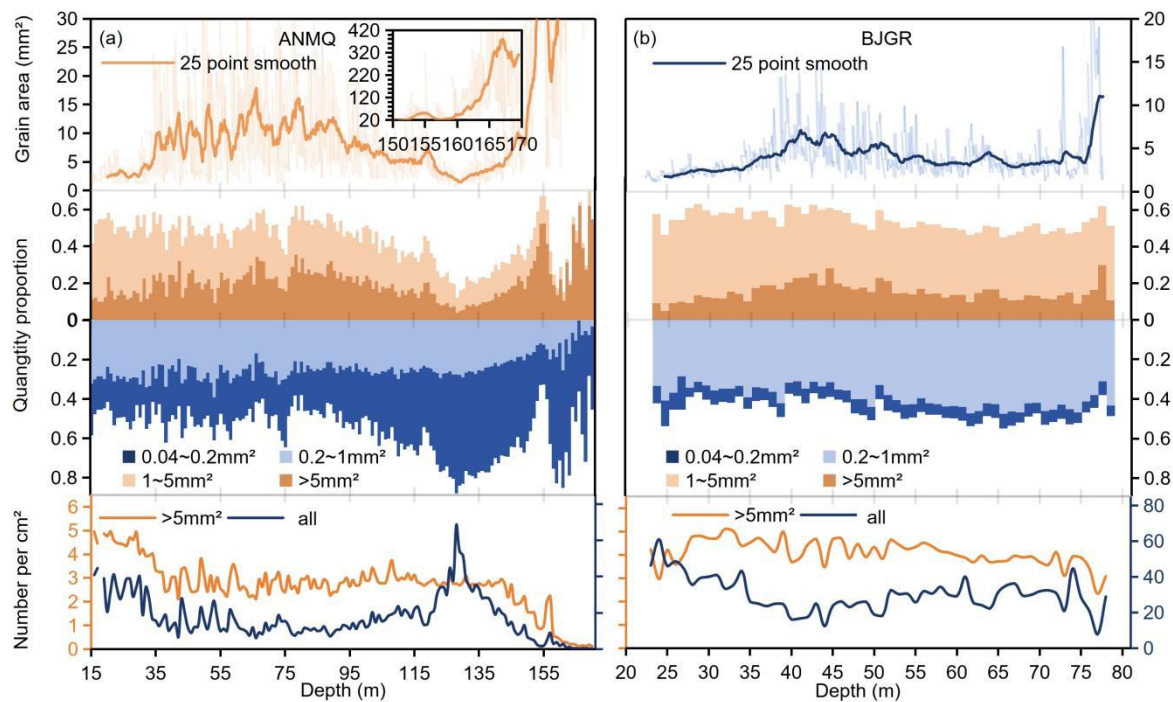


Figure 4. Profiles of average grain area and proportion of grain quantities across different size ranges: (a) For the ANMQ ice core; the inset depicts rapid grain growth, with the grain area reaching $\sim 400 \text{ mm}^2$ near the base of the core; (b) For the BJGR ice core. Thin lines represent 2 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.

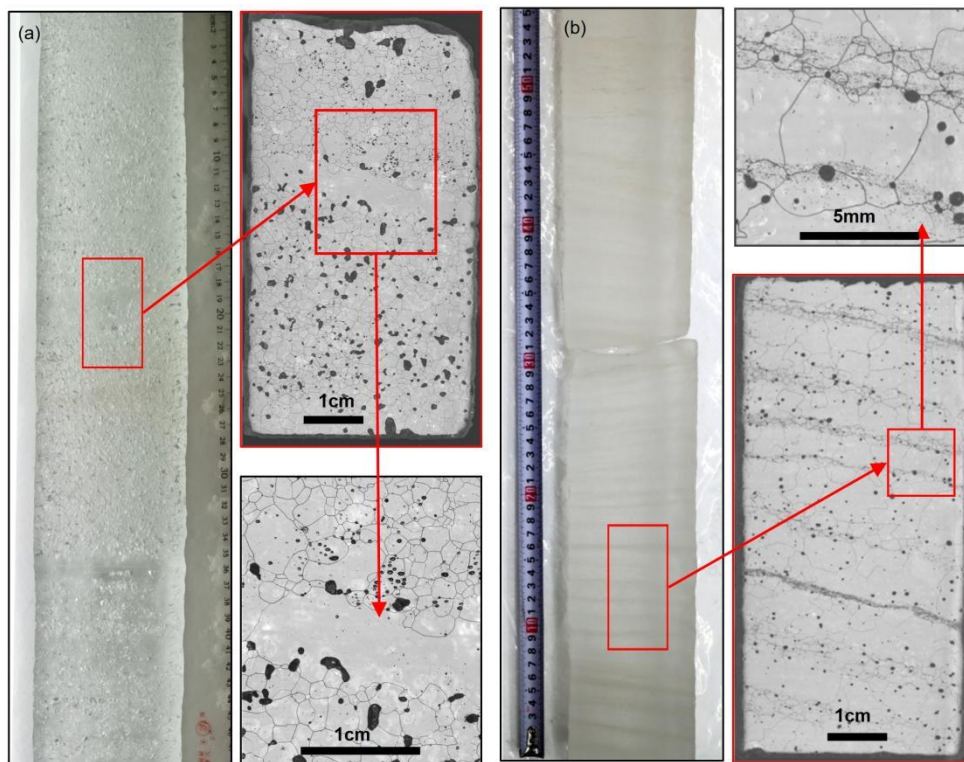


Figure 5. Illustrations of centimeter-scale fluctuations in the ANMQ ice core: (a) Photograph of a melt-refrozen layer in the firn layer, with a magnified inset showing abrupt enlargement of grain area; (b) Photograph of a dense zone of impurity layers, with a magnified inset displaying clustering of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

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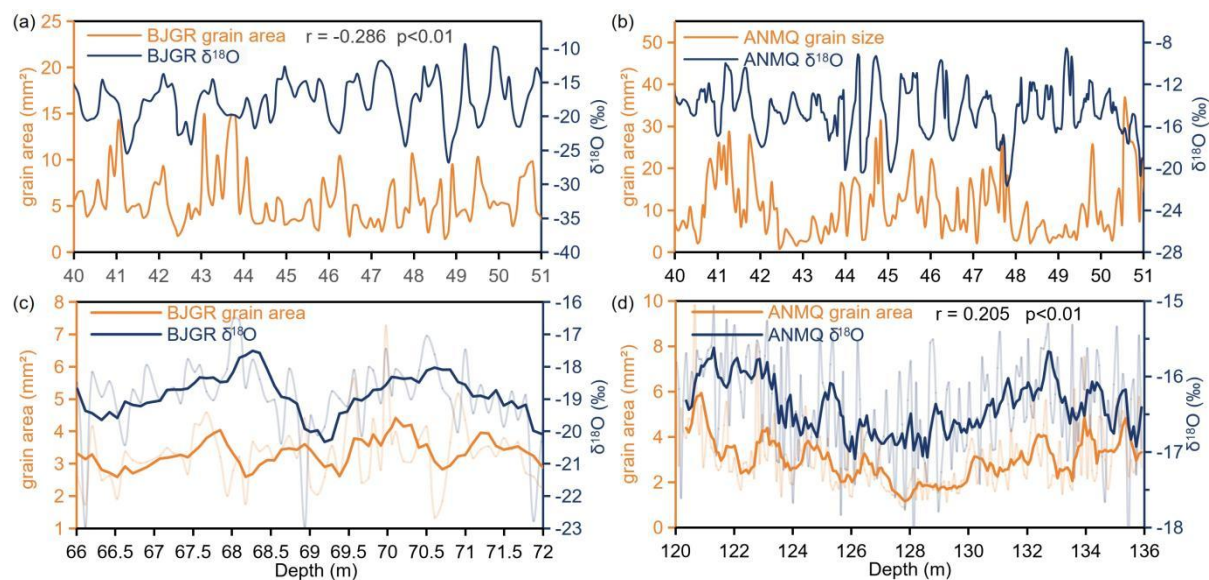
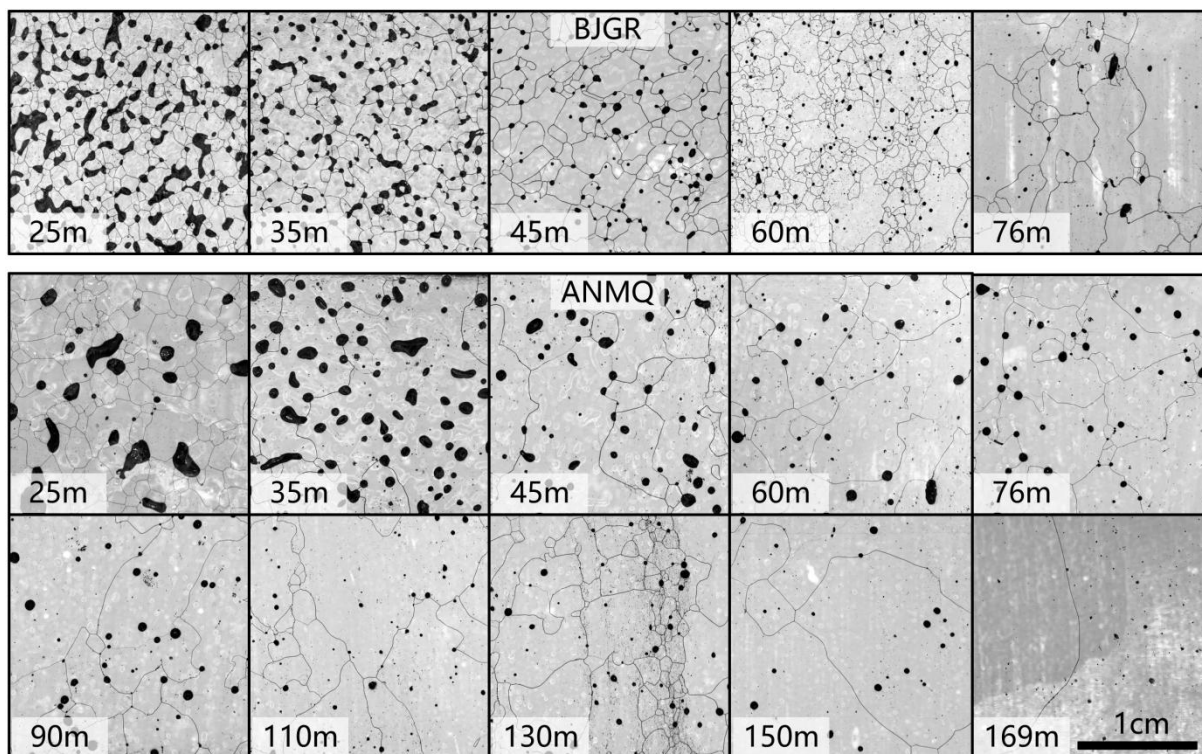


Figure 6. Comparison between average grain area and $\delta^{18}\text{O}$ values: (a) and (b) in the 40–51 m interval show inverse fluctuations because the "amount effect" results in lower $\delta^{18}\text{O}$ values in summer and higher values in winter (Yang, 2024, Unpublished doctoral dissertation). (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.

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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.**

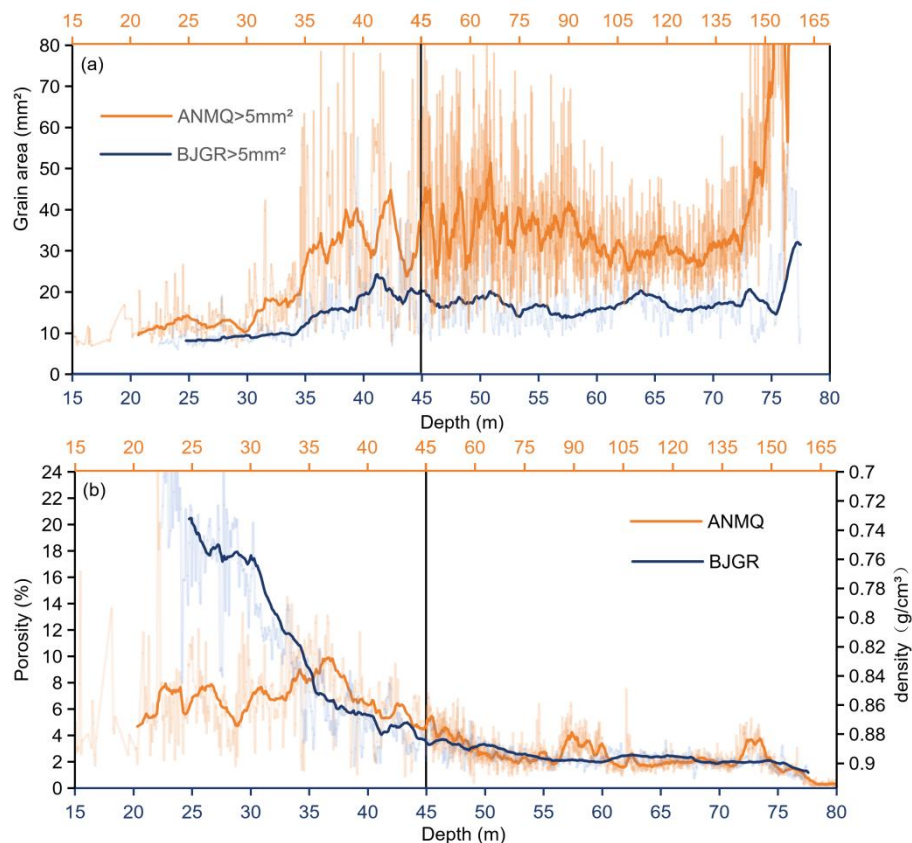


Figure A2. (a) Average area of **grains > 5 mm²** profiles of ANMQ and BJGR ice cores. The average area of all grains is significantly correlated with the average area of **grains > 5 mm²** (ANMQ: $r_s = 0.847$, $p_s < 0.01$; BJGR: $r_s = 0.909$, $p_s < 0.01$); (b) The porosity and **slice density** 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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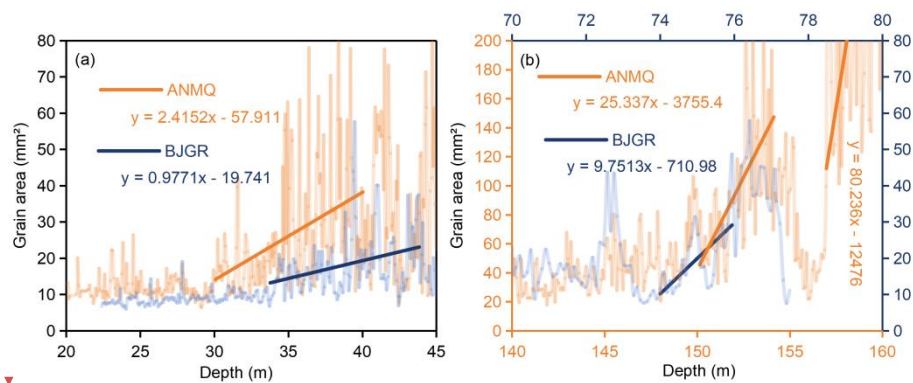
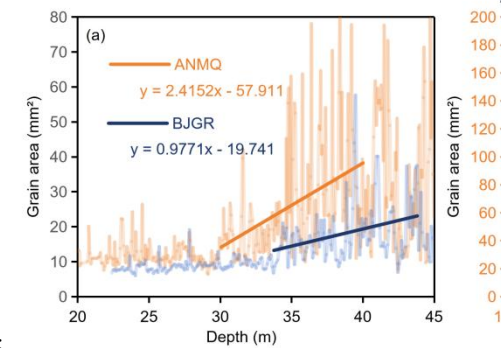


Figure A3. Growth rate of grains > 5 mm²: (a) Firn-ice transition layer; (b) SIBM layer; The thin lines represent 2 cm resolution data, the bold lines represent linear fitting results.



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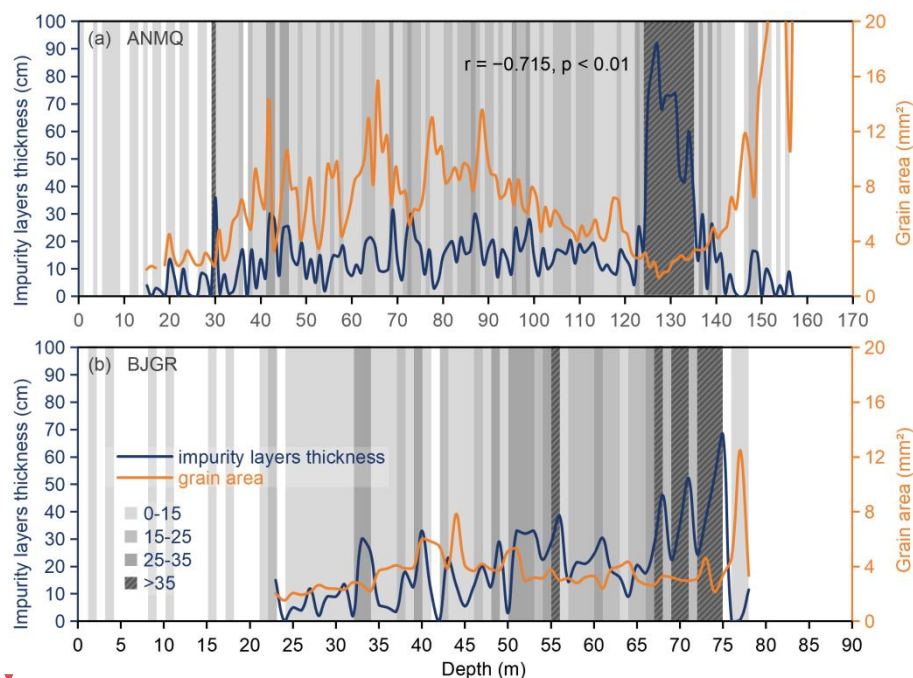
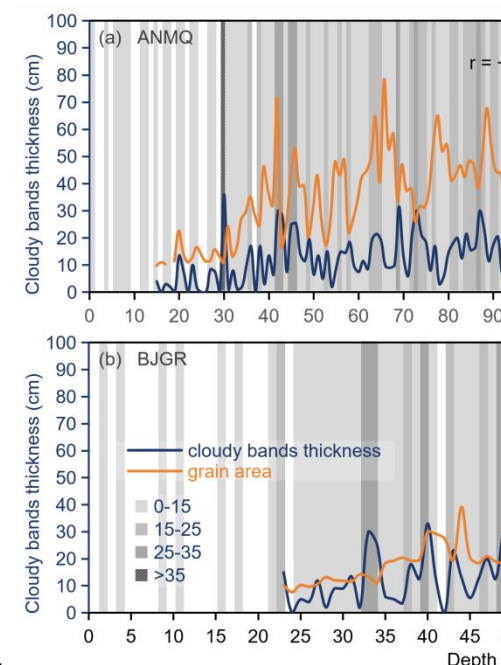


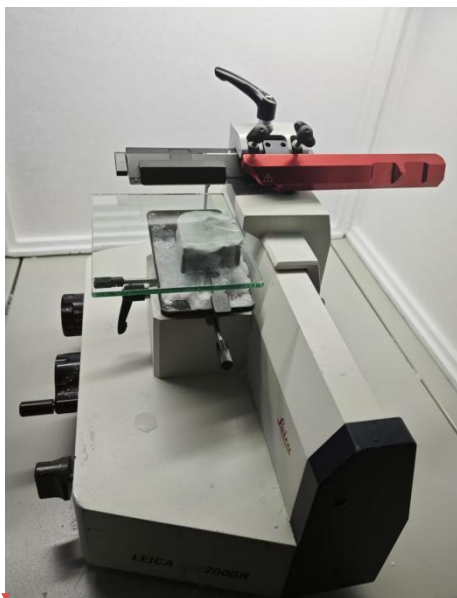
Figure A4. Variation sequences of impurity layers thickness and average grain area: (a) ANMQ; (b) BJGR; Background colors also indicate the thickness of impurity layers.



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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.

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

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