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Firn: Applications for the interpretation of ice-core records and estimation of ice-sheet mass balance

Drake McCrimmon[1,2], A. Ihle[3], K. Keegan[1] and S. Rupper[4]

Firn—old snow slowly densifying into glacial ice—provides valuable information for interpreting ice-core records, modeling meltwater runoff and sea-level rise, and improving our understanding of glacier dynamics through the interpretation of remote-sensing signals.

A glacier's cross section can be split into three main components: (1) a low-density layer of fresh snow at the surface, (2) a ~50–100-m-deep transition zone of densifying old snow called firn, and (3) hundreds to thousands of meters of high-density glacial ice at the bottom (Fig. 1). Firn is an important section of a glacier or ice sheet because the densification process and the grain structure impact how climate information is preserved by glacial ice. The microstructure of the firn (the size and shape of snow grains and pore space within the firn, Fig. 1c) influences both the movement and fate of air and water through the firn (Blackford 2007). These processes affect the interpretation of ice-core paleoclimate records, estimation of the capacity for firn to store glacier surface meltwater, and the use of remote sensing to study ice-sheet mass balance.

Interpretation of ice-core records

Gases trapped in ice cores generally reflect the atmosphere at a time in the past, thus allowing scientists to use ice-core gas records to reconstruct past atmospheric composition (Banerjee et al. p. 104), including greenhouse gases, extending back hundreds of thousands of years (Wendt et al. p. 102). The densification of firn is a major control on how gases are preserved in ice, so understanding this process is imperative for studying past climate.

Like surface snow, firn contains pore space between ice grains in which air can flow and liquid water can infiltrate. As firn density increases with burial depth, the space between snow grains shrinks until pores are closed off from one another (Fig. 1b, c). This depth, called the pore close-off depth, is the point when atmospheric gas becomes permanently trapped as bubbles enclosed in ice. Since gas is not trapped until the pore close-off depth, the air that is trapped in bubbles is younger than the surrounding ice (Schwander and Stauffer 1984). This difference in age is called Δage (delta age) and must be known to accurately date gas records from ice cores (Martin et al. p. 100). The Δage makes it possible to determine what the atmospheric composition was at specific points in Earth's climate history. Firn densification models, annual layer counting, and gas-diffusion models allow us to estimate Δage by determining the time it takes for firn to transition into glacial ice, as well as the time it takes for atmospheric gas to move through the firn to reach the pore close-off depth.

Since the densification rate of firn is strongly controlled by local climate, empirical firn densification models rely predominantly on site temperature and snow accumulation rate (Herron and Langway 1980). Typically, sites with higher temperatures densify more quickly, and sites with higher accumulation rates tend to have thicker layers of firn. While temperature and accumulation are the strongest controls on the compaction rate and these empirical models predict firn density well, there are other physical processes that also impact firn compaction (Fujita et al. 2014). An active area of firn research is the development of physics-based firn-compaction models that take into account firn microstructure and the underlying physical processes driving firn densification (Keenan et al. 2021). Improved firn-compaction models will allow us to better interpret ice-core paleoclimate records and estimate ice-sheet mass balance from remote sensing, especially in locations where empirical firn compaction models do not predict firn density well enough.

The movement of gas through the firn can also be modeled to help determine Δage. This becomes complicated as atmospheric gas composition is altered as it flows through firn pore spaces. Several physical processes alter how gas moves through firn, such as the settling of heavy gasses due to gravity and temperature-gradient-driven gas separation (Severinghaus et al. 1998). This means that the heavier isotopes of gases settle deeper into the firn and also towards cooler

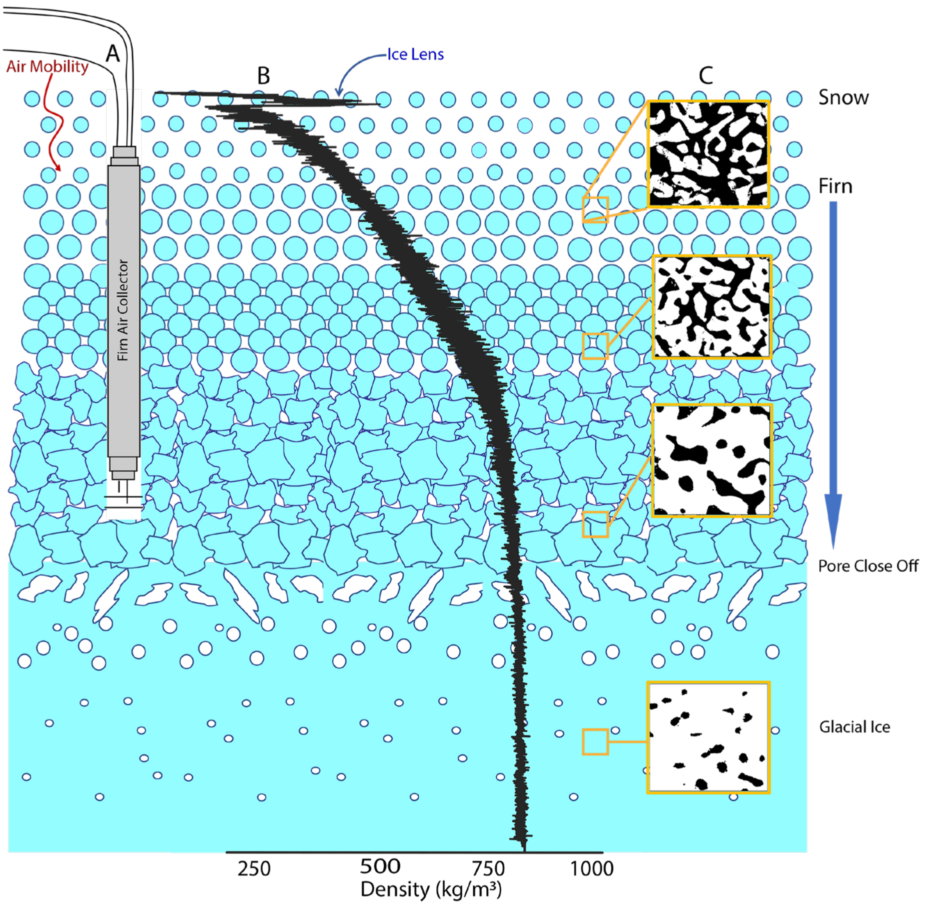

Figure 1: Background illustration shows the evolution of snow to firn to ice. **(A)** The firn-air collection apparatus. **(B)** Example density profile from snow surface through pore close-off to glacial ice (Burgener et al. 2013). **(C)** Example microCT images at differing densities, with black denoting pore space and white denoting ice grains.

temperatures. This results in a slight difference in gas composition between when the gas enters the firn column and when the gas reaches pore close-off. Gas diffusion models are tuned to many different gas species in order to accurately model the movement of different gasses through firn (Buizert et al. 2012). Optimizing these models allows researchers to correct for the change in gas composition within the firn and improve the age estimation of gases. In addition, the air that is traveling through the firn column can also be collected and measured to understand the atmospheric composition in recent history (Fig. 1a; Butler et al. 1999). This firn air is a link between current atmospheric composition and that which is trapped within ice-core bubbles, which may be hundreds to thousands of years old.

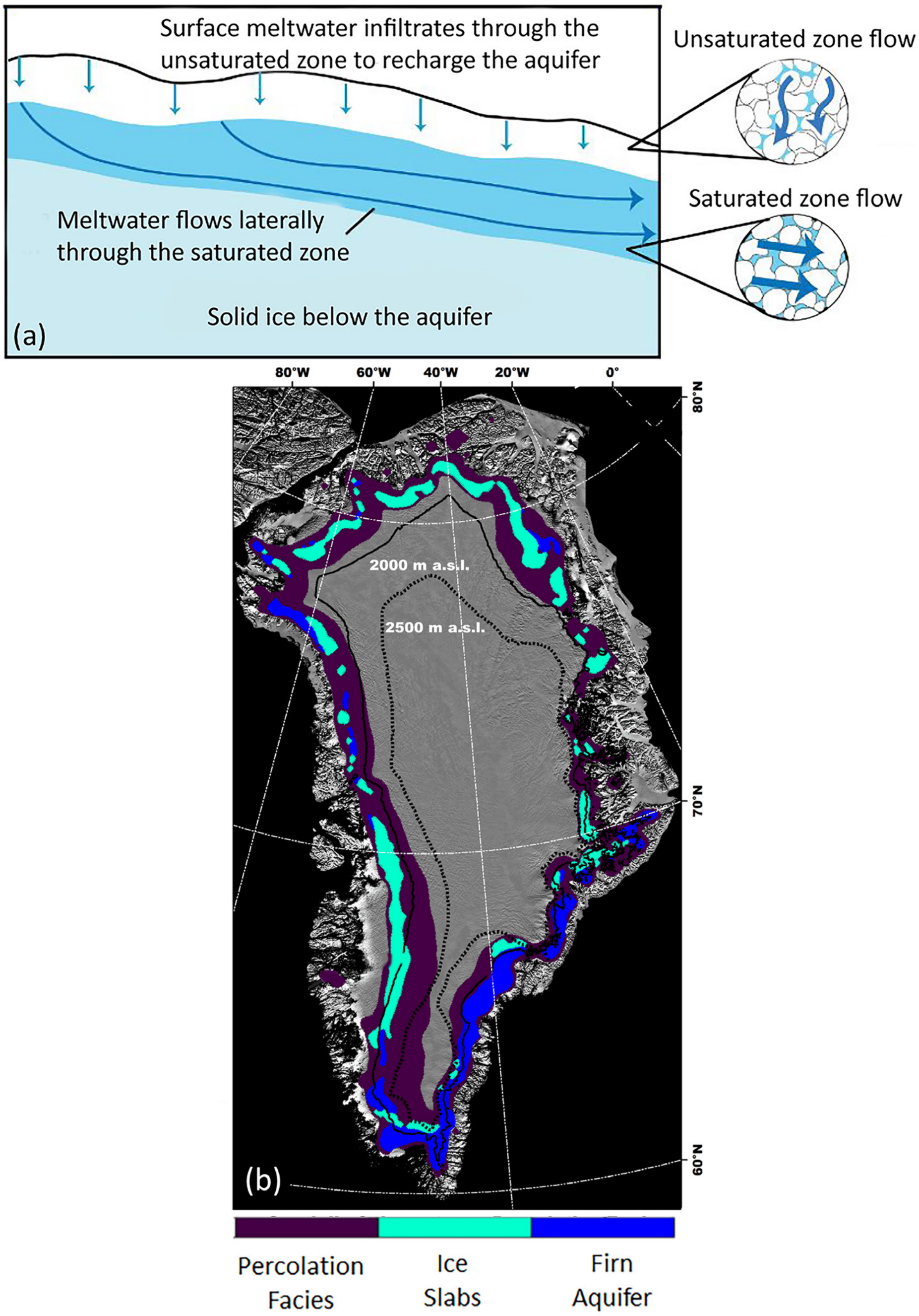

Figure 2: (A) A conceptual illustration of meltwater percolation into a firn aquifer (adapted from Miller et al. in review); and **(B)** Current firn aquifer extent in Greenland (adapted from Miller et al. 2022).

Modeling meltwater runoff and sea-level rise

The fate of ice-sheet surface meltwater depends strongly on firn. Instead of running off the ice sheet directly into the ocean, surface meltwater can percolate into the open pore spaces in firn, leading to the development of firn aquifers (Fig. 2a). Remote sensing has shown that there are large areas on both the Greenland and Antarctic ice sheets that have conditions conducive to forming firn aquifers. These conditions include high rates of melting and snow accumulation (Forster et al. 2014). High snow accumulation leads to a thicker layer of firn pore space and insulation to retain meltwater (Kuipers Munneke et al. 2014). In Greenland, large firn aquifers are found on the perimeter of the ice sheet (Fig. 2b) where such conditions are met (Koenig et al. 2014; Miller et al. 2022). Because firn aquifers can slow or entirely prevent meltwater runoff, determining the conditions under which firn aquifers develop will ultimately lead to more accurate estimates of how much surface meltwater will be stored within the firn, versus how much will runoff to the sea (Christ et al. p. 116).

Remote sensing for ice-sheet mass balance

Changes in the thickness and density of firn are a significant uncertainty in estimates of ice-sheet mass change using satellite measurements of surface elevation (Smith et al. 2020). For satellite measurements using microwave radiation, scattering related to snow grain and pore sizes can limit the ability of microwave radiation to penetrate into the ice sheet (Rott et al. 1993). This scattering complicates the use of remote sensing to understand the underlying structure of firn, its meltwater buffering capacity, and changes in ice-sheet surface elevation. Current work aims to use firn microstructure to inform the interpretation of microwave remote sensing on ice sheets in order to improve our understanding of ice-sheet mass balance, both today and in a warming future (Keenan et al. 2021).

Conclusion

Understanding the firn transitional zone is crucial to the accurate reconstruction of past climates, realizing the fate of ice-sheet surface meltwater, and improving estimates of ice-sheet mass balance. Firn provides an important link between processes in the modern atmosphere and ancient atmosphere that is trapped in deep glacial ice. The structure of firn also has major controls on the interpretation of remote sensing signals of glacier surfaces. Ultimately, improving our understanding of firn will deepen our insight of many processes on glaciers and ice sheets.

AFFILIATIONS

[1]Department of Geological Sciences and Engineering, University of Nevada Reno, USA

[2]Division of Hydrologic Sciences, Desert Research Institute, Reno, NV, USA

[3]Department of Earth and Environmental Sciences, University of Rochester, NY, USA

[4]Department of Geography, University of Utah, Salt Lake City, USA

CONTACT

Drake McCrimmon: drake.mccrimmon@dri.edu

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