doi.org/10.22498/pages.31.2.84

Investigating the unexplored paleoclimatic information of Greenland Ice Sheet basal materials

Lisa Ardoin

Debris-rich basal ice layer of an ice sheet are shaped by processes at the bedrock which alter the paleoclimatic signal preserved in the ice. Basal layers offer insights on past ice-sheet dynamics and environmental conditions that emerged during ice-free conditions.

Greenland basal layers

Ice cores are a valuable source of information on past climate change because they provide insights into past atmospheric composition and temperature through the analysis of entrapped air and ice properties. In the Greenland Ice Sheet (GrIS) (Fig. 1a), the ice layers are well-defined and arranged in stratigraphic order down to a depth of a few hundred meters above the bedrock. Currently, the oldest continuous paleoclimatic record from the GrIS dates back to approximately 123,000 years ago (Landais et al. 2006). Below this depth, the ice becomes folded but still preserves some of the original paleoclimatic signal (Dahl-Jensen et al. 2013). However, even though basal ice may be less ideal for paleoclimatic research, the deepest part of the ice sheets still hold significant potential for preserving important paleoclimatic information. This is particularly true since silty ice dating back as far as 1 Myr has been retrieved from the deepest sections of the GrIS (Bender et al. 2010; Willerslev et al. 2007; Yau et al. 2016).

The basal ice can be divided into two categories: the so-called silty ice is made up of basal layers which contain debris incorporated from the bedrock (Fig. 1b), contrary to the basal clean ice that is already stratigraphically disturbed, but free of debris (sometimes referred to as “deep ice”). The gases (Fig. 2a) and water-isotopes measurements (Fig. 2b) from silty ice near the bottom of the ice sheet raises concerns about the preservation of paleoclimatic records (Fig. 2; Bender et al. 2010; Souchez et al. 2006; Verbeke et al. 2002).

Alteration of the paleoclimatic signal in basal ice?

The basal ice layers in the GrIS have unique properties that distinguish them from the overlying meteoric ice layers (derived from snow precipitation), including differences in ice texture, debris content, and gas composition (Bender et al. 2010; Goossens et al. 2016; Souchez et al. 2006; Tison et al. 2015). These layers exhibit heterogeneity at different scales, potentially involving a complex history of successive episodes of dynamic instability, melting and refreezing (Goossens et al. 2016), in situ biogeochemical processes, and diffusion from the sediments below.

The basal ice layers exhibit low gas concentrations, between 2 to 80% (Fig. 2a) of a typical meteoric ice concentration (Goossens et al. 2016; Tison et al. 2015). This is due to various processes such as gas rejection during melting/refreezing processes and pressure-expulsion of gas into subglacial cavities at lower local ambient pressures, e.g. downstream from bedrock obstacles.

However, a large accumulation of greenhouse gases in the silty ice are reported (up to 12% and 0.6% of CO_2 and CH_4, respectively), associated with a decrease in the O_2/N_2 ratio down to anoxic conditions (Fig. 2a; Herron et al. 1979; Souchez et al. 2006; Verbeke et al. 2002). This distribution cannot be solely explained by physical processes and requires mediation of microbial activity to account for it, either in the underlying sediments, in the ice itself, or in the soils prior to ice-sheet build up (Herron et al. 1979; Souchez et al. 2006; Verbeke et al. 2002). As the silty ice is at the interface between two contrasted environments (meteoric ice vs. underlying sediments/bedrock), its trapped gas signature may result from the mixing of two endmembers (Souchez et al. 2006). Mechanical ice mixing between a meteoric endmember and a locally derived endmember may explain both the incorporation of debris and changes in gas chemistry, superimposed on diffusion processes generated by potential gradients between contrasting endmember properties (water isotopes, impurities, and gas concentrations). However, the locally derived component must have been affected by microbial processes, resulting in a depletion of O_2 (Souchez et al.

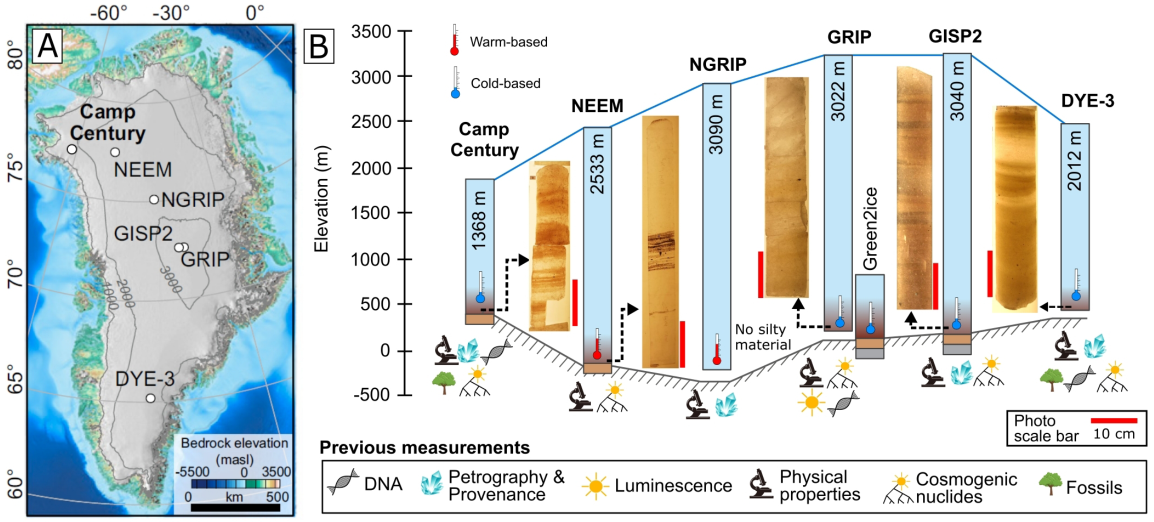

Figure 1: Synthesis of the studied ice cores from Greenland. **(A)** Ice-core locations and ice-surface elevation contours. **(B)** Ice-core thickness above the bedrock elevation (gray line), basal material thickness (exaggerated) and pictures of silty layers. Ice and gas chemistry were measured for all the ice cores. Modified from Christ et al. (2021).

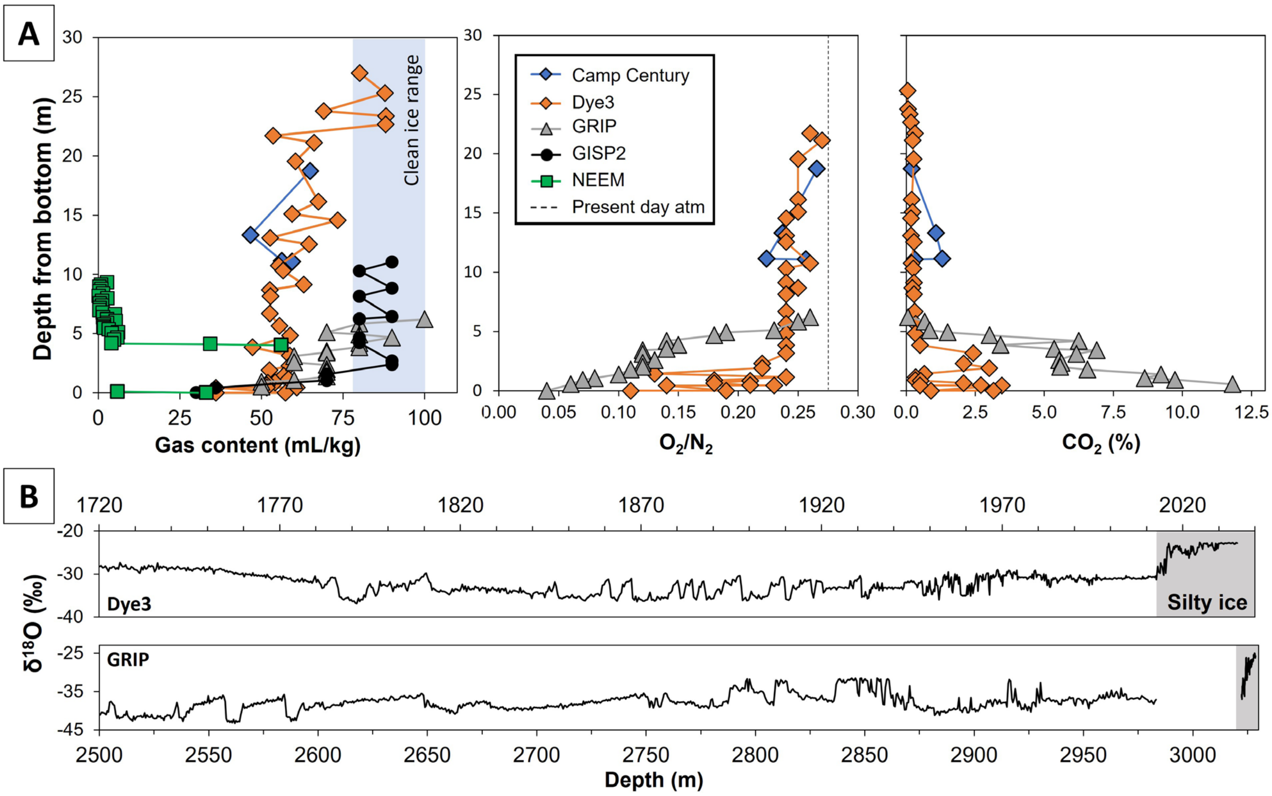

Figure 2: (A) Chemical proxies indicating variations between clean ice containing an atmospheric paleoclimatic signal and the silty layers of the Greenland Ice Sheet. **(B)** Ice $\delta^{18}O$ record for the deepest section of Dye3 and GRIP. Data from Bender et al. (2010), Goossens et al. (2016), Herron et al. (1979), Souchez et al. (2006), Verbeke et al. (2002), and Yau et al. (2016).

2006) and an accumulation of CO_2 and CH_4. This microbial signature may originate from a pre-existing marshy environment (Tison et al. 1998), which was eventually covered by the GrIS and trapped within the ice, or from the ecosystem prevailing in the subglacial environments.

Stable water isotopes ($\delta^{18}O_{ice}$ and δD_{ice}) serve as useful tools for identifying stratigraphic discontinuities in basal ice layers, as they provide a clear paleoclimatic signal, being a proxy of air temperature in both Greenland and Antarctic ice-core records (Dahl-Jensen et al. 2013). Melting and refreezing processes can affect the relationship between $\delta^{18}O_{ice}$ and δD_{ice} (Souchez and Jouzel 1984), a process that could happen close to the bedrock. Therefore, stable water isotopes can shed light on the processes that affected basal ice layers during and after their formation. Another interesting feature observed in some silty ice layers in the GrIS is that their $\delta^{18}O_{ice}$ and δD_{ice} values are higher than those found in the overlying meteoric ice (Fig. 2b). This suggests that these layers may be the remnants of an earlier stage of the ice sheet's growth, possibly from a time when the snow deposition occurred at a lower altitude (Souchez et al. 2006).

Unexplored paleoclimatic information in silty ice

Apart from traditional paleoclimatic proxies, the silty layers of the GrIS are becoming recognized as a valuable source of information on past ice-sheet dynamics. In addition, fossil remains, organic matter, and ancient biomolecules found in these layers provide insights into the types of ecosystems and environmental conditions that existed during periods of ice-free conditions (Fig. 1b). Recent research has demonstrated the potential of these layers to shed light on such key topics (Christ et al. 2021; Willerslev et al. 2007).

Analyses of mineral grains incorporated into the silty ice add constraints on the past waxing and waning (i.e. advance and retreat) of the GrIS. In situ-produced cosmogenic isotopes and the luminescence signal are two complementary methods constraining the past exposure and burial histories of under-ice sediments. The luminescence signal is indeed reset when the sediment is exposed to light. Under the ice cap, it rises because of the radioactive background of the geological environment. Thus, this luminescence signal can be used to date the last burial of the sediments during the last glacial advance. Alternatively, in situ-produced cosmogenic nuclides accumulate in quartz during ice-free conditions and decrease in concentration over time due to radioactive decay under the ice sheet. By coupling both methods, it is thus possible to constrain both the date of the last glacial ice-sheet readvance and the duration of the previous deglaciation (Christ et al. 2021; Schaefer et al. 2016). Additional constraints are provided by directly dating the basal ice, using dating techniques such as the ^{40}Ar accumulation/degassing rate (Bender et al. 2010; Yau et al. 2016) and ^{81}Kr in entrapped air (Buizert et al. 2014).

The ecosystems that occupied Greenland prior to the ice-sheet build-up, and during ice-free intervals, are poorly known because much of the fossil evidence is hidden below the kilometer-thick ice sheet. Terrestrial plant macrofossils, ancient molecules (DNA and lipid biomarkers, including their carbon and hydrogen isotopic composition) hold promises to unravel prevailing climatic conditions during ice-free intervals (Willerslev et al. 2007).

Despite stratigraphic disturbance and metamorphism effects, the basal layers of the GrIS, therefore, offer a unique opportunity to extend our knowledge about the history of the ice sheet and its (in)stability in a changing climate. The European Research Council Green2Ice synergy project will investigate this opportunity in the years to come (shorturl.at/kDFLN).

AFFILIATION

Laboratoire de Glaciologie, Université Libre de Bruxelles, Belgium

CONTACT

Lisa Ardoin: lisa.ardoin@ulb.be

REFERENCES

Bender ML et al. (2010) Earth Planet Sci Lett 299: 466-473

Buizert C et al. (2014) Proc Natl Acad Sci 111: 6876-6881

Christ A et al. (2021) Proc Natl Acad Sci 118: e2021442118

Dahl-Jensen D et al. (2013) Nature 493: 489-494

Goossens T et al. (2016) The Cryosphere 10: 553-567

Herron S et al. (1979) J Glaciol 23: 193-207

Landais A et al. (2006) Clim Dyn 26: 273-284

Schaefer J et al. (2016) Nature 540: 252-255

Souchez R, Jouzel J (1984) J Glaciol 30: 369-372

Souchez R et al. (2006) Geophys Res Lett 33: 24

Tison JL et al. (1998) J Geophys Res Atmos 103: 18885-18894

Tison JL et al. (2015) The Cryosphere 9: 1633-1648

Verbeke V et al. (2002) Ann Glaciol 35: 231-236

Willerslev E et al. (2007) Science 317: 111-114

Yau AM et al. (2016) Earth Planet Sci Lett 451: 1-9