General comments

Ardoin et al. present a comprehensive investigation of gas composition (N2, O2, Ar, CO2, and CH4), water isotopes, and DNA data from the basal ice and underlying sediments of the Camp Century and GRIP ice cores. The authors suggest that CH4 produced in subglacial sediments can diffuse into the overlying basal ice, where it may undergo partial oxidation to CO2. They further suggest that the elevated CH4 and CO2 concentrations observed in the upper sections of basal ice are likely due to mechanical mixing. Finally, authors suggest that CH4 consumption by methanotrophs is likely in the basal ice in Camp Century, whereas evidence for methanotrophic activity in GRIP appears limited.

The dataset is valuable particularly within the context of the special issue, as it revisits a unique legacy core that reached the ice–bed interface and applies modern analytical approaches. The study also has potential to contribute to ongoing discussions on subglacial carbon cycling and the interpretation of extreme gas signatures in debris-rich basal ice.

Overall, I find the data set interesting and potentially valuable. However, in its current form, the manuscript is very difficult to read. I do not recommend publishing this manuscript in a journal as prestigious as 'The Cryosphere', unless the authors can address significant issues described below and thoroughly revise the manuscript.

Specifically, the authors need to clearly state the central research questions their study aims to answer. The current presentation lacks a cohesive narrative, making it challenging for the reader to follow the progression of ideas and the connection between different sections. Furthermore, the broader implications of their findings are not sufficiently explained, leaving the reader to question the true contribution of this work to the field of cryospheric sciences. Without a more focused and clearly articulated argument, supported by a well-structured and engaging presentation, the manuscript fails to meet the high standards expected for publication in 'The Cryosphere'.

Authors: We thank the reviewer for this suggestion and appreciate their comments aimed at improving the clarity of the manuscript. In response, we substantially revised several sections of the paper, including the Abstract, Introduction, and parts of the Discussion, to better articulate the scientific motivation, objectives, and implications of our findings.

In particular, the Introduction has been reorganized to more clearly emphasize: (i) the role of subglacial environments in carbon cycling, with a focus on CH_4 production and emissions; (ii) the microbial processes responsible for greenhouse-gas production; (iii) the uncertainties surrounding the production, transport, and consumption of greenhouse gases beneath ice sheets; (iv) the value of basal ice and underlying sediments as unique archives for investigating these processes directly at the bed; and (v) the scientific approach and objectives of the present study.

The Discussion was also substantially revised. We reorganized the section titles and streamlined the text and transitions to provide a more coherent narrative focused on methane production (Section 4.1), transport (Section 4.2), and preservation within basal ice (Section 4.3). The final two paragraphs (lines 713-752) now discuss these processes under both cold- and warm-based ice-sheet conditions, allowing us to place our findings in a broader glaciological context and compare them with observations of subglacial CH_4 export from the Greenland Ice Sheet (see also our response to Reviewer 1).

As noted above for reviewer 1, we interpret these broader implications with caution. Rather than providing robust quantitative constraints, our analysis is intended to highlight a potentially important overlooked process that may contribute to subglacial greenhouse-gas emission in the future and warrants further investigation.

Beyond the scope of the special issue, our dataset provides the first continuous gas measurements across the full basal sequence of an ice sheet, from debris-free ice to debris-rich ice and to underlying sediments.

* I note that as the DNA analysis falls outside my primary area of expertise, I do not provide detailed comments on the DNA-related methods or interpretations. My review focuses on the gas composition data, physical and chemical processes at the ice–bed interface, and its implications for subglacial greenhouse gas dynamics.

Specific comments

Abstract

The abstract reads primarily as a technical summary of the methods and analyses performed, rather than clearly conveying the main contribution of the work to existing previous knowledge. The authors should more explicitly explain the background information of the research topic, the general problem of what this study is addressing, and implications of the new finding on, for example, subglacial carbon cycling and/or greenhouse gas dynamics.

Authors: The abstract was re-written and clarified accordingly.

Line 34: "There is no evidence of CH4 consumption by methanotrophs at GRIP, suggesting that variations of bed conditions, ice dynamics and the nature of the organic material control the fate of CH4 produced in the subglacial environments." The logical flow would be clearer if the abstract first explain that methanotrophic activity is likely in Camp Century, contrary to GRIP.

Authors: The abstract was re-written, and the request made by the reviewer is now integrated in the new version.

"**Abstract**

Subglacial environments host diverse microbial communities and store organic carbon, representing a potentially significant source of CH_4 and CO_2 to the atmosphere. However, the processes controlling the fate of subglacial CH_4, whether it is preserved, transported, or consumed, remain poorly constrained. Here, we investigate CH_4 dynamics at the bed-ice interface using basal ice and sediment samples recovered from two deep Greenland ice cores: Camp Century and GRIP. Both cores contain debris-rich ice with elevated CO_2 (up to 13%) and CH_4 (up to several thousand ppm) reflecting biological activity such as respiration and methanogenesis. This activity is thought to occur in subglacial bed-material prior to incorporation into the ice. The vertical gas profiles (N_2, O_2, Ar, CO_2, CH_4) combined with microbial DNA analyses reveals methanotrophy within debris-rich ice layers at Camp Century, where CH_4 produced in subglacial sediments diffuses into the ice and is partially oxidized to CO_2. In contrast, at GRIP, CH_4 and CO_2 in debris-rich ice is transported into the ice predominantly through mechanical mixing processes such as shearing and folding, with no evidence for methanotrophic consumption despite the presence of oxygen. These observations suggest that local bed conditions, ice dynamics, and organic matter availability control the fate of CH_4 beneath ice sheets. By providing an integrated geochemical and microbial assessment across these two contrasting sites, our

study highlights the role of debris-rich ice as a dynamic, site-dependent component of the subglacial carbon cycle and its potential contribution to greenhouse gas fluxes from ice sheets."

Introduction

The introduction currently lacks necessary background information that would help readers follow the manuscript. For example, it would be nice to briefly explain that ancient atmospheric air can be trapped and preserved as air bubbles in ice. This is important before discussing anomalous greenhouse gas concentrations trapped in basal ice. Also, previous studies conducted on basal debris-rich ice are not sufficiently described. Providing a summary of what has been found in previous studies and what remains unresolved would help convey the significance of the present study. Finally, the central scientific question of this study is not clearly stated. That is, it is unclear what the main research objective is. It will be nice to explain why greenhouse gas dynamics across the sediment-ice interface matter and what knowledge gap this study aims to address.

Authors: We rewrote the Introduction to better articulate the motivation and objectives of the study. The revised text now begins by highlighting that ancient atmospheric air is trapped and preserved within the ice matrix, while emphasizing that processes occurring near the ice-sheet bed can alter its composition. We then introduce subglacial carbon cycling and its potential contribution to CH_4 emissions by reviewing previous studies, which have primarily relied on analyses of subglacial runoff. This provides the rationale for investigating basal sequences such as Camp Century, which preserves the complete transition from glacier ice to underlying subglacial sediments and therefore offers a unique opportunity to study these processes directly beneath the ice sheet.

Previous studies of basal ice have largely focused on the stratigraphy and origin of basal ice layers (Bender et al., 2010; Souchez et al., 2006; Verbeke et al., 2002). In contrast, the present study expands the scope to investigate the production, transport, and preservation of CH_4 at the ice-bed interface under cold-based conditions. To the best of our knowledge, we are not aware of any study which directly measure interface in term of methane production, transport and consumption, except Michaud et al., (2017) which investigate similar process but under warm-bed conditions in Antarctica (discussed in lines 718-720).

"**Introduction**

Air bubbles trapped during the transformation of snow into firn, and ultimately ice, preserve a record of past atmospheric composition (Loulergue et al., 2008; Lüthi et al., 2008). Near the ice-sheet bed, however, gas concentrations and compositions can be altered by ice deformation, microbial activity, and geochemical processes, obscuring the original atmospheric signal (Bender et al., 2010; Herron et al., 1979; Verbeke et al., 2002; Souchez et al., 2006; Tison et al., 2015). Large enrichments in CH_4 and CO_2 relative to atmospheric concentrations are commonly observed in basal ice (Verbeke et al., 2002; Souchez et al., 2006), indicating active carbon cycling beneath ice sheets (Wadhams et al., 2019). These observations suggest the presence of substantial subglacial carbon reservoirs, yet their size, origin, and dynamics remain poorly constrained because direct access to subglacial environments is limited. Organic matter derived from ancient sediments, soils, and vegetation buried beneath ice sheets may fuel microbial activity and serve as a source of carbon-rich gases (Wadham et al., 2008; Souchez et al., 2006; Hatton et al., 2026).

The discovery of diverse and metabolically active microbial communities in subglacial environments has transformed our understanding of subglacial ecosystems (Doyle et al., 2013; Sharp et al., 1999; Skidmore et al., 2005, 2000). Microbial respiration of organic matter consumes O_2 and produces CO_2 (Pain et al., 2021; Souchez et al., 2006; Tranter et al., 2002), creating anoxic conditions that favor methanogenesis and the production of CH_4 (Adnew et al., 2025; Dieser, 2014; Lamarche-Gagnon et al., 2019; Pain et al., 2021; Souchez et al., 2006; Verbeke et al., 2002; Wadham et al., 2008). As a result, subglacial environments can generate and release substantial quantities of CH_4 and CO_2, with methane emissions from the Greenland Ice Sheet (GrIS) subglacial runoff comparable, on an area-normalized basis, to those of major world rivers (Lamarche-Gagnon et al., 2019; Pain et al., 2021; Hatton et al., 2026).

Despite growing evidence for subglacial greenhouse-gas production, the processes controlling the fate of CH_4 and CO_2 beneath ice sheets remain poorly understood. Once produced, CH_4 may accumulate within subglacial reservoirs, be oxidized through aerobic or anaerobic methanotrophy, or be exported in subglacial runoff (Michaud et al., 2017; Adnew et al., 2025; Pain et al., 2021). CO_2 concentrations are similarly influenced by multiple biological and geochemical processes, including respiration and chemical weathering reactions that consume O_2 and modify carbon pools (Tranter et al., 2002). Consequently, the balance between greenhouse-gas production, consumption, and transport remains uncertain, limiting our ability to assess the role of ice sheets in the global carbon cycle.

Most current understanding of subglacial greenhouse-gas cycling derives from analyses of subglacial runoff collected at ice-sheet margins. While valuable, runoff integrates processes occurring over large spatial and temporal scales and therefore provides only indirect information on gas transformations occurring at the ice-bed interface. In contrast, the basal ice layer of an ice sheet is largely shaped by processes occurring at the ice-bed interface, and records interactions among ice, sediments, microorganisms, and gases at the base of the ice sheet. A few deep-drilling projects beneath the Greenland Ice Sheet have successfully recovered this basal interface, revealing several meters (up to 25 meters) of debris-laden ice overlying bed material (Bender et al., 2010; Christ et al., 2021; Goossens et al., 2016; Souchez et al., 1994; Verbeke et al., 2002). This debris-rich ice has been shown to contain exceptionally high concentrations of CO_2 (up to 13%) and CH_4 (up to 5000 ppmv), along with O_2 depletion (Herron et al., 1979; Souchez et al., 1995; Verbeke et al., 2002). These elevated CO_2 and CH_4 concentrations, together with the presence of organic carbon, suggest accumulation and preservation of greenhouse gases in the deepest ice layers, offering a rare observational window into subglacial environments.

Here we investigate gas dynamics directly at the ice–bed interface using basal materials from two deep-drilling projects: Camp Century and GRIP. Located at the northwest margin of the GrIS, the Camp Century ice core preserves the complete transition from debris-free basal ice to the bed material (Bierman et al., 2024; Hansen and Langway, 1966; Herron et al., 1979), offering a unique opportunity to study the production, transport, and consumption of greenhouse gases across the sediment-ice interface. The GRIP ice core, drilled at the summit of the Greenland Ice Sheet, did not recover bedrock, but the final 6 meters of debris-rich ice contained up to 13 % of CO_2, the

highest concentration measured in any ice core to date (Souchez et al., 1995). Despite the exceptional nature of these records, detailed observations of their basal ice remain sparse.

In this study, we apply a multiparametric approach combining gas composition, ice water isotopes, and prokaryotic metagenomic analyses to investigate the production, transport and consumption of CH_4 and CO_2 beneath the Greenland Ice Sheet. By substantially increasing the number of measurements across the basal sequences of both Camp Century and GRIP, we evaluate the mechanisms responsible for greenhouse-gas production, transport and preservation at the ice-bed interface. Through a comparison of a site near the ice-sheet margin and a site in the ice-sheet interior, we assess the factors controlling the formation and evolution of subglacial greenhouse-gas reservoirs directly beneath the Greenland Ice Sheet."

Line 39–40: This sentence stating that ice sheets were not considered contributors to the global carbon cycle seems inconsistent with the following sentence, which emphasizes recent findings of active carbon cycling and greenhouse gas emissions from the Greenland Ice Sheet.

Authors: We thank the reviewer for highlighting this inconsistency. We agree that the original phrasing was confusing, and we have therefore removed the sentence to improve clarity.

Line 43: It will be nice to provide quantitative information on CH4 emissions from subglacial runoff and indicate how significant these emissions are relative to global CH4 budget.

Authors: We now compare an estimate of subglacial CH_4 runoff for the Greenland Ice Sheet (Hatton et al., 2026) with an estimate of the stock of CH_4 in basal ice in Greenland in the discussion. This inventory exceeds the estimated annual CH_4 export through glacial runoff by one to two orders of magnitude, highlighted the potential importance of debris-rich ice as a methane source. Moreover, this estimate accounts only for CH_4 stored within the basal ice and excludes potentially much larger reservoirs of organic carbon (and methane) contained within underlying frozen sediments and soils, which may reach thicknesses of several hundred metres (Yang et al., 2025).See lines 735-753.

"Present-day subglacial runoff is primarily sourced from warm-based regions of the Greenland Ice Sheet (GrIS), where the limited available observations indicate little to no CH_4 accumulation in basal ice and a net CH_4 export of approximately 2.5×10^{-3} Tg CH_4 yr^{-1} through glacial runoff (Hatton et al., 2026). This runoff-derived CH_4 appears to originate largely from relatively young (~5 kyr old) organic carbon buried in subglacial sediments near the ice-sheet margin during the most recent Holocene readvance (Hatton et al., 2026). Continued warming is expected to expand meltwater production and hydrological connectivity farther into the ice-sheet interior (Box et al., 2022), potentially accessing previously isolated carbon reservoirs and CH_4-rich subglacial environments, including those associated with the cold-based regions. Based on the estimate of MacGregor et al. (2016) that ~24% of the GrIS bed is likely frozen, ~43% likely thawed, and ~33% thermally uncertain, extrapolation of the integrated CH_4 content measured in the debris-rich ice of GRIP and Camp Century ($3.1 * 10^{-2}$ and $1.9*10^{-2}$ mol m^{-2}, respectively) yields a Greenland-wide CH_4 inventory of 0.12 – 0.48 Tg CH_4 associated with the debris-rich ice in cold-based regions. This inventory exceeds the estimated annual CH_4 export through glacial runoff by one to two orders of magnitude, highlighting the potential importance of debris-rich ice as a methane source. Moreover, this estimate accounts only for CH_4 stored within the basal ice and excludes potentially much larger reservoirs of organic carbon (and methane) contained within underlying frozen sediments and soils, which may reach thicknesses of several hundred meters (Yang et al., 2025)."

Line 62: The phrase “influence CO2 and O2 concentrations” is unclear. Specify where these CO2 and O2 concentrations are being modified. Atmospheric air? Basal ice? Subglacial sediment?

Authors: This sentence has been modified, and agreement with reviewer 1, we now state more clearly that CO_2 and O_2 are produced and consumed by multitude of processes, including respiration and chemical weathering reactions that consume O_2 and modify carbon pools (Lines 62-63).

“CO_2 concentrations are similarly influenced by multiple biological and geochemical processes, including respiration and chemical weathering reactions that consume O_2 and modify carbon pools (Tranter et al., 2002).”

Line 79–84: This part would fit better in the “Materials and methods” section. In addition, the term “Unit 5” is not clearly defined. Please clarify what “Unit 5” represents and ensure it is properly introduced before being used.

Authors: The Unit 5 is the first unit of the sediments underneath the ice sheet. It represents the first 0.6m of sediments in contact with the ice and is fully described in Bierman et al. (2024). To streamline the Introduction and avoid excessive site-specific detail, we removed the description of the Camp Century sedimentary sequence and transferred it to the Materials and Methods section (Lines 102–111). In addition, because these stratigraphic units are referenced only occasionally in the manuscript, we removed the “Unit #” terminology throughout the text and instead describe the deposits directly (e.g., ice lens below fluvial deposits).

“The Camp Century ice core was completed in 1966 in northwest Greenland (77° 10' N; 61° 08' W; 1885 m above sea level (Hansen and Langway, 1966; Herron et al., 1979). The basal section of the Camp Century ice core in this study spans the last lowermost 27 meters of ice above the bed material. This section includes the transition from the debris-free to the debris-rich basal ice (16.8 m above the sediment) and from the basal ice to the bed materials, at 1387.4 m below the surface (Fig. 1) (Bierman et al., 2024; Hansen and Langway, 1966). The transition between the bed and the ice is abrupt, with sediment comprising 84 weight percent of the total sample in the unit in contact with the ice (Bierman et al., 2024). Approximately 3.44 m of bed material was recovered beneath the basal ice at Camp Century. Prior workers divided this section into five stratigraphic units, representing different depositional environment including basal till and fluvial sediments (Bierman et al., 2024; Christ et al., 2024, Collins et al., 2025). Luminescence dating of the uppermost sediment samples indicates it was last exposed to light 416 ± 38 ka ago, corresponding to MIS 11 interglacial period (Christ et al., 2023).”

Materials and methods

Line 94: Please explain how “debris-free”, “debris-rich basal ice”, “basal ice”, and “bed materials” were defined. It is currently unclear whether these terms are based on visual observations, sediment content thresholds, stratigraphic boundaries, or previously established classifications.

Authors: We thank the reviewer for pointing out this lack of clarity. We have added a paragraph to clearly define “debris-free ice”, “debris-rich basal ice”, “basal ice”, and “bed materials”, including the criteria used for their distinction (line 93 to 100)

“In this manuscript, the term basal ice refers to the deepest part of the ice sheet, when the stratigraphy is disturbed and the paleoclimatic signal unclear (from loss of stratigraphy, lack of dating, or interactions with the bed). Basal ice can be subdivided in debris-free ice, and debris-rich ice based on visual observations. The debris-rich layers is called “silty ice” in some previous

studies (Goossens et al., 2016; Herron et al., 1979; Hubbard et al., 2009; Souchez et al., 1994; Verbeke et al., 2002) and "dirty ice" in others (Bender et al., 2008). However these terms can be misleading because the entrained debris span a wide range of particle size (Blard et al., 2023; Herron et al., 1979; Marschalek et al., 2024), and is not restricted to silt-size materials (particles 2 to 62 µm in diameter, Wentworth, 1922). The bed material refers to the substrate on which the ice sheet built up and flows over. It can be sediment or bedrock, but it often remains undefined because it is not reached or recovered by coring. "

Line 99: Please define "GrIS" at its first occurrence before using the abbreviation.

Authors: "GrIS" is now defined at its first occurrence in the Introduction (Line 55).

Line 101: At the surface, there is snow not ice. Please remove "ice" from "ice surface".

Authors: The term has been revised accordingly.

Line 105: The term "cold bed conditions" needs clarification. Does this refer to the absence of partial melting?

Authors: Exactly. We have revised the text to specify that "cold bed conditions" refer to the absence of basal melting (line 120).

"The basal borehole temperature is -13°C and -9.2°C at Camp Century and GRIP, respectively; implying cold bed conditions, and therefore the absence of partial basal melting, for both sites (MacGregor et al., 2016). In contrast, elsewhere under Greenland's ice sheet warm-based conditions are characterized by temperatures at or near the pressure-melting point, allowing partial melting at the interface between the ice and the bed material."

Line 112: "describe" to "described".

Authors: It has been corrected.

Line 114: It is unclear how the 1 SD reproducibility was determined. Was it calculated from a combination of SD of internal standard measurements and triplicate analyses of each sample?

Authors: It was calculated from the internal standard measurements (0.04 ‰ and 0.35 ‰ for $\delta^{18}O$ and δD respectively) and we checked that the triplicate was in the same order of magnitude (the average SD of the triplicates is 0.05 ±0.03 ‰.and 0.15 ±0.15 ‰ for $\delta^{18}O$ and δD respectively). We clarified in the text that the 1 SD reproducibility is from the internal standard measurements (line 132).

"Standard deviation (SD) was calculated using internal standards during each batch of measurements and monitored by performing triplicate analysis for each sample. From internal standard measurements, we report median 1 SD reproducibility of 0.04 ‰ and 0.35 ‰ for $\delta^{18}O$ and δD, respectively."

Line 124: Please clearly define what "Unit 2" refers to before using the term. It may be helpful to introduce both Unit 2 and 5 together earlier in the manuscript.

Authors: We thank the reviewer for this helpful suggestion. To improve clarity, we have removed the term “Unit 2” and revised the corresponding description to make the stratigraphic context clearer without relying on the unit’s label described in Bierman et al. (2024).

Line 166–171: It is unclear how the concentrations of O2, Ar, CH4, N2, and CO2 were measured in the bubble free ice (BFI)? Does this imply that residual gas remained in the BFI? Is BFI is not actually bubble-free?

Authors: We now clarify how BFI was used as a procedural blank (Lines 185-186): “To quantify blanks, BFI samples were processed using the same analytical procedure as described above for regular samples.”

Line 168 and 209: “milliQ” to “Milli-Q”.

Authors: “Milli-Q” has been corrected accordingly at both locations.

Results

Line 253: The order of figure explanation is not consistent. Figure 3 is discussed before figure 2, which interrupts the logical flow. Please consider reordering the figures so that they are introduced consecutively.

Authors: We refer to the figure sooner in the text (e.g., material and methods) to ensure a correct order of figure in the text.

Line 253–255: In the “results” section, the focus should be on presenting the findings of this study rather than summarizing previous work. In addition, it is unclear why ice crystal diameters and c-axes orientations should be described here.

Authors: We disagree with the reviewer on this point. We consider that describing the physical characteristics of basal ice, including facies, debris content, and ice-fabric properties, is essential for establishing the context in which the gas, prokaryotic DNA, and isotopic measurements are interpreted. These observations provide the stratigraphic framework of the basal sequence. The title of this section has been modified accordingly (“Basal ice stratigraphy: Facies, ice $\delta^{18}O$ and δD, and debris content”).

Line 258: Why is Fig. 2c referenced here?

Authors: The figure reference has been corrected from Fig. 2c to Fig. 1c.

Line 268: Are clotted debris visible in Fig. 1e?

Authors: Clotted debris are not clearly visible in Fig. 1e. However, the cloudy appearance of the ice suggests the presence of fine debris (likely clay), consistent with observations reported in Tison et al. (1994).

Line 272: It is unclear of “top 1.5 m”. Does this refer to 1.5 m above the ice-bed interface?
Authors: We thank the reviewer for pointing out this ambiguity. Here, “top 1.5 m” refers to the uppermost 1.5 m of the debris-rich ice, i.e., near the transition between clear ice and debris-rich basal ice (line 288). The text has been clarified accordingly.

“In the uppermost ~1.5 m of the debris-rich ice, these layers are associated with alternating crystal fabrics, ranging from large interlocking crystals with weak preferred orientation to finer-grained ice exhibiting a single maximum fabric”

Line 275–276: The phrase “exceeding those of both Holocene and Eemian ice” requires clarification. Are you referring to Holocene and Eemian ice from GRIP? What is the range of δ18O values for Eemian ice from GRIP?

Authors: We are now referring to the Holocene and Eemian sections of the GRIP ice core (lines 291-292). At GRIP, $\delta^{18}O$ values range from -34 to 35 ‰ during the Holocene (Souchez et al., 1994) and from −35 to −32 ‰ during the Eemian (Johnsen et al., 1995).

While Camp Century falls within glacial-interglacial values, GRIP basal ice show especially high $\delta^{18}O$ near the bottom of the core, falling outside interglacial values (Fig. 3b,h), supporting previous interpretations with now deposition at lower elevation during the ice-sheet buildup (Souchez et al., 1994, 2006).

Line 276–277: Please provide a reference supporting the statement that elevated δ18O values are consistent with ice formed at the ground surface in the absence of an ice sheet.

Authors: We added two references (Jouzel & Souchez, 1982; Souchez et al., 2000).

Line 280: “At Camp Century, δ18O depth variations oscillated between glacial and higher than Holocene values” Do you mean glacial and Holocene values from Camp Century ice?

Authors: We are referring to the glacial (- 41 ‰) and Holocene (- 29 ‰) values of the Camp Century ice core (Dansgaard & Tauber, 1969). To avoid ambiguity, we revised the text (line 298-299) to explicitly identify these reference intervals and report their corresponding $\delta^{18}O$ values.

“In Camp Century ice core, $\delta^{18}O$ depth variations oscillated between glacial (~ - 41 ‰) and higher than Holocene values (~ - 29 ‰; Dansgaard and Tauber, 1969; Fig. 3b).”

Line 285–286: Are the water isotope values derived exclusively from basal ice, or do they include all debris-free ice and debris-rich ice?

Authors: Yes, they are derived from the basal ice. For GRIP, debris-rich ice only, and for Camp Century it’s covering the transition from debris-free to debris-rich ice (see Fig. 3b). This information has been added in the figure caption of figure 2.

Line 291: The regression lines for GRIP and Camp Century are difficult to distinguish in the figure. Please consider using different colors.

Authors: We agree with the reviewer, and this has been modified in Fig. 2.

Line 293: This section is difficult to follow in its current form. It may improve readability to divide it into subsections (e.g., 3.2.1 Total gas content, 3.2.2 Greenhouse gases, 3.2.3 Major air (N2, O2, and Ar)).

Authors: We added the subsections accordingly, with 3.2.1 Total gas content, 3.2.2. Major gas content (N_2, O_2, Ar) and 3.2.3. Greenhouse gases (CH_4 and CO_2).

Line 295: Figure B5 is referenced before Appendix A and figures B1 to B4 are introduced. Please revise the order of references to maintain a logical and sequential flow.

Authors: We thank the reviewer to pointed this out. We reorganized the Appendix accordingly.

Line 316–317: This sentence is difficult to understand. What is being contrasted here? Clarify the comparison and make the intended contrast explicit.

Authors: We agree that this sentence was not clear, we decided to remove it and reorganized the section accordingly to the 3 subsections to clarify the main messages of our data.

Line 324: Please check "40 794 ± 2 217 ppm". Is a comma missing?

Authors: No, there is no comma missing. We measured 4% of CH_4 in the sediment of Camp Century. For CH_4, we gave all the measurements in ppm in the manuscript for consistency. We measured variation from 0.93 ppm to 40 794 ppm of CH_4 in the basal section of Camp Century.

Line 334: "2.2 ± 0.1" missing "%"?

Authors: Corrected.

Line 350: The x-axis labels for CH4 in Figure 3d are difficult to read.

Authors: Corrected, we changed the labels and display them in 2 layers to clarify it.

Line 362: "Fig. A1" Again, please ensure that figures are discussed consecutively and introduced in a logical order.

Authors: We reorganized the introduction and the order of the figures.

Discussion

Line 406: Respiration is mentioned earlier at line 388 as a potential in situ process, but it is not discussed in this paragraph. If in situ respiration is considered important as you mentioned at line 388, please explain on how it may influence the observed gas signatures. If not, earlier statement should be clarified or revised to avoid confusion.

Authors: Thank you for noticing this. We added 2 sentences about respiration to clarify (line 432-437).

"In such environments, aerobic respiration is expected to be the primary pathway consuming O_2 and producing CO_2 during the early stages of organic matter degradation. This interpretation is consistent with the increase in O_2 $\delta^{18}O$ accompanying O_2 consumption observed at GRIP (Souchez et al. 2006). As O2 become depleted, microbial metabolism typically shifts toward anaerobic pathways, including respiration using alternative terminal electron acceptors such as nitrate, sulfate, or Fe(III), before methanogenesis becomes energetically favourable under strongly reducing conditions (Wadham et al., 2010)"

Line 416: Remove the unnecessary space in "ice- bed".

Authors: Corrected.

Line 426: This is confusing. In line 410, in situ CH4 production is suggested as possible. However, in line 426, it is stated that the data do not support methanogenesis.

Authors: The DNA data shows that the potential for in-situ CH_4 production is in the ice. However, it doesn't mean that methanogenesis is happening. We reformulate the section to avoid confusion (lines 437-444)

"In our study, we used a DNA-based approach and did not focus on viable organisms, however viable microorganisms, including methanogens, are commonly observed in subglacial waters (Boyd et al., 2010; Lanoil et al., 2009; Sharp et al., 1999; M. L. Skidmore et al., 2000; Stibal et al., 2012). Our DNA measurements show that all genes encoding the enzymes required for methanogenesis are present at the base of the Camp Century ice core, indicating a genetic

potential for in situ CH_4 production and a complete methanogenesis pathway (Figs. 1d). In contrast, samples located further above the ice–bed interface at Camp Century, as well as those from GRIP, contain only partial methanogenesis pathways, with 20–80% of the associated genes identified (Fig 1f, l)."

Line 427: The term "incomplete" needs clearer explanation. What exactly is incomplete? Please explain what is meant and why it is considered incomplete?

Authors: We reformulate the sentence, to avoid ambiguity (lines 437-444), see previous answer.

In addition, in section 3.3 (lines 383-386), we give the definition of "complete" metabolic pathway: "Specifically, we measured the completeness of each metabolic pathway as the fraction of necessary genes encoding the key enzymes in these processes for methanogenesis and methanotrophy (% of biological pathway in Fig. 3 d, j)."

Line 428: "Figs. 1d, j" appears to be incorrect. There is no panel "j" in Fig 1.

Authors: Corrected.

Line 440: Please provide the r2 and p values for the regression line to support the stated relationship.

Authors: We clarify that our interpretation is not based on a linear regression analysis, but on a conceptual two-endmember mixing framework between debris-free basal ice and a debris-rich basal endmember (Souchez et al., 1995).

The observed covariations between independent variable (ice $\delta^{18}O$, gas composition, and debris content) are consistent with this mixing hypothesis and support a first-order mechanical mixing control on basal ice properties.

In any case, Pearson correlation coefficients indicate a significant positive relationship between $\delta^{18}O$ and CH_4 ($r = 0.81$, $p < 0.05$) and between $\delta^{18}O$ and debris content ($r = 0.84$, $p < 0.05$). These values have been added to the manuscript (lines 473, see answer below).

Line 445–446: I am not fully convinced by the statement that there is compelling evidence for mechanical mixing. Please clarify what specific observations or quantitative evidence support this interpretation.

Authors: All measured properties tend to converge, albeit with some scatter, toward a mixing line between two end-members: clear ice and bed material. The fact that independent tracers, including debris content, ice $\delta^{18}O$, and gas composition, approximately follow the same mixing relationship indicates that mixing is the primary control on the chemical composition of the basal ice. This behavior is not observed at Camp Century, particularly near the ice–bed interface, where significant deviations from simple mixing occur. Nevertheless, we have revised the discussion to clarify this point (lines 468-479).

"Shearing and folding are well-established mechanisms by which mechanical mixing entrains debris into basal ice (Alley et al., 1997; Knight, 1997), potentially incorporating sediments-rich ice with low gas content, low O_2 concentrations and high CO_2 and CH_4 concentrations. Souchez et al (1995) attributed gas variations in the GRIP debris-rich ice to mechanical mixing between buried sediments or soils and debris-free ice. This interpretation is supported by the strong co-variation among independent proxies, including ice $\delta^{18}O$, debris content, and gas composition (Pearson's $r > 0.80$, $p < 0.05$; Fig. 4), which follows a mixing line between debris-free ice and a basal

endmember (see also Fig. A2 for all measured properties). Alternative mechanisms would not be expected to affect these properties proportionally. For example, diffusion primarily modifies gas concentrations, whereas biological activity is unlikely to substantially alter ice $\delta^{18}O$ or debris content. The deviations from the mixing line observed in some samples suggest that additional processes may influence the distribution of properties (Fig. 4a), such as differential diffusion rates near concentration peaks (Fig. 4b). These peaks may indicate localized injections of substrate material caused by shearing processes (Tison et al., 1994)."

Line 472: Please provide the typical range of gas content in meteoric ice for comparison. Including reference values would help readers assess whether the observed concentrations are anomalous. In addition, ice does not form directly at the surface of the ice sheet. It forms at depth, typically 50–100 m below the surface, after snow compaction and firn densification.

Authors: Thank you for pointing this out. We reformulated the sentence (line 497-499).

"Whereas the gas content of the debris-free ice at GRIP is consistent with that expected for meteoric ice formed through firn densification (about 100 ml kg-1) (Cuffey and Paterson, 2010; Martinerie 1990), the corresponding debris-free basal ice at Camp Century exhibits substantially lower gas contents (58.4 ± 2.3 ml kg-1)."

Line 486–494: This paragraph is difficult to follow due to the dense description of ice fabric observations and radar interpretations. Consider restructuring the paragraph and more clearly explaining how these observations support differences in deformation history between Camp Century and GRIP. In addition, it is not clear how this paragraph relates to the discussion of gas loss; please clarify the intended connection.

Author: We substantially revised this section (line 512 to 520) to improve its clarity and streamline the narrative. We first describe the observed gas loss and then discuss the processes responsible for it (ice deformation and regelation), highlighting how the two sites exhibit distinct gas-loss dynamics consistent with our interpretation. We subsequently demonstrate that gas loss does not produce measurable fractionation among the major gas species. This provides a framework for identifying deviations from the gas-loss relationship, which we interpret as evidence for upward diffusive transport near the ice–bed interface, or biological production and consumption. In the case of CO_2 and CH_4, those sources overcome gas loss.

"The more extensive gas loss observed higher in the Camp Century sequence is consistent with its location near the ice-sheet margin, at lower elevation, where ice-flow conditions are more dynamic than at GRIP. This is reflected by the reorientation of crystal fabrics and a reduction in crystal size within the lower 300 m of the core (Herron and Langway, 1982). In the debris-rich basal section, a strong preferred orientation of the optic axes within the last 10 m above the bed indicates intense shear deformation (Herron et al., 1979). In contrast, GRIP exhibits more limited deformation. Crystal size increases with depth until the first occurrence of debris (Thorsteinsson et al., 1997; Tison et al., 1994). The top 1.5 m of debris-rich ice shows alternating coarse- and fine-grained layers with variable fabric strength, suggesting localized rather than pervasive shearing (Tison et al., 1994). These contrasting deformation regimes indicate a stronger influence of ice-flow processes at Camp Century than at GRIP, consistent with enhanced gas loss extending tens of meters above the ice–bed interface."

Line 523:CH4 accumulation is attributed to biological activity, whereas at line 426–428, the authors state that methanogenesis is incomplete and not supported by the data. These statements appear inconsistent.

Authors: We thank the reviewer for pointing this out. In situ methanogenesis within the basal ice is not supported by our data, as the methanogenesis pathway is not fully represented in the metagenomic dataset, except in the lowermost samples located near the ice–bed interface of Camp Century (Fig. 3f). Instead, our interpretation is that methane accumulates within the underlying bed material and is subsequently transported into the overlying ice, by both mechanical mixing and upward diffusion. The text has been modified accordingly (lines 455-462).

"Our data presents a clear methanogenesis signature, with a complete methanogenesis pathway near the ice-bed interface, but we cannot assess whether it occurs in situ, in the debris rich ice, or in the underlying bed materials.

At both Camp Century and GRIP, CH_4 accumulation becomes apparent above the depth at which anoxic conditions are reached, while the greatest CH_4 accumulation is found deeper within the debris-rich ice. This distribution is consistent with a CH_4 originating from the underlying bed material and subsequently being transported into the overlying ice through mechanical mixing (Sect. 4.2.1) and/or diffusion (Sect. 4.2.3), despite partial gas loss from the basal ice (Sect. 4.2.2)."

Line 526–529: This paragraph does not seem closely related to Section 4.2.2 ("Gas expulsion at the ice–bed interface") and, as written, it is likely to confuse readers. I suggest either removing it from this section or revising it to make the connection to gas expulsion explicit (e.g., by clearly stating how this information supports the interpretation of gas loss/expulsion at the ice–bed interface).

Authors: We have revised parts of the discussion, and this section in particular, to better integrate it into the overall narrative of the manuscript, i.e., methane production, transport, and consumption. Gas loss affects all gases similarly and therefore explains the decrease in concentration observed for all species except CO_2 and CH_4. The enrichment of CO_2 and CH_4 cannot be explained by gas loss alone and instead requires an additional source, likely involving a combination of diffusive input and in situ production, compensating for gas loss. This has been clarified in the manuscript (lines 558 -564).

"Deviations from this idealized gas-loss behavior are observed only when additional processes become significant. Ar, and to a lesser extent N_2, show evidence of enrichment through upward diffusion near the ice-bed interface at Camp Century, whereas CH_4 and CO_2 at both Camp Century and GRIP show enrichments relative to the idealized gas-loss trend, reflecting the influence of biological activity (Fig. 5d; Appendix A, Figs. A5). For both CH_4 and CO_2, bulk concentrations increase toward the ice–bed interface, in contrast to the depletion expected from gas loss alone. This enrichment therefore requires an additional source that compensates for gas loss, such as in situ production and diffusion from the underlying bed material."

Line 530: There is no red curve in Fig. 5d.

Authors: It is now added.

Line 563–569: Some of the sentences in this part could be moved to line 546 to better support and clarify the proposed hypothesis of selective removal of N2 gas. Presenting the explanation immediately after introducing the hypothesis would improve the logical flow.

Authors: The text has been modified accordingly (lines 570-575).

"The positive residuals observed for Ar near the ice–bed interface, and to a lesser extent for N_2, relative to the idealized gas-loss trend suggest an additional contribution from the underlying bed material through diffusion (Fig. A6). The occurrence of diffusive transport across the ice–bed interface inferred from these gases suggests that diffusion may also contribute to the observed enrichments of CH_4 and CO_2, in addition to in situ biological production. N_2 and Ar are particularly useful for constraining diffusive transport because of their well-understood sources and largely conservative behavior once incorporated into the ice."

Line 592: Provide the molecular size of CH4 and Ar and related references.

Authors: We believe this point can be developed further and warrants a more nuanced discussion. Diffusion coefficients in both air and liquid phases are inversely related to molecular mass; consequently, CH_4 diffuses more rapidly than N_2 and Ar. Solubility is also influenced by molecular mass, but even more strongly by charge distribution. Nevertheless, CH_4 remains more soluble, and thus more readily transferred, than N_2 and Ar in these phases.

In the solid phase, however, the situation is more complex, as molecular size and interactions with the ice lattice become important factors.

As noted in the manuscript, the diffusivity coefficients required to explain our observations would need to be several orders of magnitude higher than those measured in solid ice, given the relatively young age of the ice (< 400 kyr). This indicates that the process cannot be explained by solid-state diffusion alone.

We have modified the text accordingly to acknowledge this complexity (line 585 to 593).

"In solid ice where gas inclusions are not interconnected, molecular diffusion occurs through the ice lattice via gas molecules dissolved in the solid phase, which are in equilibrium with air bubbles or clathrates (Ahn et al., 2008; Ikeda-Fukazawa et al., 2005; Oyabu et al., 2021). This process involves two steps: (a) gas transfer from the gas inclusion to the surrounding ice, where concentration depends on the mixing ratio in gas inclusions according to Henry's law; (b) diffusion within the solid ice downside a concentration gradient. Dissolved gas concentrations are higher near gas inclusions with higher mixing ratios, even if the total gas content is lower. Consequently, N_2 diffuses upward from the sediments into the basal ice along a gradient in the mixing ratio (Fig. 3f). Even in the hypothetical case of interconnected gas or liquid inclusions, where transport bypasses diffusion through the solid ice lattice, diffusion would occur in the same direction because gas concentrations within the connected inclusions remain proportional to the gas mixing ratio."

Line 652–654: The link between the transformation of labile organic matter and reduced methanotrophic activity at GRIP is not fully explained. Please clarify how the availability of organic carbon directly constrains methanotrophy in this context. Also, the statement that basal ice at GRIP likely contains less bioavailable carbon appears speculative.

Authors: This has been clarified (lines 708 - 711). Microbial metabolism (not only methanotroph) in a dominated heterotrophic system is a function of organic matter availability (see discussion in

Hatton et al., 2026). Higher availability of organic matter would therefore boost microbial community, which would be beneficial to methanotrophs.

"Over such timescales, labile organic carbon may be progressively transformed into more recalcitrant forms that are less easily metabolized by microorganisms. Consequently, the older basal ice at GRIP may contain less readily bioavailable carbon, thereby limiting microbial activity (including methanotrophy) relative to the younger basal ice at Camp Century. "

Line 656: In lines 650–654, the authors suggest that reduced availability and quality of organic carbon may limit methanotrophic activity at GRIP. However, in Line 656, the thermal state at the base of the ice sheet is described as the primary control on the preservation of a methanotrophy signature. It is not clear how these two factors are related.

Authors: These two factors are independent and act on different aspects of the system. Basal thermal conditions primarily control the preservation of a methanotrophic signature through their influence on gas diffusion, whereas the quality and availability of organic matter may influence the extent of methanotrophic activity itself. We clarified this distinction in the revised manuscript (lines 700–711).

"Under either scenario, basal ice may at times have approached the pressure melting point, favoring intense deformation and migration recrystallization (Tison et al., 2015). These processes promote the development of interconnected water veins, which could provide efficient "transient" pathways for gas diffusion, and help reconcile the high effective diffusivities required to reproduce the observed vertical mixing-ratio profiles (section 4.2.3).

Another factor influencing methanotrophic activity is the quality of the organic matter incorporated within the debris-rich ice which might differ between locations (Wadham et al., 2008). Even if similar vegetation was initially buried at both GRIP and Camp Century (Bierman et al., 2024a), the present-day gas content reflects prolonged sediment-ice interaction, over ~ < 400,000 yrs at Camp Century versus ~1 million years at GRIP (Christ et al., 2023; Willerslev et al., 2007)."

Line 657: The term "warm-bed setting" requires clarification.

Authors: We clarify the term "cold" and "warm" bed conditions in Material and Methods, line 120 to 123.

Conclusion

Line 683: Was in situ respiration discussed in detail earlier in the manuscript? If respiration is considered an important process influencing gas composition, it should be more clearly discussed before being mentioned in the conclusion. Furthermore, in lines 28–29 (Abstract), CO2 accumulation is attributed to the oxidation of CH4, without consideration of respiration as a potential contributing process.

Authors: Respiration is discussed in Section 4.1, which addresses the in situ biological production of both methane and carbon dioxide, while noting that CO_2 concentrations are influenced by a wide range of additional biological and geochemical processes. Beyond respiration, a distinct CO_2 peak is observed at Camp Century and is interpreted as evidence of methane oxidation (Section 4.3).

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