Reviewer #1

The interface between ice sheets and bedrock represents a potential "hot spot" for geochemical reactors, and could potentially harbor life forms in one of the most extreme environment on Earth. Yet due to the difficulty in accessing subglacial samples, the (bio)chemical systematics underneath the ice sheet is poorly understood. An alternative approach is by utilizing basal ice right above the bedrock-ice interface and study the gas composition. Lisa Ardoin et al. here presents one such efforts targeting two Greenland ice cores: Camp Century and GRIP. The authors measured the depth profiles of various gases and conducted DNA sequencing to explore possible subglacial biological activities. The conclusion is that Camp Century and GRIP have distinct processes that account for their greenhouse gas profiles. While the basal ice in GRIP is subject to intense mechanical mixing, the methane content in the basal ice in Camp Century more likely results from the upward diffusion of CH4 produced underneath the bedrock-ice interface.

A comparative study like this will help us understand what subglacial bio- and geochemical processes are at play. It is therefore in principle suitable for publication TC. This work is a timely contribution to the Special Issue. However, there are some aspects of the manuscript—mostly concerning its presentation—that needs to be clarified. Although the substantive materials are in good shape already, a minor revision in my view is still needed to improve the clarity.

Authors: We thank the reviewer for recognizing the relevance of this study. We have revised the manuscript to improve its clarity and overall readability, as was also requested by reviewer 2. In particular, we rewrote the abstract, introduction, and parts of the discussion to better articulate scientific motivation, objectives, key findings, and broader implications of our study.

"**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

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."

Most importantly, while the title seems to hint at methane and carbon dioxide, the manuscript is clearly more dedicated to methane production and consumption. Carbon dioxide will be produced by methanotrophy, but other processes could also lead to CO2 production, such as sulphide oxidation and direct organic carbon oxidation coupled with carbonate dissolution and/or silicate weathering. The point is that since there is a whole suite of inorganic geochemical reactions that could modify CO2 (but not necessarily CH4), and the current manuscript doesn't have the necessary measurements to constrain them, perhaps it is more suitable to focus the manuscript on CH4.

Authors: In accordance with the reviewer's suggestion, we revised the title to focus exclusively on methane and modified the abstract accordingly. We also streamlined the introduction and discussion to focus on the production, transport, and preservation of CH_4 in subglacial environments. Throughout the manuscript, we now place greater emphasis on methane, while acknowledging that several processes can affect CO_2 (lines 61–62).

"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)."

The accumulation of those potent greenhouse gases underneath ice could become a power positive feedback during deglaciation (e.g. Wadham et al 2008, which the author cites). If true, a large methane reservoir underneath the Greenland Ice Sheet, which the author measures, bears

implication for the current warming and glacier retreat. Focusing on CH4 and discussing the implications for future warming will increase the interest of the present study to a broader cryosphere/geoscience community.

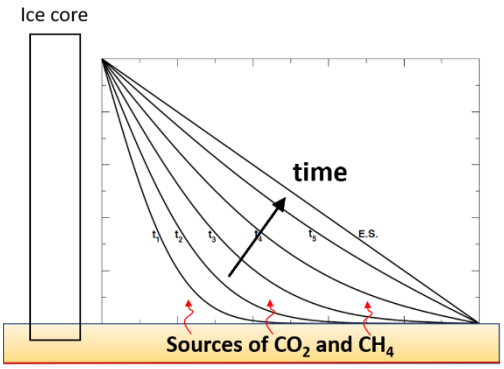
Authors: We added a paragraph at the end of the Discussion (Lines 736–752) addressing these perspectives. We now estimate the CH_4 reservoir potentially stored within basal ice layers under cold-bed conditions and discuss its implications in the context of future warming and deglaciations. However, given the substantial uncertainties associated with these estimates, we believe these results should be interpreted with caution. Rather than providing robust quantitative constraints, they are intended to highlight a potentially relevant process that warrants further investigation.

"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). These subglacial carbon reservoirs could sustain methanogenesis over extended timescales and therefore represent a potentially important, yet largely unconstrained, source of methane beneath the Greenland Ice Sheet. Their potential mobilization under future warming, or during periods of rapid climate change such as deglaciations, warrants further investigation."

Second, the hypothesis of upward diffusion of CH4 is interesting. However, this is indirectly deduced from N2 and Ar. Is it possible to model the methane diffusion directly? Of course the challenge is we don't really know how high the methane concentration is in the soil, but perhaps this is a good opportunity to do the opposite by running a series of sensitivity test. It would be interesting to know the range of CH4 concentration in the basal ice, which may inform the readers the extent of methanogenesis in the ice/soil.

Authors: We focused on N_2 and Ar because they can be considered relatively inert once incorporated into the ice and are therefore well suited for constraining upward diffusive transport. In any case, the observed CH_4 profile can be reproduced relatively easily using a diffusion model with boundary conditions defined by a CH_4-enriched basal endmember. We have already performed such simulations (e.g., see figure below) using a standard diffusion equation as follows:

$$\frac{\partial C}{\partial t} = K_D \frac{d^2 C}{dz^2}$$



However, obtaining quantitatively meaningful results requires constraining several key parameters, including the effective diffusivity coefficient, the dominant diffusion pathway (e.g., solid-state diffusion versus diffusion through interconnected liquid veins, or ?), the magnitude of the subglacial CH_4 flux, and the age of the basal ice. These parameters remain poorly constrained at present. Furthermore, a more realistic representation of the system would need to account for additional processes, particularly advection, and potentially CH_4 production and consumption reactions. We are currently developing a one-dimensional advection–reaction model to address these complexities, but a detailed treatment is beyond the scope of the present study.

Finally, there are some minor typos/grammatical errors, such as in Line 38 (subglacial and below ice sheets are repetitive) and Line 539 (their and its are repetitive). Please proofread it more thoroughly.

Authors: We have corrected these typographical and grammatical errors and carefully reviewed the manuscript to identify and address any similar issues.

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