



Organic and inorganic proxy development for advective heat flux in a basal-melt-dominated glacial system: Petermann Fjord, North Greenland

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Abstract. Mass loss from the Greenland Ice Sheet directly impacts sea level rise and the freshwater balance of the ocean. Petermann Glacier, North Greenland, provides a unique setting to explore atmosphere-ocean-ice interactions in a basal melt–
 15 dominated system using proxy records. We analyse organic (sea ice-associated highly branched isoprenoids (HBIs) and open water phytoplankton sterols) and inorganic (¹⁰Be, ²³⁰Th) proxies from five sediment cores spanning the inner to outer Petermann Fjord to investigate oceanic advection and glacial dynamics, during times when the ice shelf occupied extended (after 0.6 ka BP) and reduced (pre-0.6 ka BP) positions. Results show higher fluxes of ¹⁰Be, HBIs, and sterols during the reduced ice shelf phase. However, ¹⁰Be, HBIs, and sterols are also present in sediments deposited when the ice shelf was extended, suggesting lateral
 20 advection and glacial meltwater contribute to their deposition. Whilst ¹⁰Be has previously been applied as a proxy for ice shelves and perennial sea ice, in Petermann Fjord our results indicate that lateral advection, enhanced by buoyant subglacial melt, is the dominant source of ¹⁰Be, with glacial melt providing secondary input. Our study highlights the potential to use a multi-proxy approach to reconstruct circulation regimes and advective heat flux patterns in basal-melt-dominated environments.

1 Introduction

25 Melting of the Greenland Ice Sheet is a major contributor to global sea level rise (Imbie Team, 2018; Shepherd et al., 2020). Between 1992 and 2018, roughly half of the Greenland Ice Sheet mass loss is attributed to oceanic forcing (Imbie Team, 2018; Straneo and Heimbach, 2013; Wood et al., 2021), driven by melting of the submerged ice at the termini of marine based glaciers around Greenland. The factors controlling submarine melt are twofold: 1) the heat content of proximal seawater and 2) the heat flux from the ocean to ice controlled by turbulent processes (Holland and Jenkins, 1999; Sutherland et al., 2019). Historically,
 30 accelerated ice flow has been linked to ocean temperatures that drive submarine melting at the ice terminus (e.g. Holland et al., 2008; Straneo and Heimbach, 2013; Wood et al., 2021). However, recent studies document the link between atmospheric conditions and submarine mass loss (Prakash et al., 2025; Slater and Straneo, 2022).

Above-freezing atmospheric temperatures melt the ice sheet surface during summer and generate supraglacial meltwater that flows through the ice sheet each melt season (Chu, 2014). This freshwater mixes with basal meltwater produced from friction and
 35 geothermal heat (Cai et al., 2017) and is discharged subglacially at the grounding line, creating localized buoyant plumes at the



ocean/ice interface (Jackson et al., 2020; Johnson et al., 2011; Mankoff et al., 2016). The input of freshwater at depth into seawater can drive estuarine circulation within glacial fjords (Bonneau et al., 2024; Carroll et al., 2017; Cowton et al., 2015; Sciascia et al., 2013; Slater et al., 2018) and subsequently enhance submarine melt via entrainment of warm ocean currents that travel towards the glacier grounding line (Slater and Straneo, 2022; Washam et al., 2019). Between 1979 and 2018, reconstructions show that variability in submarine melt was driven by oceanic temperatures in south Greenland, but atmospheric temperatures dominated glacial melt in the northwest region (Slater and Straneo, 2022; Tedstone and Machguth, 2022).

Petermann Glacier terminates in a floating ice shelf (~60 km in length) that occupies a narrow fjord in northern Greenland and drains approximately 4% of the Greenland Ice Sheet (Millan et al., 2023; Rignot and Kanagaratnam, 2006). Collectively, the glaciers of North Greenland contain enough ice to raise sea levels by 2.1 m (Millan et al., 2023). Unlike many of the larger ice shelf systems in Antarctica, Petermann Glacier primarily loses mass (~80%) by submarine ice melt (Rignot and Steffen, 2008), whilst calving events and surface mass losses are secondary (Falkner et al., 2011; Nick et al., 2012, 2013). Average basal melt rates at the grounding line of Petermann Glacier are between 60 and 100 m/yr (Cirací et al., 2023). Beneath the ice shelf of Petermann Glacier, concentrated melt forms inverted channels close to the grounding line (Rignot and Steffen, 2008; Washam et al., 2019). In situ measurements show that increased subglacial runoff from surface melt draining to the glacial bed creates buoyant meltwater plumes, that, in turn, enhances basal melt rates in such channels via the entrainment of warm water (Washam et al., 2019, 2020); modelling resolves the detailed physics of this process (Prakash et al., 2025). Collectively this highlights the importance of atmospheric warming in controlling basal melt rates of Northern Greenland glaciers (Slater and Straneo, 2022).

The short length of observational records, along with challenges in accessing sub-ice shelf ocean cavities, results in under-constrained parameterizations in models, limiting our understanding of ice-ocean-atmospheric interactions and processes. Yet, resolving these processes is key to estimate heat fluxes and submarine melt rates at glacial termini, important for projecting freshwater export and contributions to sea level rise under future warming. Examining the sedimentary record in an ice shelf environment provides an alternate means to assess these processes over varying climatic conditions. Specifically, paleo-ice shelf margins provide insightful observations as to how atmospheric and oceanic forcing contributes to the stability and/or retreat dynamics of marine terminating ice margins under changing climate states.

Existing reconstructions document changes in glacial dynamics, including ice shelf extent (Jakobsson et al., 2018; Reilly et al., 2019) and sea-ice cover (Detlef et al., 2021) in Petermann Fjord throughout the Holocene. Such reconstructions, and the well-constrained geometry of the Petermann Ice Shelf together with understanding of the general ocean circulation patterns in Petermann Fjord, make it a useful site to investigate the use of inorganic and organic proxies for reconstructing oceanic heat flux and glacial dynamics. Whilst many studies use lithologic and/or microfossil observations in sediment cores to reconstruct paleo-ice glacial and oceanic histories at high latitudes, there is growing interest in the development of geochemical proxies to study ice-shelf processes and extent, ocean circulation, upwelling and sea-ice cover (Aldahan et al., 1997; Behrens et al., 2022; Frank et al., 2008; Jeong et al., 2018; Scherer et al., 1998; Sjunneskog et al., 2007; Sproson et al., 2022; White et al., 2019; Yokoyama et al., 2016). In this study, we apply sea-ice and, phytoplankton lipid biomarkers, as well as meteoric ^{10}Be and $^{230}\text{Th}_{\text{xs}}$ as a constant flux proxy, to reconstruct these processes in Petermann Fjord, North Greenland.



2 Background

2.1. Regional Setting

Petermann Fjord, located in Northern Greenland, is separated from Hall Basin in Nares Strait via a bathymetric sill (350-450 m deep) (Fig. 1; Jakobsson et al., 2018). The extent of Petermann ice shelf is dependent on numerous factors, including atmospheric and oceanic forcings, the dynamics of the glacier at the grounding line and sea-ice conditions (Straneo and Heimbach, 2013). Petermann Glacier lost more than 40% of its ice shelf area during dramatic calving events in 2010 and 2012 (Fig. 1b; Johnson et al., 2011; Nick et al., 2012), likely due to ice shelf thinning in basal channels that structurally weakened the ice shelf (Münchow et al., 2014). The 2012 calving event was associated with a 10% acceleration of Petermann Glacier ice velocities (Rückamp et al., 2019). In 2026, Petermann Glacier calved a 76 km² ice island. Prior to these events, between 1876 and 2010, the terminus of Petermann Glacier was considered relatively stable (Falkner et al., 2011) and geologic data indicate similar ice shelf extents for the last ~600 years (Reilly et al., 2019). However, between 1992 and 2021 the grounding line retreated by 4 km in western and eastern sectors, and by 7 km in the central part (Millan et al., 2022).

Bottom waters in Petermann Fjord are renewed by Atlantic Water (AW) that travels across the sill separating the fjord from Hall Basin (Fig 1c; Johnson et al., 2011). Based on hydrographic observations in Petermann Fjord, the inflow of relatively warm (~0.3 °C) and saline (34.9 g kg⁻¹) AW (Millan et al., 2022; Washam et al., 2019) towards the glacier is observed at depths below ~400 m (Fig 1c; Heuzé et al., 2017; Johnson et al., 2011; Washam et al., 2019). The mid water column is a mixture of glacial meltwater, subglacial freshwater discharged at the grounding line and AW, due to ice-ocean interactions (Heuzé et al., 2017; Washam et al., 2019). Polar Water (PW) occupies the upper water column and is separated from the mid water column by a strong seasonal pycnocline (Washam et al., 2019). Meltwater flows out mainly through ice shelf channels at the ice front, then bends to the right to exit on the Northeast side of the fjord (Heuzé et al., 2017; Johnson et al., 2011; Washam et al., 2018).

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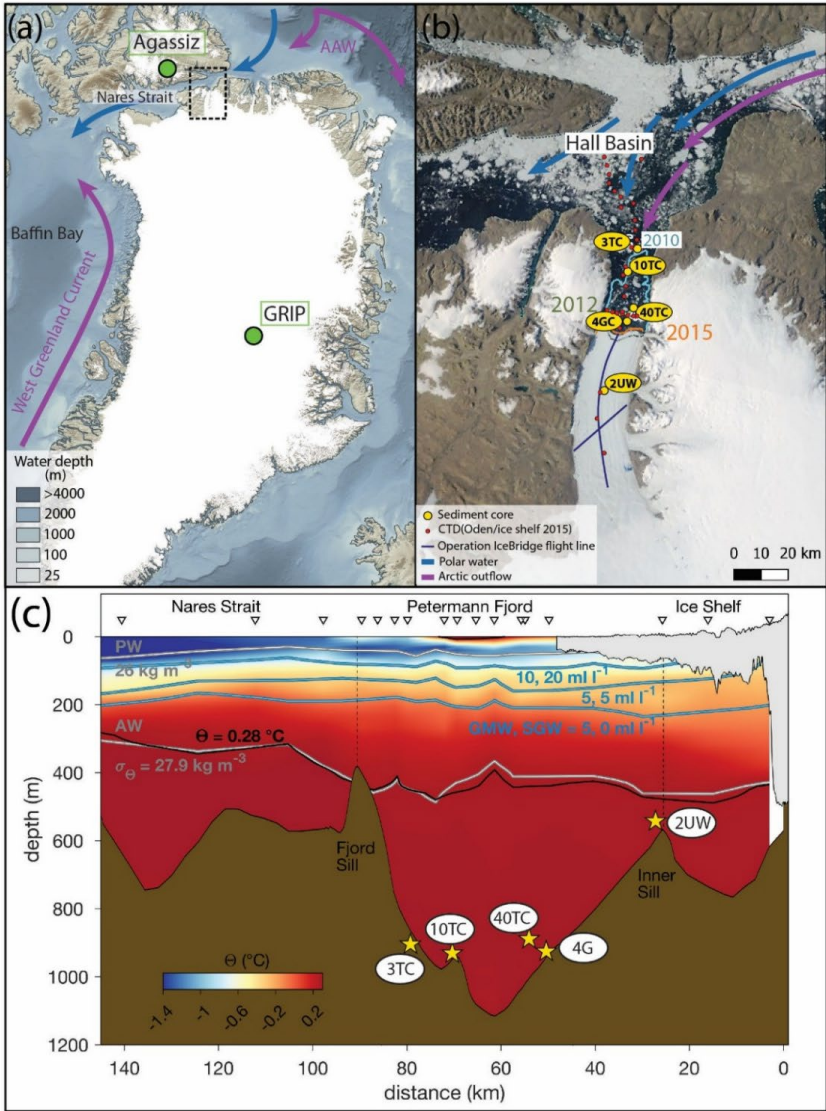


Figure 1: (a) Overview map of the study site showing key ocean circulation patterns from the region: Atlantic Water (AW) currents (West Greenland Current) and Arctic outflow (purple) and cold Arctic Polar Water (PW) outflow (blue). The location of Greenland Ice Core Project (GRIP) and Agassiz Ice Core is shown (green circles). (b) A closeup of Petermann Fjord showing the location of sediment cores used in this study (yellow circles), CTD data (Washam et al., 2018) (red circles), Operation IceBridge flight line (2010/15) and key ocean currents. Past ice tongue extents are shown: 2010 (blue), 2012 (green) and 2015 (orange). The ocean bathymetry comes from GEBCO and from Jakobsson et al., 2018 in the fjord. Satellite images courtesy of the NASA Worldview (<https://worldview.earthdata.nasa.gov/>). (c) Ocean Conservative Temperature section from Nares Strait to Petermann Glacier, data from the 2015 research expedition (Washam et al., 2018). PW and AW are with isopycnal surfaces shown (grey lines). Glacial meltwater (GMW) and subglacial freshwater (SGW) concentrations are shown (blue lines and text). Bathymetry comes from gravity cores taken beneath PGIS, multibeam data the Petermann research expedition (2015). Cores are marked (yellow stars). The ice shelf geometry comes from a 2011 NASA Operation Ice Bridge flight over the central channel of Petermann Glacier's ice shelf.



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2.2. Proxies

In this study we analyse organic (highly branched isoprenoids (HBIs) and open water phytoplankton sterols) and inorganic (^{10}Be , ^{230}Th) proxies to investigate oceanic advection and heat flux and glacial dynamics, summarised in Table 1.

2.2.1. Lipid biomarkers

Sea-ice biomarkers (IP_{25} , HBI II), together with open water phytoplankton biomarkers (brassicasterol, sitosterol, cholesterol, dinosterol), are used to reconstruct semi-quantitative estimates of sea ice across the Arctic (Davies et al., 2024, 2025; Detlef et al., 2021, 2023; Harming et al., 2025; Stein et al., 2017; Syring et al., 2020). The mono-unsaturated highly branched isoprenoid (HBI) with 25 carbon atoms (HBI I; sea ice proxy IP_{25}) is produced by specific Arctic sea-ice dwelling diatoms. HBI II is also produced by Arctic sympagic diatoms and has been observed in Arctic and Antarctic sediments; it is frequently well correlated with IP_{25} concentrations in the Northern hemisphere sediments, but usually in higher concentrations (Belt, 2018). As sea ice melts, IP_{25} and HBI II are deposited and preserved in marine sediment, providing a record of seasonal sea-ice cover (Belt et al., 2007). Analysis of surface sediments and comparison with satellite data throughout the Arctic show that IP_{25} is present in areas of seasonal sea ice, and absent in open water and perennially covered areas respectively (Belt et al., 2015; Kolling et al., 2020; Navarro-Rodriguez et al., 2013). Therefore, additional biomarkers are required to distinguish between these two-contrasting conditions (e.g. sea ice absence and perennial sea ice).

Open water phytoplankton biomarkers (e.g. brassicasterol, dinosterol, sitosterol and cholesterol), sourced from marine diatoms, dinoflagellate species as well as terrestrial sources (see Table 1), are used to distinguish perennial sea ice and open water environments, in which IP_{25} and HBI II are absent. In general, sterols are absent in regions covered by perennial sea ice, as it limits the availability of light, and found in higher concentrations in ice free regions and in the marginal ice zone (Xiao et al., 2015).

2.2.2. ^{10}Be

Meteoric ^{10}Be is produced by cosmic ray interactions with Earth's atmosphere, deposited to the surface via dry and wet deposition, and delivered to the seafloor via adsorption onto sinking particles (Kaste and Baskaran, 2012; Lal and Peters, 1967). As a result, the three possible sources of ^{10}Be to the fjord environment are from direct atmospheric deposition to open (ice-free) waters beyond the ice shelf margin, lateral advection of ^{10}Be from open waters to waters under the ice shelf, and meltwater input of ^{10}Be from melting glacial ice (Graly et al., 2018; Sjunneskog et al., 2007). Previously, ^{10}Be has been applied as a proxy for ice sheet and perennial sea-ice reconstructions in Antarctica (e.g. Scherer et al., 1998; Yokoyama et al., 2016) and the Arctic (e.g. Aldahan et al., 1997; Frank et al., 2008), as the ice directly blocks ^{10}Be delivery to the seafloor. More recently, ^{10}Be has been used to reconstruct changes in meltwater flux in ice sheet marginal marine environments (e.g., Behrens et al., 2022; Sproson et al., 2022; Valletta et al., 2018). Studies show that upwelling waters (e.g., Jeromson et al., 2024, 2025) and sub-ice shelf ocean circulation and depositional patterns are also sources of ^{10}Be in Antarctica (White et al., 2019), highlighting potential for paleo-reconstructions.

2.3. Sediment flux proxy – $^{230}\text{Th}_{\text{xs}}$

^{230}Th is produced at a constant rate by the decay of uranium in seawater and thereafter removed to the sediments by particle scavenging. In the open ocean, where seawater uranium is well mixed, ^{230}Th production is uniform throughout the water column (Bacon, 1984; Costa et al., 2020; Francois et al., 2004). The burial rate of ^{230}Th is thus treated as equal to its production rate in the



water column and it is assumed to be unaffected by other environmental factors that limit the exchange between the atmosphere and ocean, such as the presence of an ice shelf (Costa et al., 2020; Francois et al., 2004). ^{230}Th is highly particle reactive and is removed quickly by sinking particulate matter. As such, it has proved a valuable tool for calculating high-resolution sediment mass fluxes in paleoceanographic reconstructions, even in the absence of high resolution temporal constraints (Bacon, 1984; Costa et al., 2020; Francois et al., 2004). However, in fjord settings, large freshwater fluxes associated with ice melt can introduce additional uncertainties into $^{230}\text{Th}_{\text{XS}}$ normalization by potentially altering the water column production rate of ^{230}Th from predicted seawater values. We discuss this complication in more detail in Sect. 3.4.2 and 5.1.

Table 1: Summary of organic proxies used for sea-ice reconstructions in this study. Adapted from Detlef et al., 2021.

Proxy	Source	Application in this study	References
IP ₂₅	Diatoms that reside in seasonal sea ice	Seasonal sea-ice indicator	(Belt et al., 2007)
HBI II	Sympagic diatoms in the Antarctic and likely in the Arctic	Seasonal sea-ice indicator	(Brown et al., 2014)
Brassicasterol	Produced by marine diatoms, and, to a lesser extent, by freshwater algae	Open marine sterol	(Volkman, 2003, 1986; Yunker et al., 2005)
Dinosterol	Produced by dinoflagellate species and diatoms	Open marine sterol	(Belicka et al., 2004; Volkman, 2003)
Cholesterol	Zooplankton and phytoplankton in the marine environment. Terrestrially derived organic carbon is also a source	Open marine sterol	(Meyers and Ishiwatari, 1993; Volkman, 2003; Yunker et al., 2005)
Sitosterol	Produced by vascular plants and by marine organisms to a lesser extent	Green algae	(Rontani et al., 2014; Volkman, 1986; Yunker et al., 2005)

Table 2: Summary of inorganic proxies used for sea-ice reconstructions in this study.

Proxy	Source	Transport mechanisms	Application in this study	References
^{10}Be	Cosmic ray spallation in the atmosphere	Direct deposition from atmosphere, carried by currents when dissolved in sea water, released from glacial meltwater	Proxy for ice shelf, perennial sea ice, heat fluxes, advection and glacial dynamics	(Aldahan et al., 1997; Behrens et al., 2022; Frank et al., 2008; Jeromson et al., 2024, 2025; Scherer et al., 1998; White et al., 2019; Yokoyama et al., 2016)
$^{230}\text{Th}_{\text{XS}}$	Decay of ^{238}U in sea water	Adsorbed onto particles (e.g. organic matter)	Calculating sediment flux rates	(Bacon and Anderson, 1982; Costa et al., 2020; Francois et al., 2004; Nozaki et al., 1981)



3 Methods

We analyzed IP₂₅, HBI II, sterols, ¹⁰Be, and the constant flux proxy ²³⁰Th_{xs} from sediment core samples collected between 25 and 80 km distance from the modern grounding line of Petermann Glacier to investigate depositional patterns in ice shelf environments.

3.1. Sediment core collection and preparation

Five sediment cores, OD1507-10TC, OD1507-2UW, OD1507-3TC, OD1507-40TC, OD1507-4GC, henceforth 10TC, 2UW, 3TC, 40TC and 4GC are used in this study (Table 1; Fig. 2). These include three trigger cores (TC) and one gravity core (GC). A fifth core (2UW) was collected from beneath the ice shelf using a UWITEC (UW) corer. These cores were all collected from the Petermann Fjord during the *Petermann 2015 Expedition* on the research vessel *Oden*.

Table 3: Marine sediment cores used in this study with corresponding location and environmental information.

Core name	Short name	Lat.	Long.	Core length (cm)	Distance from modern grounding line (km)	Water depth (m)
OD1507-2UW	2UW	80.737	-60.785	237	25	573
OD1507-4GC	4GC	80.970	-61.253	446	52	968
OD1507-40TC	40TC	81.01	-61.271	318	56	932
OD1507-10TC	10TC	81.108	-61.898	101	71	970
OD1507-3TC	3TC	81.190	-62.068	95	80	960

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Selected cores are from sediment deposits consistent with the conformable, stratified drapal acoustic facies III described by Hogan et al. (2020). Sediment is primarily delivered through suspension settling with or without additional deposition from ice rafted debris. Accumulation rates of these deposits in Petermann Fjord are approximately 50 cm kyr⁻¹ (Reilly et al., 2019). Following retreat of the Petermann Ice Shelf into Petermann Fjord in the early Holocene around 7.1 ka (Jakobsson et al., 2018; Jennings et al., 2022), sediments from acoustic facies III can be subdivided into three lithologic units by their clast content and degree of bioturbation (Reilly et al., 2019). These lithologic units (LU) are interpreted to reflect a calving margin with no ice shelf (LU 1C) prior to 2.25 ka, a smaller ice shelf extending ~20–40 km from the grounding zone (LU 1B) between 2.25 and 0.60 ka, and an ice shelf with lengths similar to the pre-2010 historical record ~60–90 km from the grounding zone (LU 1A) after 0.60 ka (Fig. 2; Reilly et al., 2019; ages updates based on the chronology of Girard et al., 2024). Holocene reconstructions of sea ice in the outer part of Petermann Fjord indicate variable conditions since 6.9 ka (Detlef et al., 2021). These results highlight the link between sea ice and ice tongue growth. Specifically, the formation of landfast sea ice which promotes favourable conditions for ice shelf growth and the reduction in landfast sea ice results in ice shelf destabilisation (Detlef et al., 2021).

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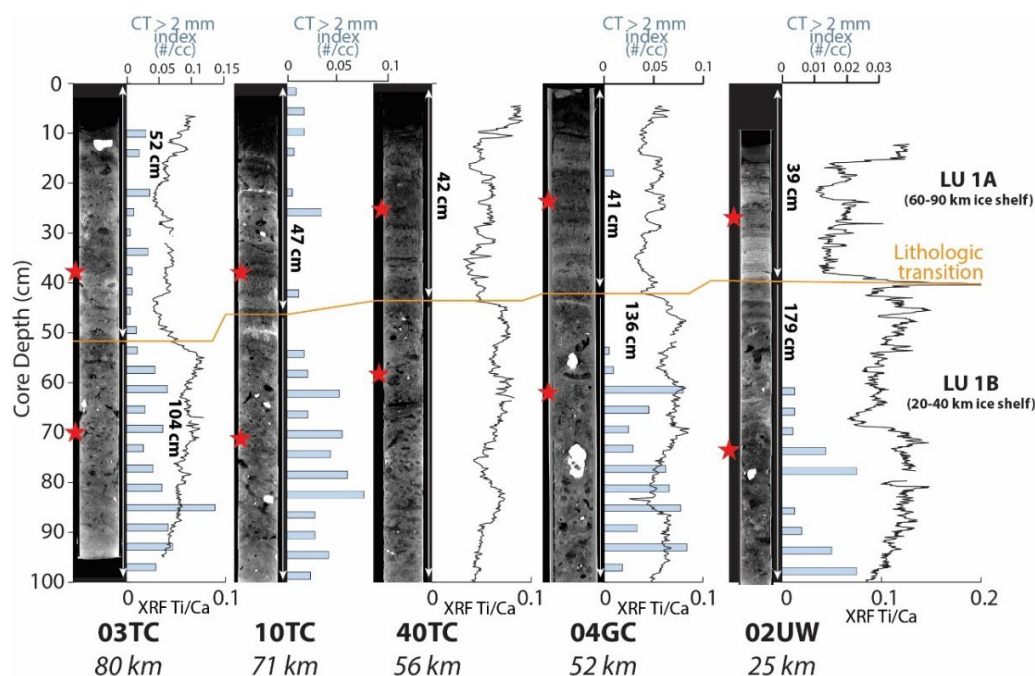


Figure 2: Overview of upper 100 cm of five sediment cores used in this study, displayed in order of distance from the current Petermann grounding line. XRF data (Ti/Ca; black line) and ice rafted debris identified from CT scans (>2 mm; see Reilly et al., 2019 for methodology) are shown. The location of the lithologic transition from LU 1B to LU 1A, when Ti/Ca values decline and sediment lithology shifts from bioturbated with IRD to laminated, is highlighted (orange line). The thickness of units 1A and 1B are marked on each core (white arrows and bold text). The location of sediment samples taken in this study are shown (red stars). Figure adapted from Reilly et al., 2019.

Two sediment samples were taken from each of the five cores: one from the laminated section of LU 1A and one from the bioturbated section of LU 1B, representing an extended and reduced ice shelf environment, respectively (Fig. 2; Reilly et al., 2019). Samples were selected from intervals of approximately the same age, based on the correlated equivalent depth scale constructed using density and X-ray fluorescence (XRF) data (Reilly et al., 2019). As the ice shelf extent had changed considerably in the 5 years prior to sediment core collection, we choose to focus on samples within these defined lithologic units rather than surface samples. Samples were weighed, freeze-dried and homogenised using a dichloromethane (DCM) cleaned pestle and mortar. Approximately five grams (dry weight) of sediment was taken for biomarker analysis, and two grams (dry weight) for inorganic proxy analysis.

3.2. Lipid Biomarkers

Measurements were made in the LDEO Organic Geochemistry Lab. Internal standards were added to the homogenised sediment prior to extraction for lipid biomarker quantification: 9-octylheptadec-8-ene (9-OHD) and 5 α -androstane-3 β -ol (Androstanol). Lipid were extracted in a sonication water bath (70 °C for 1 hour) with 0.5N potassium hydroxide (KOH) and in methanol (MeOH):organics-free demineralized water (v/v 95:5). Non-saponifiable lipids were recovered by liquid-liquid phase separation with hexane three times. Silica gel chromatography was performed to separate lipid classes using pre-cleaned 100% active silica gel: HBI I (IP₂₅) and HBI II were eluted with 4 ml of hexane (F₁) and sterols with 4 ml of 3:1 v/v Hexane/ Ethyl acetate (F₂). Sterols were derivatised using 100 μ l N,O-bis(trimethylsilyl)trifluoroacetamide (BSTFA) and 100 μ l pyridine (catalyst) in a heating block at 70 °C for 1.5 hours.



HBIs and sterols were analyzed using an Agilent 7890A gas chromatograph (GC) equipped with a mass selective detector (MSD) and an Agilent HP-5ms column (30 m, 0.25 mm ID, 0.25 μ m film thickness). The relative response factor was monitored during each run for IP₂₅, HBI II, 9-OHD, all sterols (brassicasterol, cholesterol, dinosterol, and sitosterol) and androstanol by running dilution sequence with each batch of samples.

225 Compounds were identified based on their retention times and mass spectra and were quantified using target ion response relative to that of a known quantity of internal standard. The HBIs were identified in SIM mode with the following monitoring ions: IP₂₅ at m/z 350, HBI II at m/z 348. The identification of the HBI III peak was not possible due to the interference of a neighbouring peak, similar to the issues reported by Detlef et al., 2021 in Petermann Fjord samples. Sterols were identified in SIM mode with the following monitoring ions: epi-brassicasterol (24-methylcholesta-5,22-dien-3 β -ol) at m/z 470, dinosterol (4 α ,23,24-Trimethyl-
 230 5 α -cholest-22E-en-3 β -ol) at m/z 500, and sitosterol (24-ethylcholest-5-en-3 β -ol) at m/z 486. Results were normalized to ²³⁰Th_{XS}, total organic carbon and the dry sediment weight, the latter two are presented in the supplement.

3.3. Bulk geochemistry

At the University of Colorado Boulder's Earth Systems Stable Isotope Laboratory, freeze-dried and decalcified (1N HCl) marine surface sediment subsamples were analyzed for bulk elemental (%TOC, %TN) on a Thermo Flash 2000 elemental analyzer (EA)
 235 interfaced to a Thermo Delta V isotope ratio mass spectrometer (IRMS). Samples were analyzed against a suite of secondary laboratory standards that are extensively calibrated to international standard reference materials to correct for size, blank-mixing and linearity. Biomarkers are normalised to %TOC, presented in the Supplementary Material.

3.4. Inorganic proxies

3.4.1. ¹⁰Be

240 Samples for ¹⁰Be analysis were prepared at Lamont-Doherty Earth Observatory using 100 mg samples of freeze-dried sediment combined with 200 mg of SPEX CertiPrep ⁹Be carrier, following the methods described in Middleton et al., (2026). Beryllium isotope measurements were then conducted at the Lawrence Livermore Center for Accelerator Mass Spectrometry (CAMS). The 1 σ analytical uncertainty in reported concentrations of ¹⁰Be are <4%.

3.4.2. ²³⁰Th normalisation for estimates of fluxes

245 The constant flux proxy excess thorium-230 (²³⁰Th_{XS}) can help discern whether changes in sediment proxy concentrations are caused by changes in proxy deposition rates or changes in proxy dilution by background sedimentation rates associated with variable depositional environments (Costa et al., 2020; Francois et al., 2004). Analysis of ²³⁰Th, and related U-series isotopes required to calculate excess ²³⁰Th (²³⁸U and ²³²Th), was performed at Lamont-Doherty Earth Observatory. Samples (100 mg of freeze-dried sediment) were spiked with ²³⁶U, ²²⁹Th and complete acid digestion and column chromatography were conducted
 250 following the methods outlined in Fleisher and Anderson (2003). U-series isotopes were measured on an Element 2 ICP-MS. The 1 σ analytical uncertainty in sediment concentrations of ²³⁰Th, ²³²Th, and ²³⁸U, based on the reproducibility of 3 internal standards, are 2%, 3% and 2%, respectively. Excess ²³⁰Th concentrations and ²³⁰Th_{XS}-normalized mass fluxes were calculated following Costa et al. (2020), and assuming a local lithogenic U/Th activity ratio of 0.45. Proxy fluxes were then computed for each sample by multiplying its ²³⁰Th_{XS}-normalized sediment mass flux by its specific proxy concentration. Although analytical uncertainties in
 255 reported excess ²³⁰Th concentrations are minor, the practical uncertainties associated with ²³⁰Th_{XS}-derived sediment fluxes in the Petermann fjord environment are likely higher, due to complications surrounding the application of ²³⁰Th_{XS} as a constant flux proxy in shallow water (<1000 m) environments and those with significant freshwater inputs (Costa et al., 2020).



4 Results

All sea ice, productivity, and ice shelf proxy data (IP₂₅, HBI II, brassicasterol, sitosterol, dinosterol, cholesterol and ¹⁰Be) are presented as ²³⁰Th_{XS}-normalized fluxes (Fig. 3). Concentration data of all proxies generally exhibit similar trends to the ²³⁰Th_{XS}-normalized fluxes and are presented in the Supplementary Material.

4.1. Lipid biomarkers

Lipid biomarker analyses indicate the presence of HBIs when the ice shelf was less extensive (i.e., in bioturbated units) (Fig. 3). Broadly, IP₂₅ and HBI II fluxes generally follow the same pattern. In the bioturbated units, IP₂₅ and HBI II are moderately high closest to the grounding line, before decreasing at 52 km. In the laminated sediments, concentrations of IP₂₅ and HBI II are lower than in the bioturbated sediments at all sites. Fluxes are lowest, or biomarkers are absent, between 56 and 25 km from the grounding line. In contrast, fluxes are higher in the outer fjord at 71 and 80 km from the grounding line.

Fluxes of sterols, brassicasterol, sitosterol, dinosterol and cholesterol, follow similar patterns to each other (Fig. 3). In bioturbated sediments, fluxes of all sterols apart from dinosterol are highest closest to the grounding line. Fluxes are lower at 52 km, before increasing at 56 km and gradually declining towards in the outer fjord. In the laminated sediments, all sterols are slightly higher in the inner fjord, but low between 52 and 56 km from the grounding line. Fluxes increase between 71 and 80 km in the outer fjord.

4.2. Inorganic proxies

¹⁰Be fluxes are generally high in the bioturbated sediments at all sites (Fig. 3). In contrast, fluxes are lower in the laminated sediments at all sites. Fluxes are lower at the site closest to the grounding line in both the laminated and bioturbated sediments.

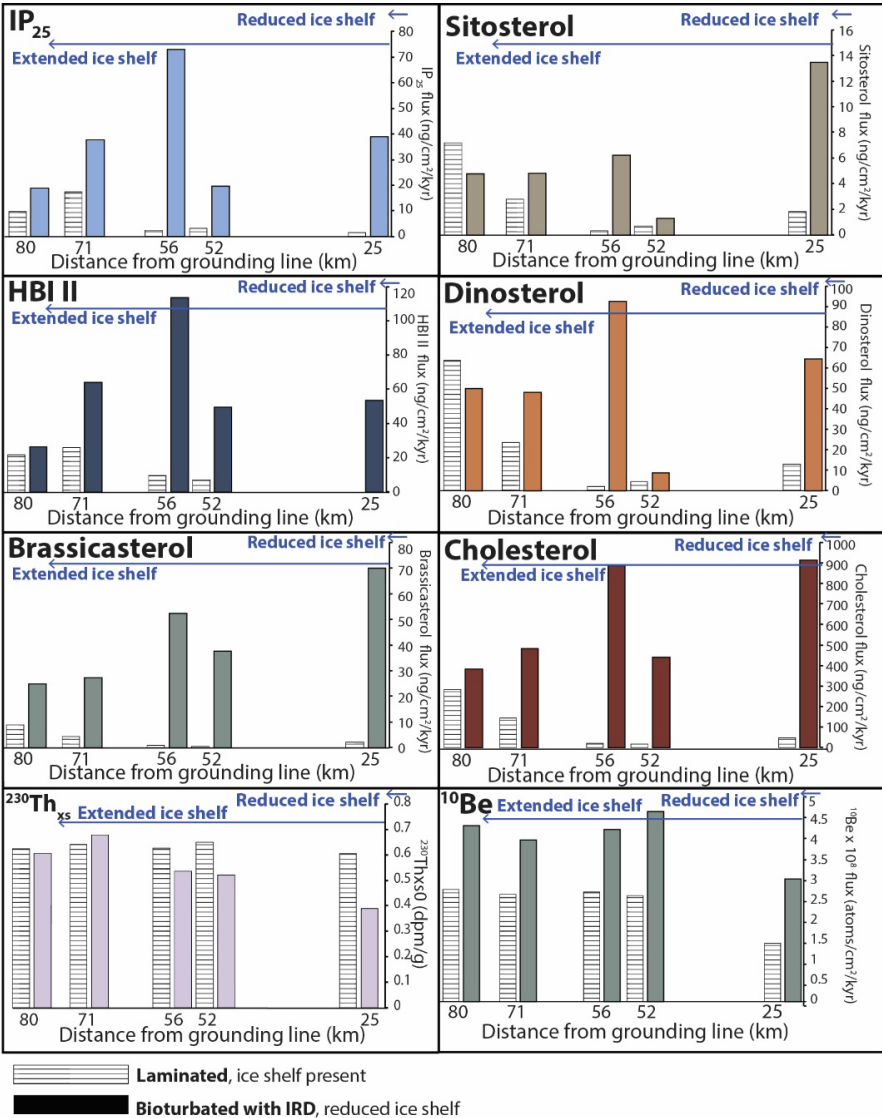


Figure 3: Biomarker and inorganic proxy flux results for marine sediment cores shown with distance from the modern grounding line for bioturbated units with IRD (reduced ice shelf; shaded in block colours) and laminated units (extended ice shelf; shaded in black horizontal lines). All data are presented as $^{230}\text{Th}_{\text{xs}}$ -normalized proxy fluxes. The extent of the Petermann Ice Shelf in its extended and reduced state is marked (blue arrows) according to Reilly et al., 2019.

5 Discussion

5.1. $^{230}\text{Th}_{\text{xs}}$ normalisation in Petermann Fjord

We find relatively similar concentrations of $^{230}\text{Th}_{\text{xs}}$ at all sites in Petermann Fjord in the reduced and extended ice shelf environments, as would be expected for samples with similar sedimentation rates and from similar depths in the water column. In addition, the distribution of biomarkers and ^{10}Be when presented as fluxes and concentration data are very similar, resulting in the same interpretation for each dataset. As such, despite the complexities associated with using $^{230}\text{Th}_{\text{xs}}$ in a fjord environment due to its shallow water depths (< 1,000 m) and strong lateral advection (Costa et al., 2020), we proceed with discussion of $^{230}\text{Th}_{\text{xs}}$ -



normalized proxy fluxes to reduce uncertainties associated with possible dilution impacts or other fjord processes on concentration-based proxy distributions.

5.2. Distribution of lipid biomarkers in Petermann Fjord

5.2.1. Lateral advection of biomarkers beneath Petermann ice shelf

Broadly, IP₂₅, HBI II and sterol fluxes are higher at almost all sites when Petermann ice shelf was reduced in extent. However, the presence of these biomarkers beneath the ice shelf at most sites when the ice was extended indicate the lateral transport of biomarkers within the water column is occurring, given the expected absence of sea-ice diatom and phytoplankton productivity beneath the relatively thick ice shelf. As strong buoyancy driven circulation that entrains AW characterises Petermann Fjord today (Washam et al., 2019, 2020), the transport of biomarkers beneath the ice shelf via lateral advection is somewhat expected. Whilst lateral advection complicates the interpretation of sea ice reconstructions in this region more broadly, this effect can provide important information about ocean circulation patterns and advection within the fjord. These insights can be useful for paleo-reconstructions, if lithological units and other proxies are carefully assessed.

Other studies also report the lateral transport of sediments via ocean currents which influence the distribution and deposition of biomarkers, resulting in complications for palaeoceanographic reconstructions and interpretation (Benthien and Müller, 2000; Mollenhauer et al., 2006; Navarro-Rodriguez et al., 2013). For example, Navarro-Rodriguez et al. (2013) report the presence of IP₂₅ in surface sediments from the Barents Sea beyond the maximum winter sea-ice extent, implying allochthonous input through advection. Similarly, on the continental margins of East Greenland, Müller et al. (2011) suggest a blend of in-situ produced IP₂₅ and allochthonous input influencing the absolute concentrations found in marine sediments, based on ice drift and a dynamic current system that characterise the study area. However, in fjord systems where modern circulation patterns are well constrained, such as Petermann Fjord, we could use such results to our advantage. Specifically, the lateral transport of biomarkers may provide useful information about the strength of advective heat flux when combined with sediment lithology and other proxy constraints.

5.2.2. High primary productivity at the glacier terminus

Observational data show high phytoplankton productivity in fjords with marine terminating glaciers around Greenland (Juul-Pedersen et al., 2015; Meire et al., 2017). High phytoplankton productivity in these settings is attributed to rising subsurface meltwater plumes which entrain deeper waters, rich in nutrients, to the ocean surface (Meire et al., 2017). In contrast, fjords with land terminating glaciers are characterised by lower phytoplankton productivity (Meire et al., 2017). In Petermann Fjord, all sterol fluxes are highest in sediments closest to the terminus of the ice shelf: 80 km from grounding line when the ice shelf was extended and 25 km from the grounding line when the ice shelf was reduced; this is consistent with modern observations of primary productivity and could provide useful information for paleo-reconstructions of ice shelf dynamics and productivity.

5.3. Transport mechanisms of ¹⁰Be to Petermann Fjord

Sediment fluxes and concentrations of ¹⁰Be are lower throughout the fjord when the ice shelf of Petermann Glacier was extended, and higher when the ice shelf was reduced in extent. In both instances, ¹⁰Be fluxes are lowest closest to the grounding line. The environmental factors controlling the delivery of ¹⁰Be to the seafloor in Petermann Fjord are threefold: 1) advection of ¹⁰Be into Petermann Fjord via ocean currents, 2) subglacial runoff and basal melt of ¹⁰Be entrained in the ice of Petermann Glacier, and 3) direct atmospheric deposition to the fjord surface waters (susceptible to blocking from the ice shelf and perennial sea ice) followed by delivery to the sea floor via scavenging. Here, we provide estimates of ¹⁰Be delivered to the fjord from the aforementioned transport mechanisms. Given the complexities and uncertainty associated with calculating scavenging rates and residence time of



¹⁰Be within the fjord, we do not estimate ¹⁰Be delivery to sediments but rather estimate delivery to the entire fjord. Details of these calculations are presented in the Supplement.

We estimate the total ¹⁰Be delivered to Petermann Fjord via atmospheric deposition to be 6.4×10^{18} atoms yr⁻¹ (reduced ice shelf) and 1.5×10^{18} atoms yr⁻¹ (extended ice shelf) respectively. This estimate indicates approximately four times the total ¹⁰Be atoms are delivered to Petermann Fjord via atmospheric deposition when the ice shelf was reduced, compared to an extended configuration. Estimates of delivery via basal melt and subglacial runoff are 1.6×10^{20} atoms yr⁻¹, approximately two orders of magnitude greater than the contribution from atmospheric deposition in the reduced and extended ice shelf configurations. Our estimate of ¹⁰Be transported via lateral advection is 1.3×10^{21} atoms yr⁻¹. This is approximately three times the order of magnitude from atmospheric deposition in the reduced/extended ice shelf environment, respectively, and approximately one order of magnitude larger than ¹⁰Be delivered via subglacial runoff and basal melt. Thus, despite uncertainty in these estimates we suggest that lateral advection is contributing to the majority of ¹⁰Be found in the marine sediments of Petermann Fjord, with glacial processes secondary in their contribution, followed by atmospheric deposition.

5.3.1. Using inorganic and organic proxies to assess advective heat flux

In the previous sections we argue that lateral advection is a key transport mechanism for the delivery of ¹⁰Be, sea-ice biomarker and sterols to sediments in Petermann Fjord. As such, the distribution of these proxies in this environment could provide information relating to advective heat flux, useful for paleo-reconstruction of ice-ocean interactions.

When Petermann ice shelf was reduced in extent, ¹⁰Be concentrations are higher in the marine sediments at all sites. This aligns with higher temperatures (0.86 °C warmer between 0.6 to 2 ka, relative to pre-industrial temperatures), compared to the extended ice shelf configuration after 0.6 ka (0.19 °C warmer), as inferred from the Agassiz ice cap (Ellesmere Island, Canada) ^δ¹⁸O atmospheric temperature reconstruction (Fig. 4; Lecavalier et al., 2017). Warmer air temperatures increase surface melt of Petermann Glacier, leading to enhanced subglacial runoff and amplify melt rates at the grounding line, via entrainment of warmer AW in buoyant plumes, as shown in modern observations (Washam et al., 2019, 2020) and modelling (Cai et al., 2017; Prakash et al., 2025) studies. As such, we argue that the higher atmospheric temperatures caused enhanced subglacial runoff and thus drove strong circulation and the entrainment of ¹⁰Be into Petermann Fjord when the ice shelf was reduced, resulting in higher ¹⁰Be concentrations in sediments. This observation indicates that there is potential to use ¹⁰Be to reconstruct oceanic heat fluxes in fjord environments dominated by subglacial melt.

¹⁰Be has previously been used as a proxy for permanent sea-ice cover and ice shelves. Low ¹⁰Be concentrations, or absence, in sediments located beneath the Ross Ice Shelf during the late Holocene indicate little advection from the open ocean or contribution from glacial meltwater (Yokoyama et al., 2016). Similarly, during glacial periods, samples from the Arctic Ocean and Nordic Seas show a decrease in ¹⁰Be, in part attributed to longer lasting sea ice which blocks meteoric ¹⁰Be from reaching sediments (Aldahan et al., 1997). However this application assumes limited sub-ice shelf circulation and advection, and limited basal melt which releases ¹⁰Be from glacial ice (e.g. Scherer et al., 1998; White et al., 2019; Yokoyama et al., 2016). As modern observations document strong sub-ice shelf circulation and melting in Petermann Fjord, the use of ¹⁰Be as shelf proxy in Petermann Fjord is complicated by advection and subglacial melt sources. Similar to Petermann Fjord, high ¹⁰Be concentrations are found in core tops under the Amery Ice Shelf, attributed to subglacial melt, strong bottom currents and calving (White et al., 2019). Here, some of the sub-ice shelf sites, mainly those at the front of the ice shelf, had almost identical ¹⁰Be concentrations to modern open water environments in nearby Prydz Bay, suggesting that ¹⁰Be is almost entirely advected from the open marine environment (White et



al., 2019). In these examples, it is important to note that the ice-shelf sites are far away from the presumed ice edge (between 100 and 200 km), in contrast to the smaller spatial scale of Petermann Fjord.

Results from Petermann Fjord, together with existing studies from the Ross and Amery Ice Shelves, show that environmental factors, primarily sub-ice shelf circulation patterns and submarine melt rates, must be considered when interpreting ^{10}Be concentrations in marine sediments for paleo reconstructions. In cases where there is limited sub-ice shelf circulation and subglacial melt, the use of ^{10}Be as an ice shelf proxy is less complicated. Yet, for environments with strong sub-ice shelf currents (e.g. Petermann Fjord and Amery Ice Shelf), and glacial systems that have high basal melt rates, interpreting ^{10}Be signals is more complicated (White et al., 2019). In our study from Petermann Fjord we use the combination of organic and inorganic proxies, as well as sediment lithofacies, to infer variations in past advective heat flux and circulation. For example, laminated sediments without IRD, characteristic of a proximal glacial marine environment with perennial sea ice or an ice shelf present, together with sea-ice biomarkers, sterols and ^{10}Be presence, imply lateral transport of proxies driven by ocean circulation, as observed in Petermann Fjord and on the Amery Ice Shelf (White et al., 2019). Similarly, if sea-ice biomarkers and sterols were absent, but ^{10}Be still present, it would imply input of glacial meltwater, which is a source of ^{10}Be , but not HBI IIs and sterols. In contrast, laminated sediments with no IRD, together with absence of sea-ice biomarkers, sterols and ^{10}Be would suggest a calving dominated mass loss regime, with limited basal melt, similar to those observed in the Ross Ice Shelf system (Yokoyama et al., 2016).

In this study, we show that lateral advection, enhanced by buoyant meltwater plumes is a key transport mechanism carrying inorganic and organic proxies to our sites, whilst glacial melt is providing secondary input of ^{10}Be to sediments. As such, we highlight potential for using a multi-proxy approach, with lithofacies analysis, to reconstruct advective heat-flux in a basal dominated melt environment, such as Petermann Fjord. More work is needed to develop these proxies for paleo-reconstructions as their distribution is likely regionally dependent and variable (e.g., effects of bathymetry and ocean circulation, glacial meltwater, amongst others). However, these findings provide motivation to conduct higher-resolution downcore analysis of inorganic and organic proxies in Petermann Fjord sediments, to improve our understanding of the ice-ocean-atmosphere interactions on longer timescales.

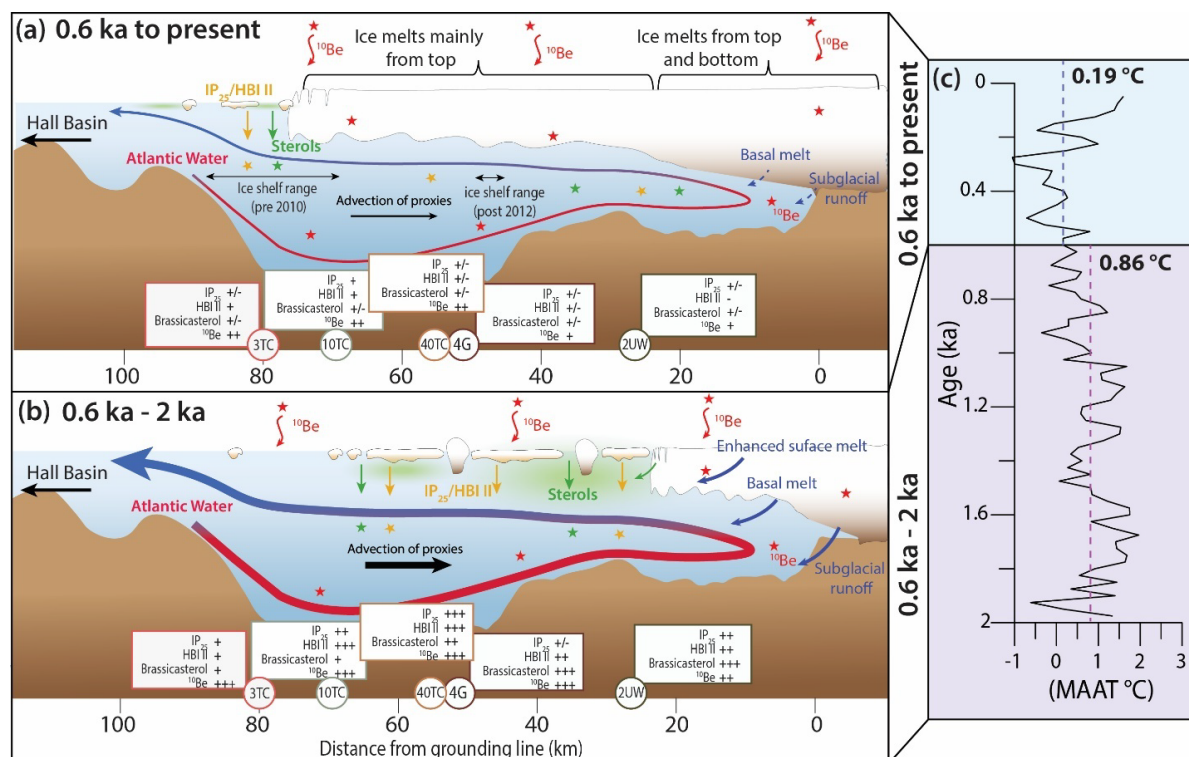


Figure 4: Schematic displaying the distribution of proxies (IP₂₅, HBI II, brassicasterol, ¹⁰Be) during the extended ice shelf configuration ((a), 0.6 ka to present) and in a reduced ice shelf state ((b), 0.6 to 2 ka). The fluxes of each proxy are shown, ranging from – (absent), +/-, +, ++, +++ (highest flux). Schematic includes input pathways for meteoric ¹⁰Be (red stars and arrows), the direction of advection (black arrow), ocean circulation patterns (red and blue arrow), basal and subglacial melt (blue arrow; dotted arrow indicates less intense signal), and phytoplankton blooms (green). The production, transport and deposition of sterols (green arrows and stars) and IP₂₅/HBI II (orange arrows and stars) are shown. Locations of the ice shelf dominated by surface melt and surface and basal melt are depicted and labelled, based on Johnson et al., (2011). The bathymetric profile is the gravity modelled east transect (Tinto et al., 2015). (c) Mean annual air temperature (MAAT) anomaly, relative to pre-industrial values, based on δ¹⁸O at Agassiz ice cap, 25-year resolution, with warmer air temperatures (purple) and cooler (blue) shaded; the average temperature between 2-0.6 ka cal BP and 0.6-present are marked in bold text and marked with a dotted line (Lecavalier et al., 2017).

6 Conclusions

Organic and inorganic proxies from sediment cores collected from Petermann Fjord capture information about circulation regimes, important for reconstructing advection patterns and basal melt rates from glacial-marine environments, specifically:

1. The presence of IP₂₅ and phytoplankton sterols beneath the ice shelf, where a lack of light inhibits algae from growing, suggest that lateral advection is a key process transporting these lipids into Petermann Fjord.
2. Transport of ¹⁰Be via advection from outside the fjord, enhanced by buoyant subglacial melt plumes driven by atmospheric temperatures, is the dominant ¹⁰Be source to the fjord, with glacial meltwater providing secondary input. ¹⁰Be cannot be used as solely an ice shelf proxy in this environment given the strong sub-ice shelf circulation which transports these proxies beneath the ice.
3. High sterol and IP₂₅ concentrations close to the edge of the ice shelf when it was reduced in extent suggests a productive and seasonal sea-ice environment, consistent with observational records from other Greenland fjords that show high productivity close to the glacial terminus.



Observations of ^{10}Be , sea-ice biomarkers and sterol concentrations from Petermann Fjord cores indicate their potential for reconstructing advective heat flux in a basal-melt dominated glacial environment. Such findings are important given the role that atmospheric warming plays in governing the stability of ice shelves via supraglacial melt linked to subglacial freshwater discharge and buoyancy driven circulation in fjord systems that enhances entrainment of warm ocean currents. Application of these proxies in future reconstructions in basal-melt-dominated environments will thus be important for improving our understanding of the interactions at the ice-ocean interface.

Data availability

Data will be available on PANGAEA.

Author Contribution

JD, BR and JM designed this experiment. JD carried out formal analysis of sea-ice biomarkers with the help of WD. JD and JM carried out formal analysis of inorganic proxies, and DH undertook analysis for organic carbon measurements. PW performed modelling in Petermann Fjord. JD prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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