

1 **Fate of dissolved organic matter along the supra-permafrost flow: role of arctic**
2 **subterranean estuaries**

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12 **Abstract**

13 Increasing coastal erosion and permafrost thaw along the Arctic shoreline represent major lateral sources of
14 dissolved organic matter (DOM) to the Arctic coastal ocean, where the fate of DOM depends on its composition
15 and transport pathways. One key and still underseen transport mechanism is non-point source supra-permafrost
16 groundwater flow that discharges through the sandy beach in front of the coastal bluffs. Here, we explore the
17 fate of DOM and dissolved organic carbon (DOC) along the supra-permafrost flow, with a specific focus on
18 the discharging zone of the sandy beach area, where fresh supra-permafrost groundwater mixes with
19 recirculated seawater. To address this, we sampled meltwater, beach groundwater, and seawater along coastal
20 bluff transects extending up to 2 km offshore. Along these salinity and redox gradients, we observed sharp
21 declines in DOC and chromophoric DOM (CDOM), indicating substantial removal along the short-distance
22 flow path. Optical indices (aCDOM₃₅₀, SUVA₂₅₄, HIX) and PARAFAC-based fluorescence analysis revealed
23 a shift from humic-like, high molecular weight (HMW) DOM in meltwaters to protein-like, low molecular
24 weight (LMW) DOM in nearshore adjacent seawaters. The inverse correlation between humic- and protein-like
25 components, together with high content of reactive Fe-hydroxide coatings on sandy sediment surfaces,
26 intermittently high total dissolved iron (Fetot) and elevated dissolved inorganic carbon (DIC) in beach
27 groundwater, suggests that microbial degradation and mineral-organic interactions jointly contribute to the
28 degradation and retention of supra-permafrost groundwater DOM pool before it reaches and becomes diluted
29 in coastal waters. These findings highlight the potential role of nearshore and intertidal zones, particularly the
30 mixing zone of subterranean estuaries (STEs), as key regulators of DOM composition and persistence.
31 However, whether Arctic beaches primarily act as transient filters, permanent carbon sinks, or dynamic
32 biogeochemical reactors remains an open question, underscoring the need for further research into their
33 contribution to the transfer of carbon from permafrost to the ocean.

34 **Keywords:** permafrost, Arctic coastal ocean, dissolved organic matter, dissolved organic carbon, iron
35 hydroxide.

1 Introduction

Permafrost stores around 1,300 Pg of organic carbon (OC) within its 13.9×10^6 km² surface area, which represents 60 % of the world's soil organic carbon stored in 15 % of global soil area (Obu et al. 2019; Schuur et al. 2015). The Arctic permafrost coastline is heavily impacted by global changes, resulting in unprecedented thawing rates and the deepening of the active layer, which, in turn, increases subsurface transport (Lantuit et al. 2012; Jones et al. 2020). Unlithified and ice-bonded permafrost cliffs, such as those along the Beaufort Sea, are highly susceptible to coastal erosion. Over the past twenty years, these cliffs have experienced one of the highest coastal erosion rates recorded in the Arctic, with a recorded rate of 1.1 m yr⁻¹ between 1950 and 2000. This rate has increased by 80 – 160 % in the last two decades (Lantuit et al. 2012; Jones et al. 2020). Accelerating coastline erosion is supplying increasing quantities of terrestrial materials (Kipp et al. 2018), associated nutrients (e.g., nitrogen and phosphorus; Fritz et al. 2017) carbon (including organic carbon and methane; Bristol et al. 2021), and contaminants (as heavy metals and organic pollutants; Kwasigroch et al. 2018) to the nearshore and coastal ocean. Recent studies indicate that land-derived nutrients from coastal erosion contribute ~30 to 50% of primary production in the Arctic Ocean, underscoring the critical biogeochemical role of permafrost-derived nutrient recycling on Arctic shelves (Terhaar et al., 2021; Vonk et al., 2025). These diffuse, non-point sources release solutes that are remobilized in late summer, when thaw depths and coastal hydraulic gradients peak (Walvoord & Striegl, 2007; Lecher, 2017).

Dissolved organic matter (DOM) represents a fundamental link between terrestrial and aquatic carbon cycles, playing a significant role in the biogeochemistry of aquatic ecosystems (Hedges & Keil 1995). At the ocean-basin scale, newly mobilized organic matter from Arctic watersheds may lead, among other things, to enhanced emissions of CO₂ or other greenhouse gases (Vonk et al. 2015, 2025; Kaiser et al. 2017; Tanski et al. 2019; Lapham et al., 2020) and modifications in the productivity of primary producers (Thingstad et al. 2008; McMeans et al. 2015; Nguyen et al., 2022) that sustain the marine Arctic food web, with unknown impacts on the communities that rely on these food sources. This new input affects ocean chemistry by altering carbon and nutrient cycling (Guo et al. 2007; Stedmon et al. 2011; Vonk et al. 2014) and changes optical conditions,

61 reducing light penetration and limiting primary production (Matsuoka et al. 2012; Fichot et al. 2013). A fraction
62 of this terrestrial DOM can be rapidly mineralized through microbial and photochemical processes, affecting
63 nutrient budgets, air-sea CO₂ exchanges, biological productivity, as well as acidification, in coastal waters
64 (Kaiser et al. 2017a; Kaiser et al. 2017b). For example, Kaiser et al. (2017a) showed that ~50% of the annual
65 DOC discharged by Siberian rivers was mineralized in estuaries and on Eurasian continental shelves, indicating
66 significant removal before reaching the open ocean. Therefore, only a small fraction of terrestrially-derived
67 compounds potentially persists in the ocean over centuries and millennia (Fichot & Benner 2014; Kaiser et al.
68 2017a). While the export of terrestrial dissolved organic carbon is known to significantly influence the Arctic
69 marine ecosystem, with an estimated 25 – 38 Tg C per year discharged into the Arctic Ocean (Holmes et al.,
70 2012), the role and significance of inputs from coastal erosion and permafrost thaw in shaping the
71 biogeochemistry and ecology of nearshore Arctic waters remain poorly understood. This knowledge gap stems
72 not only from the stochastic and episodic nature of erosion- and thaw-related fluxes, which complicates their
73 quantification, but also from the complex interactions between mineral and organic phases that control the
74 stabilization, degradation, transformation, and transport of the DOM pool along flow paths. The mechanisms
75 of organic matter transformations occurring at mineral-organic interfaces are complex (see Li et al., 2023; and
76 references therein), particularly in intertidal sandy sediment, where biological, geochemical, and redox
77 conditions interplay to influence DOM concentrations and molecular compositions. In addition to dilution and
78 bacterial degradation, a key process in these dynamic transitional environments is also the formation of iron
79 (Fe) curtains at the redox interface, which may serve as major zones for the storage and transformation of
80 terrigenous organic carbon (Chen et al., 2014; Linkhorst et al., 2017; Sirois et al., 2018; Zhou et al., 2023, 2024;
81 Amoako et al., 2025).

82 At the shoreline, beach subterranean estuaries (STEs) - where terrestrial groundwater mixes with recirculating
83 seawater (Moore, 1999) - act as biogeochemical hotspots (Anschutz et al., 2009) with the Fe cycle playing a
84 central role in both the remineralization and sequestration of organic carbon (Charette & Sholkovitz, 2002;
85 Sirois et al., 2018; Chaillou et al., 2024). Redox oscillations driven by fluctuations in water levels (e.g., tide
86 amplitude, waves, sea-level rise, and water table variations; Santos et al., 2012) shape the zones where reactive

minerals such as Fe-hydroxides precipitate, forming transient or persistent geochemical barriers that influence the mobility of elements, including DOM and DOC, and thereby modulate their export to adjacent coastal waters (Riedel et al., 2013; Linkhorst et al., 2017; Sirois et al., 2018; Waska et al., 2024; Amoako et al., 2025). While most studies on beach STEs and their associated biogeochemical processes have focused on lower-latitude systems, our understanding of their occurrence and functioning in Arctic environments remains scarce. The remoteness of Arctic beaches, the logistical challenges of sampling, and the high associated costs limit our understanding of these systems. However, recent research in Alaskan coastal lagoons by Demir et al. (2024) has confirmed that supra-permafrost groundwater flows, originating from the seasonally thawed active layer, can extend beyond coastal bluffs and beaches, even in areas underlain by permafrost. The presence of unfrozen, permeable coastal sediments thus creates pathways for fresh groundwater flow that mixes with recirculating seawater (as in STEs; Moore, 1999) and discharges into coastal zones, as observed in the Laptev Sea (Charkin et al., 2017) and in the Beaufort Sea along the Alaskan and Mackenzie coasts (Bullock et al., 2024; Kipp et al., 2025).

Absorbance- and fluorescence-derived indices are widely used to characterize the origin, reactivity, and transformation of aquatic DOM (Stedmon et al., 2003; Fichot & Benner, 2014; Meilleur et al., 2023). For instance, Fouché et al. (2020) identified permafrost-derived DOM as being predominantly low molecular weight (LMW), proteinaceous, and low in aromaticity, while DOM from the seasonally thawed active layer is characterized by high molecular weight (HMW), aromatic, and condensed organic compounds. In low-latitude STE, a lateral segregation of organic molecules occurs along the flow path, shaping the export of terrestrial-derived organic compounds to adjacent coastal waters (Couturier et al., 2016; Linkhorst et al., 2017; Hébert et al., 2022). The fate of the seasonally mobilized compounds at the land–ocean interface, particularly beyond beaches and coastal bluffs and along supra-permafrost flow paths, remains largely unknown in Arctic coastal environments. This study aims to characterize the transformation pathways of DOM released from the thawing of coastal Arctic bluffs and to highlight the role of sandy beaches as active zones of transport and transformation of terrigenous DOM at the shoreline. We suggest that Arctic beaches act as both a sink and a biogeochemical reactor, altering terrigenous DOM derived from the permafrost thaw before their export and dilution into the

coastal ocean. A fine-scale sampling strategy (<2 km) was deployed in the Kugmallit Bay region (NWT, Canada) to monitor the optical characteristics of DOM (including CDOM and FDOM) and behavior of DOC along the supra-permafrost flow, from coastal bluffs to the adjacent nearshore waters.

2 Materials and methods

2.1 Site Description

The study area is situated in the Inuvialuit Settlement Region of the Northwest Territories, near the Mackenzie Delta, the fourth-largest river system discharging into the Arctic Ocean (Macdonald et al., 1998). The Mackenzie River is a major source of freshwater, sediments, dissolved organic matter (DOM), and nutrients, exerting a strong influence on the salinity and biogeochemistry of the Beaufort Sea (Holmes et al., 2012). The tidal amplitude in Kugmallit Bay region is small (~ 0.3 m). Two field campaigns were conducted: the first from July 24 to August 6, 2019, and the second from June 22 to August 31, 2021, coinciding with peak thaw conditions. Approximately 60 samples were collected from four coastal sites characterized by continuous permafrost and active thaw slumps, bordered by sandy and clay-rich beaches: Tuktoyaktuk Island, Peninsula Point, Crumbling Point, and Reindeer Island (Fig. 1).

Tuktoyaktuk Island, the primary sampling site ($N = 34$; Fig. 2A), features a coastal bluff roughly 9 m high, 1.5 km long, and 100 m wide (Ouellette, 2021). Located southeast of Kugmallit Bay and opposite the Hamlet of Tuktoyaktuk, the island is undergoing rapid coastal retreat, losing approximately 1.8 m of shoreline annually due to storm events and permafrost thaw. This erosion rate has increased by 22% over the past 15 years (Berry et al., 2021; Tanguy et al., 2023; Whalen et al., 2022), and the entire site is projected to vanish within the next 20–30 years (Jones et al., 2020). In front of the bluff lies a 50-m-wide beach composed of fine to medium sands (0.3–0.5 m deep) overlying a frozen clay horizon (Fig. 2A). The exact submarine extension of this permafrost layer is unknown. Peninsula Point ($N=7$), southwest of Tuktoyaktuk Island within the Pingo Canadian Landmark, features a complex retrogressive thaw slump system underlain by a massive ice body ranging from

5 to 20 m in thickness (Mackay, 1986). Large, muddy lobes of thawed permafrost material and meltwater flow downslope toward the coast, intermittently covering the sandy intertidal zone (Fig. 2B). The shoreline has retreated at an average rate of $\sim 3.4 \text{ m yr}^{-1}$ between 1985 and 2018 (Hayes et al., 2022). Crumbling Point (N=5), located at the northwest edge of Kugmallit Bay, is another retrogressive thaw slump system with similar geomorphological characteristics. Reindeer Island (N=11), north of Richards Island, is part of a lagoonal complex formed by thermokarst lakes and surrounded by coastal bluffs. Although specific erosion rates for this site are not yet available, they are likely comparable to regional averages for the Canadian Beaufort Sea ($\sim 0.5 \text{ m yr}^{-1}$; Solomon, 2005). However, localized retreat rates can be substantially higher as seen in nearby Pullen Island, where erosion exceeds 12 m yr^{-1} (Berry et al., 2021). The width of the intertidal zone along these beach systems varies from a few meters to several tens of meters, depending on oceanographic conditions (e.g., wind regime and seasonal beach morphology).

2.2 Water and Sediment Sampling

At each site, we carried out a localized sampling along a transect, from coastal thawed bluffs, through beaches and intertidal zones, to nearshore seawater as presented in Kipp et al. (2025). Meltwater and beach groundwater (here defined as porewater in sandy sediment) samples were collected from coastal permafrost slumps and the adjacent sandy shore, respectively, while seawater samples were collected 0.5 to 1.0 km offshore from each study site. Surficial sandy sediments from beaches in front of permafrost bluffs were also collected during the 2019 field campaign at Tuktoyaktuk Island (N = 3) and Peninsula Point (N = 2). Meltwater was sampled directly in puddles formed on the thaw slumps using a submersible pump. Beach groundwater was collected using push-point piezometers inserted $\sim 50 \text{ cm}$ depth into the sandy ground, above the frozen clay layer, within the intertidal zone, with continuous pumping via a Solinst[®] peristaltic pump. A massive ice sample was collected from a permafrost core collected at Richard Island, which was sectioned and thawed in a hermetically sealed, acid-cleaned bucket, before collecting the meltwater via a peristaltic pump. Finally, seawater samples were collected using a submersible pump placed 0.5 and 1.0 m below the surface from a small vessel in front of the slump systems. At each site, water samples were pumped into an online flow cell where salinity (S), temperature, pH (at NBS scale), and oxygen saturation were monitored with a daily calibrated multiparametric probe (600QS,

YSI Inc.). Note that these stations were likely under the influence of the Mackenzie River plume, which mainly controls the water chemistry and optical signature in the region (see Lizotte et al., 2022, and references therein). Water samples were collected for CDOM/FDOM into acid-washed 60 mL glass amber bottles after on-line filtration through a 0.22 μm Millipore Opticap® XL4 cartridge with a Durapore® membrane. The samples were stored in the dark at 4 °C. Total dissolved Fe (Fetot) samples were collected in 60 mL metal-free Falcon® tubes after filtration through the same 0.22 μm Millipore Opticap cartridge. The samples were acidified with 3 drops of 70 % nitric acid to prevent the re-oxidation of reduced trace metals and stored at 4 °C. DOC samples were taken using 60 mL acid-cleaned polypropylene syringes and rapidly filtered with pre-combusted (450 °C for 5–6 hours) 25mm Whatman GF/F (0.7 μm) and stored in pre-combusted and acid-washed 12 mL borosilicate EPA tubes with PTFE caps. The same day, the DOC samples were acidified to pH <2 with high-purity HCl 2N and stored in the dark at 4 °C until analysis. During the 2019 campaign, samples were also collected in 30 ml scintillation vials, hermetically sealed for further water stable isotope analysis.

2.3 Chemical and Optical Analysis

Total organic carbon (TOC) content was measured on freeze-dried, ground and homogenized sediment using a CHNSO analyzer (Costech ECS 4010 CHNSO analyzer®; accuracy < 0.3%). Reactive Fe-hydroxide content was determined on the same sediment samples, extracted using the citrate-dithionite-bicarbonate (CDB) reduction method of Mehra and Jackson (1960), as modified by Lalonde et al. (2012), and previously applied to sandy sediments by Sirois et al. (2018). Briefly, reactive Fe-hydroxides are reductively dissolved with dithionite at circumneutral pH (bicarbonate buffer) using citrate as a complexing agent to keep dissolved Fe in solution. Fe in solution was analyzed using a Microwave Plasma Atomic Emission Spectrophotometer (4200 MP-AES; Agilent Technologies). The detection limit of the method is 2.4 $\mu\text{g L}^{-1}$ for Fe concentration at a wavelength of 391 nm and analytical uncertainties were <5%.

Stable isotopes of water were analyzed by EA-IRMS during the following year after the collection. Accuracies are ± 0.05 ‰ and ± 1 ‰ for $\delta^{18}\text{O}$ and $\delta^2\text{H}$, respectively. Reference materials were used throughout the isotopic water analyses and isotopic analyses are reported compared to the international Vienna Standard Mean Ocean

Water (VSMOW). DOC samples were analyzed a few weeks after data collection by Total Organic Carbon analyzer (TOC-VCPN Shimadzu) based on the method of Wurl and Tsai (2009). The analytical uncertainty was less than 4 %, while the detection limit was $5.8 \mu\text{mol L}^{-1}$. To ensure instrument stability, fresh acidified deionized water (blank) and a standard solution were regularly analyzed. The concentration of total dissolved iron (Fe_{tot}) was measured according to the ferrozine method proposed by Stookey (1970) and adapted by Viollier et al. (2000). The detection limit of the method was $0.4 \mu\text{mol L}^{-1}$ and the reproducibility was better than 0.3 %.

Absorbance and fluorescence spectroscopy were used for the measurement of the chromophoric and fluorescent fractions of DOM (CDOM and FDOM) a few weeks after sampling. The CDOM absorbance was measured using a Lambda 850 UV-VIS Perkin Elmer spectrophotometer with 1 cm path-length quartz cuvettes. Measurements were taken from 220 to 800 nm at 1 nm intervals with a scanning speed of 100 nm min^{-1} and a 5 nm slit width. Blanks and references were measured using fresh Milli-Q water. The FDOM was measured concomitantly using a Varian Cary Eclipse spectrofluorometer. Fluorescence spectra were measured within the emission wavelengths of 220 to 600 nm and the excitation wavelengths of 220 to 450 nm at 5 nm intervals as described by Couturier et al. (2016). Similarly, fresh Milli-Q water was used as a blank to rinse the cuvette in between samples. Fresh deionized water was used as a blank and absorbance measurements were used to correct the inner-filter effect and the dataset was corrected for Rayleigh and Raman scattering, according to the method used by Pucher et al. (2019).

2.4 Optical-derived indices and PARAFAC model

Absorbance and fluorescence indices were extracted using the staRdom toolbox on the R Studio Software (Pucher et al. 2019). Different indices were explored, including aCDOM₃₅₀, BIX, HIX, FI, SUVA₂₅₄ and SR. However, only three were reported here to characterize the DOM pool, as they showed distinct variations among the different categories of samples (e.i. beach groundwater, meltwater, massive ice, and seawater). The spectral absorption coefficient at 350 nm (aCDOM₃₅₀) was used as a tracer of CDOM absorption and content. It was calculated as 2.303 times the absorbance at the wavelength $\lambda=350 \text{ nm}$ divided by the path length of the cuvette (m). The specific UV absorbance (SUVA₂₅₄ in mgC L^{-1}) was calculated as the absorbance at the wavelength

$\lambda=254$ nm divided by the DOC concentration. It allows tracking the CDOM aromaticity (Weishaar et al. 2003): greater SUVA₂₅₄ values correspond to a greater degree of aromaticity (Helms et al. 2008). It has also been shown as positively correlated with the molecular weight of the DOM compounds. In the FDOM pool, the humification index (HIX) corresponds to the peak area under emission of 435–480 nm divided by the peak area under emission of 300–345 nm, at an excitation of 254 nm. HIX is an indicator of humic substances and the extent of humification of DOM compounds (Hansen et al., 2016; Ohno, 2002): higher HIX indicates a greater humification of the DOM source and HMW compounds.

In combination with the absorbance and fluorescence indices, a PARAFAC model – based on over 250 Arctic and subarctic coastal water samples – was developed to investigate further the composition and the sources of FDOM across samples (Bro 1997; Murphy et al. 2013; Stedmon et al. 2003). Three components were validated using the method adapted from Pucher et al. (2019), in R studio ($R^2>92\%$). The components were also matched with the literature for identification and external validation, using OpenFluor (Murphy et al. 2013). The three fluorescing peaks (C1-3) identified are presented in Fig. 3, and their theoretical characteristics based on the literature are summarized in Table 1. Briefly, C1 and C3 components are mainly related to terrestrial and humic-like compounds of high (HMW) and low molecular weight (LWM), respectively. In contrast, the C2 component is likely related to freshly produced protein-like compounds of autochthonous origin and is mainly composed of LMW compounds.

3 Results and discussion

3.1 Physico-chemical characteristics along the permafrost-nearshore continuum

In this study, we refer to samples collected at the nearshore as “seawater”; nevertheless, we acknowledge that these samples more accurately represent a brackish environment, with salinity S values ranging from 0.5 to 20, mostly related to the Mackenzie River plume occurrence. The massive ice and meltwater samples exhibited the lowest salinities with $S<1$, whereas the salinity of beach groundwater samples ranged between 0.2 and 5.4. The S range measured in beach groundwater samples mostly reflected the tidal and wave pumping effect and the

recirculation of the infiltrated seawater within the permeable sediments (Santos et al., 2012). The higher salinities ($5.4 < S < 20.0$) were only measured in seawater samples. The temperature varied between 8.1 and 16.7 °C (with a mean value of 13.0 ± 2.6 °C), with the higher temperatures measured in meltwater and some beach groundwater samples. Oxygen saturations ranged from 6 to 141 % of saturation. The nearshore surface seawater and the meltwater samples were all oversaturated due to mixing and photosynthetic processes. However, the low-salinity beach groundwater samples exhibited low oxygen saturation (6 - 48 %) despite the recirculation of well-oxygenated seawater. Redox oscillations and transitory oxygen-depleted conditions are observed in micro- and meso-tidal sandy intertidal zones (Hébert et al. 2022; Sirois et al. 2018; Waska et al. 2021), where oxygen input from tidal processes is rapidly consumed by heterotrophic processes (Chaillou et al., 2018, 2024; Moore et al., 2024). The total dissolved iron (Fetot) concentrations ranged from 0 $\mu\text{mol L}^{-1}$ (or below detection limits) in well-oxygenated seawater samples to more than 1400 $\mu\text{mol L}^{-1}$ in a deoxygenated meltwater sample. In beach groundwater samples, most Fetot concentrations were on the order of a few $\mu\text{mol L}^{-1}$, but one sample reached values above 600 $\mu\text{mol L}^{-1}$, corresponding to lower oxygen saturation levels. Regarding pH (NBS scale), the highest median values were observed in both meltwater and seawater (7.9), while beach groundwater exhibited a slightly lower median pH of 7.5, ranging from 7.0 to 8.0, with one sample dropping to 6.5 (also associated to the highest Fetot concentrations of $\sim 600 \mu\text{mol L}^{-1}$). Although pH data for massive ice samples were not available, their values likely fall within the lowest range of measured pH. This assumption is based on the origin of the massive ice in the region, which is thought to result from intrasedimental processes (e.g., ice intrusion and segregation) rather than from relict glacial ice (Mackay and Dallimore, 1992). Surficial beach sediments (<50 cm below the beach floor) are relatively poor in particulate organic carbon ($\text{TOC} < 0.45\%$) and mainly composed of elastic sediment coated with reactive iron-oxide (Table 2).

3.2 Origin of the subsurface water flow in the intertidal zone

Little is known about the hydro(geo)logical connectivity between supra-permafrost groundwater and Arctic coastal seawater (Letcher et al., 2017). However, recent studies and conceptual models, mostly developed for lower-latitude regions, suggest that key transport mechanisms of water and permafrost-derived solutes to the coastal zone are likely governed by three main pathways (Walvoord & Kurylyk, 2016): (i) riverine transport,

which includes both active layer runoff and contributions from deeper groundwater (Dittmar & Kattner, 2003; Demir et al., 2024); (ii) coastal erosion, which directly delivers organic-rich permafrost soils and particulate matter into the marine environment (Kipp et al., 2018); and (iii) submarine groundwater discharge (SGD) through subterranean estuaries (STEs), where supra-permafrost groundwater mixes with recirculating seawater before entering nearshore waters (Demir et al., 2024; Kipp et al., 2025). The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ results support the theoretical model in which beach groundwater represents a mixture of supra-permafrost groundwater flowing seaward and recirculating seawater advected landward (Fig. 2). The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values measured in water samples collected in 2019, mostly at Tuktoyaktuk Island, Peninsula Point sites, and Crumbling Point (Fig. 1), ranged from -28 to -10 ‰ and from -215 to -82 ‰, respectively, the massive ice sample (N=1) presents the most depleted signature (Fig. 4). These depleted values are largely explained by low air temperatures and are typical of permafrost hydrology reported in the western Arctic (Fritz et al. 2011; Utting et al., 2012). The samples are well aligned along the local meteoric water line (LMWL; $\delta^2\text{H} = 7.39 \times \delta^{18}\text{O} - 6.70$; Fritz et al., 2022), regardless of their salinity values, except for the three (3) meltwater samples that are slightly below it, likely due to evaporation processes at the surface. The alignment of the different samples along the LMWL regression line suggests a common meteoric origin, probably from the permafrost watershed. The supra-permafrost groundwater flow that transits through the beach sediment does not seem to be affected by surficial processes (e.g. evaporation process), as observed in a few meltwater samples, likely limiting photochemical degradation of the flowing CDOM/FDOM. However, the high range of isotopic values in beach groundwater samples, from -25 to -12 ‰ and -192 to -112‰ for $\delta^{18}\text{O}$ and $\delta^2\text{H}$, respectively, suggested a mixing between depleted thawed waters (as surficial meltwater and supra-permafrost groundwater) and enriched seawater, as expected in a STE system. These results are consistent with the recent study by Kipp et al. (2025), which reported elevated activities of radon isotopes (^{222}Rn) in the same beach groundwater samples. Radon, a noble gas, escapes rapidly upon exposure to the atmosphere, indicating a groundwater origin and minimal atmospheric interaction. These authors proposed that thaw water derived from massive ground ice is transported into the supra-permafrost groundwater system, where it becomes diluted by recirculating seawater (e.g. offshore water from the Mackenzie River) percolating through the beach sediments. Our findings support the presence of this

dynamic mixing zone at the beach shoreline, where stable isotopes, salinity, oxygen saturation, and pH fluctuate due to the infiltration and dilution of offshore seawater.

The absence of light and the combined fluctuations in pH, salinity, and redox conditions in beach groundwater samples were conducive for a complex network of redox reactions, including the remineralization of organic matter and the cycling of iron between its oxidized (Fe(III)) and reduced (Fe(II)) states.

3.3 Behaviour of the DOC and DOM pool

The DOC concentrations dropped from 2,360 $\mu\text{mol L}^{-1}$ in meltwater samples to 236 $\mu\text{mol L}^{-1}$ in the saltiest seawater sample (S=20; Fig. 5A). The concentrations declined sharply along the supra-permafrost flow path to reach values below 400 $\mu\text{mol L}^{-1}$ in beach groundwater samples. DOC concentrations in seawater samples, and, to a lesser extent, in beach groundwater, closely followed the theoretical mixing line connecting the freshest and saltiest endmembers. This pattern suggests that dilution becomes the dominant process controlling DOC behaviour once supra-permafrost flow enters the STE and is exported to adjacent coastal seawaters. Absorption coefficients at 350 nm ($a_{\text{CDOM}350}$) ranged from 2.0 to a maximum of 134.0 m^{-1} , the latter observed in a meltwater sample (Fig. 5B). Like DOC concentrations, the $a_{\text{CDOM}350}$ values declined sharply along the flow path, with a median value of 24.0 m^{-1} in meltwater samples and median values of 8.4 and 7.8 m^{-1} in beach groundwater and seawater, respectively. However, unlike DOC, $a_{\text{CDOM}350}$ values in beach groundwaters and seawater did not follow a simple dilution trend between the freshest and saltiest endmembers. The HIX indices showed a wide range of values across all sample types. Median values tended to decrease along the continuum, from 3.5 (unitless) in meltwater samples to 1.4 in beach groundwater, and 0.8 in seawater (Fig. 5C). Similar to $a_{\text{CDOM}350}$, HIX values in beach groundwater and seawater did not follow a dilution pattern along the salinity gradient. Whereas DOC, $a_{\text{CDOM}350}$, and HIX values declined along the flow path, SUVA_{254} indices showed an increasing trend from the massive ice and meltwater samples toward beach groundwater and adjacent nearshore seawater. The median SUVA_{254} value rose from 2.4 mg C L^{-1} in the meltwater to 2.9 mg C L^{-1} in beach groundwater and further reached to 3.4 mg C L^{-1} in seawater samples (Fig. 5D). With a few exceptions,

SUVA₂₅₄ values in beach groundwater and seawater closely followed the theoretical dilution line along the salinity gradient.

DOC concentration and aCDOM are commonly used as proxies to assess both the quantity and optical properties of the DOM pool in aquatic systems. The relationship between these two parameters provides insights into the biogeochemical sources and transformation processes shaping the DOM pool composition along environmental gradients (Massicotte et al., 2017; Fichot and Benner, 2011; Spencer et al., 2013; Stedmon et al., 2003). A strong correlation between DOC and aCDOM typically indicates that CDOM represents a stable and consistent fraction of the total DOM pool, a linear relation frequently observed in freshwater systems, where DOC and aCDOM are tightly coupled (Frenette et al., 2012; Massicotte et al., 2017 and references therein). However, deviations from this relationship, referred to as DOC-CDOM decoupling, suggest shifts in DOM composition and point to selective processing of specific DOM fractions. Microbial degradation, photo-oxidation and organo-mineral interactions mechanisms selectively degrade specific organic compounds and they lead to shifts in CDOM composition or a loss of CDOM along the land-ocean continuum (Nelson et al., 1998; Del Vecchio & Blough, 2004; Weyhenmeyer et al., 2012; Nelson & Siegel, 2013). In subarctic siliciclastic STE, Couturier et al. (2016), for example, reported a strong decoupling between CDOM-DOC, where high molecular weight (HMW) CDOM compounds were largely retained, limiting their export to nearshore adjacent seawater. In such environments, the so-called “iron curtain” (e.g. a zone of intense Fe cycling at the oxic-anoxic interface) acts as a geochemical barrier, promoting the sequestration of terrestrial organic compounds (Sirois et al., 2018). As in soils and cohesive marine sediments, molecular fractionation of DOM within STEs tends to promote the *in situ* degradation and/or preferential export of non-Fe-stabilized, marine protein-like derived DOM to coastal waters (Linkhorst et al., 2017; Sirois et al., 2018; Waska et al., 2022; Zhou et al., 2023).

The strong decoupling between DOC and aCDOM₃₅₀, particularly in meltwater, massive ice, and beach groundwater samples (Fig. 6), indicates that DOC and aCDOM₃₅₀ follow different trajectories (Fig. 5A and 5B) and are subject to selective processes. Given the light-limited conditions in beach groundwater environments, microbial degradation and mineral–organic interactions likely control the fate and composition

of the DOM pool. Acting concurrently, these processes contribute to the reduction of both DOC and CDOM concentrations along the supra-permafrost flow path and drive compositional changes in DOM pool, notably a decrease in humification and a shift toward lower molecular weight material as revealed by HIX indices (Fig. 5A to 5C). Despite this general decline in the DOM pool, the impact on DOM aromaticity (as indicated by SUVA₂₅₄) remains relatively weak. SUVA₂₅₄ values tend to increase slightly along the flow path, likely reflecting the dilution effect with the offshore seawater (Fig. 5D). The low fluorescent and biological indexes (FI<1.5, 0.5<BIX<0.9; data not shown) together with elevated SUVA₂₅₄ values of seawater samples, suggest that the “marine”-derived DOM is more decomposed and refractory, likely influenced by extensive terrestrial input and degradation during the transport in the Mackenzie River watershed and plume (McKnight et al. 2001; Huguet et al. 2009).

3.4 The decoupling between DOC and DOM

The *in situ* production of a new DOM pool, characterized by more degraded components with lower molecular weights and higher aromaticity, along the supra-permafrost flow path cannot be ruled out despite the low TOC content in the surficial sandy sediment (TOC< 0.50% dry sediment; Table 2). Similar patterns have been observed in transgressive subarctic STEs (Hebert et al., 2022) and in areas with buried peat lenses (Waska et al., 2021), where ancient sedimentary organic matter preserved in paleosols acts as a hotspot for terrestrial DOM production along the groundwater flow path. Such inputs can significantly influence the chemical and optical properties of beach groundwater DOM pool. Moreover, the presence of permafrost extending below the STE suggests that additional particulate organic matter reservoirs may be mobilized under thawing conditions, further contributing to newly mobilized DOM transformation and export. These deeper *in situ* inputs may explain the very depleted stable water isotopic signature of a few beach groundwater samples and the high radon activities reported by Kipp et al. (2025). Further efforts are needed to improve our understanding of Arctic beach hydrogeology by using geochemical and molecular proxies.

Despite their low TOC content, sandy sediments can act as hotspots of redox activity (Anschutz et al., 2009). Elevated DOC and CDOM concentrations, combined with fluctuating oxygen levels and salinity gradients,

promote the reductive dissolution and oxidative precipitation of redox-sensitive elements at oxic–anoxic interfaces, as well as coagulation processes. The presence of reactive Fe-hydroxide coatings on sandy sediment surfaces (Table 2), along with intermittently high total dissolved iron (median F_{TOT} of $1.6 \mu\text{mol L}^{-1}$ reaching $671.0 \mu\text{mol L}^{-1}$; Fig. 7A) concentrations in beach groundwater, suggests the formation of Fe-OM associations by oxidative precipitation of reactive Fe-hydroxide. The extent of Fe-OM coprecipitation or coagulation is governed by several factors, including the Fe : DOC molar ratio, organic matter composition, Fe speciation, and physicochemical parameters such as pH and salinity. As previously explained, the chemical nature of DOM pool plays a critical role in its interaction with mineral surfaces: higher molecular weight, aromatic, oxygen-rich terrigenous DOM tends to bind more strongly to Fe(III) than aliphatic, marine-derived DOM (Linkhorst et al., 2017). Additionally, slightly acidic conditions promote Fe(III)–DOM coagulation (Nierop et al., 2002; Amoako et al., 2025). The elevated dissolved inorganic carbon (DIC) concentrations measured in 2019 samples, which exceeded $3,000 \mu\text{mol L}^{-1}$ (Lizotte et al., 2022), the oxygen saturation and the presence of total dissolved Fe, support the idea of microbial respiration, organic matter degradation processes, proton release and redox gradients. Furthermore, the high Fe : DOC ratio observed in beach groundwater (median of 0.00844, ranging from 0.00353 to 0.92404 in more acidic beach groundwater sample; Fig. 7B) indicates strong interactions between dissolved iron and organic carbon in these environments. The exact mechanism controlling the molecular fractionation of the DOM pool in supra-permafrost groundwater remains to be determined, and further studies are required to explore the role of the organic-mineral and Fe-OM interaction to better quantify the export of thaw material.

3.5 PARAFAC components in the DOM pool

Among the three fluorescent components identified by the PARAFAC model, the protein-like component C2 dominated the FDOM pool across all sample types and salinities (Table 1; Fig. 8B). No clear trend in the distribution of components was observed along the salinity gradient. However, C2 exhibited a strong negative correlation with both humic-like components (C1 and C3) and the humification index (HIX), with correlation coefficients of $r^2 = -0.89$ ($p < 0.001$) for C1/C3 and $r^2 = -0.92$ ($p < 0.001$) for HIX. The median values of C2 increased progressively along the continuum, peaking in the seawater samples. In contrast, the humic-like

components C1 and C3 were positively correlated with each other ($r^2 = 0.81$, $p < 0.001$) and with HIX ($r^2 = 0.85$ and 0.69 , respectively; $p < 0.001$). Similar to the patterns observed for HIX, DOC, and aCDOM₃₅₀, both C1 and C3 declined along the flow path (Fig.8A, C), with the lowest median values found in seawater.

Massive ice and meltwater samples were predominantly composed of humic-like, high molecular weight (HMW), and terrestrially derived FDOM (component C1), and were rich in both terrestrial DOM and DOC. This composition is consistent with active layer-derived FDOM described by Fouché et al. (2020), who emphasized the key role of the active layer in seasonally mobilizing humic-like material. Our findings support this, suggesting that meltwater and massive ice act as important precursors of supra-permafrost solutes flowing to the coastal ocean through Arctic sandy beaches. As the DOM pool is transported along the flow path, a marked loss of humic-like compounds is observed, coinciding with an increase in biologically derived, tyrosine-like FDOM (component C2), typically associated with microbial production (Table 1 and references therein). This shift mirrors transformations reported by Fouché et al. (2020), where microbial processing converts DOM into lower molecular weight, protein-like material. In this context, the presence of non-Fe-stabilized DOM and redox-active conditions likely favour microbial mineralization, contributing to the formation of low molecular weight (LMW) and protein-like compounds that are ultimately dilute in the adjacent coastal waters.

4 Conclusion

This study reveals rapid declines in DOC and CDOM concentrations along the diffuse and non-point source supra-permafrost groundwater flow from coastal permafrost bluffs through sandy beach sediments and to adjacent nearshore seawater. The findings highlight the importance of microbial degradation and mineral-organic interactions in transforming and retaining supra-permafrost groundwater DOM pool. These processes occur primarily within STE, where they selectively degrade humic-like, high molecular weight DOM and alter its composition before it reaches and dilutes with coastal waters. Our results highlight the potential role of nearshore and intertidal zones, particularly subterranean estuaries where supra-permafrost groundwater mixes with recirculated seawater, as key regulators of DOM composition and persistence. However, whether Arctic

beaches primarily act as transient filters, permanent carbon sinks, or dynamic biogeochemical reactors remains an open question, underscoring the need for further research into their contribution to the transfer of carbon from permafrost to the ocean. Given accelerating permafrost thaw and coastal erosion, understanding these nearshore processes is critical for constraining Arctic carbon budgets and predicting their role in global climate feedback.

Data availability: Along with this submission, the dataset used in this research was submitted and accepted for publication to Pangaea Data Publisher (www.pangaea.de). Once this article accepted for publication, the moratorium in place will be lifted and the dataset generated during the study will be freely available in the Pangaea repository. Here is the hyperlink and DOI toward the dataset: <https://doi.pangaea.de/10.1594/PANGAEA.960986>

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TABLES

Table 1 : Description of the EEM-PARAFAC modelled FDOM components based on the literature results of literature references. PARAFAC components and their characteristics

Comp.	Peak max Ex/Em	Coble peak	Description	Literature
C1	250-335/466	A, C	Humic-like terrestrial, HMW, aromatic	C _C : <240-340/452 (Olefelt et al., 2014) ALL1: 250-350/459 (Pitta and Zeri 2021) C3: <240-355/476 (Stedmon and Markager, 2005a) C3: 260-370/490 (Murphy et al., 2018) C4: <255-360/460 (Fouché et al., 2020)
C2	265/296	B	Protein-like, tyrosine, biological, microbial autochthonous origin. LMW phenolic compounds.	C _{Ty} : 270/<300 (Olefelt et al., 2014) ACT-10 C3: 270/302 (D'Andrilli and McConnell 2021) C6: 280/338 (Stedmon and Markager, 2005a) C1:275/<300 (Murphy et al. 2008) C1: 275/306 (Fouché et al., 2020)
C3	250-295/414	A, M	Humic-like, terrestrial, autochthonous production and microbial processing, LMW.	C _M :<240,305/404 (Olefelt, Persson et al. 2014) C2: <300/396 (Søndergaard, Stedmon et al. 2003) C2 : 315/418 (Murphy et al., 2008) C2: 310/ 415 (Fouché et al., 2020)

Table 2 : Particulate fraction characteristics of sandy beach sediment collected at Tuktoyaktuk Island and Peninsula Point.

	Tuktoyaktuk Island N=3	Peninsula Point N=2
Sediment depth layer (cm)	0-50	0-30
Total organic carbon (% dry sediment)	0.43 ± 0.12	0.21 ± 0.07
Reactive sediment Fe (ppm; µg Fe/g dry sediment)	2.246 ± 0.850	1.320± 0.250

FIGURE CAPTIONS

Fig. 1 Map of the four sampling sites (red dots) located in the Northwest Territories, Canada.

Fig. 2 Schematic cross-sections and photographs illustrating the coastal permafrost landscape at Tuktoyaktuk Island (A) and Peninsula Point (B; not to scale) as examples of a retrogressive thaw slump system. Black arrows show theoretical surface (solid lines) and subsurface (dashed lines) flow paths, while blue arrows represent recirculating seawater driven by tidal and wave inputs into the intertidal zone of sandy beaches. Blue dots in panel B mimic melt ponds. The locations of the different sample types (“massive ice,” “meltwater,” “beach groundwater,” and “seawater”) are indicated. These conceptual models are adapted from Kipp et al. (2025) based on Hayes et al. (2022) for Peninsula Point and Whalen et al. (2022) and Warren et al. (2025) for Tuktoyaktuk Island.

Fig. 3 Excitation-emission matrix (EEM) fluorescence spectra of the 3-component PARAFAC model. Fluorescence is expressed in Raman Unit (R.U.).

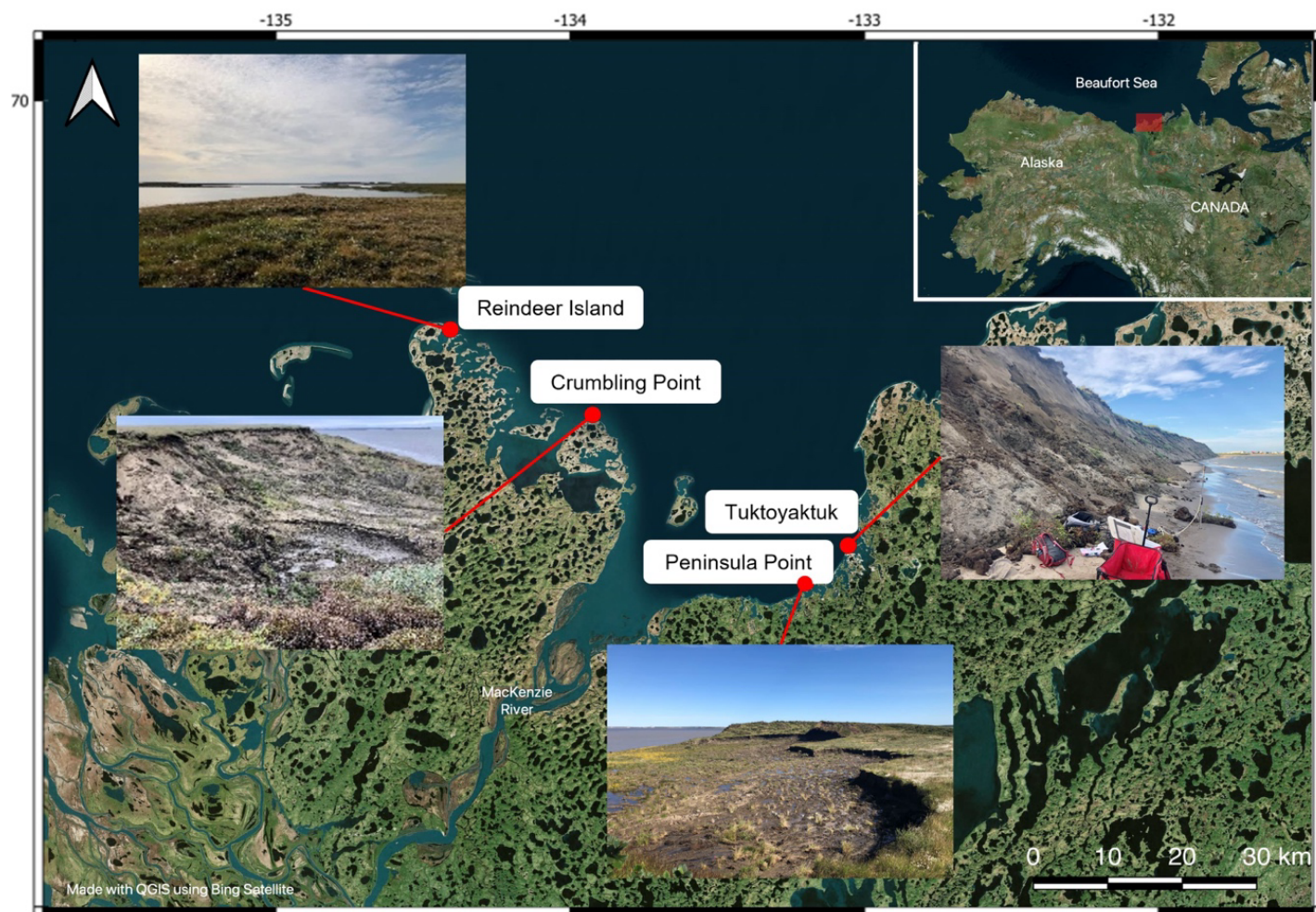
Fig. 4 Isotopic composition of massive ice, meltwater, beach groundwater and seawater samples collected in 2019 showing the mixing line between samples across the salinity gradient, from the meltwater to the seawater. The global meteoric water line (GMWL; Craig, 1961) and the local meteoric water line for Inuvik (LMWL, Fritz et al., 2022) are also reported. Note that only one massive ice sample (N=1) was collected in 2019.

Fig. 5 Distribution of (A) DOC, (B) aCDOM₃₅₀, (C) HIX, and (D) SUVA₂₅₄ across the salinity gradient (S) and among the different sample types (i.e., beach groundwater, massive ice, meltwater, and seawater). Note that only one massive ice sample is included. The zoomed-in panels display only beach groundwater and seawater samples, along with a theoretical mixing line (dashed black line) connecting the “fresh” and “salty” endmembers. These endmembers were defined based on the most enriched and depleted stable isotope signatures in the dataset, corresponding to salinity values of 20.08 (N = 1) and 0.18-0.30 (N = 8), respectively. In the boxplots, black lines indicate the medians, whiskers represent the full range of data, and individual points denote outliers.

Fig. 6 Global relationship between absorption coefficients at 350 nm (aCDOM₃₅₀ in m⁻¹) and DOC concentrations (in μmol L⁻¹) along the permafrost to nearshore aquatic continuum. Note that the data is reported in Log units.

Fig. 7 Distribution of total dissolved Fe (Fe_{tot}, μmol L⁻¹) (A), and Fe-DOC ratio (B) across the salinity gradient (S), and by sample type. The y-axis in each panel is shown on a logarithmic scale to accommodate the broad range of Fe concentrations. Note that there is no Fe_{tot} data from the massive ice samples and Fe : DOC ratios were calculated only for Fe_{tot} concentration higher than the detection limit.

Fig. 8 Distribution of PARAFAC components (A) C1, (B) C2, and (C) C3 along the salinity gradient (S) and for the different types of collected samples (i.e., beach groundwater, massive ice, meltwater and nearshore seawater samples). Note that only one massive ice sample is reported here. For the boxplots, the black lines represent the median values, the whiskers represent the extent of the data, and the dot points represent the outlier values. Note that there is only one massive ice data.



780 **Fig. 1** Map of the four sampling sites (red dots) located in the Northwest Territories, Canada.

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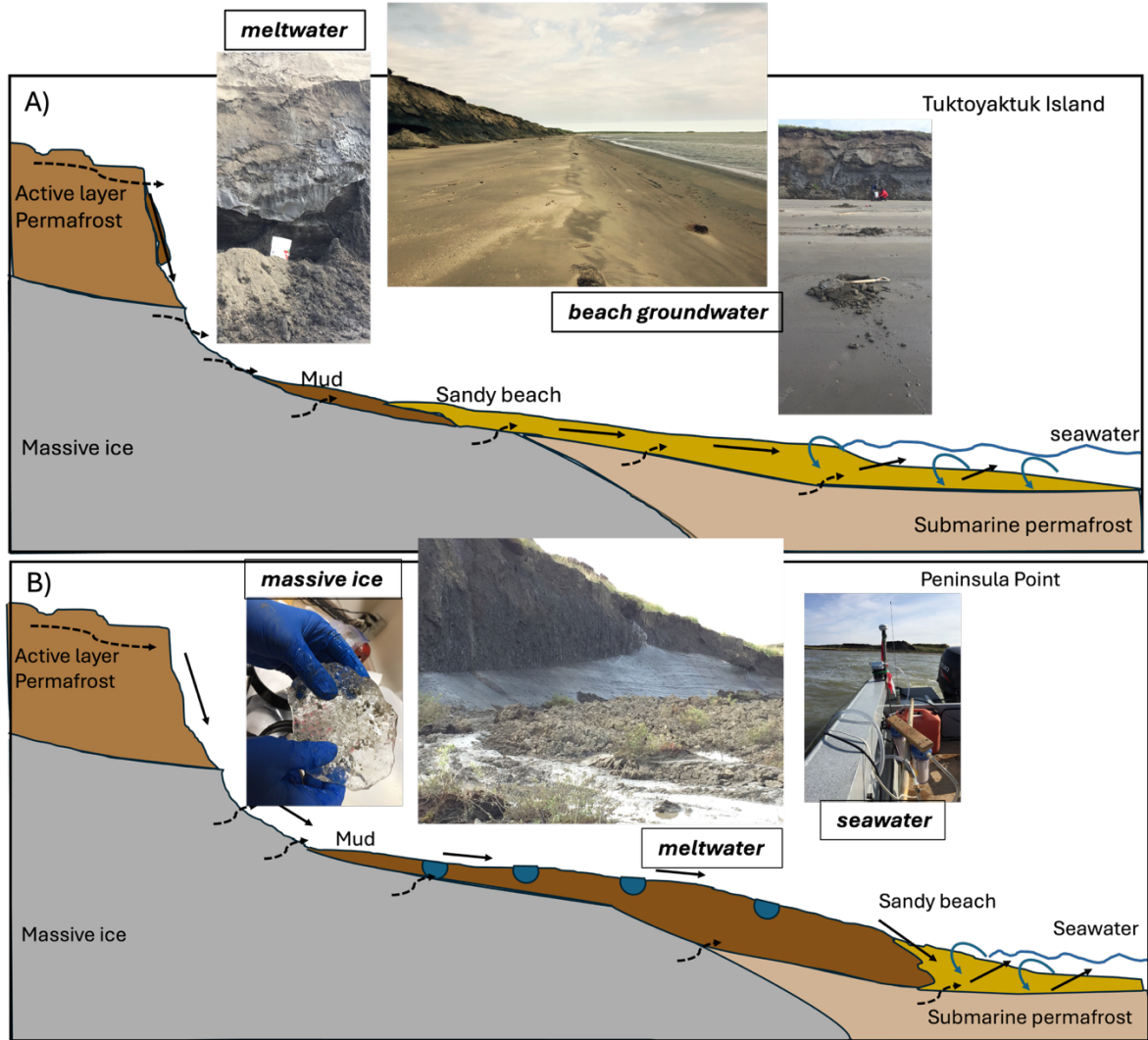


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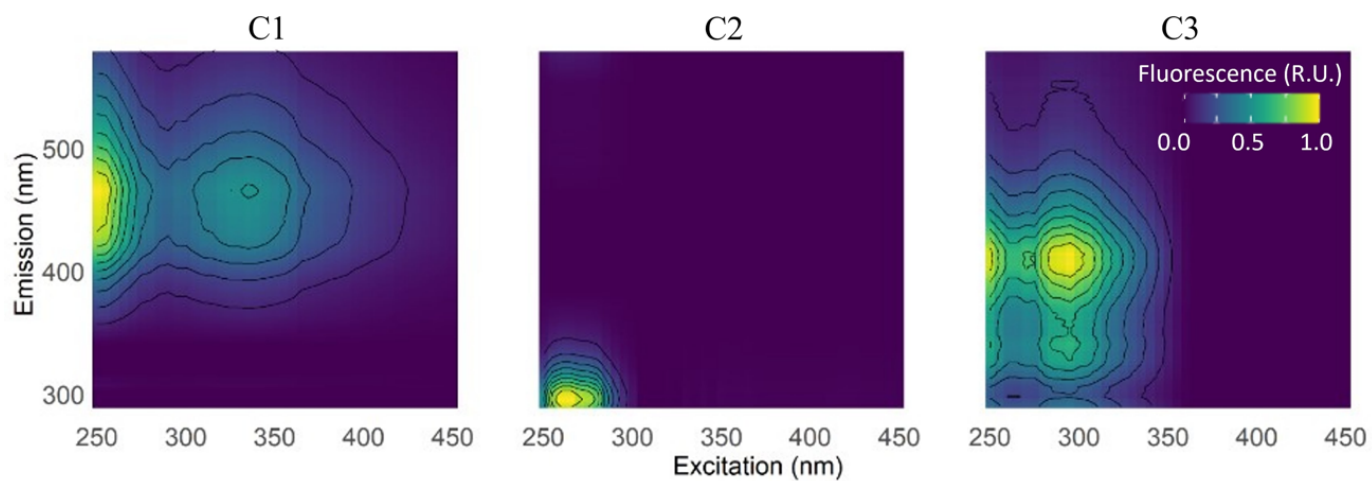


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Fluorescence is expressed in Raman Unit (R.U.).

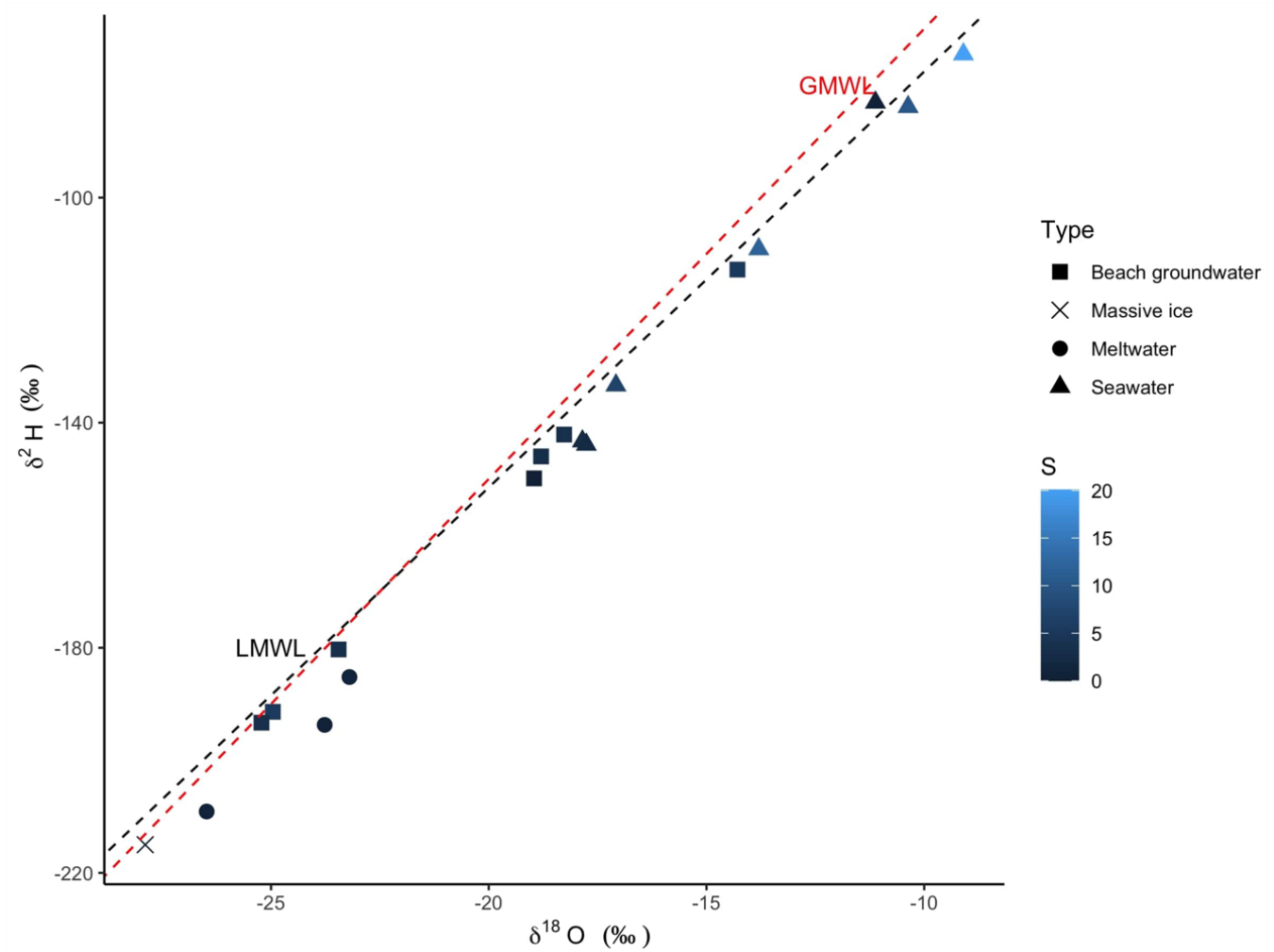


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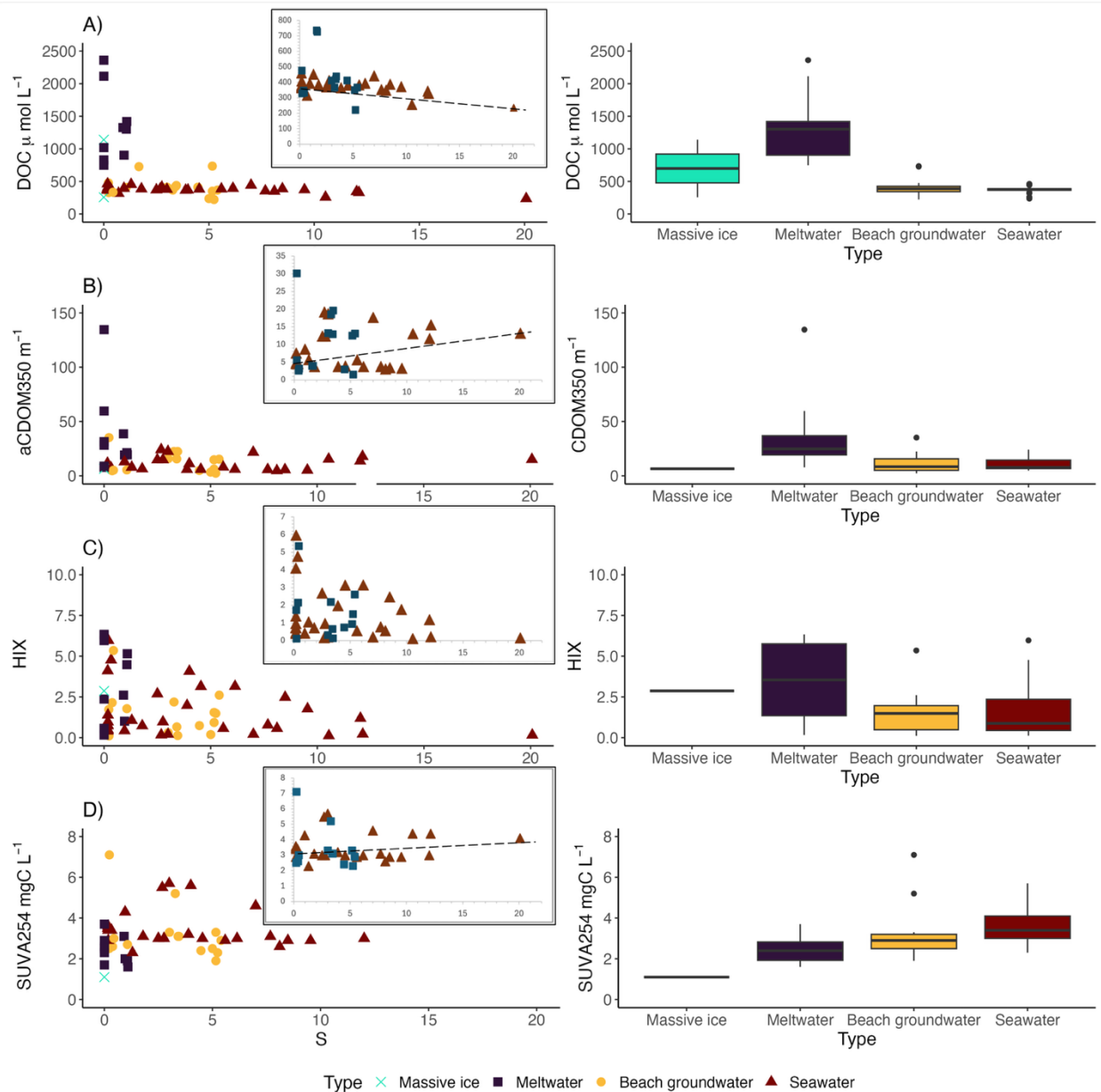


Fig. 5 Distribution of (A) DOC, (B) aCDOM350, (C) HIX, and (D) SUVA254 across the salinity gradient (S) and among the different sample types (i.e., beach groundwater, massive ice, meltwater, and seawater). Note that only one massive ice sample is included. The zoomed-in panels display only beach groundwater and seawater samples, along with a theoretical mixing line (dashed black line) connecting the “fresh” and “salty” endmembers. These endmembers were defined based on the most enriched and depleted stable isotope signatures in the dataset, corresponding to salinity values of 20.08 (N = 1) and 0.18-0.30 (N = 8), respectively. In the boxplots, black lines indicate the medians, whiskers represent the full range of data, and individual points denote outliers.

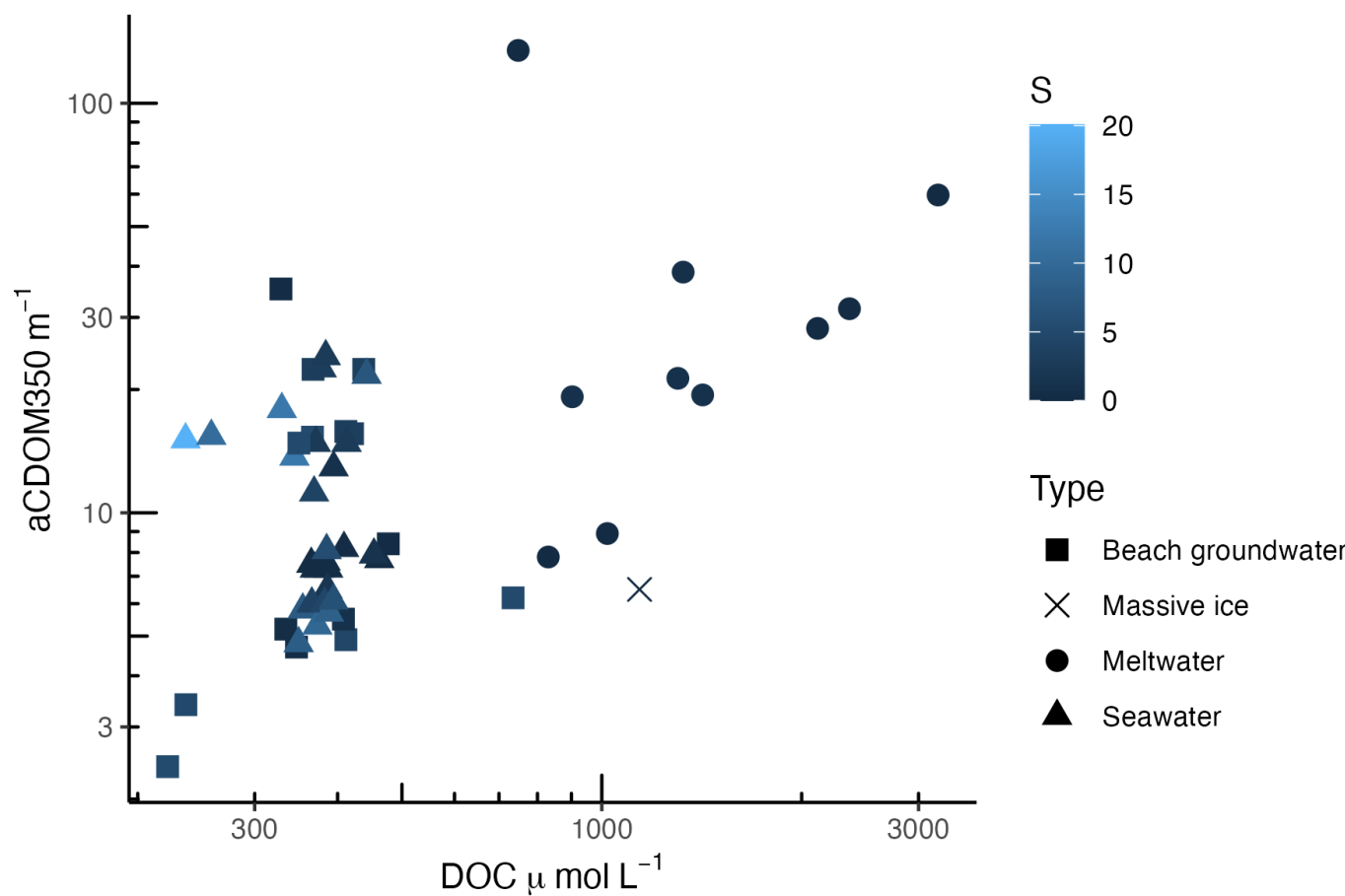


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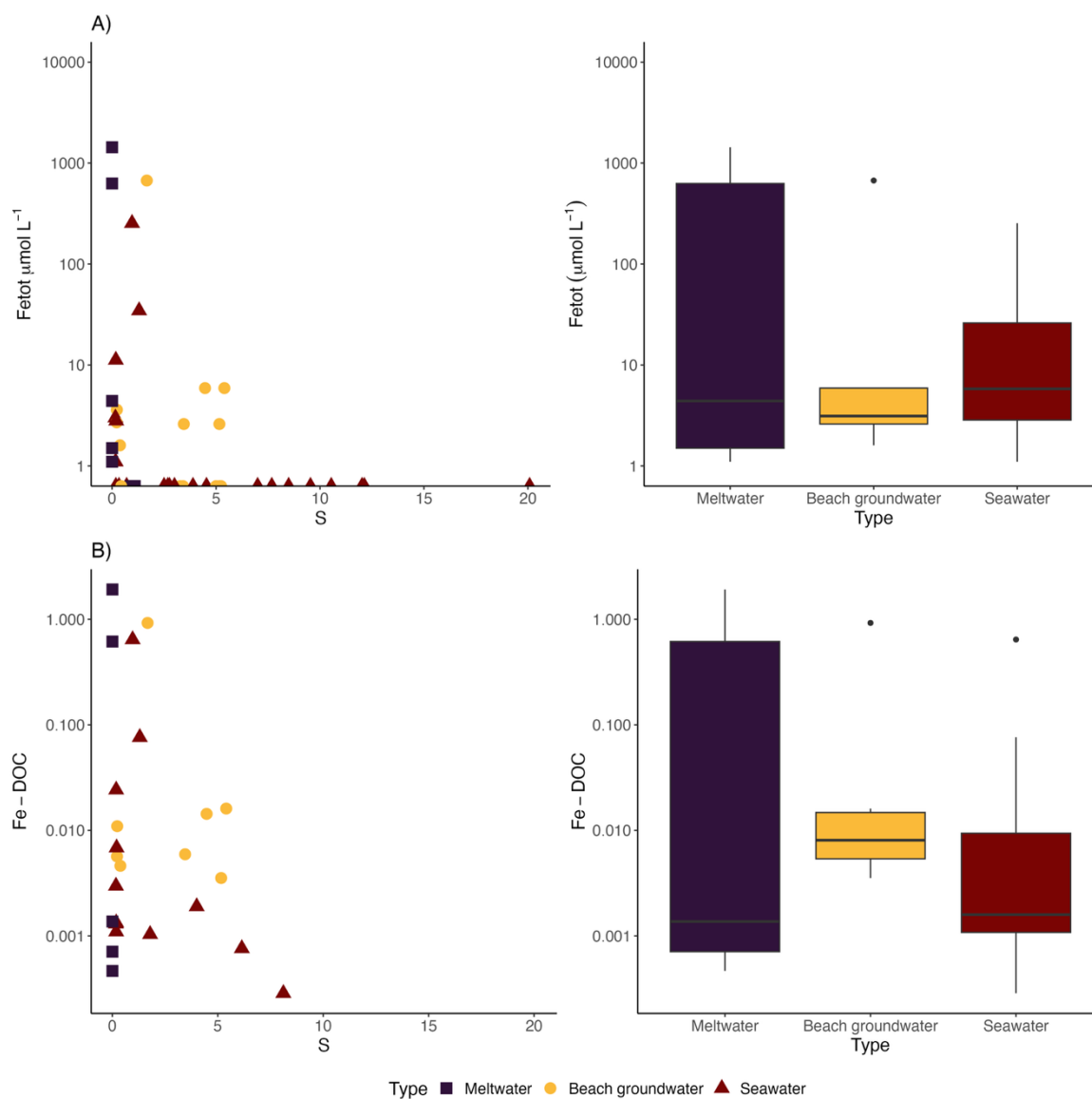


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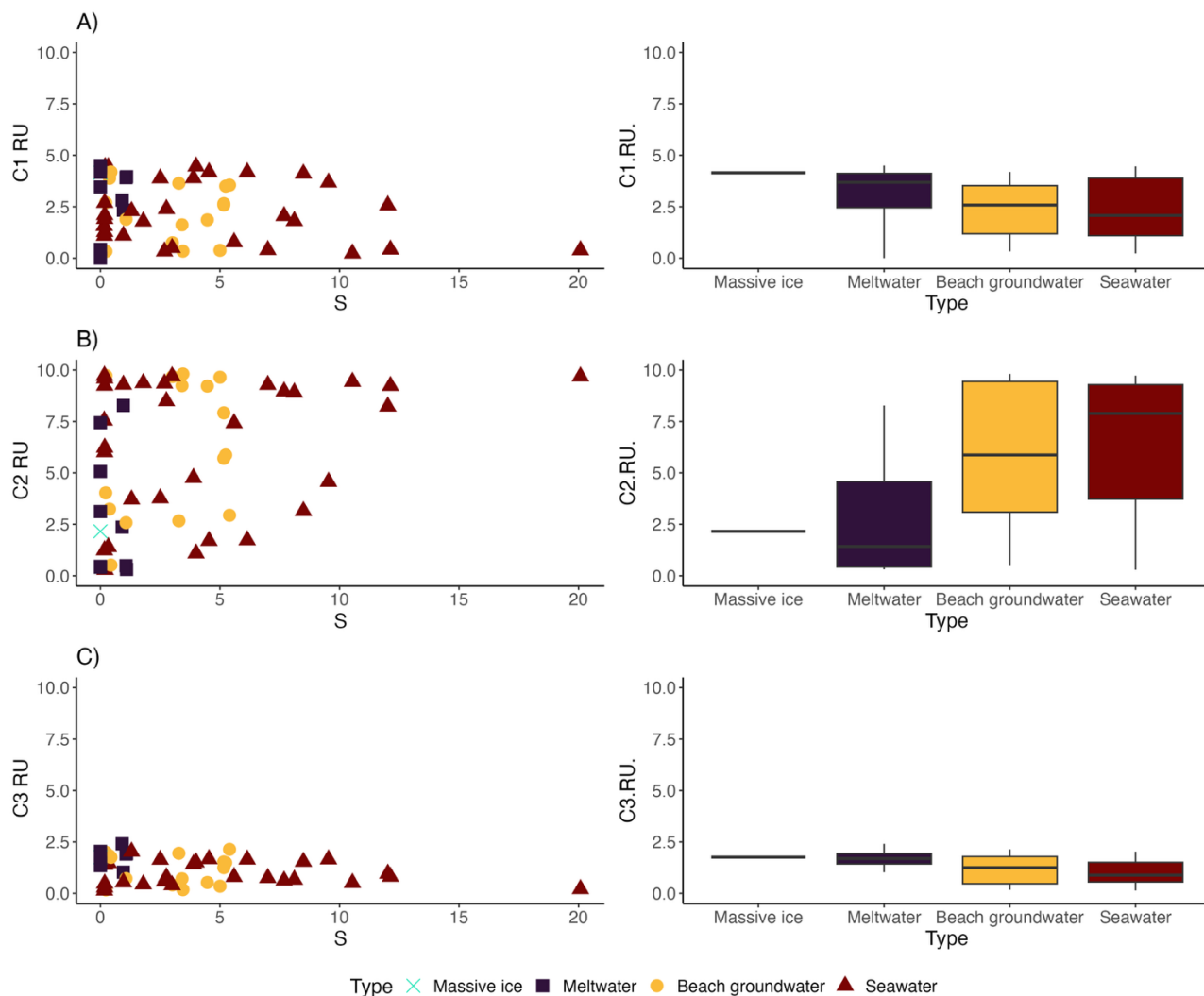


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