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Key Points:

- Particulate organic carbon (POC) carried by glacial Zackenberg river shows uniform composition despite diverse inputs from tributaries
- Geology and hydrologic conditions control POC composition in small periglacial streams with rain events eroding more ancient carbon
- Organic matter in soils and river sediments throughout Zackenberg valley is largely associated with minerals

Supporting Information:

Supporting Information may be found in the online version of this article.

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Contrasting Export of Particulate Organic Carbon From Greenlandic Glacial and Nonglacial Streams

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Abstract On-going shrinkage of Greenland's icecap, permafrost thaw, and changes in precipitation are exposing its landscapes to erosion and remobilization of ancient organic carbon (OC) held in soils and sedimentary rocks. The fate of this OC and potential feedbacks to climate are still unclear. Here, we show that the glacial Zackenberg river (Northeastern Greenland) exports aged particulate OC (POC, uncalibrated radiocarbon ages of ~4,000 years). Many of the smaller periglacial streams affected by abrupt permafrost thaw transport substantially older POC (up to 32,000 years), especially with enhanced discharge following intense precipitation. Mineralogical analysis, and density and size fractionation of soils and both glacial and nonglacial river sediments reveal that OC is largely associated with phyllosilicate minerals, suggesting stabilization against microbial processing. Enhanced export of ancient, mineral-associated OC as a consequence of summer rainfall may accelerate translocation of OC from terrestrial to marine environments, but could have limited consequences for climate.

Plain Language Summary On-going Arctic warming leads to shrinking ice sheets and permafrost thaw, which promotes erosion of ancient carbon stocks. The decomposition of this remobilized carbon to CO₂ or CH₄ would in turn fuel further climate warming. Here we show that the glacial Zackenberg river in Northeastern Greenland likely exports a mixture of aged soil organic matter, recent bacteria and ice algae biomass residues, and deposited organic aerosols. In contrast, many of the smaller, nonglacial streams in the study area carried significantly older carbon from deeper soil layers or sedimentary rocks. More intense rainfall will likely increase these carbon fluxes. However, close interactions of organic matter with mineral surfaces may hamper greenhouse gas production and instead promote burial in marine sediments. Therefore, the impact on atmospheric CO₂ and climate may be limited.

1. Introduction

With rising temperatures, glaciers are retreating globally. The Greenland icecap has experienced record melt in the past decade (The IMBIE Team, 2020), amplifying freshwater discharge and transport of sediment and dissolved constituents (Hawkins et al., 2015; Meire et al., 2016). Cascading effects on downstream ecosystems remain uncertain, as additional nutrient input could enhance primary productivity in marine environments (e.g., Arrigo et al., 2017; Meire et al., 2017). Conversely, increased turbidity caused by the generally high suspended sediment loads of glacial outflow limits light penetration and thereby suppresses phytoplankton growth (Holding et al., 2019; Hopwood et al., 2020). In addition, retreating icecaps and glaciers expose previously covered landscapes to erosion, generally causing elevated sediment release until stabilization by colonizing vegetation (e.g., Ballantyne, 2002). Erosion rates are projected to increase throughout the Arctic due to rapid thaw and destabilization of permafrost (e.g., Hugelius et al., 2020; Olefeldt et al., 2016; Turetsky et al., 2020), as well as intensifying rain events caused by a shift from snow- to rain-dominated precipitation (e.g., Bintanja & Andry, 2017). Erosion of soils or recent vegetation litter can act as a carbon sink on geological timescales if the released organic carbon (OC) is rapidly buried in marine sediments (e.g., Hilton et al., 2015; Hovius et al., 2011). On the other hand, erosion constitutes a carbon source to the atmosphere if ancient permafrost soil or rock-derived (petrogenic) carbon is mineralized during transport or in marine environments (e.g., Bröder et al., 2018; Hemingway et al., 2018; Zolkos et al., 2018).

The fate of the mobilized OC depends on the interplay between many different factors: its chemical composition (e.g., Bröder et al., 2021; Hobbie et al., 2000), the availability of mineral matrices to interact with (e.g., Doetterl et al., 2016; Hemingway et al., 2019; Hirst et al., 2022; Keil & Mayer, 2014), and the surrounding environmental conditions (e.g., temperature, pH, oxygen availability, microbial community structure; e.g., Opfergelt, 2020; Schmidt et al., 2011). Dissolved OC released from permafrost soils has been shown to degrade relatively rapidly upon release (e.g., Abbott et al., 2014; Drake et al., 2015, 2018; Vonk et al., 2013), whereas its particulate counterpart (POC) can be traced through the Arctic fluvial network and appears to be preferentially buried in marine sediments (Bröder et al., 2019, 2021; Vonk et al., 2010, 2014; Wild et al., 2019). The age of exported OC is commonly expected to decrease with increased flow, as high discharge generally occurs during the spring freshet with snowmelt, as well as after high precipitation events, both generally flushing modern-aged OC through overland-flow from the upper soil layers into rivers (Ward et al., 2017). However, this relationship is likely more complex for glacially fed rivers and watersheds underlain by permafrost as soil thaw depths and the seasonality of the high discharge events determine whether deeper soil layers, and thereby older carbon stocks, are accessible to erosion. Thermokarst (abrupt permafrost thaw features) development within smaller catchments can exert primary control on the export of old POC (Lamoureux & Lafrenière, 2014). In glacial rivers, POC can comprise a significant fraction of ancient carbon with increasing discharge as increasing glacial melt mobilizes POC from subglacial reservoirs as well as old residues of in situ microbial activity (Bhatia et al., 2013; Kohler et al., 2017).

Here, we investigate the export of sediments and POC from a glacial river and a network of smaller streams fed by snowmelt and rain, draining deglaciated permafrost landscapes in the Zackenberg valley, northeastern Greenland. We collected suspended sediment samples from the glacially fed Zackenberg river and its nonglacial tributaries, as well as the separate, much smaller Grænse stream complex in August 2019 at the end of a particularly warm and dry summer (Christensen et al., 2020). Grænse serves as an example for headwater streams affected by abrupt permafrost thaw, and by sampling during contrasting hydrological conditions, we evaluate the impact of precipitation events on sediment export. By examining Total Suspended Solid (TSS) loads, POC concentrations and composition (carbon isotopes ^{13}C and ^{14}C) as well as mineralogy, we investigate sources and controls of the mobilized material. For comparison, we also analyzed soil samples from eroding river banks and abrupt permafrost thaw features in the watershed. Furthermore, we performed particle-size and density fractionations of soils and riverine sediments to investigate OC interactions with minerals, which play an important role in mediating the fate of eroded OC. These results therefore aim to improve our understanding of anticipated consequences of the rapidly changing glacial and periglacial landscapes for OC dynamics in Greenland.

2. Local Setting

The Zackenberg valley is located in the high Arctic on the northeastern coast of Greenland (74°28' N, 20°34' W, Figure 1), and is underlain by continuous permafrost. Active layer depths are spatially variable, yet have exhibited a net increase over the past 25 years (0.7 cm per year on average) and reached a mean maximum of 85 cm in 2019 (Christensen et al., 2020). The study area covers two main geological units: Caledonian gneiss and granite bedrock predominate west of Zackenberg river, while Cretaceous sandstones, black shale, conglomerates and Tertiary basalts underlie the eastern part of the drainage basin (Koch & Haller, 1971). At mountain slopes, weathered bedrock is exposed, foothills consist of solifluction deposits and moraines, and valley bottoms are characterized by peatlands, alluvial fans, and deltaic deposits (Cable et al., 2017). Estimates of the timing of deglaciation of Zackenberg valley range from 13.7 to 10.1 ka ago (Bennike et al., 2008; Garcia-Oteyza et al., 2022; Gilbert et al., 2017). Upon deglaciation, areas lying below ~40 m elevation were first inundated and then emerged during the early Holocene due to glacio-isostatic uplift, with the stabilization of present sea level at around 5–6 ka (Christiansen et al., 2002).

Zackenberg river drains a watershed of ~500 km² and is fed by two main water sources, a glacial lake that collects runoff from the A.P. Olsen glacier complex, and tributaries in the lower part of the catchment that mostly drain Lindemans valley and are fed by meteoric waters (Docherty et al., 2018; Hasholt & Hagedorn, 2000; Hasholt et al., 2008). Discharge during the sampling period was between 3.5 and 23.1 m³ s⁻¹ (GEM database: <https://g-e-m.dk/>, GeoBasis Zackenberg, Hydrology and Figure S1 in Supporting Information S1). In contrast, Grænse stream catchment with a size of about 8 km² can be regarded as a case study of a high-Arctic nonglacial headwater stream complex as it is sustained by a seasonal snowpack and summer rain, and directly discharges into Young

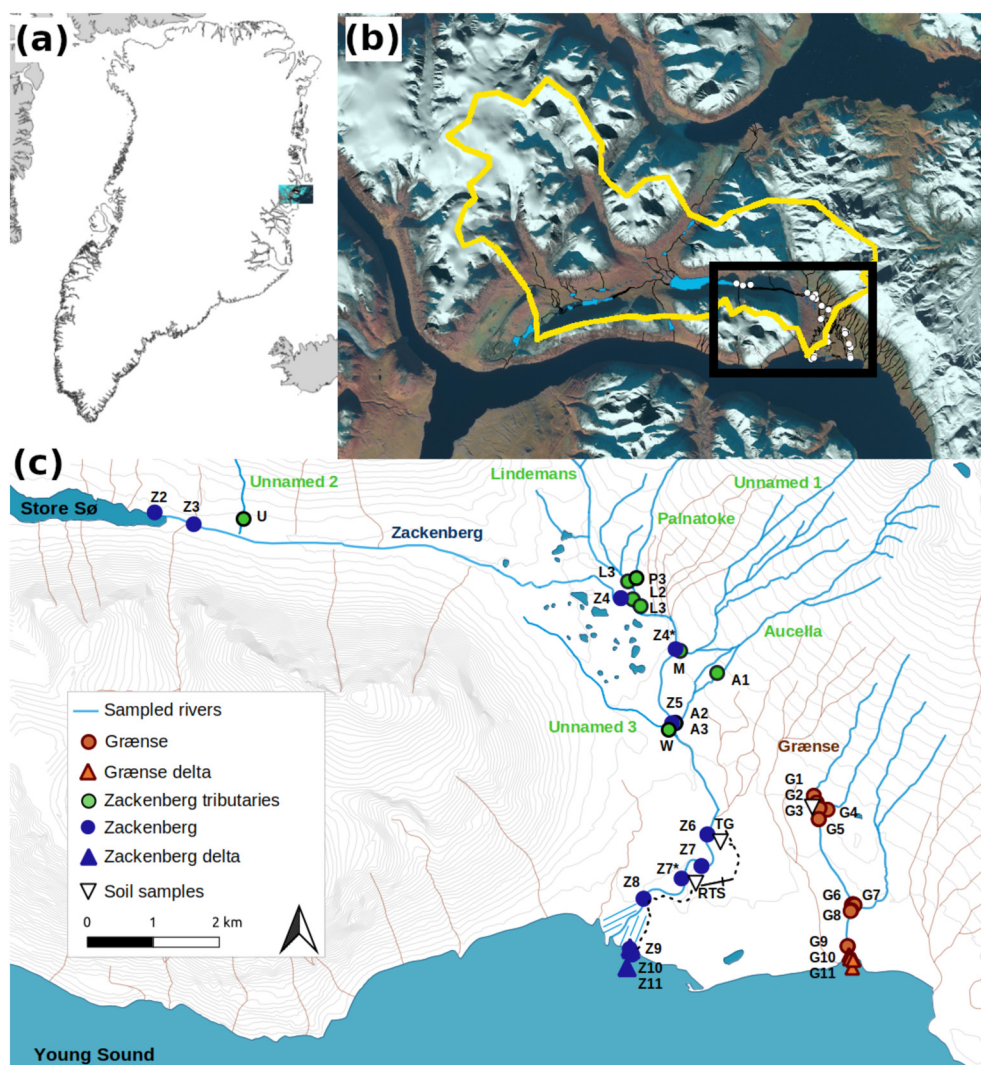


Figure 1. (a) Overview of the location of the study area in Northeast Greenland. (b) Approximate extension of Zackenberg watershed outlined in yellow (according to Hasholt et al. (2008); aerial photograph from Sentinel-2, European Space Agency). (c) Sampling sites for suspended sediments from rivers and marine-influenced deltas are indicated by circles and triangles, respectively (blue for Zackenberg, green for tributaries, and brown for Grænse). Additional soil and sediment sampling sites within a thermo-erosion gully (TG), a retrogressive thaw slump (RTS) and along the eroding Grænse stream bank are marked with white triangles.

Sound (Figure 1). During dry periods, it discharges $<10^{-3} \text{ m}^3 \text{ s}^{-1}$, yet after a rain storm, Docherty et al. (2018) measured up to $\sim 0.19 \text{ m}^3 \text{ s}^{-1}$.

3. Materials and Methods

We collected 68 river surface water samples for suspended sediment analyses (20 from Zackenberg mainstem; 18 from six separate Zackenberg tributaries, namely Aucella, Palnatoke, Lindemans, and three unnamed streams; and 30 from the Grænse headwater complex, Figure 1) between 15 and 31 August 2019. For Grænse stream, samples were collected during low and high flow conditions following an intense precipitation event (see Text S1.1, Figure S1, and Table S1 in Supporting Information S1). Those different periods will in the following be classified as “dry” and “wet” conditions.

In addition to the suspended sediment samples, we collected deposited sediments from the glacial lake (Store Sø), Zackenberg river delta, and from Grænse stream at the most upstream and downstream sampling locations,

as well as in the vicinity of an eroding stream bank (total river deposit samples $n = 5$). Furthermore, we sampled the outflow of a recently formed retrogressive thaw slump (RTS, $n = 8$) and a thermo-erosional gully along the Zackenberg river (TG, $n = 3$). For comparison, we also collected topsoil ($n = 3$) and subsoil ($n = 10$) samples that were exposed in these abrupt permafrost thaw features (RTS and TG) and along the Grønsø stream bank (Figure 1 and Table S4 in Supporting Information S1). The deepest soil layer sampled in TG (at ~ 100 cm depth) was frozen at the time of sampling and is denoted as “upper permafrost layer” since maximum thaw depths had already been reached during the sampling period (GEM database, GeoBasis Zackenberg, Soil properties).

For a detailed description of the laboratory procedures to analyze OC concentrations, stable and radiocarbon isotopes, mineralogy, grain size distributions, mineral surface area, and the fractionation of soil and sediment samples, we refer to Texts S1.2–S1.5 in Supporting Information S1.

4. Results and Discussion

4.1. Variability in the Concentrations of Suspended Sediment and POC in Streams

TSS concentrations in streams varied over almost four orders of magnitude (Figure 2a and Tables S2 and S3 in Supporting Information S1). While TSS concentrations for the Zackenberg river mainstem displayed relatively little variation with values between 80 and 160 mg L⁻¹, the glacial lake Store Sø showed a higher value of 350 mg L⁻¹ (Figure S4 in Supporting Information S1). Zackenberg tributaries ranged from 0.96 to 99 mg L⁻¹ with one unnamed stream (M) having an exceptionally high TSS load of 1,300 mg L⁻¹. Grønsø stream had TSS concentrations between 0.5 and 29 mg L⁻¹ during low flow, which significantly increased to values between 6 and 1,700 mg L⁻¹ after a 26 mm rain event. These values agree well with earlier reports for Zackenberg (GEM database, GeoBasis Zackenberg, Hydrology) and Grønsø (Docherty et al., 2018). The POC concentrations tracked TSS (Figure 2b): values for Zackenberg mainstem were relatively consistent between 0.3 and 0.9 mg L⁻¹, with a higher value of 2.1 mg L⁻¹ close to the outflow of the RTS. POC concentrations in Zackenberg tributaries ranged from 0.03 to 21 mg L⁻¹. For Grønsø stream, POC concentrations were between 0.07 and 0.27 mg L⁻¹ (average of 0.23 mg L⁻¹, $n = 19$) for low flow and increased to values between 0.24 and 28 mg L⁻¹ (average of 8.5 mg L⁻¹, $n = 10$) with elevated discharge after the rain event. Sediment and POC export from the headwater stream complex are thus disproportionally driven by precipitation events, the latter increasing by several orders of magnitude. Larger systems, such as the glacial Zackenberg river are less responsive to single rain events, yet due to its much higher discharge, glacial outflow dominates the overall sediment and POC delivery to Young Sound. POC concentrations for Zackenberg river fall within the lower range of reported values for glacial rivers in central Greenland (Bhatia et al., 2013), but are within the same range as POC concentrations recorded for runoff from the Leverett Glacier in southwestern Greenland (Kohler et al., 2017), glacial and nonglacial streams in southeast Alaska (Hood et al., 2020), and a glacial river in Svalbard (Zhu et al., 2016). The POC concentrations in nonglacial streams were similar to reported values for permafrost landscapes affected by (thermo-)erosion (Keskitalo et al., 2021; Lamoureux & Lafrenière, 2014; Shakil et al., 2020).

4.2. Organic Carbon Content and Composition of Suspended Sediments, River Deposits and Soil Samples

To allow for comparison with sediments and soils, we also report the carbon content in suspended particulates (POC%, Figure 2c). These values were highest for Grønsø stream during dry conditions, varying between 1.5% and 11%, and decreased to values between 0.01% and 1.7% after rainfall. The elevated values during warm, dry periods indicate in-stream production of organic matter, whereas export of eroded soils and rock-derived OC predominates during high discharge, as indicated by the carbon isotopic composition of these samples (see discussion below). Zackenberg mainstem had POC% ranging from 0.25% to 0.74% and Zackenberg tributaries from <0.01 to 3.0%. POC% for Zackenberg are similar to values reported for a glacial river in Svalbard (0.25%–0.48%, Zhu et al., 2016).

Bulk OC concentrations for river sediment deposits from Grønsø stream varied between 0.39% and 1.5%, while Store Sø and Zackenberg river sediments had 0.38% and 0.21% OC, respectively (Figure 2d). These values are similar to outflow from the RTS (0.34%–0.99%, and one outlier of 2.2%). Values for TG sediments were generally higher (4.6%–6.5%), while subsoil samples ranged between 0.31% and 8.9%, where the lowest value was found for the uppermost permafrost layer sampled in TG. As expected, topsoils had the highest OC concentrations of

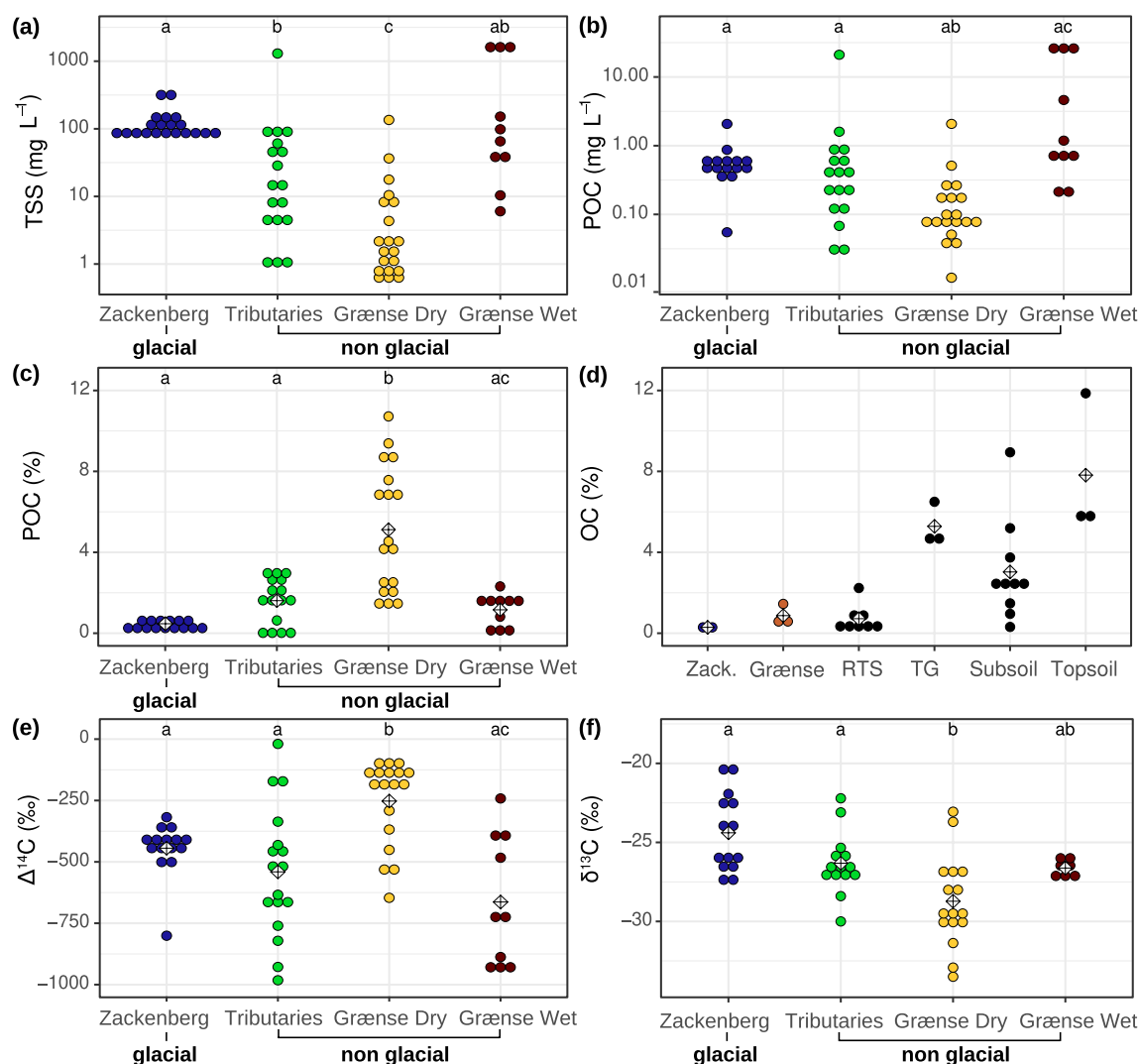


Figure 2. (a, b) Concentrations of Total Suspended Solids and particulate organic carbon (POC) for Zackenberg (blue), its tributaries (green) and Grøense during low (yellow, “dry”) and high flow conditions (brown, “wet”). (c) POC% for suspended sediments. (d) OC% for river deposits of Grøense and Zackenberg, as well as of the outflow of a retrogressive thaw slump (RTS) and a thermo-erosional gully (TG), and topsoil and subsoil samples from RTS, TG, and Grøense stream bank. (e, f) Radiocarbon ($\Delta^{14}\text{C}$) and stable carbon isotopic composition ($\delta^{13}\text{C}$) of POC for Zackenberg, tributaries and Grøense (colors as for a and b). Open diamonds mark the mean value for each group of samples. Letters indicate significant differences between rivers and the different hydrological periods of Grøense indicated by Mann-Whitney-Wilcoxon test ($p < 0.01$).

5.7%–12%. These overall patterns agree with earlier results from Cable et al. (2017) and Palmtag et al. (2018), which reported much higher soil OC stocks for the alluvial sediments of the valley compared to the overall low values for the western, upstream part of the Zackenberg catchment. The RTS is located within the paleodelta and exports deeper layers of sediments with lower OC%. Deposited sediments from Grøense and Zackenberg displayed similar bulk C/N ratios, ranging from 10.3 to 17.0 (Table S6 in Supporting Information S1). These values are also comparable to RTS and TG sediments, which had C/N ratios between 12.2 and 17.2. Bulk C/N ratios of soil samples decreased with depth, from 13.5 in topsoil to 9.8 in subsoil layers (Table S5 in Supporting Information S1). This pattern likely illustrates a greater contribution of microbial necromass, as well as root exudates to the bulk soil organic matter in deeper layers (Angst et al., 2018).

Topsoil samples contained relatively “modern” OC with radiocarbon ($\Delta^{14}\text{C}$) values of -63 to -37‰ (corresponding to uncalibrated radiocarbon ages of 460–240 years), while subsoil samples covered a broad range of $\Delta^{14}\text{C}$ values, from -847 to -222‰ (15,000–1,950 ^{14}C years, Table S5 in Supporting Information S1). The older ages for the deep soil OC reflect initial terrestrial biomass production after the deglaciation in the deltaic

and alluvial environments (Gilbert et al., 2017), preceding permafrost aggradation (Cable et al., 2017). Outflow OC from the RTS was generally very depleted in ^{14}C , with $\Delta^{14}\text{C}$ values ranging between -960 and -771‰ (25,800–11,800 years), compared to the less ^{14}C -depleted deposits within the TG ($\Delta^{14}\text{C}$ of -447 to -423‰).

POC samples from Zackenberg river tributaries covered the entire spectrum of $\Delta^{14}\text{C}$ values, from “modern” ($\sim -20\text{‰}$) to close to “radiocarbon-dead” ($\sim -980\text{‰}$) (Figure 2e, Figure S3 and Table S2 in Supporting Information S1). In contrast, POC from Zackenberg mainstem exhibited more invariant $\Delta^{14}\text{C}$ values, ranging between -514 and -318‰ . These ^{14}C ages (5,700–3,000 years) likely reflect the composite of OC inputs from different sources and ages, yet the overall interval corresponds to the Holocene thermal maximum in eastern Greenland (Briner et al., 2016), an interval when the Greenland icecap and the A.P. Olsen glacier are thought to have retreated, allowing for plant and soil development in locations currently covered by glaciers (Bhatia et al., 2013). We therefore suggest that Zackenberg river, fed mainly by subglacial flow from the A.P. Olsen glacier, currently exports POC comprising a mixture of aged soil organic matter, in-glacier necromass from present and past production (i.e., bacteria, ice algae) and deposited organic aerosols (Bhatia et al., 2013). In contrast, close to the outflow of the RTS, POC was significantly more depleted in ^{14}C ($\sim -800\text{‰}$, corresponding to 12,900 years, Figure S4 in Supporting Information S1). Grønsø stream again was more variable (Figure 2e, Figure S3 in Supporting Information S1): during dry periods, POC $\Delta^{14}\text{C}$ values ranged between -291 and -86‰ , with more depleted values of -646 to -528‰ close to the eroding stream bank; yet after the rain event, POC $\Delta^{14}\text{C}$ shifted to significantly lower values (-931 to -376‰), with lowest (most ^{14}C -depleted) values upstream (Figure S4 in Supporting Information S1).

For deposited river sediments, a similar trend was observed for Grønsø stream: upstream deposits were more depleted in ^{14}C ($\Delta^{14}\text{C}$ between -782 and -895‰), with the lowest $\Delta^{14}\text{C}$ value close to the eroding river bank, while downstream delta sediments had a $\Delta^{14}\text{C}$ value of -421‰ , potentially reflecting input of younger marine OC. In contrast, for Zackenberg, $\Delta^{14}\text{C}$ values decreased from -132‰ for Store Sø sediments to -701‰ for Zackenberg delta sediments, which could reflect the influence of old carbon from some of the tributaries and/or from point sources such as the RTS.

The fact that many of the smaller streams carried POC with radiocarbon ages that by far predate the assumed deglaciation of Zackenberg valley around 13,000–11,000 years ago, implies that in addition to the plant and soil OC, a radiocarbon-depleted OC source contributed to the overall POC export. In other permafrost environments, for example, in Siberia and Alaska, the lack of glacial cover during the late Pleistocene promoted the formation of so-called Yedoma, organic- and ice-rich aeolian deposits, which upon thaw release largely radiocarbon-free (i.e., “radiocarbon-dead”) OC (Schirrmeister et al., 2013). However, as Yedoma deposits are absent in Greenland, another ancient OC pool, that is presumably petrogenic in origin (given the prevalence of sedimentary rocks, including black shales, in the eastern part of the study area (Cable et al., 2017)), must exist. Destabilization of soils by permafrost thaw as observed along the Grønsø stream bank facilitates the erosion of deeper OC stocks and may thereby promote export of petrogenic OC. This assumption is also supported by the significant decrease in POC% for Grønsø, along with the increase in radiocarbon ages during high flow, which suggests dilution with OC-poor sediments.

Stable carbon isotope ($\delta^{13}\text{C}$) values for POC were between -33.5 and -22.2‰ and were similar for Zackenberg and its tributaries, yet significantly different for Grønsø during low flow (Figure 2f). Notably, the most ^{13}C -depleted values occurred here, providing further evidence for localized in-stream production (Shakil et al., 2020). In contrast, after the rain event, $\delta^{13}\text{C}$ values were much less variable (between -27.2 and -25.9‰), suggesting a large contribution from a single, relatively homogenous OC source (Figure 3b). Stable carbon isotope values for deposited river sediments all fell within a relatively narrow range between -25.2 and -24.5‰ , whereas RTS outflow was more variable with values between -25.3 and -22.0‰ (Figure 3). Deposits in TG were more depleted in ^{13}C (-27.8 to -27.2‰) and very similar to topsoil samples (-27.7 to -27.0‰), in agreement with commonly found ranges for C3 plants. Subsoil samples ranged between -28.5 and -24.4‰ with an overall trend of higher $\delta^{13}\text{C}$ values with decreasing $\Delta^{14}\text{C}$ values, consistent with a larger extent of microbial processing in deeper soil layers (Dijkstra et al., 2006). Alternatively, this pattern could be explained with the deposition (and subsequent preservation) of marine OC from when this area of the valley was first inundated upon deglaciation or deltaic deposits (Christiansen et al., 2002; Gilbert et al., 2017). This would fit to the relatively high $\delta^{13}\text{C}$ and low C/N ratios for the sediments, yet as for many POC samples, the very depleted $\Delta^{14}\text{C}$ values indicate OC ages beyond the suggested timing for the deglaciation of the valley, possibly due to the presence of petrogenic OC

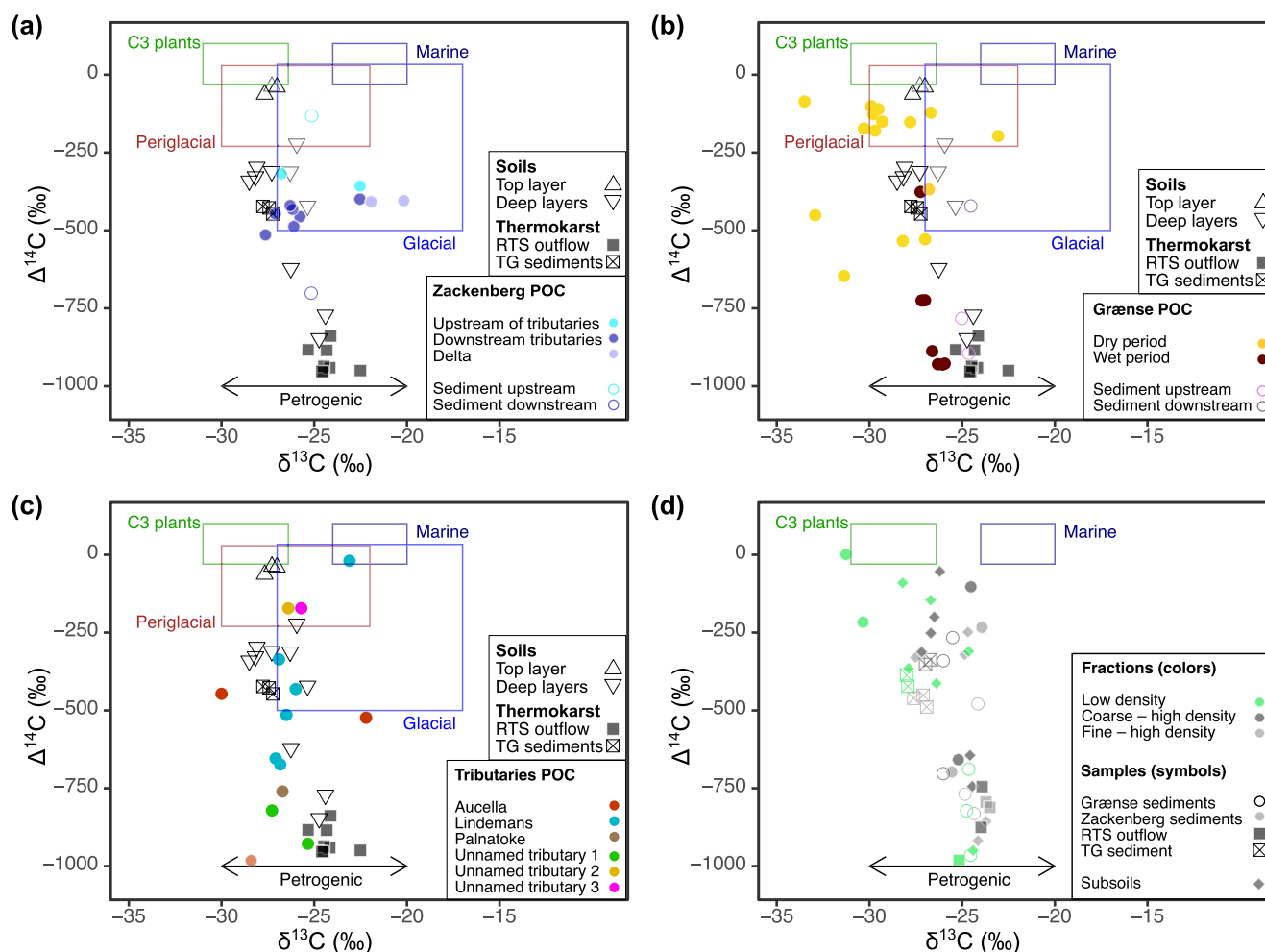


Figure 3. Carbon isotope characteristics $\Delta^{14}\text{C}$ and $\delta^{13}\text{C}$ for (a) Zackenberg mainstem particulate organic carbon (POC), (b) Grænse headwater stream complex POC, (c) Zackenberg tributary POC, and (d) fractionated soil and sediment samples. For (a–c), open symbols represent bulk soil and sediment samples from this study, while boxes denote common end members based on earlier studies: Periglacial and glacial POC values are from Bhatia et al. (2013) and Csank et al. (2019), C3 plants and Petrogenic organic carbon (OC) from Hilton et al. (2015) and Arctic Ocean Marine OC from Vonk et al. (2012).

(see also Figure 3). The comparison with the carbon isotope characteristics of POC samples from earlier studies on Greenlandic glacial and periglacial streams (Bhatia et al., 2013; Csank et al., 2019) shows some overlap (Figure 3); Zackenberg mainstem POC falls mostly within the range for glacial rivers described earlier as a mixture of soil deposits from the early Holocene thermal maximum (Bhatia et al., 2013), yet toward the lower end of the range for both $\Delta^{14}\text{C}$ and $\delta^{13}\text{C}$ values (Figure 3a). POC in our periglacial stream sample set (Grænse stream and Zackenberg tributaries), was significantly older than for any of the earlier studies, especially for Grænse after the rain event as well as Aucella and the unnamed stream with high TSS and POC concentrations (labeled M in Figure 1), where carbon isotopic signatures approach values reported for a petrogenic end member (Figures 3b and 3c, Table S2 in Supporting Information S1). However, further analyses are needed to unambiguously identify a petrogenic POC source.

4.3. Soil and Suspended Sediment Mineralogy, Density and Size Fractionation: Implications for Organo-Mineral Interactions and Reactivity

Density fractions indicated that for subsoils, TG deposits, RTS outflow, and deposited river sediments, the vast majority of the OC was associated with minerals (i.e., resided in the high-density fraction, HD): >75% for all but downstream sediments from both Grænse stream and Zackenberg river delta, where the low-density (LD) fraction contributed 28% and 36% of the OC, respectively (Table S5 in Supporting Information S1). An additional grain

size separation of the HD fraction resulted in a fine (HDF, <63 μm) fraction and a coarse (HDC, >63 μm) fraction, accounting for 21%–87% and 7%–69% of the OC, respectively. The carbon isotope analyses of the different fractions showed contrasting patterns (Figure 3d). While $\Delta^{14}\text{C}$ values of the different fractions were generally similar to those for the bulk OC (displayed in Figures 3a–3c) with no systematic differences between the fractions for subsoil layers, TG and the Zackenberg river sediment, $\Delta^{14}\text{C}$ values of the LD fractions in RTS outflow and Grønsø sediments were unexpectedly more depleted than their respective HD fractions (Table S6 in Supporting Information S1). These results oppose the general expectation of higher $\Delta^{14}\text{C}$ values (younger age) for LD than for the bulk or the corresponding HD fractions caused by a greater contribution of modern plant residues and a higher OC turnover in the LD fraction (Poeplau et al., 2018; von Lützow et al., 2007). The low $\Delta^{14}\text{C}$ values support the contribution of petrogenic OC from OC-rich shales in some of these LD fractions. Alternatively, fossil fuel-derived black carbon from atmospheric deposition could be another contributing factor to cause such low ^{14}C values (Winiger et al., 2019).

For the suspended sediments, the relatively low POC% (well below 3% for all but Grønsø stream during dry periods) indicates that “free” plant debris makes up a minor component of the overall POC, similar to subsoil samples and deposited river sediments. Diffractograms indicate the presence of quartz, plagioclase, mica (muscovite) in all soil and suspended sediment samples (Table S7 in Supporting Information S1). Notably, the soils and suspended sediments contain aluminosilicates including kaolinite, vermiculite and illite, secondary clay minerals that have previously shown to efficiently bind OC in a marine setting (Blattmann et al., 2019). The availability of these minerals throughout the study area implies that there is capacity for mineral associations to stabilize OC, protecting it from mineralization to CO_2 or CH_4 . In turn, a potential rapid burial in Young Sound sediment would entail that ancient, possibly petrogenic OC is translocated to another long-term reservoir rather than constituting a carbon source to the atmosphere. This would be contrary to findings for mountain glaciers in New Zealand, where the erosion of sedimentary rocks resulted in enhanced oxidation of petrogenic OC (Horan et al., 2017).

5. Conclusions

Suspended sediments carried by a larger glacial river, the Zackenberg river, were relatively organic-poor and did not exhibit much spatial or temporal variation in their OC composition. In contrast, smaller periglacial streams in the area were highly variable in sediment and OC concentration and responded rapidly to precipitation events, with an accompanying shift in the composition of the exported material. Soils and deposited river sediments throughout the study area contained a large proportion of mineral-associated OC. Secondary clay minerals were present also in the suspended load, suggesting a high potential for mineral stabilization of exported OC. With ongoing Arctic warming, enhancing glacial melt and permafrost thaw, as well as an increase in rain-dominated precipitation, glacial and periglacial streams are expected to experience rising water discharge with anticipated higher sediment loads as channel stability decreases. Here, we have shown that this may also lead to increased mobilization of ancient, potentially petrogenic OC from deeper soil layers in both systems. However, the close mineral association of OC with available mineral surfaces in both soils and fluvial sediments may prevent rapid decomposition and instead promote efficient reburial in the marine environment, potentially resulting in minor feedbacks to climate.

Data Availability Statement

All data used in this article are available in Tables S1–S7 in Supporting Information S1 and via the ETH Zürich Research Collection: <https://doi.org/10.3929/ethz-b-000575653>.

References

- Abbott, B. W., Larouche, J. R., Jones, J. B., Bowden, W. B., & Balser, A. W. (2014). Elevated dissolved organic carbon biodegradability from thawing and collapsing permafrost. *Journal of Geophysical Research: Biogeosciences*, 119(10), 2049–2063. <https://doi.org/10.1002/2014JG002678>
- Angst, G., Messinger, J., Greiner, M., Häusler, W., Hertel, D., Kirfel, K., et al. (2018). Soil organic carbon stocks in topsoil and subsoil controlled by parent material, carbon input in the rhizosphere, and microbial-derived compounds. *Soil Biology and Biochemistry*, 122, 19–30. <https://doi.org/10.1016/j.soilbio.2018.03.026>
- Arrigo, K. R., Dijk, G. L., Castella, R. M., Luo, H., Rennermalm, Å. K., Tedesco, M., et al. (2017). Melting glaciers stimulate large summer phytoplankton blooms in southwest Greenland waters. *Geophysical Research Letters*, 44(12), 6278–6285. <https://doi.org/10.1002/2017GL073583>
- Ballantyne, C. K. (2002). Paraglacial geomorphology. *Quaternary Science Reviews*, 21(18–19), 1935–2017. [https://doi.org/10.1016/S0277-3791\(02\)00005-7](https://doi.org/10.1016/S0277-3791(02)00005-7)

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- Bennike, O., Sørensen, M., Fredskild, B., Jacobsen, B. H., Böcher, J., Amsinck, S. L., et al. (2008). Late quaternary environmental and cultural changes in the Wollaston Forland region, Northeast Greenland. In *Advances in Ecological Research*, (Vol. 40, pp. 45–79). Elsevier. [https://doi.org/10.1016/S0065-2504\(07\)00003-7](https://doi.org/10.1016/S0065-2504(07)00003-7)
- Bhatia, M. P., Das, S. B., Xu, L., Charette, M. A., Wadham, J. L., & Kujawinski, E. B. (2013). Organic carbon export from the Greenland ice sheet. *Geochimica et Cosmochimica Acta*, 109, 329–344. <https://doi.org/10.1016/j.gca.2013.02.006>
- Bintanja, R., & Andry, O. (2017). Towards a rain-dominated Arctic. *Nature Climate Change*, 7(4), 263–267. <https://doi.org/10.1038/nclimate3240>
- Blattmann, T. M., Liu, Z., Zhang, Y., Zhao, Y., Haghipour, N., Montluçon, D. B., et al. (2019). Mineralogical control on the fate of continentally derived organic matter in the ocean. *Science*, 366(6466), 742–745. <https://doi.org/10.1126/science.aax5345>
- Briner, J. P., McKay, N. P., Axford, Y., Bennike, O., Bradley, R. S., de Vernal, A., et al. (2016). Holocene climate change in Arctic Canada and Greenland. *Quaternary Science Reviews*, 147, 340–364. <https://doi.org/10.1016/j.quascirev.2016.02.010>
- Bröder, L., Andersson, A., Tesi, T., Semiletov, I., & Gustafsson, Ö. (2019). Quantifying degradative loss of terrigenous organic carbon in surface sediments across the Laptev and East Siberian Sea. *Global Biogeochemical Cycles*, 33(1), 85–99. <https://doi.org/10.1029/2018GB005967>
- Bröder, L., Keskitalo, K., Zolkos, S., Shakil, S., Tank, S. E., Kokelj, S. V., et al. (2021). Preferential export of permafrost-derived organic matter as retrogressive thaw slumping intensifies. *Environmental Research Letters*, 16(5), 054059. <https://doi.org/10.1088/1748-9326/abee4b>
- Bröder, L., Tesi, T., Andersson, A., Semiletov, I., & Gustafsson, Ö. (2018). Bounding cross-shelf transport time and degradation in Siberian-Arctic land-ocean carbon transfer. *Nature Communications*, 9(1), 806. <https://doi.org/10.1038/s41467-018-03192-1>
- Cable, S., Christiansen, H. H., Westergaard-Nielsen, A., Kroon, A., & Elberling, B. (2017). Geomorphological and cryostratigraphical analyses of the Zackenberg Valley, NE Greenland and significance of Holocene alluvial fans. *Geomorphology*, 303, 504–523. <https://doi.org/10.1016/j.geomorph.2017.11.003>
- Christensen, T. R., Arndal, M. F., & Topp-Jørgensen, E. (2020). *Greenland ecosystem monitoring annual report cards 2019* (p. 40). Aarhus University, DCE—Danish Centre for Environment and Energy.
- Christiansen, H. H., Bennike, O., Böcher, J., Elberling, B., Humlum, O., & Jakobsen, B. H. (2002). Holocene environmental reconstruction from deltaic deposits in Northeast Greenland: Holocene of northeast Greenland. *Journal of Quaternary Science*, 17(2), 145–160. <https://doi.org/10.1002/jqs.665>
- Csank, A. Z., Czimczik, C. I., Xu, X., & Welker, J. M. (2019). Seasonal patterns of riverine carbon sources and export in NW Greenland. *Journal of Geophysical Research: Biogeosciences*, 124(4), 840–856. <https://doi.org/10.1029/2018JG004895>
- Dijkstra, P., Ishizu, A., Doucet, R., Hart, S. C., Schwartz, E., Menyailo, O. V., & Hungate, B. A. (2006). ¹³C and ¹⁵N natural abundance of the soil microbial biomass. *Soil Biology and Biochemistry*, 38(11), 3257–3266. <https://doi.org/10.1016/j.soilbio.2006.04.005>
- Docherty, C. L., Riis, T., Hannah, D. M., Rosenhøj Leth, S., & Milner, A. M. (2018). Nutrient uptake controls and limitation dynamics in north-east Greenland streams. *Polar Research*, 37(1), 1440107. <https://doi.org/10.1080/17518369.2018.1440107>
- Doetterl, S., Berhe, A. A., Nadeu, E., Wang, Z., Sommer, M., & Fiener, P. (2016). Erosion, deposition and soil carbon: A review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes. *Earth-Science Reviews*, 154, 102–122. <https://doi.org/10.1016/j.earscirev.2015.12.005>
- Drake, T. W., Guillemette, F., Hemingway, J. D., Chanton, J. P., Podgorski, D. C., Zimov, N. S., & Spencer, R. G. M. (2018). The ephemeral signature of permafrost carbon in an Arctic fluvial network. *Journal of Geophysical Research: Biogeosciences*, 123(5), 1475–1485. <https://doi.org/10.1029/2017JG004311>
- Drake, T. W., Wickland, K. P., Spencer, R. G. M., McKnight, D. M., & Striegl, R. G. (2015). Ancient low-molecular-weight organic acids in permafrost fuel rapid carbon dioxide production upon thaw. *Proceedings of the National Academy of Sciences of the United States of America*, 112(45), 13946–13951. <https://doi.org/10.1073/pnas.1511705112>
- García-Oteyza, J., Oliva, M., Palacios, D., Fernández-Fernández, J. M., Schimmelpfennig, I., Andrés, N., et al. (2022). Late glacial deglaciation of the Zackenberg area, NE Greenland. *Geomorphology*, 401, 108125. <https://doi.org/10.1016/j.geomorph.2022.108125>
- Gilbert, G. L., Cable, S., Thiel, C., Christiansen, H. H., & Elberling, B. (2017). Cryostratigraphy, sedimentology, and the late Quaternary evolution of the Zackenberg River delta, northeast Greenland. *The Cryosphere*, 11(3), 1265–1282. <https://doi.org/10.5194/tc-11-1265-2017>
- Hasholt, B., & Hagedorn, B. (2000). Hydrology and geochemistry of river-borne material in a high Arctic drainage system, Zackenberg, Northeast Greenland. *Arctic Antarctic and Alpine Research*, 32(1), 84–94. <https://doi.org/10.2307/1552413>
- Hasholt, B., Mernild, S. H., Sigsgaard, C., Elberling, B., Petersen, D., Jakobsen, B. H., et al. (2008). Hydrology and transport of sediment and solutes at Zackenberg. In *Advances in Ecological Research*, (Vol. 40, pp. 197–221). Elsevier. [https://doi.org/10.1016/S0065-2504\(07\)00009-8](https://doi.org/10.1016/S0065-2504(07)00009-8)
- Hawkings, J. R., Wadham, J. L., Tranter, M., Lawson, E., Sole, A., Cowton, T., et al. (2015). The effect of warming climate on nutrient and solute export from the Greenland Ice Sheet. *Geochimica et Cosmochimica Acta*, 151, 94–104. <https://doi.org/10.1016/j.gca.2015.07.010>
- Hemingway, J. D., Hilton, R. G., Hovius, N., Eglinton, T. I., Haghipour, N., Wacker, L., et al. (2018). Microbial oxidation of lithospheric organic carbon in rapidly eroding tropical mountain soils. *Science*, 360(6385), 209–212. <https://doi.org/10.1126/science.aao6463>
- Hemingway, J. D., Rothman, D. H., Grant, K. E., Rosengard, S. Z., Eglinton, T. I., Derry, L. A., & Galy, V. V. (2019). Mineral protection regulates long-term global preservation of natural organic carbon. *Nature*, 570(7760), 228–231. <https://doi.org/10.1038/s41586-019-1280-6>
- Hilton, R. G., Galy, V., Gaillardet, J., Dellinger, M., Bryant, C., O'Regan, M., et al. (2015). Erosion of organic carbon in the Arctic as a geological carbon dioxide sink. *Nature*, 524(7563), 84–87. <https://doi.org/10.1038/nature14653>
- Hirst, C., Mauclet, E., Monhonval, A., Tihon, E., Ledman, J., Schuur, E. A. G., & Opfergelt, S. (2022). Seasonal changes in Hydrology and permafrost degradation control mineral element-bound DOC transport from permafrost soils to streams. *Global Biogeochemical Cycles*, 36(2), e2021GB007105. <https://doi.org/10.1029/2021GB007105>
- Hobbie, S. E., Schimel, J. P., Trumbore, S. E., & Randerson, J. R. (2000). Controls over carbon storage and turnover in high-latitude soils. *Global Change Biology*, 6(S1), 196–210. <https://doi.org/10.1046/j.1365-2486.2000.06021.x>
- Holding, J. M., Markager, S., Juul-Pedersen, T., Paulsen, M. L., Møller, E. F., Meire, L., & Sejr, M. K. (2019). Seasonal and spatial patterns of primary production in a high-latitude fjord affected by Greenland Ice Sheet run-off. *Biogeosciences*, 16(19), 3777–3792. <https://doi.org/10.5194/bg-16-3777-2019>
- Hood, E., Fellman, J. B., & Spencer, R. G. M. (2020). Glacier loss impacts riverine organic carbon transport to the ocean. *Geophysical Research Letters*, 47(19), e2020GL089804. <https://doi.org/10.1029/2020GL089804>
- Hopwood, M. J., Carroll, D., Dunse, T., Hodson, A., Holding, J. M., Iriarte, J. L., et al. (2020). Review article: How does glacier discharge affect marine biogeochemistry and primary production in the Arctic? *The Cryosphere*, 14(4), 1347–1383. <https://doi.org/10.5194/tc-14-1347-2020>
- Horan, K., Hilton, R. G., Selby, D., Ottley, C. J., Gröcke, D. R., Hicks, M., & Burton, K. W. (2017). Mountain glaciation drives rapid oxidation of rock-bound organic carbon. *Science Advances*, 3(10), e1701107. <https://doi.org/10.1126/sciadv.1701107>
- Hovius, N., Galy, A., Hilton, R. G., Sparkes, R., Smith, J., Shuh-Ji, K., et al. (2011). Erosion-driven drawdown of atmospheric carbon dioxide: The organic pathway. *Applied Geochemistry*, 26, S285–S287. <https://doi.org/10.1016/j.apgeochem.2011.03.082>

- Hugelius, G., Loisel, J., Chadburn, S., Jackson, R. B., Jones, M., MacDonald, G., et al. (2020). Large stocks of peatland carbon and nitrogen are vulnerable to permafrost thaw. *Proceedings of the National Academy of Sciences of the United States of America*, 117(34), 20438–20446. <https://doi.org/10.1073/pnas.1916387117>
- Keil, R. G., & Mayer, L. M. (2014). Mineral matrices and organic matter. In *Treatise on Geochemistry*, 2nd ed., (Vol. 12, pp. 337–359). Elsevier. <https://doi.org/10.1016/B978-0-08-095975-7.01024-X>
- Keskitalo, K. H., Bröder, L., Shakil, S., Zolkos, S., Tank, S. E., van Dongen, B. E., et al. (2021). Downstream evolution of particulate organic matter composition from permafrost thaw slumps. *Frontiers of Earth Science*, 9, 642675. <https://doi.org/10.3389/feart.2021.642675>
- Koch, L., & Haller, J. (1971). Geological map of east Greenland 72°–76°N. lat. (1: 250,000).
- Kohler, T. J., Žárský, J. D., Yde, J. C., Lamarche-Gagnon, G., Hawkings, J. R., Tedstone, A. J., et al. (2017). Carbon dating reveals a seasonal progression in the source of particulate organic carbon exported from the Greenland Ice Sheet. *Geophysical Research Letters*, 44(12), 6209–6217. <https://doi.org/10.1002/2017GL073219>
- Lamoureux, S. F., & Lafrenière, M. J. (2014). Seasonal fluxes and age of particulate organic carbon exported from Arctic catchments impacted by localized permafrost slope disturbances. *Environmental Research Letters*, 9(4), 045002. <https://doi.org/10.1088/1748-9326/9/4/045002>
- Meire, L., Meire, P., Struyf, E., Krawczyk, D. W., Arendt, K. E., Yde, J. C., et al. (2016). High export of dissolved silica from the Greenland Ice Sheet: Silica export the ice sheet. *Geophysical Research Letters*, 43(17), 9173–9182. <https://doi.org/10.1002/2016GL070191>
- Meire, L., Mortensen, J., Meire, P., Juul-Pedersen, T., Sejr, M. K., Rysgaard, S., et al. (2017). Marine-terminating glaciers sustain high productivity in Greenland fjords. *Global Change Biology*, 23(12), 5344–5357. <https://doi.org/10.1111/gcb.13801>
- Olefelt, D., Goswami, S., Grosse, G., Hayes, D., Hugelius, G., Kuhry, P., et al. (2016). Circumpolar distribution and carbon storage of thermokarst landscapes. *Nature Communications*, 7(1), 13043. <https://doi.org/10.1038/ncomms13043>
- Opfergelt, S. (2020). The next generation of climate model should account for the evolution of mineral-organic interactions with permafrost thaw. *Environmental Research Letters*, 15(9), 091003. <https://doi.org/10.1088/1748-9326/ab9a6d>
- Palmtag, J., Cable, S., Christiansen, H. H., Hugelius, G., & Kuhry, P. (2018). Landform partitioning and estimates of deep storage of soil organic matter in Zackenberg, Greenland. *The Cryosphere*, 12(5), 1735–1744. <https://doi.org/10.5194/tc-12-1735-2018>
- Poeplau, C., Don, A., Six, J., Kaiser, M., Benbi, D., Chenu, C., et al. (2018). Isolating organic carbon fractions with varying turnover rates in temperate agricultural soils—A comprehensive method comparison. *Soil Biology and Biochemistry*, 125, 10–26. <https://doi.org/10.1016/j.soilbio.2018.06.025>
- Schirmermeister, L., Froese, D., Tumskey, V., Grosse, G., & Wetterich, S. (2013). Yedoma: Late Pleistocene ice-rich syngenetic permafrost of Beringia. In *Encyclopedia of quaternary science*, 2nd ed., (Vol. 3, pp. 542–552). Elsevier, 3888.
- Schmidt, M. W. I., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. A., et al. (2011). Persistence of soil organic matter as an ecosystem property. *Nature*, 478(7367), 49–56. <https://doi.org/10.1038/nature10386>
- Shakil, S., Tank, S. E., Kokelj, S. V., Vonk, J. E., & Zolkos, S. (2020). Particulate dominance of organic carbon mobilization from thaw slumps on the Peel Plateau, NT: Quantification and implications for stream systems and permafrost carbon release. *Environmental Research Letters*, 15(11), 114019. <https://doi.org/10.1088/1748-9326/abac36>
- The IMBIE Team. (2020). Mass balance of the Greenland Ice Sheet from 1992 to 2018. *Nature*, 579(7798), 233–239. <https://doi.org/10.1038/s41586-019-1855-2>
- Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A. G., et al. (2020). Carbon release through abrupt permafrost thaw. *Nature Geoscience*, 13(2), 138–143. <https://doi.org/10.1038/s41561-019-0526-0>
- von Lützow, M., Kögel-Knabner, I., Ekschmitt, K., Flessa, H., Guggenberger, G., Matzner, E., & Marschner, B. (2007). SOM fractionation methods: Relevance to functional pools and to stabilization mechanisms. *Soil Biology and Biochemistry*, 39(9), 2183–2207. <https://doi.org/10.1016/j.soilbio.2007.03.007>
- Vonk, J. E., Mann, P. J., Davydov, S., Davydova, A., Spencer, R. G. M., Schade, J., et al. (2013). High biolability of ancient permafrost carbon upon thaw. *Geophysical Research Letters*, 40(11), 2689–2693. <https://doi.org/10.1002/grl.50348>
- Vonk, J. E., Semiletov, I. P., Dudarev, O. V., Eglinton, T. I., Andersson, A., Shakhova, N., et al. (2014). Preferential burial of permafrost-derived organic carbon in Siberian-Arctic shelf waters. *Journal of Geophysical Research: Oceans*, 119(12), 8410–8421. <https://doi.org/10.1002/2014JC010261>
- Vonk, J. E., Sánchez-García, L., van Dongen, B. E., Alling, V., Kosmach, D., Charkin, A., et al. (2012). Activation of old carbon by erosion of coastal and subsea permafrost in Arctic Siberia. *Nature*, 489(7414), 137–140. <https://doi.org/10.1038/nature11392>
- Vonk, J. E., Van Dongen, B. E., & Gustafsson, Ö. (2010). Selective preservation of old organic carbon fluvially released from sub-Arctic soils. *Geophysical Research Letters*, 37(11), 5–9. <https://doi.org/10.1029/2010GL042909>
- Ward, N. D., Bianchi, T. S., Medeiros, P. M., Seidel, M., Richey, J. E., Keil, R. G., & Sawakuchi, H. O. (2017). Where carbon goes when water flows: Carbon cycling across the aquatic continuum. *Frontiers in Marine Science*, 4, 7. <https://doi.org/10.3389/fmars.2017.00007>
- Wild, B., Andersson, A., Bröder, L., Vonk, J., Hugelius, G., McClelland, J. W., et al. (2019). Rivers across the Siberian Arctic unearth the patterns of carbon release from thawing permafrost. *Proceedings of the National Academy of Sciences of the United States of America*, 116(21), 10280–10285. <https://doi.org/10.1073/pnas.1811797116>
- Winiger, P., Barrett, T. E., Sheesley, R. J., Huang, L., Sharma, S., Barrie, L. A., et al. (2019). Source apportionment of circum-Arctic atmospheric black carbon from isotopes and modeling. *Science Advances*, 5(2), eaau8052. <https://doi.org/10.1126/sciadv.aau8052>
- Zhu, Z.-Y., Wu, Y., Liu, S.-M., Wenger, F., Hu, J., Zhang, J., & Zhang, R.-F. (2016). Organic carbon flux and particulate organic matter composition in Arctic valley glaciers: Examples from the Bayelva River and adjacent Kongsfjorden. *Biogeosciences*, 13(4), 975–987. <https://doi.org/10.5194/bg-13-975-2016>
- Zolkos, S., Tank, S. E., & Kokelj, S. V. (2018). Mineral weathering and the permafrost carbon-climate feedback. *Geophysical Research Letters*, 45(1), 1–10. <https://doi.org/10.1029/2018GL078748>