

Organic carbon burial and sediment accumulation in the fjords of South Georgia, sub-Antarctic

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Abstract

Fjords are among the most efficient marine environments for trapping sediments and organic carbon (OC). They represent an important part of the global carbon cycle. Yet, quantitative data on OC burial rates are scarce in the Southern Hemisphere. Here, we present ²¹⁰Pb-derived sediment accumulation rates (SAR), OC burial rates, and sediment properties from 10 sediment cores collected in the fjords of South Georgia, the largest sub-Antarctic island: Antarctic Bay, Fortuna Bay, Stromness Bay, and Cumberland Bay. SARs range from 2.1 ± 0.4 to 14.9 ± 2.8 mm/yr, total organic carbon (TOC) from 0.28% to 2.1%, and modern OC burial rates from 17.4 ± 1.2 to 64.6 ± 12.1 gOC/m²/yr, placing them towards the upper range of values reported globally. High rates reflect large sediment supply from steep, glacierised catchments, intense precipitation, and relatively high primary productivity. A strong relationship between SAR and OC burial rate indicates sediment delivery as the primary control, with the highest modern OC burial rate at a glacier-proximal site combining the highest SAR and lowest TOC. Tidewater glacier-fed fjords show higher SAR and OC burial rates than river-dominated systems. However, the maximum recorded burial rate (95.9 ± 8.3 gOC/m²/yr) occurred in King Edward Cove during the early 20th century, driven by the whaling industry, while the modern value (55.5 ± 4.8) is about half. These results suggest that OC burial in tidewater glacier-dominated fjords may increase in the short term under warming due to enhanced meltwater discharge, but decline in the longer term as retreat transforms fjords into river-dominated systems.

Keywords

²¹⁰Pb geochronology, anthropogenic impact, glacialmarine sedimentation, organic carbon burial, organic carbon sources, sediment accumulation rate, fjords, South Georgia, sub-Antarctic

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Introduction

Organic carbon (OC) burial in sediments is a key component of the global carbon cycle and a form of ‘negative emission’ (Zhang et al., 2022), yet it remains poorly constrained (Hodgson et al., 2018). Carbon accumulation and sequestration in sediments are still poorly quantified in some environments, particularly remote polar regions (Wadham et al., 2019), including South Georgia, the largest sub-Antarctic island. This knowledge gap applies to both present-day processes and longer-term paleoenvironmental perspectives.

Fjords are highly efficient depositional environments, acting as sediment traps (Bianchi et al., 2020; Syvitski et al., 1987) and important ‘hot spots’ for marine carbon burial (Smith et al., 2015; Syvitski et al., 1990). Using data from 47 fjords worldwide, Smith et al. (2015) estimated that up to 11% of global marine carbon burial occurs in fjords, despite their total area representing only ~0.1% of the ocean. Subsequent studies across various fjord types have expanded and refined our understanding of OC burial rates (e.g. Cui et al., 2017; Duffield et al., 2017; Smeaton et al., 2021; Włodarska-Kowalczyk et al., 2019), as well as carbon sources and transport pathways (e.g. Berg et al., 2021; Cui et al., 2022; Ruben et al., 2023). However, South Georgia remains largely understudied, and fjords in the Southern Hemisphere are still underrepresented in global OC burial assessments. Moreover, the likely response of carbon sequestration efficiency in fjords to past and future environmental changes is not well understood.

There are multiple processes controlling OC input and preservation in fjord systems (Bianchi et al., 2020). They include, for instance, variability in primary production (Hopwood et al., 2020; Krajewska et al., 2020), delivery of older carbon from drainage basins (Bertrand, 2025; Cui et al., 2016; Hilton et al., 2015), and fjord circulation patterns that may promote anoxic bottom waters, enhancing OC preservation (e.g. Zaikova et al., 2010). Particularly important is sediment accumulation rate (SAR), which can be influenced by changes in erosion rate (Koppes et al., 2015; Koppes and Hallet, 2006), rapid sedimentation events (St-Onge and Hillaire-Marcel, 2001), shifts in sediment source distance due to tidewater glacier retreat (Jaeger and Nittrouer, 1999; Szczuciński and Zajączkowski, 2012), and changes in glacier mass balance that alter water discharge and sediment transport capacity (Andresen et al., 2024; Szczuciński et al., 2009). High SAR enhances OC preservation by rapidly burying recently produced organic matter, reducing exposure time to remineralization

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or consumption by organisms and promoting long-term sequestration (Berner, 1980).

In the context of OC burial as a mechanism for atmospheric CO₂ removal, the origin of the buried carbon is critical (Wang et al., 2024). In fjords, OC typically derives from petrogenic sources (older rocks), subrecent terrestrial sediments, and modern marine production, with burial of fresh marine OC being most relevant for long-term CO₂ sequestration. All three sources usually contribute to the OC pool. This balance between sources has recently been altered by anthropogenic impacts, both globally – through changes in the carbon cycle (Falkowski et al., 2020) and sediment fluxes (Syvitski et al., 2022) – and locally. In South Georgia, the whaling industry boom during the first half of the 20th century led to the harvest and processing of over 170,000 whales, causing substantial local ecosystem disturbance and likely altering organic matter supply (Majewski et al., 2024; Platt, 1978, 1979). Understanding how these disturbances affected sediment and carbon burial is essential for interpreting both recent impacts and the Holocene records preserved in South Georgia fjords.

Here, we present the first comprehensive assessment of OC burial rates and SAR for four major fjord systems in South Georgia. Our objectives are to: (i) quantify recent SAR and OC burial rates based on ²¹⁰Pb dating and sediment geochemistry, (ii) identify the dominant environmental controls on OC burial, with emphasis on differences between glacier-fed and river-dominated fjords, and (iii) evaluate the extent to which past human activity, particularly the whaling industry, has influenced OC burial. By addressing these aims, we provide a robust baseline for detecting and interpreting both past and future changes in carbon burial in a region already experiencing air and ocean warming (Nel et al., 2023; Whitehouse et al., 2008) and accelerated glacier retreat (Cook et al., 2010; Gordon et al., 2008).

Study area

General setting

South Georgia is a mountainous subantarctic island, ~170 km long and ~30 km wide (Figure 1). A central mountain chain runs along its axis, with many peaks exceeding 2000 m a.s.l. The island's climate and environment are strongly influenced by its location within the core of the Southern Hemisphere Westerlies and within a major oceanographic transition zone between the Southern Antarctic Circumpolar Current Front, the Polar Front, and the Subantarctic Front (Figure 1).

The geology of South Georgia is dominated by thick sequences of Early Cretaceous deep-sea turbidites (Dalziel et al., 2021), which are erosion-prone and provide an important source of petrogenic carbon to fjords. The drainage basins of the studied fjords are underlain mainly by the Cumberland Bay and Sandebugten formations (Figure 1). These are composed chiefly of andesitic volcanoclastic sandstones (greywackes), quartzose turbiditic sandstones, and mudstones.

The climate is maritime subantarctic, characterized by persistent winds and high precipitation. It is highly sensitive to shifts in large-scale atmospheric circulation, as reflected in pronounced variability documented for the Holocene and Late Pleistocene in marine, lacustrine, and peat bog records (Graham et al., 2017; van der Bilt et al., 2017; Wilkin et al., 2024; Zwier et al., 2022). Meteorological data from Grytviken and King Edward Point, both next to King Edward Cove, for 1951–1980 indicate a mean annual temperature of 2.0°C and annual precipitation of 1590 mm (Bannister and King, 2020). Between 1907 and 2016, average annual air temperature rose by 0.13°C/decade, precipitation increased by ~45 mm/decade, and both westerly airflow and the frequency of associated warm föhn winds intensified (Bannister and King, 2020; Thomas et al., 2018).

Approximately 63% of South Georgia is glacier-covered (Farias-Barahona et al., 2020). Most glaciers have retreated since their Little Ice Age maxima in the late 19th century (Gordon et al., 2008; van der Bilt et al., 2017), with the most rapid changes along the northeastern coast (Cook et al., 2010; Gordon et al., 2008). Average retreat rates accelerated from ~8 m in the 1950s to ~35 m/yr by the early 21st century (Cook et al., 2010). Over the past decade, continued negative mass balance (Farias-Barahona et al., 2020) has driven even faster retreat (Pelto, 2017).

Fjord hydrography (Geprägs et al., 2016; Majewski et al., 2023; Römer et al., 2014; Zanker et al., 2024) is characterized by a stratified water column during austral spring to autumn. The surface layer, with reduced salinity (sometimes <30 PSU) and temperatures occasionally exceeding 5°C, is typically thin (~2 m) at fjord mouths but thickens to ~30 m near tidewater glaciers. Beneath this layer, salinity increases to ~34 PSU and temperature falls to just above 0°C. In the deepest outer basins, near-bottom waters are slightly warmer and show properties characteristic of Upper Circumpolar Deep Water (Geprägs et al., 2016; Majewski et al., 2023).

Studied fjords

The coast of South Georgia is incised by more than 20 fjords (locally referred to as 'bays'), most of them located along the northern coast. The fjords selected for this study (Figure 1) represent the main environmental settings of the region, including small coves and the island's largest fjord (Cumberland Bay), fjords with and without tidewater glaciers, basins affected by past whaling activity as well as pristine systems, and areas where basic seafloor, sediment, and hydrographic data are already available (Hodgson et al., 2014; Majewski et al., 2023). All selected fjords share a uniform bedrock geology, which facilitates comparison because the petrogenic carbon sources are likely similar across sites. The coring sites were primarily selected within the central basins of the fjords and bays, based on existing data on seafloor morphology and sediments. Basic site characteristics, including water depth, core length, and distance to primary sediment sources, are provided in Table 1.

Antarctic Bay is a steep-sided fjord with a drainage area of ~24 km², over 80% glacier-covered (Figure 1). The fjord is ~2–2.5 km wide and over 10 km long, divided by submarine morainic ridges into inner and outer basin (Hodgson et al., 2014). Surface sediments are mainly composed of poorly sorted glacial marine mud with TOC content of 0.5%–0.6%, and OC δ¹³C values range from –24.4‰ to –24.5‰ (Majewski et al., 2023). Core SG-03 was collected in the outer basin, ~10 km from the tidewater Crean Glacier.

Fortuna Bay is ~6 km long, up to 2.5 km wide, and >150 m deep, with a sill at its mouth. Its drainage to fjord area ratio is relatively high ~6:1. Over half of the catchment is glacier-covered, though all glaciers now terminate on land. Sediment-laden meltwater from the largest glacier, König Glacier, flows through König Lake before entering the fjord (Figure 1). Surface sediments resemble those in Antarctic Bay (Majewski et al., 2023). Studied cores were taken close to each other, ~3 km from the fjord head.

Stromness Bay (33 km²) splits into three <100 m deep inner branches: Husvik Harbour, Stromness Harbour, and Leith Harbour. These are separated from the outer bay by submarine moraines and islands (Hodgson et al., 2014). The catchment is sparsely glacierised (<3.5%). Surface sediments are mainly mud, coarsening offshore into sandy mud and fine sand (Majewski et al., 2023). TOC content in those sediments increases from 0.2% to 0.6% in the outer bay to 1.3% in inner branches, and up to 2.9% near Grass Island at the mouth of Stromness Harbour. OC δ¹³C decreases offshore from –22.8‰ to –25.3‰ (Majewski et al., 2023). Three whaling stations (Figure 1) operated there during the first half of the 20th century, with Husvik and Stromness

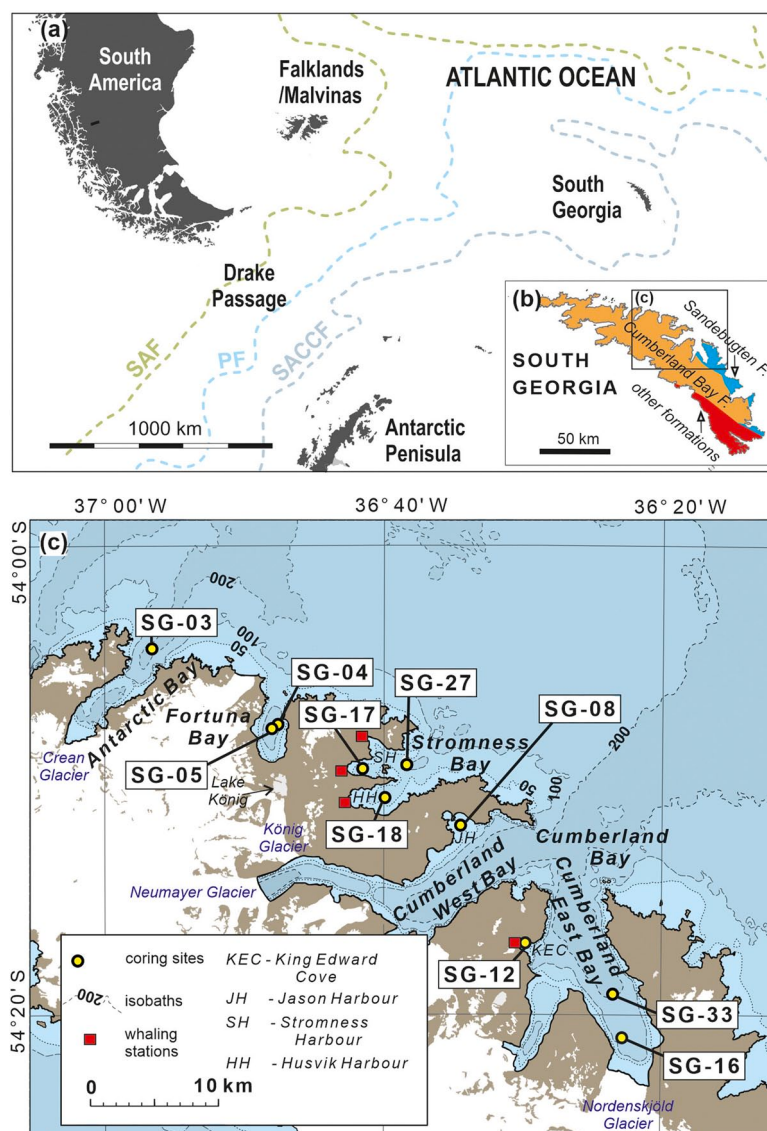


Figure 1. (a) Location of South Georgia in the southwestern Atlantic (base map from <https://freevectormaps.com>), showing major oceanographic features: the Southern Antarctic Circumpolar Current Front (SACCf), Polar Front (PF), and Subantarctic Front (SAF), after Orsi et al. (1995), (b) simplified geology of South Georgia after Dalziel et al. (2021), highlighting the Cumberland Bay Formation and Sandebugten Formation; remaining units are grouped as 'other formations', and (c) study area map (based on 'South Georgia and The Shackleton Crossing' map, scale 1:200,000, British Antarctic Survey, 2017, and 'Admiralty Chart 3588: Approaches to Stromness and Cumberland Bays', scale 1:50,000, edition 2003) showing coring sites. Marked whaling stations ceased operations before 1965. Figure modified from Majewski et al. (2023).

Table 1. Basic data on the investigated cores and sampling sites.

Core ID	Latitude S	Longitude W	Fjord	Water depth (m)	Core length (cm)	Approximated distance from the main local sediment source
SG-03	54° 4.180'	36° 56.812'	Antarctic Bay	250	16	10 km from the tidewater glacier front
SG-04	54° 7.658'	36° 47.598'	Fortuna Bay	125	10	2.7 km from the river mouth
SG-05	54° 7.800'	36° 48.148'	Fortuna Bay	154	30	2.9 km from the river mouth
SG-08	54° 12.038'	36° 34.267'	Jason Harbour (Cumberland West Bay)	23	42	1.5 km from inlet to Jason Lagoon
SG-12	54° 16.978'	36° 29.981'	King Edward Cove (Cumberland East Bay)	21.2	49	0.5 km from the major creek outlet
SG-16	54° 21.260'	36° 22.938'	Cumberland East Bay	124	48	2 km from the tidewater glacier front
SG-17	54° 9.567'	36° 41.575'	Stromness Harbour	92	18	1.2 km from the local river mouth
SG-18	54° 10.783'	36° 39.979'	Husvik Harbour	99.5	16	2.7 km from the local river mouth
SG-27	54° 8.542'	36° 36.592'	Stromness Bay	136	38	>3 km from several river mouths
SG-33	54° 19.146'	36° 23.800'	Cumberland East Bay	210	56	6 km from tidewater glacier front

stations most active between ~1910 and 1930 CE. Cores were collected in the outer basin (SG-27), Husvik Harbour (SG-18), and Stromness Harbour (SG-17), respectively ~5.0, 2.7, and 1.3 km from the nearest major river mouth.

Cumberland East Bay is ~18 km long and 3–5 km wide. The fjord reaches 270 m depth in the outer part, shoaling towards the head, which is fed by the largest glacier in South Georgia – the Nordenskjöld Glacier, which retreated by ~1 km between

1989 and 2015 (Pelto, 2017). Nearly 70% of the catchment is glacier-covered. The fjord contains at least 50 m of layered sediments (Geprägs et al., 2016; Graham et al., 2017; Hodgson et al., 2014; Römer et al., 2014). Mean SAR over the last ~2,300 years was 0.9 mm/yr in the outermost part of the bay (Graham et al., 2017). Fjord-floor sediments are poorly sorted glacial-marine mud, with grain size coarsening towards the head (Majewski et al., 2023). Their TOC increases offshore from ~0.3% to ~0.7% (Berg et al., 2021; Geprägs et al., 2016; Majewski et al., 2023), while OC $\delta^{13}\text{C}$ rises from -26‰ to ~-24‰ (Majewski et al., 2023). Biomarker and bulk ^{14}C data show predominantly petrogenic OC (~60%) at the head, with marine-derived OC (50%–70%) dominating distally (Berg et al., 2021). Cores SG-16 and SG-33 were collected ~2 and ~6 km from the fjord head (Figure 1).

King Edward Cove is a small embayment (~1 km²) on the central-west side of Cumberland East Bay (Figure 1). The basin is up to ~20 m deep, with core SG-12 collected ~0.6 km from the main stream outlet. It is separated from the main fjord by a 13 m deep sill and has the highest drainage-to-area ratio (7.6) among the studied bays. Deep-basin sediments consist of periodically anoxic mud with ~1% TOC and show the heaviest OC $\delta^{13}\text{C}$ values among the studied fjords (-22.5‰; Majewski et al., 2023). Sediment-trap data indicate strong resuspension and downslope redeposition in the bay, with sedimentation rates near the seafloor ranging from <10 g/m²/day in May to >180 g/m²/day in summer (Platt, 1979). Whaling activity at the Grytviken station, which operated until 1965, caused substantial organic matter enrichment of bay sediments, the development of anoxic conditions, and heavy metal and hydrocarbon contamination. Benthic ecosystems required several years to recover after operations ceased (Majewski et al., 2024; Platt, 1978, 1979).

Jason Harbour is a small cove (~3.3 km²) on the north side of Cumberland West Bay (Figure 1). It is widely open to the main fjord. The catchment (~6.3 km²) is almost glacier-free. The inner bay hosts Little Jason Lagoon, separated by a shallow (~1.5 m) sill, with SAR of ~1.5 mm/yr over recent centuries (Berg et al., 2019, 2021). Core SG-08 was collected ~1.9 km from the lagoon outlet and receives sediment from the local stream as well as from distant tidewater glaciers around Cumberland West Bay. Surface sediments are composed of mud, showing slight offshore fining and an increase in ice-rafted debris (Majewski et al., 2023). TOC declines from ~3% in the lagoon (mainly marine and terrigenous; Berg et al., 2021) to ~1% in periodically anoxic shallow bay areas, and to ~0.5% in more offshore oxic zones. OC $\delta^{13}\text{C}$ decreases offshore from -23‰ to ~-25‰ (Majewski et al., 2023).

Material and methods

Coring and sample treatment

Sediment cores (up to 56 cm long) were collected between 26 November and 6 December 2019 during a cruise aboard SRV *Saoirse* (Table 1). A Kajak corer (KC Denmark) with a transparent 46 mm inner diameter tube was used, ensuring undisturbed water–sediment interface recovery. Cores were described and sectioned on board into 2 cm slices of known volume, sealed in airtight bags, and stored at 4°C. In the laboratory, they were dried to determine dry bulk density (DBD). All samples were homogenized before further analyses.

Geochemical analyses

Geochemical analyses followed the procedures described by Racka et al. (2010) and Majewski et al. (2023). Total carbon (TC) and total inorganic carbon (TIC) were determined using an Eltra CS-500 IR analyser equipped with a TIC module and calibrated with 15 Eltra-certified standards, at the Institute of Earth Sciences, University of Silesia. TC was measured by high-temperature combustion under an oxygen atmosphere, with CO₂ quantified by an

infrared detector (IR). TIC was determined by acidification of samples with 50% phosphoric acid, and the released CO₂ was measured using the same IR detection system. Total organic carbon (TOC) was calculated as the difference between TC and TIC. The standard deviation for TIC and TOC was 0.068% and 0.542%, respectively.

The stable carbon isotopes of bulk organic matter ($\delta^{13}\text{C}_{\text{TOC}}$) in the sediments were analysed using a Thermo Electron DeltaV Advantage isotope ratio mass spectrometer (IRMS) with ConFlo II and a Carlo Erba NA-1500 elemental analyser at the University of Florida. Prior to $\delta^{13}\text{C}$ analysis, carbonate was removed from samples by repeated acidification with 10% HCl in 15 ml centrifuge tubes. Samples were reacted overnight, centrifuged and the supernatant decanted; the procedure was repeated with fresh acid until no visible reaction occurred. The residues were then rinsed repeatedly with deionized water and dried before measurement. The data accuracy was tested using the USGS40 (United States Geological Survey) standard for 28 replicates, resulting in a standard deviation of 0.081. The results are presented in standard delta notation relative to Vienna Pee Dee Belemnite (VPDB).

Sediment accumulation rate

A combined ^{210}Pb and ^{137}Cs approach was applied to establish sediment chronologies and calculate SAR. ^{210}Pb is widely used for dating the past ~150 years, while ^{137}Cs has been present in measurable quantities since the 1950s. Detailed principles and limitations of the methods are described elsewhere (e.g. Andersen et al., 2017; Appleby, 2008; Barsanti et al., 2020; Sanchez-Cabeza and Ruiz-Fernández, 2012).

The radionuclides were measured by gamma spectrometry at the Institute of Geology, Adam Mickiewicz University, Poznań. Dried, homogenized samples were sealed for 3 weeks before analysis and measured with Canberra HPGe detectors GX2520 (cores SG-03, SG-33) and BE3830 (other cores). Activities of total ^{210}Pb , ^{137}Cs , as well as ^{214}Pb and ^{214}Bi , the average of which is used as supported ^{210}Pb , were obtained. Excess ^{210}Pb ($^{210}\text{Pb}_{\text{ex}}$), used for SAR calculation, was determined as the difference between the total and supported ^{210}Pb .

$^{210}\text{Pb}_{\text{ex}}$ profiles were used to derive minimum inventories, minimum atmospheric fluxes, SAR (mm/yr), and mass accumulation rates (MAR; g/cm²/yr, from SAR and DBD). SARs were estimated using the following models: constant flux – constant sedimentation rate (Krishnaswamy et al., 1971), constant initial concentration (Robbins, 1978), and constant rate of supply (Appleby and Oldfield, 1978). Incomplete inventories precluded the use of the constant rate of supply model, and the constant initial concentration was unreliable in some cores. Therefore, a constant flux – constant sedimentation rate model was adopted as the primary approach, yielding results consistent with constant initial concentration where applicable. The *serac* R package (Brul and Sabatier, 2020) was used for most computations.

Carbon burial rate and efficiency

Organic carbon burial is commonly estimated by multiplying MAR (g/cm²/yr) by the TOC content (TOC%/100). However, the TOC value used in this calculation varies among studies, depending on whether it is taken from surface sediments, averaged over the entire core, or measured in deeper, diagenetically altered layers. When TOC from surface sediments is used, the resulting value represents an OC accumulation rate, because TOC typically declines with depth owing to post-depositional mineralization, meaning that the amount ultimately buried (long-term OC burial) is lower than the amount initially deposited. The proportion of OC that remains after mineralization (burial efficiency) may reach ~90% in fjords (Bianchi et al., 2020), but varies widely among sites (Koziorowska et al., 2018) and lacks a universal method of estimation (Bradley et al., 2022). Downcore

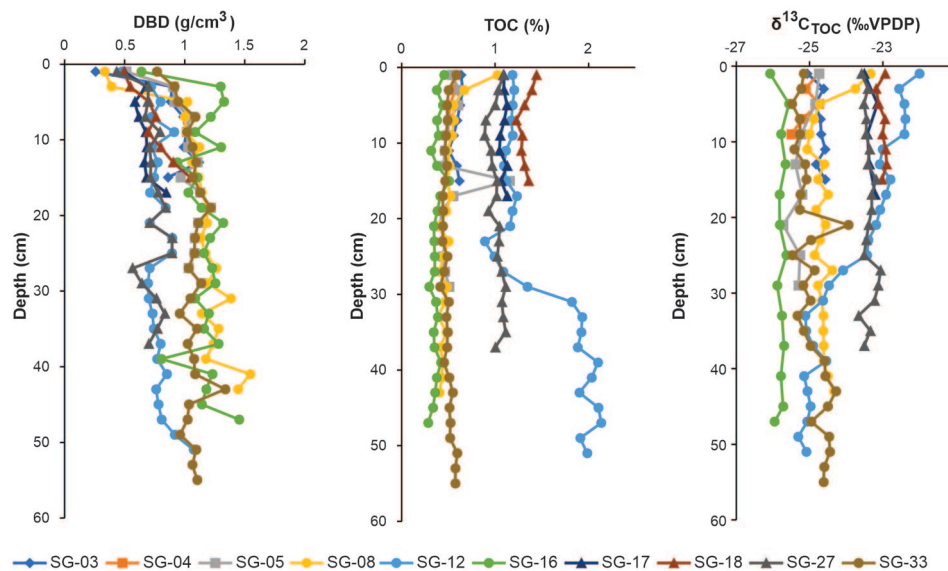


Figure 2. The downcore variability of dry bulk density (DBD), total organic carbon (TOC), and bulk organic carbon isotopic composition ($\delta^{13}\text{C}_{\text{TOC}}$) in the studied sediment cores.

TOC changes may also reflect variations in primary productivity and OC supply, which can mimic mineralization trends (Pieńkowski et al., 2024). Such changes in productivity are plausible in regions undergoing climate warming, including South Georgia (Nel et al., 2023; Whitehouse et al., 2008). For these reasons, using a core-averaged TOC provides a more integrated estimate of net OC burial under varying environmental conditions. To account for these uncertainties, we applied three complementary approaches that differ in how TOC is used: OC accumulation rate, OC burial rate, and burial efficiency (derived from long-term OC burial).

- OC accumulation rate: calculated as MAR multiplied by TOC in the surface sediment layer (0–2 cm). This metric reflects the amount of OC initially delivered to the seafloor before substantial mineralization and therefore represents input rather than long-term burial. Because MAR is derived as a core-averaged value, this estimate should be regarded as an approximation of short-term OC accumulation.
- OC burial rate: calculated as MAR multiplied by core-averaged TOC. This metric integrates OC preserved over the full length of the analysed core and therefore reflects the net amount of OC remaining after post-depositional mineralization. However, it includes the surface sediments, where TOC may be slightly elevated due to recently deposited organic matter still subjected to mineralization and, in some cases, due to changes in recent primary productivity. As a result, this estimate may slightly overestimate long-term OC burial.
- OC burial efficiency: expressed as the ratio (%) of long-term OC burial to OC accumulation. It was calculated using the OC accumulation rate (based on surface-sediment TOC) and the long-term OC burial rate, which uses mean TOC from sediments deeper than 8 cm. In our cores, TOC profiles tend to stabilize below ~8 cm (Figure 2), and values from this interval provide a more reliable measure of the fraction of OC preserved over centennial timescales.

For SG-12, the only core with a pronounced downcore TOC change, burial rates were additionally calculated for (i) the entire core, (ii) the upper 0–30 cm (characterized by low TOC), and (iii) the lower section, below 30 cm depth (high TOC).

Results

All raw data are provided in the Supplemental File available with the online version of the article and are also archived in the Zenodo repository (<https://doi.org/10.5281/zenodo.17629432>).

Sediment properties

All cores consist predominantly of homogeneous mud, with minor ice-rafted debris occurring only in Antarctic Bay and Cumberland Bay. Sediments from glacier-dominated fjords (Antarctic Bay, Fortuna Bay, Cumberland East Bay) are light grey to grey and show limited downcore variability, except for thin dark laminae in SG-16 and a light surface layer in SG-03.

By contrast, fjords with limited modern glacial influence (Stromness Bay, King Edward Cove, Jason Harbour) display more pronounced colour changes. Notably, SG-12 from King Edward Cove shows a strong transition from olive-grey surface muds to black, organic-rich sediments below 10 cm, consistent with elevated TOC and the presence of gas pockets below 30 cm depth.

The DBD is relatively uniform within individual cores, apart from the uppermost 2 cm, which are 25%–70% less dense than deeper sediments (Figure 2). Between fjords, DBD is the highest ($>1 \text{ g/cm}^3$) in Cumberland East Bay, and the lowest in cores from Stromness Bay and King Edward Cove ($0.7\text{--}0.8 \text{ g/cm}^3$).

Carbon content and its isotopic composition

TIC content is low in all cores ($<1\%$ of TC), except in SG-33 and SG-16, where it reaches 2.3% and 8.9% of TC, respectively. Thus, TC largely reflects TOC (Figure 2). The TOC values range from 0.28% to 2.14% and fall into three broad groups (Figure 2). Cores from the most glacier-affected fjords have consistently low TOC (0.37%–0.6%). Intermediate TOC values (1.0% to 1.3%) are in cores from Stromness Bay, the upper part of the core SG-12, and the surface of SG-08. The high TOC (around 2%) is found only in samples from the lower part of the SG-12.

Downcore TOC variations are minor in most cores and limited to a slight downward decrease in the uppermost 4–8 cm (Figure 2). The main exception is SG-12, where TOC shifts from ~1.1% near the surface to ~0.9% at ~22 cm, and then increases to 1.8%–2.1% below 30 cm (Figure 2).

$\delta^{13}\text{C}_{\text{TOC}}$ values also cluster into three ranges (Figure 2). The lightest values (-23.9‰ – -26.8‰) occur in most glacier-dominated fjords and in the deepest section of SG-12. Intermediate

values (−23.75‰–22.75‰) characterize Stromness Bay, parts of SG-08, and the mid-section of SG-12. The heaviest $\delta^{13}\text{C}_{\text{TOC}}$ values, between −22.6‰ and −22.0‰, are restricted to the upper 10 cm of the SG-12 core. The downcore changes in $\delta^{13}\text{C}_{\text{TOC}}$ are minor in most cores, except for SG-08 and SG-12 (Figure 2).

The sediment and mass accumulation rates

SARs were derived primarily from downcore $^{210}\text{Pb}_{\text{ex}}$ activity profiles (Figure 3). Because equilibrium depth (where no $^{210}\text{Pb}_{\text{ex}}$ remains) is not reached in any core, the $^{210}\text{Pb}_{\text{ex}}$ inventories represent minimum values (Table 2), ranging from low values in Jason Harbour to highest in the longest core SG-33. Accordingly, the minimum $^{210}\text{Pb}_{\text{ex}}$ fluxes range from 248 to 1712 Bq/m²/yr.

The $^{210}\text{Pb}_{\text{ex}}$ activity profiles generally show an exponential decline with depth, with the coefficient of determination (r^2) ranging from 0.56 to 0.95 (Figure 3). According to the applied constant flux – constant sedimentation rate model, the SARs and MARs (Table 2) range from 2.1 to 14.9 mm/yr and 0.15 to 1.7 g/cm²/yr, respectively. The uncertainty of these assessments, based on combined analytical uncertainty and the accuracy of the fit to the model exponential activity decline curve, is from $\pm 6\%$ to $\pm 31\%$ (Table 2). The studied cores cover various periods: the shorter cores represent approximately the last 20 years, whereas the longer cores span almost 100 years. Because of small differences in DBD (Figure 2), the SAR and MAR are strongly correlated (Table 2).

The SARs are calculated assuming a constant sedimentation rate, although changes in the slope of $^{210}\text{Pb}_{\text{ex}}$ activity profiles suggest possible variations through time. For instance, for the SG-05 core, it is possible to interpret the profile as consisting of two independent segments: 0–8 and 8–29 cm. The SARs and r^2 values calculated for them are, respectively, 5.26 ± 1.47 ($r^2=0.81$) for the upper and 9.11 ± 4.89 mm/yr ($r^2=0.27$) for the lower one. However, since their uncertainty ranges overlap with the value calculated for the whole core (5.01 ± 0.9 mm/yr, $r^2=0.689$) and the fit to the exponential decline curve in the lower section is poor. We therefore use the core-average SAR for further calculations.

The lowest SARs (2.1–2.3 mm/yr) occur in Husvik Harbour and Stromness Bay (SG-18, SG-27), both >2.5 km from the nearest river mouth (Table 2). By contrast, at a more river-proximal site in Stromness Harbour (SG-17), the rate is higher, reaching 7.9 mm/yr. Moderate SARs occur in small coves – Jason Harbour (4.7 mm/yr), King Edward Cove (6.3 mm/yr), as well as in Fortuna Bay (5–5.2 mm/yr). The highest SARs occur in fjords dominated by tidewater-glaciers sediment supply. In Cumberland Bay East, SARs decrease from 14.9 to 9.4 mm/yr with increasing distance from the glacier front, while in Antarctic Bay, a site farther from the glacier front reveals a rate of 6.6 mm/yr.

Trace activities (<1.16 mBq/g) of ^{137}Cs are detected only in SG-12 and SG-33 cores. In core SG-12, this radioisotope occurs at very low levels within the upper ~14 cm and appears again near 26–28 cm. In core SG-33, ^{137}Cs is present in several shallow and mid-depth horizons, with >1.0 mBq/g only in the deepest detected intervals 48–50 and 52–54 cm. The results suggest that at least the upper 28 cm in SG-12 and the top 54 cm in SG-33 were deposited after the late 1950s. This interpretation is consistent with the ^{210}Pb -based constant flux-constant sedimentation rate age model, which places the deepest ^{137}Cs occurrence at c. 1974 CE in SG-12 and at c. 1963 CE in SG-33, corresponding to the peak of global ^{137}Cs fallout.

Combining average SAR values with distance from the dominant sediment source reveals distinct relationships for fjords with marine-terminating glaciers (Antarctic Bay and Cumberland Bay East) and those supplied mainly by rivers and creeks (Figure 4a). Although specific river-discharge data are not available for these

catchments, the rivers are small and of broadly comparable size. Overall, sedimentation rates decrease more rapidly with distance in river-influenced bays than in glacier-fed fjords.

The OC burial rates

The OC accumulation rates are in the range of 18.6–77.8 gOC/m²/yr, while OC burial rates are from 17.4 to 64.6 gOC/m²/yr and are almost the same as long-term OC burial rates, which range from 17.4 to 63.9 gOC/m²/yr. Burial efficiency is very high in most of the cores (Table 2). In SG-03, SG-05, SG-12, and SG-17 it is c. 100% as the calculated OC accumulation rates are equal or even slightly lower than OC burial rates. Most other cores display a burial efficiency of 82%–94%. Only SG-08 shows noticeably lower efficiency (43.3%).

The OC burial rates (Table 2) are the highest (64.60 ± 12.1 gOC/m²/yr) in the inner Cumberland East Bay and decrease with distance from the tidewater glacier. High values (~40–50 gOC/m²/yr) also occur in King Edward Cove, Stromness Harbour and Antarctic Bay. Carbon burial is moderate (~20–30 gOC/m²/yr) in Jason Harbour and Fortuna Bay. The lowest carbon burial rates (<20 gOC/m²/yr) are in outer Stromness Bay and Husvik Harbour. The correlation coefficient of the OC burial rates and SARs between all cores is high, reaching 0.87 (Figure 4b). In contrast, the correlation of the OC burial rate with average TOC is not significant (correlation index = −0.17). This pattern reflects the limited variability in TOC among cores (Figure 2) compared with the much larger range in MAR, which varies by an order of magnitude (Table 2).

Core SG-12 is exceptional due to a twofold downcore increase in TOC (Figure 2). The carbon burial averages 72 gOC/m²/yr, but differs markedly between the upper (55.5 gOC/m²/yr) and lower (95.9 gOC/m²/yr) sections – the latter being the highest recorded in South Georgia fjords. The change is dated to the late 1960s, coinciding with the termination of the whaling industry in the bay.

Discussion

Critical assessment of sediment accumulation rates

The observed strong correlation between OC burial rates and SAR (Figure 4b), combined with the lack of correlation with TOC content, suggests that SAR may be the key driver in carbon burial. Thus, its accurate assessment is of fundamental importance. Although the applied ^{210}Pb dating technique is often successfully applied in fjords (e.g. Andresen et al., 2024; Boldt et al., 2013; Harden et al., 1992; Szczuciński et al., 2009), it always needs to be critically assessed and verified with independent dating approach, as some factors, for example, sediment mixing, may affect the resulting accumulation rates (e.g. Abril-Hernández, 2023; Barsanti et al., 2020; Smith, 2001).

Most frequently, the verification is conducted by comparison of the ^{210}Pb -based age models with the anthropogenic radionuclide ^{137}Cs , commonly found in sediments younger than the 1950s and often revealing the maximum fallout peak dated to c. 1963 CE (Pennington et al., 1973). However, we measured the very low ^{137}Cs activities only in some samples from the cores SG-12 and SG-33. Although the ^{137}Cs presence agreed with the ^{210}Pb -based ages, it does not permit us to fully verify the ^{210}Pb age models. The lack, or very low activities, of measurable ^{137}Cs in marine sediments was commonly reported from the circum-Antarctic region (e.g. Harden et al., 1992; Masqué et al., 2002; Pieńkowski et al., 2024) and is mainly due to its low fallout in the region (Foucher et al., 2021; UNSCEAR, 2000), and in case of a high sediment accumulation rate also due to the dilution effect.

An alternative way to assess the accuracy of ^{210}Pb -based SAR is provided by core SG-12 from King Edward Cove, where a rapid downcore TOC increase occurs at ~30 cm depth (Figure 2). A similar change was observed in cores collected from the same

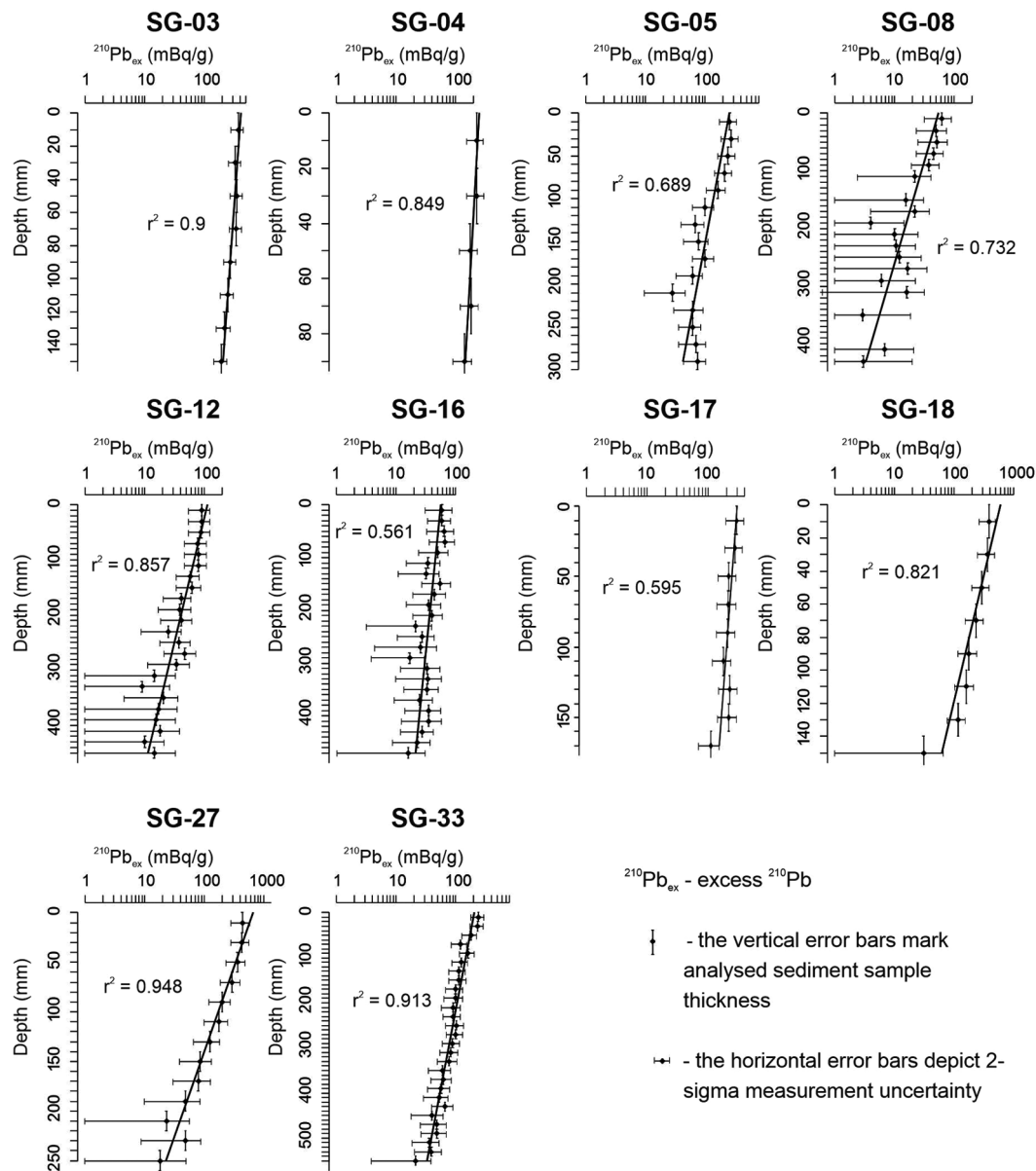


Figure 3. Semilogarithmic profiles of excess ^{210}Pb ($^{210}\text{Pb}_{\text{ex}}$) activity for the studied sediment cores. Plots were partially generated using the serac package in R (Bruehl and Sabatier, 2020).

Table 2. Measured minimum inventories and fluxes of excess ^{210}Pb , calculated sediment accumulation rate (SAR) and mass accumulation rate (MAR), core-averaged TOC, OC accumulation rate (using surface sediment TOC, 0–2 cm), OC burial rate (using core-averaged TOC), and burial efficiency (based on long-term OC burial calculated from mean TOC below 8 cm; see Material and methods for details).

Core ID	Minimum excess ^{210}Pb inventory (Bq/m ²)	Minimum excess ^{210}Pb flux (Bq/m ² /yr)	SAR (mm/yr)	MAR (g/cm ² /yr)	Core average TOC (%)	OC accumulation rate (gOC/m ² /yr)	OC burial rate (gOC/m ² /yr)	OC burial efficiency (%)
SG-03	39.95 ± 3.6	1242 ± 113	6.55 ± 0.9	0.61 ± 0.1	0.60	39.05 ± 4.6	40.11 ± 4.3	100
SG-04	16.36 ± 2.5	509 ± 78	5.23 ± 1.3	0.47 ± 0.1	0.52	27.07 ± 6.1	24.76 ± 5.9	85.77
SG-05	35.47 ± 3.7	1103 ± 117	5.01 ± 0.9	0.53 ± 0.1	0.54	28.57 ± 5.5	28.82 ± 5.5	99.05
SG-08	7.98 ± 1.8	248 ± 57	4.75 ± 0.7	0.55 ± 0.1	0.51	58.84 ± 9.0	27.97 ± 4.4	43.30
SG-12	15.59 ± 1.8	485 ± 57	6.27 ± 0.5	0.49 ± 0.04	1.50	57.72 ± 5.0	72.59 ± 6.3	100
SG-12 (above 30 cm)	-	-	6.27 ± 0.5	0.49 ± 0.04	1.15	-	55.52 ± 4.8	-
SG-12 (below 30 cm)	-	-	6.27 ± 0.5	0.49 ± 0.04	1.98	-	95.87 ± 8.3	-
SG-16	20.47 ± 2.5	637 ± 78	14.88 ± 2.8	1.73 ± 0.3	0.37	77.80 ± 14.6	64.60 ± 12.1	82.22
SG-17	25.02 ± 2.8	778 ± 90	7.86 ± 2.5	0.51 ± 0.2	1.09	55.81 ± 17.0	56.01 ± 17.1	100
SG-18	23.36 ± 3.0	725 ± 94	2.05 ± 0.4	0.15 ± 0.02	1.33	21.31 ± 3.3	19.66 ± 3.1	90.99
SG-27	31.04 ± 4.2	965 ± 130	2.31 ± 0.2	0.17 ± 0.1	1.02	18.60 ± 1.3	17.44 ± 1.2	93.76
SG-33	55.06 ± 3.7	1712 ± 114	9.40 ± 0.6	1.02 ± 0.1	0.49	59.59 ± 3.7	50.26 ± 3.1	83.62

Burial efficiency values are capped at 100%, even if calculations yield higher ratios. For SG-12, where TOC shows a pronounced downcore shift, OC burial rates were additionally calculated for the upper 0–30 cm (low TOC) and the lower >30 cm interval (high TOC).

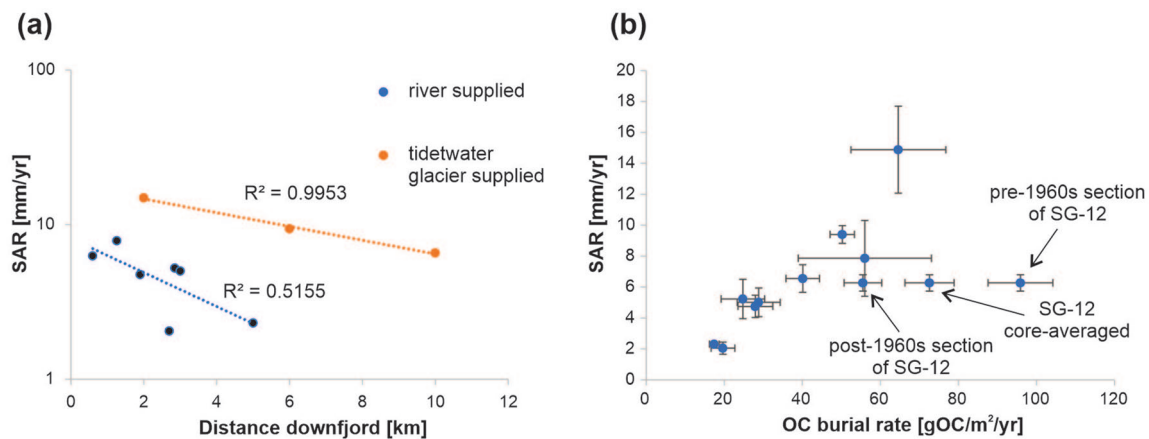


Figure 4. (a) Changes in SAR (logarithmic scale) with distance from the dominant sediment source: tidewater glaciers (Antarctic Bay and Cumberland Bay East) and rivers (Stromness Bay, Fortuna Bay, King Edward Cove, and Jason Harbour). (b) Relationship between SAR and OC burial rate. Also shown are OC burial rates calculated for SG-12 sections dated to pre- and post-1960s CE (below and above 30 cm core depth), corresponding to the termination of the whaling industry in Grytviken.

deepest part of the bay in early 1976 by Platt (1979). According to age model, the 30 cm depth is dated to ~1969 CE (range 1965–1974), giving a SAR of 6.27 mm/yr. Platt (1979) reported a comparable TOC increase at ~6 cm depth. Since this change must predate the 1976 coring, applying our SAR yields an age of ~1965 CE, consistent with Platt's interpretation linking the horizon to the termination of the whaling industry the same year. Thus, the ^{210}Pb chronology agrees well with the independent observation of Platt (1979).

The dating model assumes a constant ^{210}Pb flux and sedimentation rate. While this condition may be broadly valid, in the studied fjords the flux derives not only from direct atmospheric ^{210}Pb deposition, and sedimentation is not solely from suspension settling. Sediment trap experiments in King Edward Cove (Platt, 1979) showed seasonal variability and demonstrated that much of the material accumulating in the deepest basin results from wave-induced redeposition from shallower areas. Our sediment cores were collected mainly in the axial, deeper parts of the fjords, that is, settings where sediment focussing from redeposition is likely (Syvitski and Normandeau, 2023). This effect is evident when minimum $^{210}\text{Pb}_{\text{ex}}$ fluxes, calculated from measured $^{210}\text{Pb}_{\text{ex}}$ inventories (Table 2), are compared with atmospheric $^{210}\text{Pb}_{\text{ex}}$ fluxes (Zhang et al., 2021). Although sub-Antarctic data are sparse, atmospheric deposition fluxes are generally $<100 \text{ Bq/m}^2/\text{yr}$, several to more than 10 times lower than the minimum fluxes derived from the cores (Table 2). This indicates that a significant fraction of sediments, and associated OC, accumulated in the fjord's central parts was redeposited material carrying $^{210}\text{Pb}_{\text{ex}}$ scavenged in shallower parts.

In the interpretation of the $^{210}\text{Pb}_{\text{ex}}$ downcore profiles, potential SAR changes must also be taken into account. Core SG-05 provides an example of a possible change at c. 8 cm depth, corresponding to 2003 CE (range 1998–2008). The decline in the accumulation rate after this time is possible, as the König Glacier, the biggest glacier in the Fortuna Bay catchment, rapidly retreated and a proglacial König Lake (Figure 1) was formed at that time (Gordon et al., 2008). The lake is likely capturing a portion of sediments exported from the glacial system, thus limiting the supply to the fjord.

The next potential limitation not accounted for in the applied model is sediment mixing (e.g. bioturbation). Deep mixing was neglected because ^{210}Pb profiles show no surface mixed layer (Figure 3), a typical sign of mixing (Nittrouer et al., 1979), and macroscopic inspection revealed no evidence of deep bioturbation, suggesting that mixing is mainly restricted to the upper ~2 cm (the sampling interval).

In conclusion, although the obtained SAR values are partly validated by independent age markers like ^{137}Cs and the correlation of lithological change with the older cores of known sampling dates (Platt, 1979), some uncertainties resulting from changing sedimentary processes still remain. Thus, the obtained SARs must be treated as approximated rates, and the uncertainty ranges must be considered.

In OC burial studies, burial efficiency is often debated, but less attention is given to SAR uncertainties. Simplified use of ^{210}Pb age models in dynamic fjord settings can introduce large errors, and overestimates may occur when rates from central basins, where sediment and carbon focussing are common, are treated as representative of the entire fjord.

Origin of organic carbon in fjords of South Georgia

The OC in South Georgia fjords derives from a mixture of sources, including older rocks (petrogenic carbon), subrecent terrestrial sediments (e.g. peat), and modern marine production (Berg et al., 2021, 2024). This heterogeneity is reflected in the variable isotopic composition of TOC in surface sediments (Majewski et al., 2023) and in the analysed sediment cores (Figure 2). The $\delta^{13}\text{C}_{\text{TOC}}$ values alone cannot unambiguously determine sources, since they represent an average of multiple inputs and several sources overlap isotopically (Lamb et al., 2006). Nevertheless, they can highlight similarities and differences between fjords and provide insight into temporal changes in buried TOC.

Most samples from fjords with glacier-dominated catchments fall within a narrow $\delta^{13}\text{C}_{\text{TOC}}$ range of -23.9‰ to -26.8‰ (Figure 2). They include cores from Fortuna Bay, Antarctic Bay, Cumberland Bay, and an older section from Jason Harbour, partly deposited under glaciomarine influence, as indicated by ice-rafted debris (Majewski et al., 2024). The lightest values occur in SG-16, from the shallow zone next to the Nordenskjöld tidewater glacier, and may approximate an end-member value representing mainly glacially eroded bedrock. Following Berg et al. (2021), who used ^{14}C dating to show that TOC in glacier-proximal settings is predominantly petrogenic, and noting the similar bedrock across the fjord catchments (Dalziel et al., 2021; Figure 1b), we infer that samples within this isotopic range are dominated by petrogenic carbon with variable contributions from other sources. Similar patterns were observed in surface sediments by Majewski et al. (2023), who identified two isotopic groups with trends related to fjord position and TOC content. Likewise, Berg et al. (2021) documented a gradient from marine-dominated TOC near fjord mouths to petrogenic and/or terrestrial sources near fjord

heads. An exception is the older core section from King Edward Cove (SG-12), which shows a similar isotopic composition to glacier-proximal zone but a much higher TOC content, suggesting dominance of another source, likely linked to organic matter inputs during the whaling period. Although the $\delta^{13}\text{C}_{\text{TOC}}$ in SG-12 indicates a change in the bulk organic-matter pool, this proxy alone cannot uniquely identify the source of carbon. However, multi-proxy evidence from Majewski et al. (2024), including elevated concentrations of hopanes, steranes, PAHs, sewage biomarkers (coprostanol, epicoprostanol), animal-tissue sterols and heavy metals, demonstrates that the lower part of SG-12 was strongly influenced by combined inputs of organic waste, sewage and petroleum products released during whaling operations. The absence of major changes in ^{210}Pb -derived sedimentation rates suggests that mechanical disturbance (e.g. resuspension, construction) was not the dominant driver of OC source change. Instead, the very high TOC values reflect direct deposition of organic matter and reduced remineralization under locally anoxic conditions.

The second major group of samples is dominated by heavier $\delta^{13}\text{C}_{\text{TOC}}$ values (Figure 2). It includes cores from Stromness Bay and young sediments from Jason Harbour and King Edward Cove. This group is characteristic of bays with nearly ice-free catchments, resulting in moderate to low sediment accumulation rates. As the waters around South Georgia are highly productive (Atkinson et al., 2001), TOC in these settings is likely dominated by marine inputs, with smaller contributions from subrecent terrestrial and petrogenic sources.

Temporal changes in OC type are visible in two cores, SG-08 and SG-12. In both cases, the $\delta^{13}\text{C}_{\text{TOC}}$ becomes heavier in younger sediments. In SG-12, where the change is particularly pronounced (from -23.75% to -22.00%), it marks the decline of whaling-related organic inputs following the cessation of industrial activity in the late 1960s. This temporal signal is absent in cores SG-17 and SG-18 from Stromness Harbour and Husvik Harbour, respectively, which were also affected by the whaling industry but whose shorter sequences do not extend into the period of active whaling-related waste discharge.

Burial of organic carbon in fjords of South Georgia

Recent OC burial rates in South Georgia fjords range from 17.4 ± 1.2 to 64.6 ± 12.1 gOC/m²/yr. They correlate strongly with SAR (Figure 4b) but show no consistent relationship with TOC content, underscoring that carbon sequestration is controlled mainly by the rate and mode of sediment delivery. This is clearest at the glacier-proximal site SG-16, where the combination of the highest SAR and lowest TOC yields the maximum modern burial rate. This relationship is not a mathematical artefact, as TOC varies only modestly across sites, whereas SAR (and MAR) varies by more than an order of magnitude, making sediment delivery the dominant control on the spatial pattern of OC burial. The studied fjords are also characterized by very high OC burial efficiency (generally well above 90%), also likely due to high SAR. However, our estimates apply to the recent century and long-term preservation may be lower.

Burial patterns along fjords mirror the exponential SAR decline typical of fjord depositional systems (e.g. Jaeger and Nittrouer, 1999; Syvitski, 1989; Szczuciński and Zajączkowski, 2012). Tidewater glacier-fed fjords consistently sustain higher SARs and OC burial rates than river-dominated systems (Figure 4). Importantly, the rate of decline with distance from sediment source also differs: in river-supplied bays, burial rates fall off much more steeply, reflecting rapid flocculation and near-mouth deposition of suspended matter. In contrast, subglacial outflows from tidewater glaciers transport sediment-laden meltwater

further into the fjords, maintaining higher vertical particulate matter fluxes and allowing efficient carbon burial over larger depositional areas (Szczuciński and Zajączkowski, 2012).

An exception is King Edward Cove, where the maximum burial rate (95.9 ± 8.3 gOC/m²/yr) occurred in the early 20th century, nearly double the modern value (55.5 ± 4.8 gOC/m²/yr). This reflects local enrichment during the whaling era, amplified by the cove's morphology: a small, shallow, silled basin that is highly sensitive to disturbance and not representative of fjord systems more broadly.

Only a few studies have addressed OC burial in South Georgia fjords. Platt (1979) carried out 2 years of sediment-trap experiments in King Edward Cove, reporting a mean MAR of 0.28 g/cm²/yr and an OC accumulation rate of ~ 60 gOC/m²/yr. He also emphasized the strong role of resuspension, suggesting that more than 70% of the material deposited in the deepest basin may be redeposited from shallower areas. Our post-whaling burial rate from SG-12 (55.5 gOC/m²/yr) is consistent with Platt's estimates despite methodological differences, providing confidence in the robustness of our results.

In contrast, Berg et al. (2021) reported much lower values ($4\text{--}12$ gOC/m²/yr) from Cumberland Bay, interpreting them as evidence for increasing petrogenic and biospheric carbon burial during recent glacier retreat. However, their calculations relied only on surface sediment TOC combined with speculative SAR assumptions rather than measured values. For example, at a site close to our SG-16 core, they estimated ~ 9 g C/m²/yr, whereas our ^{210}Pb -based chronology and downcore TOC profiles indicate $\sim 64 \pm 12$ gOC/m²/yr. This contrast highlights the importance of site-specific accumulation data and depth-resolved geochemistry for producing reliable and comparable burial estimates.

Comparison of OC burial in fjords of South Georgia and elsewhere

Fjords occur in a range of climates (Syvitski et al., 1987) and are commonly classified as temperate, subpolar, or polar types (Gilbert, 2000). Temperate fjords lack persistent sea ice, and glaciers, if present, are confined mainly to headwater areas. Subpolar fjords experience seasonal sea-ice breakup and summer air temperatures above 0°C. Polar fjords are typically covered by sea ice year-round. Although the fjords of South Georgia have basins with significant glacier coverage, their positive mean annual temperature and lack of frequent sea ice indicate that they are best classified as temperate fjords.

When compared with other fjords for which OC burial rates have been determined using similar approaches (radiometric dating and downcore TOC profiles) in temperate regions (Alaska, Norway, New Zealand, Patagonia, Sweden, Scotland) and subpolar settings (Svalbard), South Georgia fjords are in the upper range of values reported globally (Figure 5). In most other fjords, OC burial rates typically range between 10 and 100 gOC/m²/yr and SAR values are generally below ~ 1 cm/yr. In contrast, the South Georgia fjords exhibit some of the highest SARs and relatively high OC burial rates. This likely reflects a combination of factors, including steep, high-relief catchments composed of erosion-prone sedimentary rocks that supply petrogenic organic carbon, substantial precipitation of ~ 1500 mm/yr (Bannister and King, 2020), extensive glacier cover (Fariás-Barahona et al., 2020), and relatively high marine primary productivity (Atkinson et al., 2001).

Most data in the inter-fjord comparison (Figure 5) come from sediment cores collected in central basins and may not be fully representative of fjord-wide mean burial, especially where strong along-fjord gradients and sediment focussing occur. Organic carbon burial rates in proximal settings can be an order of magnitude higher, SARs there often reach several to tens of cm/yr or more. Such elevated rates are observed in fjord-head deltas (e.g. Hage

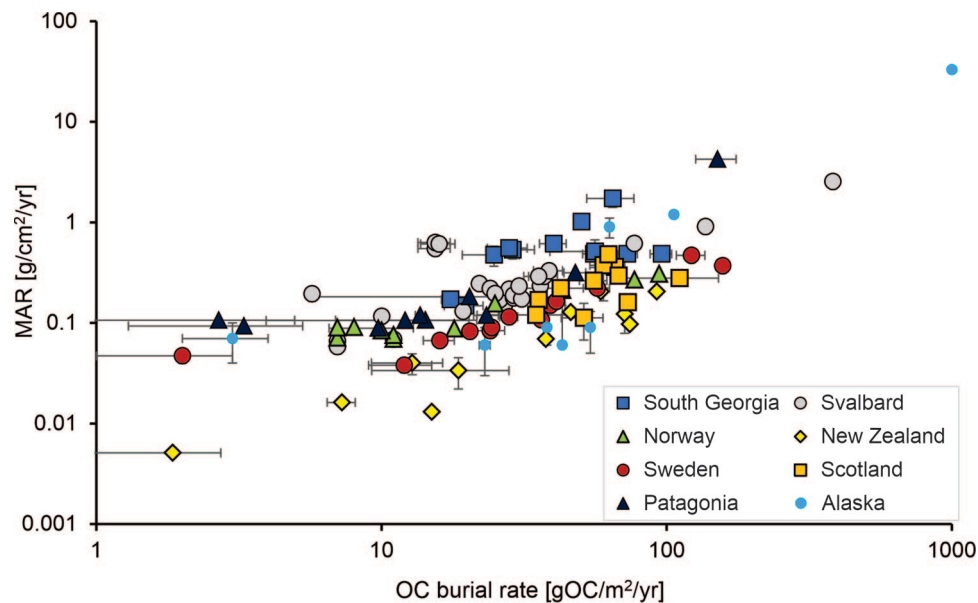


Figure 5. Comparison of mass accumulation rates (MAR) and organic carbon (OC) burial rates in temperate (Alaska, New Zealand, Norway, Patagonia, Sweden, Scotland, South Georgia) and subpolar (Svalbard) fjords, based on comparable approaches. Note the logarithmic scales. Source. South Georgia (present study), Svalbard (Koziorowska et al., 2018; Włodarska-Kowalczyk et al., 2019; Zaborska et al., 2018; recalculated from Ruben et al., 2023), Norway (Włodarska-Kowalczyk et al., 2019), New Zealand (Ramirez et al., 2016; Smith et al., 2015), Patagonia (recalculated from Sepúlveda et al., 2011; recalculated from Hage et al., 2025; Vandekerckhove et al., 2021), Sweden (Duffield et al., 2017 (core-averaged values); Watts et al., 2024), Scotland (Smeaton et al., 2021), Alaska (OC accumulation rates, OCAR, from Cui et al. (2016; based partly on data from Ullrich et al., 2009; Walinsky et al., 2009). The uncertainties are provided if they were presented in the original studies. Most cores were collected from central fjord basins; the highest extreme rates are reported from glacier-proximal and deltaic environments.

et al., 2022, 2025), near tidewater glacier fronts (e.g. Cowan and Powell, 1991; Ruben et al., 2023; Szczuciński et al., 2018; Ullrich et al., 2009), during episodes of enhanced meltwater discharge such as glacier surges (e.g. Gilbert et al., 2002), or following high-energy depositional events including turbidites and slope failures (e.g. St-Onge and Hillaire-Marcel, 2001). However, the quantitative studies of areas with the highest accumulation rates remain rare, especially in fjord-head deltas and glacier-proximal glaciomarine settings, where MAR can be extreme. As a result, even low TOC concentrations may translate into very high organic carbon burial rates. By contrast, fjord slopes may act as zones of reduced burial, with sediments and organic matter frequently remobilised and transported into deep basins, where sediment focussing takes place (Syvitski and Normandeau, 2023).

A particularly valuable comparison can be made between the cold-temperate fjords of South Georgia and the well-studied subpolar fjords of Svalbard, as well as the temperate fjords of northern Patagonia. The fjords of Svalbard share with South Georgia many physical and geomorphic features, including comparable size (length, width, depth), a mix of tidewater glaciers and river deltas, and a broadly comparable glacier coverage in their catchments (~60%). Average TOC concentrations in surface sediments are also similar (Włodarska-Kowalczyk et al., 2019), with a substantial proportion of petrogenic origin (Kim et al., 2023; Ruben et al., 2023). However, OC burial rates (Figure 5) are markedly higher in South Georgia, driven mainly by higher SARs in central basins under the island's warmer and more humid climate. South Georgia receives over seven times more precipitation (~1500 vs ~200 mm/yr) and has higher mean annual temperatures (~2.0°C vs ~-7.0°C), resulting in longer and more effective ablation seasons. Differences in primary productivity (warmer waters, absence of polar night) may also play a role, but the dominant factor appears to be the much larger meltwater flux enhancing sediment and OC delivery. This comparison suggests that, under continued climate warming, subpolar fjords such as those in Svalbard or the Antarctic Peninsula may begin to function more like the temperate fjords of South Georgia, with elevated SAR and OC burial rates.

In contrast, the fjords of northern Patagonia (Sepúlveda et al., 2005, 2011), although located only slightly farther north (44°S–47°S) than South Georgia and also within the Southern Hemisphere, differ considerably in their environmental setting. Northern Patagonia fjords are often much deeper (up to ~1000 m), experience a warmer (~10°C) and considerably wetter climate (~3000 mm/yr), and are fed almost exclusively by river discharge because glaciers do not terminate in the fjords. Catchments are densely vegetated, supporting temperate evergreen forests. Fjord sediments show TOC values ranging from ~0.1% to 3%, with a strong terrigenous component dominated by soil and plant-derived OC (Bertrand, 2025; Sepúlveda et al., 2011). Due to these differences, the OC burial rates and MAR reported from northern Patagonia fall within similar ranges to those of subpolar Svalbard and are generally lower than those observed in South Georgia (Figure 5). This contrast suggests that, with continued regional warming and associated reductions in glacier influence, the fjords of South Georgia could gradually shift towards a more northern Patagonia-like regime, characterized by reduced SAR and lower OC burial.

Future and past of OC burial rates in South Georgia fjords

South Georgia fjords act as major sediment and carbon sinks, and as previous studies indicate, the sediment accumulation responds strongly to glacier retreat and climate variability (e.g. Andresen et al., 2024; Boldt et al., 2013; Koppes et al., 2015; Koppes and Hallet, 2006; Szczuciński et al., 2009). In the coming decades to centuries, continued negative glacier mass balance (Farias-Barahona et al., 2020) and rising precipitation (Thomas et al., 2018) are expected to enhance meltwater discharge and sediment delivery from glacierised catchments, particularly those with tidewater glaciers. This will likely increase total OC accumulation and preservation, as greater sediment supply promotes rapid burial and provides micronutrients that sustain primary productivity (Bhatia et al., 2013). However, a larger part of sequestered OC will be recycled from petrographic sources rather than from fresh marine

or terrestrial sources. However, as tidewater glaciers retreat, fjord depositional areas will expand, and the distance between core sites and sediment sources will grow. Thus, local SARs and burial rates may remain stable or even decline despite higher overall sediment supply.

Over longer timescales, warming will progressively transform tidewater glacier-dominated fjords into river-dominated systems. Such transitions are expected to reduce sediment and OC supply, as observed today in South Georgia's river-dominated bays. Similar shifts likely occurred during Holocene glacier advances and retreats (e.g. van der Bilt et al., 2017; Zwier et al., 2022), which left tens of metres of sediment on fjord floors (Graham et al., 2017; Hodgson et al., 2014). Interpreting these records remains challenging, as ^{14}C chronologies rarely capture short-term accumulation rate variability, and drawing conclusions from TOC alone may be misleading. As shown here, low TOC content does not necessarily imply low OC burial.

These observations align with results from glaciated continental margins elsewhere. For instance, Cui et al. (2016) in a study on SE Alaska, showed that glacial retreat initially increases sediment and OC flux, enhancing both petrogenic and biospheric carbon burial. Yet, over longer timescales, sustained deglaciation reduces sediment supply as glacierised catchments shift towards non-glaciated, vegetated landscapes, leading to declining accumulation and burial rates. This dual response, short-term enhancement followed by long-term decline, should be considered when interpreting past records and forecasting future changes.

Conclusions

This study provides the first systematic assessment of sediment accumulation and OC burial in the fjords of South Georgia. These fjords act as highly efficient sinks, with rates exceeding many temperate and subpolar systems. High values reflect the combined influence of steep relief, erosion-prone bedrock, extensive glacier cover, intense precipitation, and relatively high marine productivity.

Sediment accumulation is the dominant control on OC burial. Burial correlates strongly with SAR but not with TOC, underscoring the role of sediment delivery and focussing. High sedimentation also promotes very high burial efficiency. Tidewater glacier-fed fjords sustain higher SARs and burial rates than river-dominated systems, showing more gradual declines of sedimentation rate towards fjord mouth. The fjords also record human disturbance. In King Edward Cove, burial nearly doubled during the whaling boom, demonstrating the sensitivity of small silled basins to local enrichment.

Comparison with both subpolar (e.g. Svalbard) and temperate (e.g. northern Patagonia) fjords shows that South Georgia's wet climate and longer ablation season drive high SARs and OC burial. As warming accelerates meltwater flux and sediment supply, glacierised subpolar fjords may increasingly resemble South Georgia. In the longer term, however, continued deglaciation may shift South Georgia's fjords towards a more river-dominated, northern Patagonia-like regime, characterized by lower SARs and reduced OC burial.

These findings also offer a process-oriented framework for interpreting Holocene records. Variability in SAR and OC burial reflects not only productivity changes but also shifts in fjord type and sediment delivery. Transitions from tidewater- to river-dominated conditions alter burial magnitude and along fjord gradients, leaving potential signatures in sediment archives. Recognizing such controls improves the use of fjord sediments as records of past glacier dynamics and environmental change.

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Author contributions

Witold Szczuciński: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Visualization; Writing - original draft; Writing - review & editing.

Wojciech Majewski: Conceptualization; Funding acquisition; Investigation; Methodology; Project administration; Writing - review & editing.

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Data availability statement

The datasets generated during and/or analysed during the current study are made available as supplemental material available online along with the paper, and are also archived in the Zenodo repository (<https://doi.org/10.5281/zenodo.17629432>).

Supplemental material

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