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IMPLICATIONS FOR PALAEOCEANOGRAPHIC RECONSTRUCTIONS IN ATLANTIFIED ARCTIC FJORDS

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Abstract: Hornsund is undergoing rapid environmental transformations, driven by ongoing atlantification of the Arctic. This study examines how foraminiferal assemblages have responded to these changes over the past two decades, providing an exceptional opportunity to link modern ecosystem dynamics with processes recorded in the sedimentary archive. The primary objective of this study aims is to establish diagnostic faunal and isotopic features of atlantification that can be applied in the interpretation of palaeoceanographic records. Results reveal clear indicators of atlantification, including the increasing dominance of boreoarctic and Atlantic Water (AW)-affiliated taxa (*Adercotryma glomeratum* Brady*, Astrononion hamadaense* Asano, *Nonionellina labradorica* Dawson, *Recurvoides turbinatus* Brady), prevalence of opportunistic species (*Cassidulina reniformis* Nørvang*, Cribroelphidium clavatum* Cushman), rising species richness and a greater abundance of agglutinated taxa, particularly in the inner fjord. Spatial distribution patterns reflect progressive AW penetration towards the fjord head, with outer and central fjord stations exhibiting high diversity and evenness, and inner glacial-proximal areas showing increased agglutinated foraminifera dominance. Stable-isotope analyses of selected foraminiferal tests demonstrate increasing $\delta^{18}O$, consistent with higher salinity, and decreasing $\delta^{13}C$, indicative of enhanced primary productivity and terrestrial organic matter input. These changes, occurring within just 22 years, reveal the high sensitivity of benthic foraminifera to environmental change in the Arctic and confirm their value as proxies for reconstructing both contemporary and palaeoceanographic changes in high time resolution.

Key words: Benthic foraminifera, fjords, modern sediments, climate change, stable isotopes.

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INTRODUCTION

The ongoing process of atlantification, the northward expansion of warm, saline Atlantic Water (AW) into the Arctic Ocean (Polyakov *et al.*, 2017; Ingvaldsen *et al.*, 2021), is one of the most profound manifestations of contemporary climate change in the polar regions. Driven by atmospheric and oceanic warming, this phenomenon is reshaping the Arctic marine environment by altering sea-ice dynamics, sea-water properties, and ecosystem functioning (Weydmann-Zwolicka *et al.*, 2021). As AW progressively flows into Arctic basins and coastal areas, it modifies temperature and salinity regimes, enhances stratification, and influences primary productivity, thereby exerting cascading effects on biological communities, including benthic ecosystems (Łącka *et al.*, 2019; Tesi *et al.*, 2021).

Recent studies have highlighted the intensifying atlantification in the Svalbard region, both on the shelf and within its fjord systems (Weydmann-Zwolicka *et al.*, 2021). On the western Svalbard shelf, increasing advection of AW through the West Spitsbergen Current (WSC) has been well-documented, resulting in pronounced oceanographic and ecological changes (Nilsen *et al.*, 2008; Strzelewicz *et al.*, 2022). In fjord environments, the degree of atlantification varies considerably, depending on fjord geometry, glacial input, and bathymetry. For instance, Kongsfjorden and Isfjorden, two extensively studied fjords on the western coast of Spitsbergen, exhibit strong and persistent influence of AW with warmer subsurface layers, reduced seasonal sea-ice cover, and benthic communities increasingly resembling sub-Arctic assemblages (Szymańska *et al.*, 2017; Bloshkina *et al.*, 2021; Kujawa *et al.*, 2021; Weydmann-Zwolicka *et al.*, 2021; De Rovere *et al.*, 2025).

In contrast, Hornsund, located in southern Spitsbergen, remains one of the most glaciated fjords in the region, with thirteen tidewater glaciers present. The inflow of AW into

Hornsund is known to be restricted due to the substantial influence of Arctic Water (ArW) supplied by the ESC (East Spitsbergen Current), as well as the fjord's shallow entrance, which limits the penetration of AW typically found at greater depths in the water column (Strzelewicz *et al.*, 2022; Kalhagen *et al.*, 2024). However, recent observations suggest that even this fjord is beginning to show early signs of atlantification (Promińska *et al.*, 2018; Szymańska *et al.*, 2025). As such, Hornsund offers a unique opportunity to study how the initial stages of AW intrusion influence benthic ecosystems, particularly benthic foraminiferal assemblages that serve as sensitive indicators of environmental change.

Benthic foraminifera are well-established proxies for reconstructing both modern and past Arctic environmental conditions, owing to their broad distribution, ecological sensitivity, and high preservation potential (Hald and Korsun, 1997; Murray and Alve, 2016; Telesiński *et al.*, 2023). Shifts in their assemblages provide valuable insights into changes in sea-ice extent, glacial retreat, and water mass properties, all of which are key features of atlantification (Wilson *et al.*, 2008; Hansen *et al.*, 2023; Nardelli *et al.*, 2023). Arctic taxa, such as *Cassidulina reniformis* and *Cribroelphidium clavatum* (Hayward *et al.*, 2025), typically indicate strong glacial influence and colder conditions (Łącka and Zajączkowski, 2016), whereas the presence of *Cassidulina neoteretis* Seidenkrantz and *Nonionellina labradorica* is indicative of enhanced AW inflow (Hald and Korsun, 1997; Ślubowska *et al.*, 2005; Jernas *et al.*, 2018). Moreover, stable-isotope analyses ($\delta^{18}O$ and $\delta^{13}C$) of foraminiferal calcite offer complementary information on changes in temperature, salinity, and primary productivity associated with atlantification (Tesi *et al.*, 2021; Gamboa-Sojo *et al.*, 2022). Foraminifera are also calcifying organisms, associated with inorganic carbon burial. They constitute up to 38% of inorganic carbon in subarctic fjords and 69% in temperate fjords (Pawłowska *et al.*, 2017; Szymańska *et al.*, 2021). Minor changes in species composition due to climate change can also affect the amount of inorganic carbon burial (Szymańska *et al.*, 2025).

While the use of benthic foraminiferal assemblages and their stable-isotope composition to trace AW inflow and atlantification has been well established in Arctic and sub-Arctic shelf environments (Ślubowska-Woldengen *et al.*, 2007, 2008; Jernas *et al.*, 2018; Łącka *et al.*, 2019; Tesi *et al.*, 2021; Gamboa-Sojo *et al.*, 2022), modern studies that explicitly apply these proxies as a diagnostic toolkit to identify the onset and progression of atlantification in fjord systems remain limited. The majority of previous work has focused on long-term Holocene trends or open-shelf settings, rather than on dynamic, glaciated fjords where AW intrusion is still in its early stages. Consequently, the ability to link modern ecological transitions in fjord foraminiferal communities with their sedimentary analogues is poorly recognised. Hornsund fjord, with its distinct gradient from glacially influenced inner areas to AW-affected outer regions, offers a unique opportunity to investigate these early-stage changes and to refine the use of foraminiferal assemblages and isotopic records as sensitive indicators of atlantification in past and present fjordic environments.

Szymańska *et al.* (2025) documented a significant shift in benthic foraminiferal assemblages in Hornsund between 2002 and 2019, building on earlier observations by Zajączkowski *et al.* (2010). In 2002, Zajączkowski *et al.* (2010) reported that the fjord was dominated by Arctic species, with Atlantic Water (AW) influence restricted to the head of the fjord. Sudden intrusions of AW were first noted from 2014 by Promińska *et al.* (2018), and their effects were investigated by Szymańska *et al.* (2025), who observed a surge of AW extending farther into the fjord by 2019. This shift coincided with a notable decline in Arctic species, such as *Archimerismus subnodosus* Brady, a transition toward smaller foraminiferal species, and a proliferation of opportunistic taxa, ultimately contributing to a reduction in total foraminiferal carbon burial. While these studies established a critical baseline for climate-driven changes in Arctic fjord foraminiferal communities and carbonate flux, the present research aims to extend this trajectory by expanding the framework of observation to include changes documented through 2024 and by incorporating stable isotope signatures of selected foraminiferal species. By comparing new data with results from previous sampling campaigns conducted in 2002 (Zajączkowski *et al.*, 2010) and 2019 (Szymańska *et al.*, 2025), the present authors aim to provide both contemporary baseline information, and reference points for interpreting AW intrusions in fjord sedimentary records.

The present approach integrates faunal analyses with metrics of alpha and beta diversity, multivariate statistical techniques including principal component analysis (PCA), and non-metric multidimensional scaling (nMDS), as well as stable-isotope analyses of oxygen and carbon in foraminiferal calcite. By resampling the same locations across multiple years apart, this study uniquely enables direct observation of modern foraminiferal assemblage changes. Unlike core-based approaches, it avoids biases from selective preservation, providing a clear advantage for ecological studies. Together, these methods provide a comprehensive framework for documenting ecosystem responses to atlantification in one of the Arctic's most vulnerable marine environments.

STUDY AREA

Hornsund, the southernmost fjord on the west coast of Spitsbergen Island in the Svalbard archipelago, is relatively small, approximately 35 km long and 12–15 km wide (Fig. 1). It reaches a maximum depth of 260 m, but its defining characteristic is a shallow entrance of approximately 100 m (Promińska *et al.*, 2018). Several land-based and tidewater glaciers significantly melt in summer, contributing to the sediment load and influencing the fjord's freshwater input. These glaciers, along with the unique bathymetry, create a complex interplay of factors that affect the fjord's hydrography and sedimentary processes (Staszek and Moskalik, 2015). Hornsund tidewater glaciers have experienced significant retreat over the 20th and early 21st centuries, driven by increases in average annual sea and air temperatures (Błaszczyk *et al.*, 2013, 2023). The local climate is primarily influenced by meteorological factors, including rising air temperatures (~1 °C per decade), a decrease in average

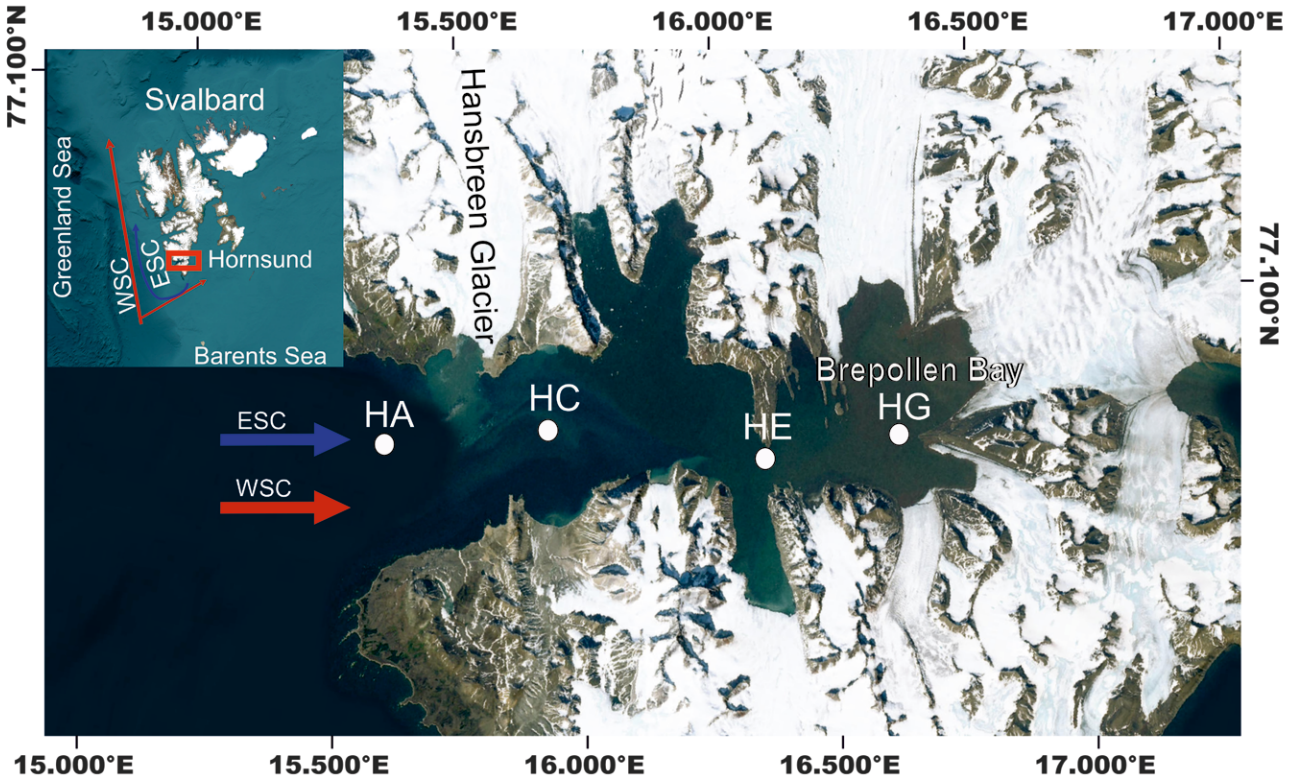

Fig. 1. Map of Hornsund showing the locations of the four sampling stations, Brepollen Bay, and the Hansbreen Glacier. Abbreviations: West Spitsbergen Current (WSC); East Spitsbergen Current (ESC).

sunshine duration since 1979 caused by increased cloudiness, and variations in relative humidity, which can reach up to 100% during the warmer months and drop considerably in winter (Wawrzyniak and Osuch, 2020; Strzelewicz *et al.*, 2022). Over the last two decades, retreating sea ice has enhanced wave energy along the Hornsund coast (Herman *et al.*, 2025). Global climate change has also led to increased intrusion of Atlantic Water (AW) and elevated primary production in Hornsund, although the magnitude of these changes is less pronounced than in other western Spitsbergen fjords (Krajewska *et al.*, 2020). The sediments in Hornsund primarily consist of mud and sandy mud, with variations including laminated mud, homogeneous to bioturbated mud, and sandy gravel (Drewnik *et al.*, 2016).

Hornsund waters are influenced by the ESC, which transports cold and fresh ArW from the northeastern Barents Sea, and the WSC that brings in warm and saline AW from the southern Norwegian Sea (Fig. 1). AW enters the fjord from the mouth, and a boundary between cold ArW and warm AW is formed, called the Polar Front (PF). The PF plays a crucial role in restricting the AW inflow further into Hornsund (Saloranta and Svendsen, 2001). The AW and ArW mix along the continental shelf, resulting in Transformed Atlantic Water (TAW), and can be observed throughout the fjord in varying amounts throughout the year (Promińska *et al.*, 2018; Korhonen *et al.*, 2024). During winter, the Surface Water (SW) is cooled, and due to the complex interplay between ice-air-sea, a dense Winter Cooled Water (WCW) is formed. During summer, this WCW is typically found in deeper parts of Brepollen.

MATERIALS AND METHODS

Four stations were sampled on 2nd September 2024 (Fig. 1) during a research cruise aboard S/Y *Oceania.* Sampling stations were distributed along the fjord: HA at the mouth, HC in the central part, HE near the head, and HG in Brepollen, a glacial bay. These stations correspond to those sampled in the summers of 2002 (July; Zajączkowski *et al.*, 2010) and 2019 (late August; Szymańska *et al.*, 2025) for which the sampling procedure and equipment were exactly the same. For this study, three replicate cores were collected from each of the four stations, resulting in the following three replicate identifiers, e.g., HAa, HAb, and HAc. In total, twelve sediment cores, 10 cm in length, were collected. A small gravity corer with a 7-cm diameter was used for collection. Sample processing was done according to the FOBIMO protocol (Schönfeld *et al.*, 2012). The present authors analysed the upper 2 cm of sediment to ensure a representative, time-averaged foraminiferal record. This depth is optimal for capturing the homogenization of seasonal populations, such as *N. labradorica* and *E. excavatum*, which are blended through bioturbation (Zajączkowski *et al.*, 2010; Łącka and Zajączkowski, 2016). This sampling strategy also accounts for the dynamic nature of Arctic benthic taxa, which Kucharska *et al.* (2019) noted can migrate vertically through glaciomarine sediments to optimize their position, relative to oxygen and nutrient gradients. Cores were cut horizontally into 1 cm slices and preserved in 70% ethanol with Rose Bengal stain right after collection. *In situ* temperature and salinity were measured at 1-second intervals at each site using a Mini-CTD Sensordata SD202. The Ocean Data View software version 5.7.0 (ODV) was used to produce the temperature and salinity graphs.

In the laboratory, the sediments were dried in a laboratory oven, weighed and then washed over sieves of 500-µm, 100-µm, and 63-µm. After drying, the sediment fractions were weighed again, and the foraminifera were picked from the 500-µm and 100-µm fractions under a stereomicroscope. Although the FOBIMO protocol recommends a 125-µm sieve, this study utilized a 100-µm mesh to better reflect Arctic conditions. Because Arctic foraminifera are typically smaller than their lower-latitude counterparts, the 100-µm fraction is more effective in capturing a comprehensive representation of the total assemblage (Dessandier *et al*., 2019). Additionally, this method was also used by Szymańska *et al.* (2025) whose database serves as a basis for comparison for this study.

The identification of foraminifera species was carried out in accordance with the classification described by Loeblich and Tappan (1987), and the database at the Institute of Oceanology, Polish Academy of Sciences. The total foraminiferal count from both 1 cm and 2 cm sediment layers was used for analysis. The relative abundance of species was calculated, and this study focuses on foraminifera species with an abundance of greater than 5%. The total counts of foraminifera are presented in Supplementary Material 1 (https://zenodo.org/records/19188042).

As the work is intended to provide background for palaeoceanographic studies of AW inflow, the total foraminiferal assemblages (living + dead) were used in the analysis. An important role in the interpretation is also played by agglutinated foraminifera, which are known to be difficult to distinguish using Rose Bengal staining (Bernhard, 2000). Furthermore, detecting trends in atlantification was a key objective of this study, rather than focusing on the short-term seasonal variability. Therefore, the present authors aimed to study the total, multiyear assemblage, with results from 2002 (Zajączkowski *et al*., 2010, 2019; Szymańska *et al*., 2025), and 2024, with sampling intervals of at least five years.

The diversity analysis was performed using the vegan package in R (Oksanen *et al*., 2025). Four diversity indices were calculated, Fisher's Alpha index (α), Shannon index (H), Species richness, and Simpson's Diversity index. To investigate the differences in foraminiferal assemblages over the years, Principal Component Analysis (PCA) using PAST (PAleontological STatistics) software and non-metric multidimensional scaling (nMDS), based on the Bray-Curtis similarity coefficient using R, were conducted. To account for the greater species richness in the replicated 2024 samples, only data from the "a" replicate core was used to calculate the percentage and number of agglutinated *vs*. calcareous foraminifera. This approach ensures consistency, when comparing with the single-core samples from 2002 and 2019.

Isotopic analysis of $\delta^{13}C$ and $\delta^{18}O$ in tests of selected species *Cassidulina reniformis, Lobatula lobatula* Walker and Jacob, and *Nonionellina labradorica*, collected in 2019 (Szymańska *et al*., 2025) and 2024 was carried out in the Light Stable Isotope Mass Spectrometry laboratory. These results were compared with the isotopic values from specimens, collected in 2002 (Zajączkowski *et al*., 2010).

RESULTS

Temperature and Salinity

The profiles of temperature and salinity for all sampling stations are presented in Figure 2. Surface Water (SW) temperature at station HA, located in the mouth of the fjord, was 8 °C. The temperature fluctuated between 2 °C to 3 °C below 50 m water depth. The SW temperature of station HC was 5 °C, and below 100 m depth, the temperature was between 2 ° C to 3 °C. Stations HE and HG both had a SW temperature of 5 °C, and below 100 m depth, the temperature was slightly above 0 °C. The SW salinity was lowest at station HA, ~5, followed by HG with salinity around 16. The SW salinity at the centre and head of the fjord was ~30 and ~28, respectively. The salinity below 100 m at stations HA and HC was slightly above 35, and at stations HE and HG, the salinity was slightly below 35.

Using the water mass classification for Hornsund after Promińska *et al*., (2018) and references therein, the CTD data shows intrusion of pure AW well into the central fjord area. The salinity of the SW of station HA was low because of meltwater from the surrounding glaciers mixing with the SW, resulting in brackish water. The same can be observed at station HG, which gets meltwater from Brepollen glaciers. The bottom water at stations HE and HG was occupied by WCW, while the central area of the entire water column was occupied by TAW.

Foraminiferal assemblage in 2024

Alpha diversity

Alpha diversity indices of the replicates of each station were highly consistent (Fig. 3). The stations in the mouth and central area of the fjord (HA, HC, HE) exhibited highly comparable alpha diversity indices. These three stations exhibited high species richness, with values from 34 to 44. Stations closer to the mouth and the central part of the fjord showed high Fisher's α (7.7 to 8.5) and Shannon H values (2.6 to 2.8). The Simpson's Diversity index demonstrated values much closer to 1 at stations HA, HC, and HE. The Fisher's α values ranged between 7.1 at HE to 8.5 at station HA, while Shannon H values ranged from 2.6 to 2.8. Whereas the inner station HG exhibited very low values of richness from 7 to 9, and low values of both α and H, ranging between 3.5–4.8 and 1.3–1.5, respectively, together with the Simpson's diversity index close to 0.

Assemblage composition at mouth region (station HA)

Analysis of cores from station HA (a, b, c) reveals *Cribroelphidium clavatum* as the dominant species (Fig. 4), constituting from 22 to 26% of all three assemblages. In HAa, *Nonionellina labradorica* occupies the second position with a 10% relative abundance, while *Adercotryma glomeratum* follows at 9%, *Cassidulina reniformis* and *Lobatula lobatula* each comprise 8% of the assemblage. *Astrononion hamadaense* occupies 5% of this assemblage. *Adercotryma glomeratum* is the second most abundant species in HAb and HAc (14%, and 16%, respectively). In the HAb assemblage, *Recurvoides turbinatus* and *N. labradorica* both constitute 11%. In HAc, their respective

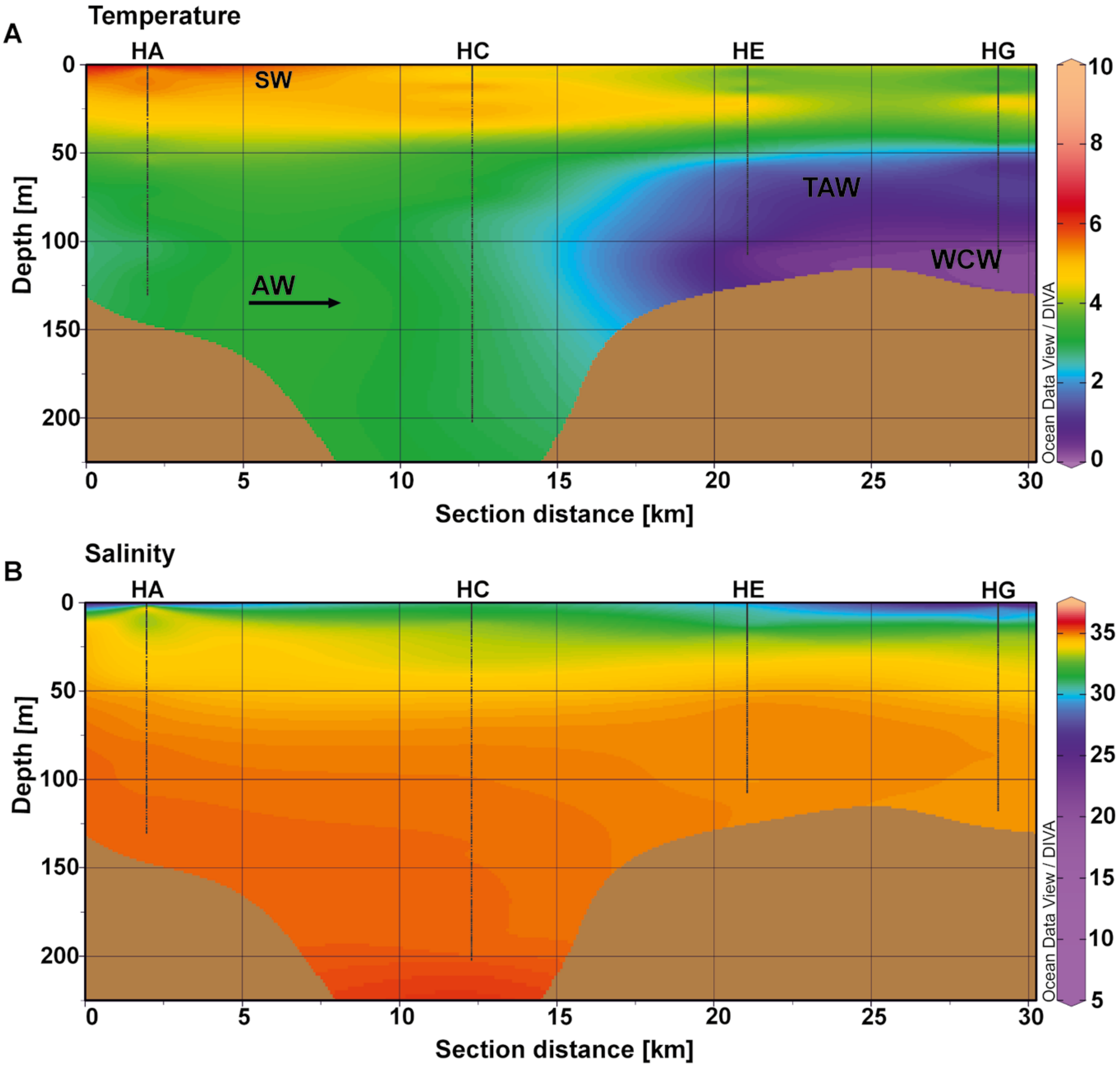

Fig. 2. Physical water properties **A.** Temperature. **B.** Salinity. Both measured at each sampling station (HA, HC, HE, HG) on the day of sediment sample recovery in September 2024. Abbreviations: Surface Water (SW), Atlantic Water (AW), Transformed Atlantic Water (TAW), Winter Cooled Water (WCW). Water mass classification based on Promińska *et al*. (2018).

contributions are 8% and 11%. In HAb, *L. lobatula* represents 6% of the assemblage, while *C. reniformis* exhibits an abundance below 5%. Conversely, in HAc, *C. reniformis* constitutes 8% of the assemblage, whereas *L. lobatula* falls below the 5% abundance threshold.

Assemblage composition at central fjord region (station HC)

The agglutinated species *Reophax fusiformis* Williamson predominates in core HCa, constituting 19% of the assemblage, followed by the calcareous species *C. clavatum*, which constitutes 16%. *Spiroplectammina biformis* Parker and Jones makes up 6% of the assemblage in HCa. HCb and HCc are dominated by *C. clavatum* occupying 19% and 20% of each assemblage. In HCb, this is followed by the agglutinated *R. fusiformis*, which makes up 15% of the assemblage. *N. labradorica* emerges as the second most dominant species in HCc with 15% abundance, followed by *R. fusiformis*, which constitutes 13%. *C. reniformis* contributes 8%, 9%, and 11% to the assemblages in HCa, HCb, and HCc, respectively. *Textularia earlandi* Parker constitutes 6% of all three assemblages.

Assemblage composition at fjord head and glacial bay, Brepollen (stations HE and HG)

Foraminifera assemblages in HE (a, b, c) cores show notable similarities. *C. reniformis* consistently dominates all three assemblages, constituting from 26 to 31% of the total. The agglutinated species *R. turbinatus* follows as the second most abundant, ranging from 13% to 15%. HEa is

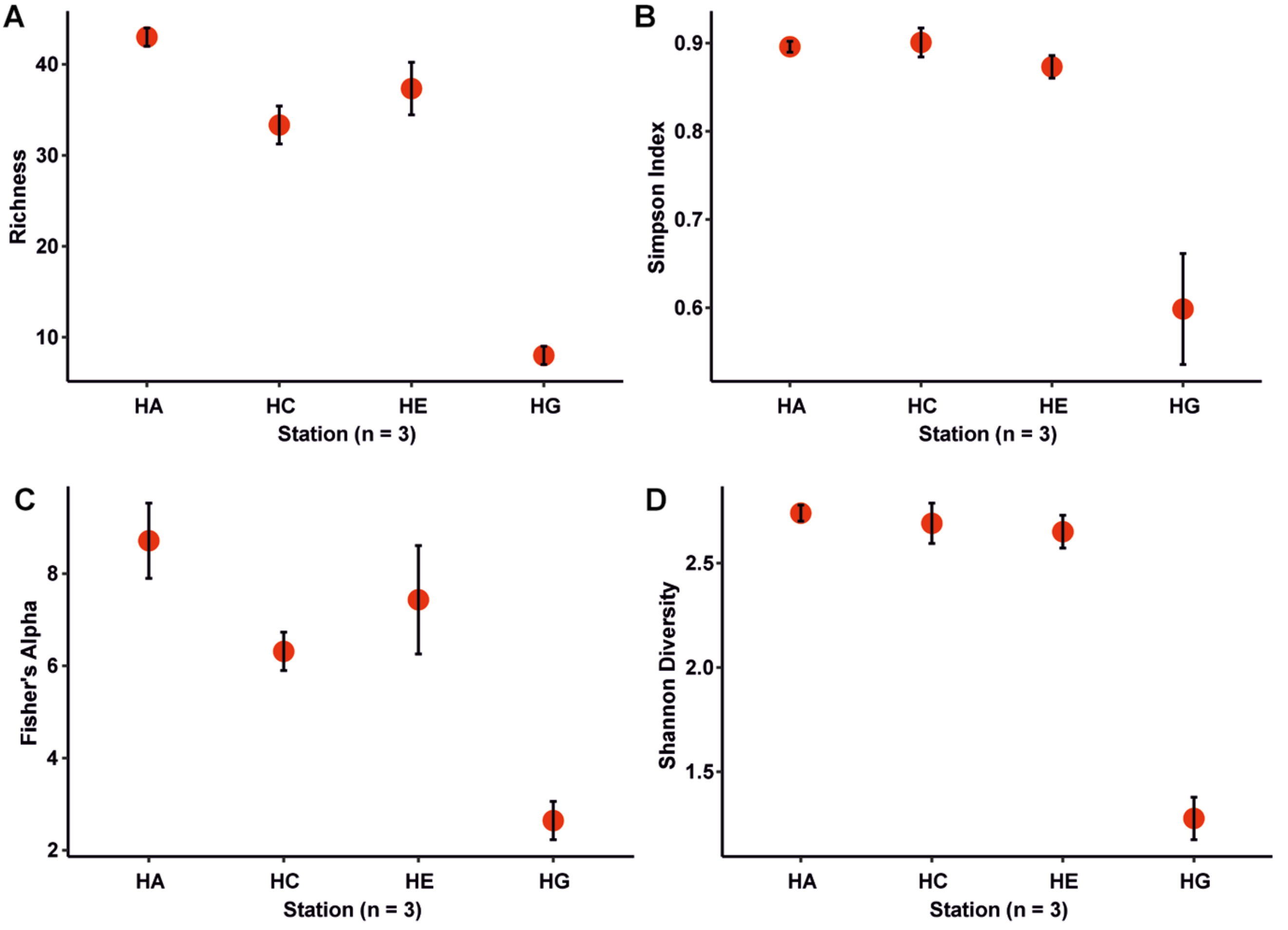

Fig. 3. Diversity indices. **A.** Richness, **B.** Simpson index, **C.** Fisher's Alpha, and **D.** Shannon Diversity of foraminifera at stations HA, HC, HE and HG.

characterised by a higher diversity of agglutinated species, with *S. biformis* contributing 8%, and *Labrospira crassimargo* Norman, 6%. In HEb, *N. labradorica* shows an increased abundance at 8%, while most agglutinated species fall below the 5% threshold. In HEc, agglutinated species, except for *L. crassimargo* (7%), exhibit abundances below 5%.

Foraminifera assemblages in HG (a, b, c) exhibit slight variations. In HGa, *C. reniformis* predominates, constituting 58% of the assemblage, followed by *N. labradorica* (22%), *Islandiella helenae* Feyling-Hanssen and Buzas and the agglutinated species *L. crassimargo* make up 7% each. In HGb, *C. reniformis* remains predominant at 66%, with *L. crassimargo* (15%) and *N. labradorica* (7%) contributing significantly. In contrast, HGc is characterised by the predominance of the agglutinated species *L. crassimargo* (49%), followed by *C. reniformis* (30%) and *N. labradorica* (9%). More than 50% of specimens were alive in all 3 assemblages.

Statistical comparison of the 2002, 2019 and 2024 foraminiferal assemblages

Beta diversity

The beta diversity, based on the nMDS analysis, reveals a distinct clustering of stations by year, indicating temporal variation in foraminiferal assemblages and a significant shift in species composition over time (Fig. 5).

Principal Component Analysis (PCA)

In the year 2002, PC1 associated with an abundance of *C. clavatum* and *C. reniformis* represents a dominant gradient, explaining 88.4% of the total variance between the sampling stations. PC2 explains only 11.4% of the variance and distinguishes HA and HC from HE and HG. This component is associated with *R. turbinatus* and *N. labradorica*. PC3, explaining only 0.17% of the variance, is not interpretable as a meaningful gradient (Fig. 6).

In the year 2019 PC1, primarily associated with *L. crassimargo* and *C. reniformis,* accounts for 71.6% of the total variance and clearly separates HE, which scores highly positive, from the remaining sites, which all show negative values. PC2 explains 19.0% of the variance and contributes to the differentiation of HA and HG. It is associated with *N. labradorica* and *C. clavatum*. PC3 (variance explained: 9.5%) distinguishes HC from the other sites. The taxa, most associated with this axis (*E. clavatum, C. reniformis*), overlap with those in PC1 and PC2.

In 2024, PC1, explaining 49% of the variance, distinguishes HA and HC from HE and HG. This axis is associated with *C. clavatum* and *R. fusiformis*. PC2, explaining

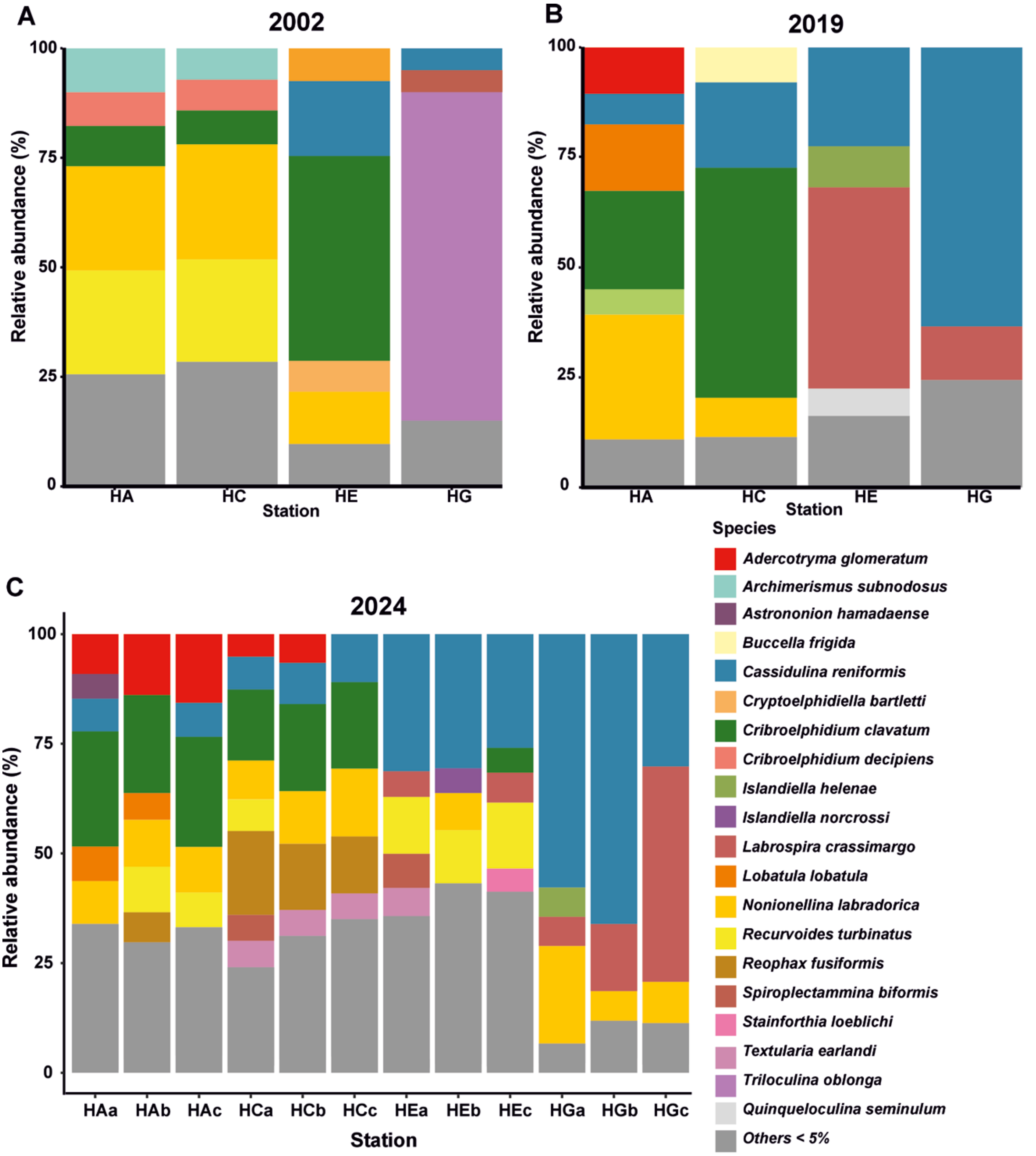

Fig. 4. Relative abundance (>5%) of predominant foraminifera species during **A.** 2002, **B.** 2019, and **C.** 2024 at stations HA, HC, HE and HG. Species with relative abundance <5% are summarised as "others".

34.9% of the variance, separates HE from HG, with *C. reniformis* and *R. turbinatus* contributing most strongly. PC3 separates HA and HC, with *C. clavatum* and *A. glomeratum* associated with this axis; however, it only explains 15% of the variance between the stations.

Isotopic analysis

Specimens from 2024, show lower $\delta^{13}C$ values in the mouth and central stations and a peak in the innermost station, HG. Conversely, the $\delta^{18}O$ values are higher for all three species in the mouth and central station and lowest in the innermost station. In general, the $\delta^{18}O$ values are higher in 2024 compared to 2019, and $\delta^{13}C$ values are lower in 2024 than in 2019 (Fig. 7). *L. lobatula* has the lowest $\delta^{18}O$ and highest $\delta^{13}C$ values in 2024, while *N. labradorica* and *L. lobatula* have equally high $\delta^{18}O$ and lower $\delta^{13}C$ values compared to *L. lobatula* (Fig. 7). The $\delta^{13}C$ and $\delta^{18}O$ values were, on average, lower in specimens from 2019 cores than in specimens from 2002 cores (Fig. 7). *L. lobatula* had the highest $\delta^{13}C$ signature. It was also the only species, for which two $\delta^{18}O$ values were lower in 2002 than in 2019,

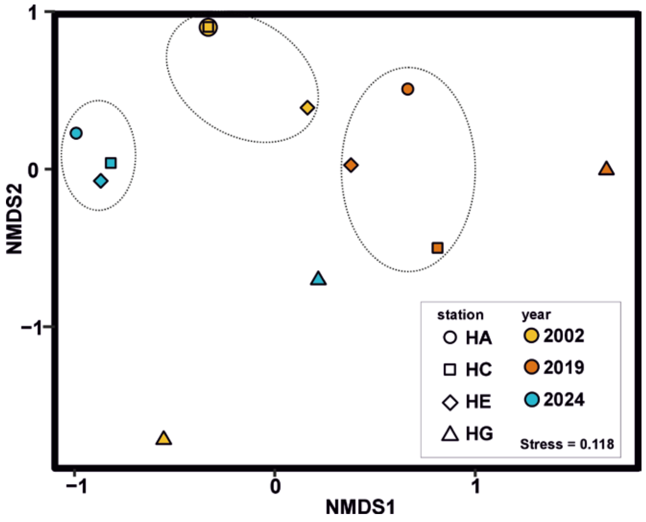

Fig. 5. Non-metric multidimensional scaling analysis (NMDS) based on(Bray-Curtis dissimilarity and on foraminiferal abundance. The colours represent different years (2002, 2019, 2024), and the shapes represent different stations (HA, HC, HE, HG).

2.25 at station HC and, –2.08 at station HA. The isotopic composition of *N. labradorica* showed a clear difference between 2002 and 2019. *N. labradorica* was also characterised by the lowest δ^{13}C values, with six measurements below –2.5 δ^{13}C, and for *C. reniformis* δ^{18}O values ranged from 3 ± 1 to 3.5 ± 1.

DISCUSSION

This study presents multi-proxy evidence of progressive atlantification in Hornsund over the past two decades. CTD data from 2002, 2019, and 2024 reveal a steady increase in the influx of warm, and saline AW, which dominated the outer and central fjord stations by 2024. This oceanographic shift is mirrored in the stable isotopic composition of foraminiferal tests. The local foraminifera underwent a substantial faunal transition from Arctic-dominated to boreoarctic assemblages. These boreoarctic communities include a significant proportion of agglutinated taxa, particularly within the glacially influenced environments of the inner fjord. The lighter δ^{13}C values collectively indicate changes in marine productivity and sedimentary carbon dynamics. The present results indicate that Hornsund Fjord is rapidly losing its distinct Arctic character (Węsławski *et al.*, 2006; Nilsen *et al.*, 2008). By combining faunal and isotopic data, this study show that these multi-proxy records provide essential signals of atlantification in glaciated fjord systems.

The comparison of Zajączkowski *et al.* (2010), Szymańska *et al.* (2025), and the present datasets provides valuable insight into the ecological consequences of atlantification in a glaciated Arctic fjord. By including replicate sediment cores, the present study reduces the influence of small-scale spatial patchiness and strengthens the reliability of faunal interpretations. In contrast to the declining trends reported by Szymańska *et al.* (2025), the present results indicate a relatively stable and a more adjusted benthic foraminiferal assemblage over the observed period, suggesting resilience

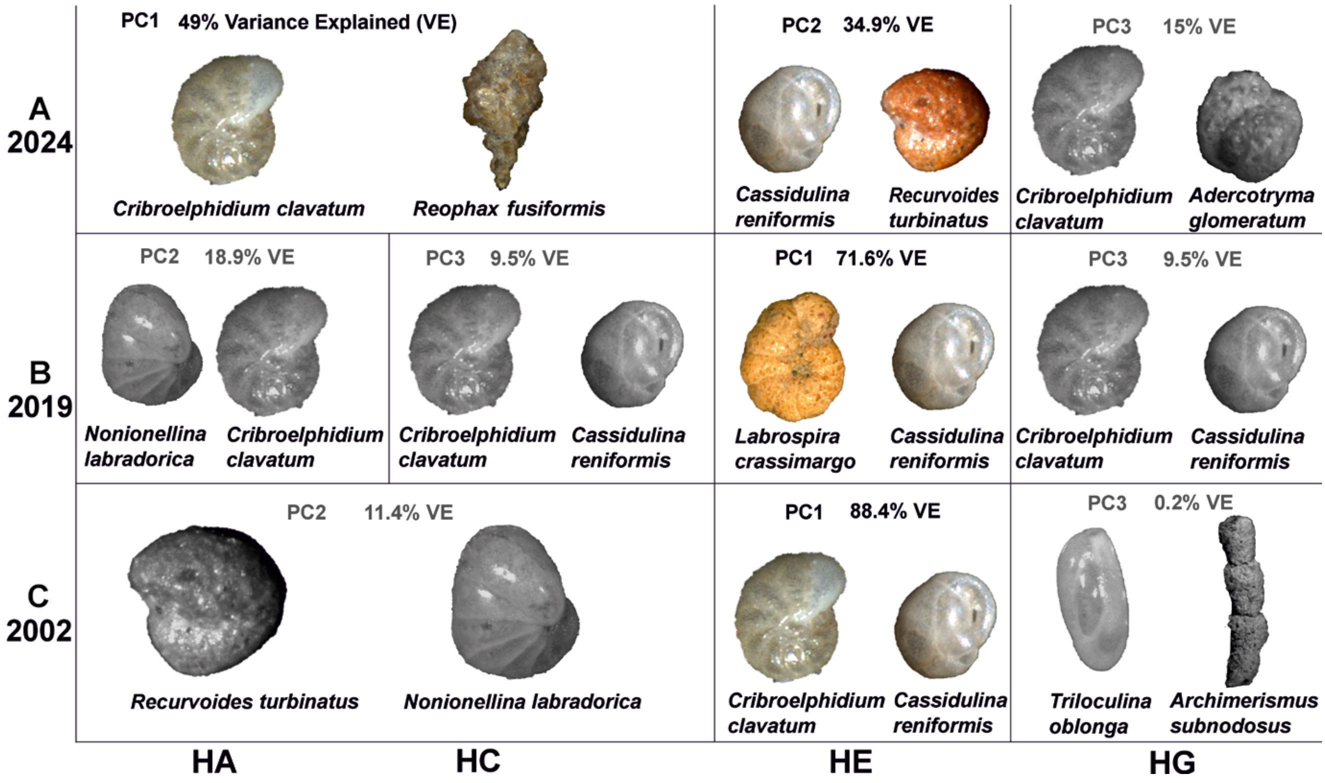

Fig. 6. PCA plot of foraminiferal assemblages from four stations (HA, HC, HE, HG). **A.** 2024 assemblage, **B.** 2019 assemblage, **C.** 2002 assemblage. Each principal component (PC) is illustrated with images of the dominant (first image) and secondary (second image) species contributing most to the explained variance, with the percentage of variance explained (VE) indicated. Grayscale imaging is used for PCs that account for less than 20% of the variance.

or adaptation of the community to ongoing environmental changes. Although the temporal resolution of the present study is limited to three discrete years and cannot resolve high-frequency seasonal fluctuations, the consistency across oceanographic, ecological, and isotopic indicators supports this conclusion. Furthermore, while the low preservation potential of agglutinated taxa and species-specific isotopic vital effects present challenges for long-term reconstructions, the present multi-proxy approach provides a robust modern analogue for assessing rapid environmental shifts in Arctic fjords.

The foraminiferal assemblage in Hornsund in 2024

The mouth and central regions (stations HA and HC) of the fjord are strongly influenced by AW (Fig. 5) as a result, boreoarctic assemblages dominate. *Cribroelphidium clavatum,* an opportunistic species, that dominates here thrives under a wide range of environmental conditions in the Arctic (Hald *et al.*, 1994). It is known to tolerate freshwater influence (Korsun *et al.*, 2014) which in these areas may result from the input of meltwater from tidewater glaciers. *Adercotryma glomeratum, Astrononion hamadaense*, *Nonionellina labradorica,* and *Reophax fusiformis*, all associated with AW were also present (Hald and Korsun, 1997; Lloyd, 2006; Krishnapriya *et al.*, 2019; Chatterjee and Ghosh, 2023; Guilhermic *et al.*, 2024). In the fjord mouth, the presence of species *Lobatula lobatula* is characteristic of regions with high bottom current activity (Wollenburg *et al.*, 2021), which can be explained by the station's location in a shallower area where water exchange is more pronounced. Additionally, Wollenburg and Mackensen (1998) reported a high correlation between an assemblage of *L. lobatula* and *A. hamadaense* and increased water salinity, further highlighting the strong influence of AW on the species composition at this site.

These stations also exhibit elevated species richness, along with high values of Fisher's α, Shannon H, and Simpson's Diversity index (approaching 1), all of which indicate both high diversity and evenness. Such diversity levels in these stations are likely driven by increased water exchange and higher salinity, conditions consistent with the persistent intrusion of AW in these regions.

The water mass characteristics of the inner fjord (stations HE and HG) are associated with TAW. In the fjord head (station HE) the presence of TAW is evidenced by a high number of agglutinated specimens (Fig. 8) represented by *R. fusiformis* and *A. glomeratum.* The main dominating species at this station, however, is *Cassidulina reniformis*. The glacial bay area (station HG) is dominated by *C. reniformis* and *Labrospira crassimargo*. While *C. reniformis* is a typical dominant species in glacio-proximal zones, *L. crassimargo* is commonly found in areas with high sedimentation rates, which may result from increased

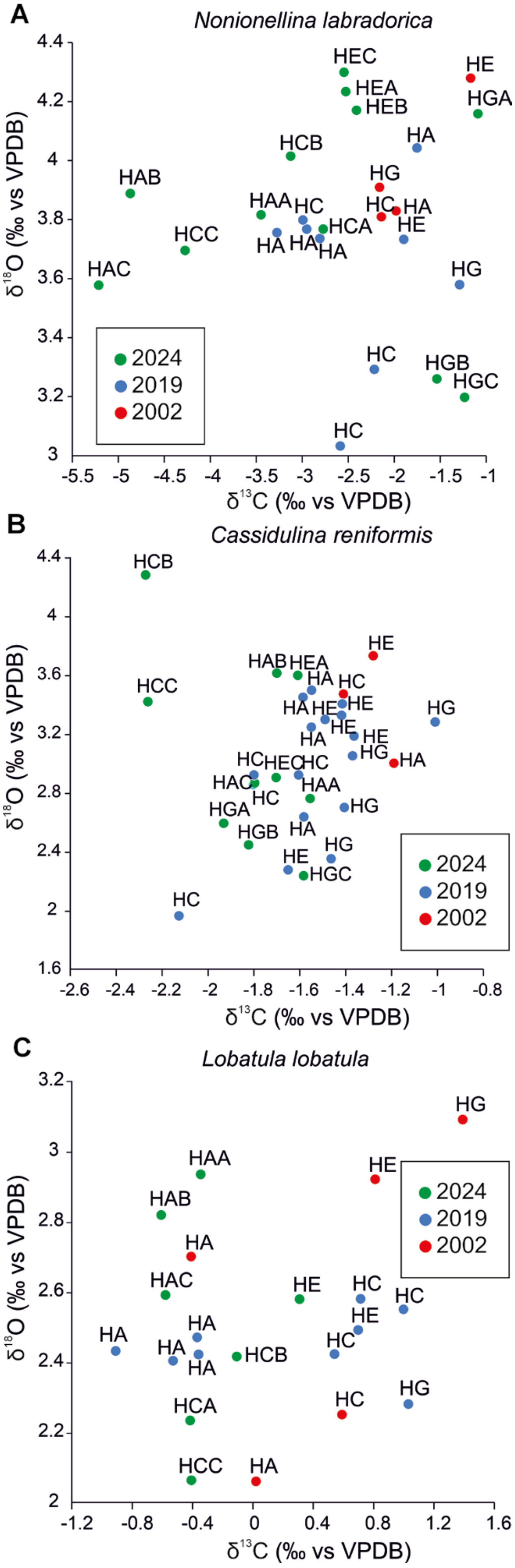

Fig. 7. Scatter plot of stable isotope values, $\delta^{18}O$ and $\delta^{13}C$, % vs VPDB (Vienna Pee Dee Belemnite) for three species at each station from 2002, 2019, and 2024. **A.** *Nonionellina labradorica*, **B.** *Cassidulina reniformis*, and **C.** *Lobatula lobatula*.

sedimentary input from the retreating glaciers (Hald and Korsun, 1997; Zajączkowski *et al.*, 2010; Szymańska *et al.*, 2017; Jennings *et al.*, 2020; Fossile *et al.*, 2022).

Station HE is characterised by high species richness and elevated diversity metrics, including Fisher's α, Shannon H, and a Simpson's Diversity index approaching 1. These values reflect a well-balanced and diverse foraminiferal community, comparable to that observed at the mouth and central fjord stations. The abundance and number of foraminiferal species at station HG are significantly lower compared to all other stations (Figs 3, 4). The low biodiversity is also reflected in low values of Fisher's α and Shannon H. Simpson's Diversity index, being much closer to 0, also indicates a less diverse assemblage that is dominated primarily by one species. This is most likely a direct result of the stressful environment and high sediment accumulation rates characteristic of this setting.

Nonionellina labradorica is generally associated with the polar front, where the AW meets the ArW (Ślubowska *et al.*, 2005) and is found throughout the fjord in varying amounts. In 2002, this species had dominated the outer and central fjord, in 2019 due to changes in the type of organic matter deposition*, N. labradorica* remained restricted to the outer station (Zajączkowski *et al.*, 2010; Szymańska *et al.*, 2025). In 2024, *N. labradorica* dominated the innermost station (HG). This suggests the polar front may have extended further into the fjord. At the same time, this species is also known to survive in the Arctic fjords even in low oxygen environments because of its ability to retain chloroplasts after a season of high productivity (Cedhagen, 1991; Racine *et al.*, 2023). Its presence throughout the fjord under varying conditions may result from its ability to adapt to stressful environments, as well as its preference for AW, as previously observed in Kongsfjorden by Guilhermic *et al.* (2024).

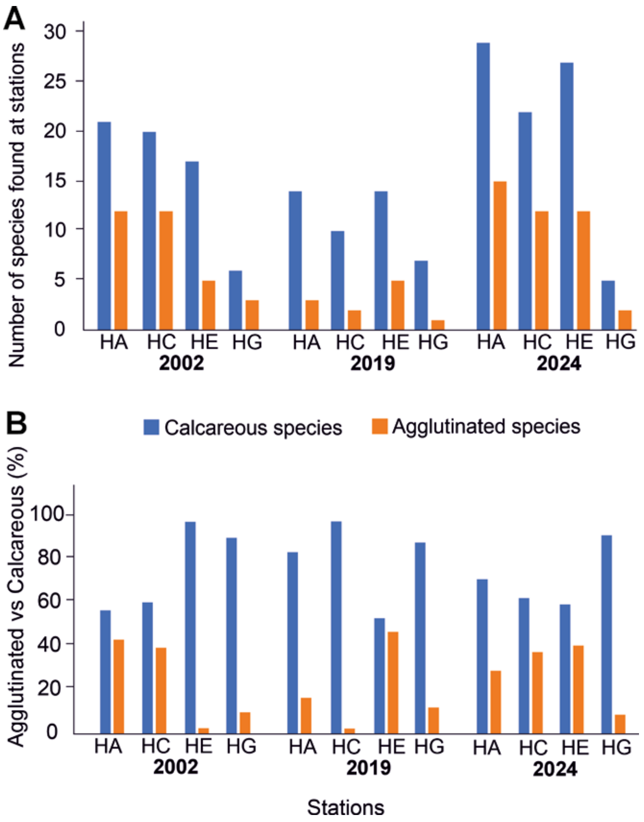

Fig. 8. Agglutinated and calcareous foraminifera from the years 2002, 2019, and 2024. **A.** Number of species found at stations, **B.** Percentage of agglutinated vs calcareous foraminifera.

Statistical comparison of the 2002, 2019, and 2024 datasets

The NMDS analysis of foraminiferal abundance data from 2002, 2019, and 2024 reveals that sampling year is the primary factor, influencing assemblage composition at stations HA, HE, and HC. In contrast, at station HG, located in the glaciated bay of Brepollen, the assemblage appears to be strongly shaped by local environmental conditions rather than interannual variability (Fig. 6).

In 2024, agglutinated foraminifera played a significant role in shaping the principal components identified across all stations. Most notably, two agglutinated species, recognised as indicators of AW, were dominant contributors to the principal components at the innermost stations, highlighting the influence of AW in these areas. *Recurvoides turbinatus* emerged as a significant contributor to a PC, identified at station HE. Previous studies consistently recognise *R. turbinatus* as a reliable indicator of AW inflow (Hald and Korsun, 1997; Majewski and Zajączkowski, 2007; Rasmussen and Thomsen, 2015). The second agglutinated species found in PC at the inner fjord station, *A. glomeratum,* is also indicative of AW, and was previously positively related to high bottom water salinity in Kongsfjorden (Jernas *et al.*, 2018).

In 2019, *L. crassimargo* contributed to PC1 at station HE, which explained a substantial proportion of the variance (71.6%). This suggests that the high abundance of *L. crassimargo* was a major factor, shaping assemblage differences among stations that year. This species is typically found in regions with high sedimentation rates, which in Hornsund result from enhanced sediment input, caused by retreating glaciers (Hald and Korsun, 1997; Zajączkowski *et al.*, 2010; Szymańska *et al.*, 2017; Jennings *et al.*, 2020; Fossile *et al.*, 2022).

In 2002, *R. turbinatus* was the dominant species in the outer fjord, while *Archimerismus subnodosus* Brady (previously known as *Hyperammina subnodosa*) dominated the innermost station. The dominance of *R. turbinatus* can be readily explained by its known preference of AW, but the prevalence of *A. subnodosus* is more difficult to interpret (Hald and Korsun, 1997; Zajączkowski, 2007; Rasmussen and Thomsen, 2015). This large, agglutinated foraminifer is typically rare and not commonly reported in Svalbard fjords, but it is relatively common further offshore, for example at the Hovgaard Ridge (Kaminski *et al.,* 2015). Its occurrence most likely reflects an unusual combination of environmental conditions, or perhaps an unknown factor that favoured its growth over the more typical calcareous species.

A general trend of increased presence of agglutinated foraminifera at the innermost stations is apparent in the present data (Figs 6, 8). Previous studies describe a typical distribution pattern in Svalbard fjords, where agglutinated taxa dominate outer stations, and calcareous species prevail closer to the glacier fronts (Majewski and Zajączkowski, 2007). The statistical comparison reveals that this distribution pattern in Hornsund has shifted over time, and the current prominence of agglutinated species in the assemblages of Hornsund may reflect either increased sediment supply driven by glacier retreat, enhanced influence of AW, or, most likely, an interconnected combination of these factors.

Stable isotope analysis and short-term records

Habitat preferences and environmental factors, such as sea ice cover, temperature, and salinity, influence foraminiferal isotopic signatures (Pearson, 2012; Murray, 2014; Hoogakker *et al.*, 2024). The epifaunal species *L. lobatula* shows slightly lower $\delta^{18}O$ and higher $\delta^{13}C$ values compared to the infaunal species *N. labradorica* and *C. reniformis*, likely reflecting species-specific vital effects (Fontanier *et al.*, 2008; Zajączkowski *et al.*, 2010; Theodor *et al.*, 2016; Jöhnck *et al.*, 2021). The isotopic record of *N. labradorica* indicates progressive atlantification in Hornsund, with increasing $\delta^{18}O$ values linked to higher salinity and decreasing $\delta^{13}C$ values associated with enhanced primary productivity (Fig. 7). High-productivity environments typically exhibit lower $\delta^{13}C$ values in dissolved inorganic carbon and foraminiferal tests (Hoogakker *et al.*, 2024). Primary productivity in Hornsund has increased since 2002, as reflected by decreasing $\delta^{13}C$ values across all studied species (Fig. 7), consistent with sedimentary organic matter observations (Krajewska *et al.*, 2020) and broader productivity increases reported from Svalbard fjords (Arrigo *et al.*, 2015; Caroppo *et al.*, 2017). Additional $\delta^{13}C$ depletion may result from increased terrestrial organic matter input linked to glacier retreat and expanding vegetation in the fjord catchment, as terrestrial plants typically exhibit low $\delta^{13}C$ values (Ehleringer, 1991).

Salinity exerts a strong control on $\delta^{18}O$ values (Pados *et al.*, 2015). Stations HA and HC, influenced by saline Atlantic Water, show elevated $\delta^{18}O$ values despite relatively higher temperatures. In contrast, inner fjord stations affected by less saline Transformed Atlantic Water and glacial meltwater display lower $\delta^{18}O$ values. Reduced $\delta^{18}O$ at station HC may additionally reflect freshwater runoff from adjacent land areas.

The diagnostic criteria for early atlantification in fjords

The patterns of ecological shifts, observed in Hornsund foraminifera assemblages, can serve as diagnostic indicators of atlantification in high-latitude fjord systems, both in studies focusing on recent changes, as well as in reconstructions of geological past. The increasing presence of agglutinated taxa, such as *A. glomeratum, R. fusiformis,* and *R. turbinatus,* along with calcareous species, such as *A. hamadaense,* and *N. labradorica*, at the innermost stations is one factor that has been previously documented in fjords undergoing atlantification (Jernas *et al.*, 2018; Kujawa *et al.*, 2021). However, agglutinated foraminifera, such as *R. fusiformis,* have low preservation rates and hence are rarely seen in palaeorecords (Devendra *et al.*, 2023) as compared to modern studies, where they are seen as dominating (Majewski *et al.*, 2023; Racine *et al.*, 2023). This indicates that, for a robust reconstruction of oceanographic change, additional approaches, such as sedimentary ancient DNA, can help detect the full spectrum of changes in foraminiferal species (Nguyen *et al.*, 2023).

Elevated species richness and high values of Fisher's α, Shannon H, and Simpson's Diversity indices in the outer, central, and some inner fjord stations indicate well-balanced, high-diversity communities associated with AW. In such fjords, boreoarctic (Fig. 9) taxa expand into the Arctic systems and temporarily elevate the diversity before eventual homogenization (Spielhagen *et al.*, 2011; Polyakov *et al.*, 2017; Guilhermic *et al.*, 2024). Conversely, low diversity and dominance by a few stress-tolerant, opportunistic species, such as *C. reniformis* and *C. clavatum*, in glacially influenced areas reflect the harsh environmental conditions and high sediment accumulation, characteristic of these settings. Temporal analyses further reveal that agglutinated species are increasingly prominent across the fjord over the last two decades, consistent with progressive AW intrusion and the early stages of atlantification.

The present study indicates that foraminiferal communities react over a relatively short time span, just two decades, and respond rapidly to environmental changes, such as variations in water mass properties, meltwater input, and sedimentation rates, making them excellent indicators of climate change and warming events (Dong *et al.*, 2019; Titelboim *et al.*, 2019). Complementing these faunal patterns, the isotopic records of foraminiferal tests clearly captured variations in salinity, temperature, and productivity over the 22-year span. *Cassidulina reniformis* and *N. labradorica* are typically well-preserved in fjord sediments and can be used as reliable sources of isotopic signatures, indicative of atlantification. *Lobatula lobatula*, on the other hand, shows a less pronounced and more mixed signal of atlantification. This highlights the sensitivity of foraminiferal isotopic signals and underscores their reliability as proxies for detecting multi-decadal palaeoceanographic changes, as well as the necessity of selecting appropriate foraminiferal species for analysis. At the same time, the distinct shifts in the isotopic record illustrate how dynamic these systems are, showing that even small, decadal-scale fluctuations can leave detectable imprints in longer-term archives. Such short-term variability has the potential to introduce biases in low-resolution palaeoceanographic reconstructions, emphasizing the importance of integrating modern analogues into interpretations of sedimentary records.

Replicate cores

Benthic foraminifera exhibit a patchy spatial distribution, due to their habitat preferences (Buzas, 2002; Mojtahid *et al.*, 2009; Amao *et al.*, 2019), which can lead to biased environmental assessments (Buzas *et al.*, 2019). To reduce this potential bias, replicate cores were taken at each site. In this study, replicates located in the central and outer parts of the fjord showed consistent distributions of the dominant foraminiferal species, suggesting a relatively stable community structure in these areas. At the same time, multiple cores helped increase the number of rarer foraminifera species noted, improving the overall representation of assemblage

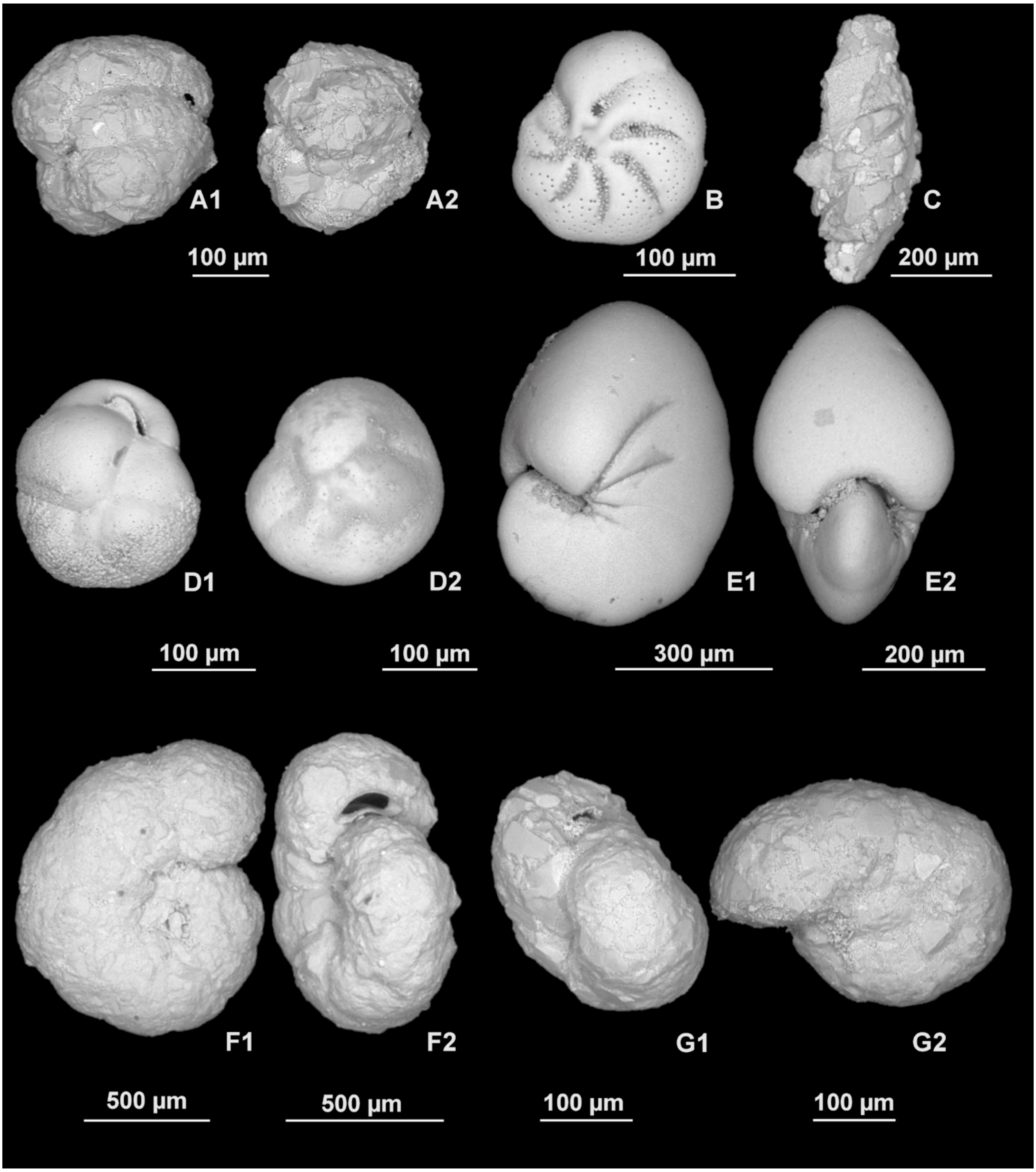

Fig. 9. Scanning Electron Microscope (SEM) images of Hornsund foraminifera from 2024. **A1, A2.** *Adercotryma glomeratum* (Brady). **B**. *Cribroelphidium clavatum* (Cushman). **C**. *Reophax fusiformis* (Williamson). **D1, D2**. *Cassidulina reniformis* (Norvang). **E1, E2**. *Nonionellina labradorica* (Dawson). **F1, F2**. *Labrospira crassimargo* (Norman). **G1, G2**. *Recurvoides turbinatus* (Brady).

diversity, compared to Zajączkowski *et al*. (2010) and Szymańska *et al*. (2025) (Fig. 8). In contrast, at station HG near the mouth of the fjord, a slight variation in dominant species was observed between replicates. However, no significant changes were detected in the overall assemblage, most likely due to the inherently low species richness and low general abundance at this station. These findings highlight the importance of including replicates in foraminiferal studies, particularly in dynamic or low-diversity environments, where variability may be more pronounced, especially in transitional zones affected by atlantification.

SUMMARY AND CONCLUSIONS

Foraminiferal assemblages from Hornsund fjord (2002–2024) reveal clear signs of atlantification. Shifts in water-mass properties, freshwater input, along with glacial retreat are already altering community composition, with foraminifera responding rapidly to changes in hydrography, meltwater, and sedimentation. These results underscore their value as sensitive indicators of ongoing Arctic climate change.

The most striking change is the progressive migration of agglutinated species further into the fjord over the 2002–2024 period. Assemblage composition shifted from being dominated solely by Arctic taxa in 2002, to a transitional mix, including opportunistic species in 2019. In 2024, boreoarctic species had become relatively dominant in both the mouth and central parts of the fjord. In the inner fjord, ongoing deglaciation has led to increased sedimentation rates, which, together with a growing AW influence, have favoured a significant rise in the agglutinated taxa *Adercotryma glomeratum* and *Recurvoides turbinatus,* both of which emerged as major contributors in PCA analyses for 2024. These trends also suggest potential reductions in carbonate burial within the fjord sediments. Since agglutinated species generally do not hold a good preservation record, the increases in calcareous species, such as *Astrononion hamadaense* and *Noninellina labradorica*, can be used as indicators of active atlantification.

Spatial gradients mirror the change in water masses over the years. Outer and central fjord stations now show higher species richness and evenness, reflecting active water exchange and sustained AW influence, whereas inner fjord and glacial bay sites remain dominated by agglutinated and stress-tolerant taxa under higher sedimentation. Elevated diversity indices (Fisher's α, Shannon H, Simpson's Diversity) in AW-affected zones indicate balanced communities, while low diversity and the prevalence of calcareous taxa in glacio-proximal areas signify harsher, unstable conditions. Isotopic signatures of reliable species that preserve well in sediments, such as *Cribroelphidium clavatum* and *N. labradorica*, can be used as AW indicators. Increasing δ^{18}O and decreasing δ^{13}C values, point to rising salinity, temperature, and productivity that are associated with atlantification. Collectively, these biological and geochemical patterns serve as diagnostic indicators of atlantification and demonstrate the rapid adaptation of benthic communities to shifting oceanographic conditions within the fjord.

Multi-decadal ecological changes are clearly visible in modern surveys, but often absent in longer sediment cores, due to time-averaging, dissolution, and selective preservation. As a result, fragile calcareous and delicate agglutinated species are underrepresented, making it difficult to pinpoint the exact onset of past atlantification or warming events. To overcome these limitations, multiproxy approaches, integrating faunal, isotopic, geochemical, and sedimentary indicators, together with high-resolution core sampling, are essential for detecting the initial stages of environmental transitions in Arctic fjords.

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