



# MASTERARBEIT | MASTER'S THESIS

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Reconstructing salt marsh development at Nith and  
Drumburgh: A foraminiferal analysis from opposing channel  
arms

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## List of abbreviations

DR	Drumburgh
NI	Nith
sp.	species (when genus is identified, but the exact species cannot be determined)
MHWST	mean high water spring tide
MHWNT	mean high water neap tide
SEM	Scanning electron microscope imagery
PAST	Paleontological Statistics software package for education and data analysis
HM	High marsh
MM	Mid marsh
LM	Low marsh
MF	Mudflat
IOL	inner organic lining
TROX	Trophic-Oxygen model
Ind/g	Individuals per gram

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## 1. Introduction

### 1.1 Background

Foraminifera are eukaryotic, single-celled protists that have existed for over 545 million years, as they stratigraphically appeared in the early Cambrian (Sabbatini et al., 2014; Camacho et al., 2015). They exhibit a wide range of sizes, from as small as 100  $\mu\text{m}$  in some species to extinct forms as large as 20 cm (Sabbatini et al., 2014). Foraminifera use pseudopodia for movement and feeding. The pseudopodia are extensions of the cytoplasm that can branch or fuse. They are used to capture food particles, for locomotion, for protection, for constructing the foraminifera shell and to interact with the environment (Greco et al., 2023).

The shells of these organisms are called tests and are composed of various materials, including calcite, aragonite, or tektin (Haslett et al., 2001; Armstrong, 2005). Foraminiferal tests are either agglutinated or calcareous. Walls of agglutinated shells consist of cemented detrital sediment particles (Murray, 1979). In order to divide the order of foraminifera into suborders, the material of the tests is the deciding factor (Gupta, 1999). To further classify the suborders, characteristics such as the position of the aperture, ornamentation, chamber arrangement and shape are considered along with environmental adaptation (Brasier, 1970; Gupta, 1999).

Important suborders in the taxonomy of foraminifera include Rotaliida, Lituolida and Miliolida. The orders of Rotaliida and Miliolida produce tests primarily made from calcium carbonate. Lituolida are agglutinated foraminifera. Rotaliida species form their tests from low-magnesium calcite, which has a low Mg/Ca ratio. Whereas Miliolida in contrast, produce porcelaneous shells composed of high-magnesium calcite, containing relatively high Mg/Ca ratios, characterized by dense, needle-like crystallites (de Nooijer et al., 2009). The tests of Rotaliida are perforated with pores and appear transparent due to their hyaline, glassy structure. In contrast, Miliolida tests lack pores and have a smooth, white, opaque texture, described as porcelaneous (Murray, 1979).

The stratigraphic utility of foraminifera is undeniable, as foraminifera are established as essential biostratigraphic index fossils in applied geosciences. Additionally to their widespread application in hydrocarbon exploration, foraminifera play a critical role in paleoclimatic reconstructions, sea level and paleobathymetric analyses, paleoceanographic investigations and geochronological studies through stable oxygen isotope analysis (Camacho et al., 2015).

Foraminifera are present in all marine and coastal environments as well as brackish environments and are found from the intertidal zone to the deep sea (Camacho et al., 2015). Of the estimated 7000 to 10 000 known species, only approximately 40 to 50 are planktonic, inhabiting the water column, whereas the vast majority are benthic species, residing on or near the sea floor (Haslett et al., 2001; Camacho et al., 2015). Only the benthic species can exist in brackish environments. For planktonic species ocean areas with a certain minimum depth are necessary (Murray, 1979).

## 1.2 Salt marsh definition

Salt marshes are defined as low-lying regions composed of alluvial or peat deposits (Radl, 2017). They are generally characterized by the presence of salt tolerant plants. Plants that are able to endure a high salinity are called halophytes (Flowers et al., 2008). Due to tidal or non-tidal sea-level fluctuations, salt marshes are flooded periodically with sea water. Species that have adapted to living in salt marsh environments have to deal with exposure to air as well as regularly being inundated with saline water (Chen et al., 2021).

The environment of a salt marsh is characterized by saline water. Foraminifera species adapted to these habitats must withstand high salinity levels. Most salt marshes are located at the mouths of major rivers or along coastlines, shielded from strong waves. Coastal salt marshes are an environment that have a global distribution. However, in the tropical and subtropical zone, they are represented by an environment consisting mainly of trees, called mangroves (Gupta, 1999).

Coastal salt marshes are a very important environment due to multiple reasons. Firstly, they have a very high productivity, because salt marshes are characterized by a high concentration of dissolved nutrients. This makes them a source of nutrients (Gupta, 1999). Moreover, salt marshes protect the shoreline against flooding or as a protection from waves (Bouma et al., 2016). Also, salt marshes create environments that offer protection and help sustain bird or fish populations (Bouma et al., 2016). Additionally salt marshes are used as grazing land for livestock and for haymaking, the former can have an affect on the ecosystem properties in salt marshes including soil properties and faunal biodiversity (Davidson et al., 2017; Chen et al., 2021).

## 1.3 Salt marsh zonation

Due to the fact that tide cycles are determined by periodically occurring astronomical phenomena, they appear constant globally (Devlin et al., 2017). Nevertheless, local geographical features cause variations in the tidal range (Khojaste et al., 2016). Naturally the sea level constantly changes due to tides, waves, atmospheric pressure and weather conditions. However, each area defines a mean sea-level. The United Kingdom defined its mean sea-level point at Newlyn in Cornwall (Bradshaw et al., 2016).

From this position, tidal cycles occur roughly every 12.5 hours, resulting in two high tides each day. This describes a typical semidiurnal tide pattern, where most coastal areas experience two high tides and two low tides every lunar day (Redzuan & Underwood, 2020). A lunar day generally last for about 24 hours and 50 minutes (NOAA, 2024a). Corresponding to the phases of the moon and the alignment of the sun, the earth and the moon, approximately every 14 days spring and neap tides alternate (NOAA, 2024b). During spring tide, the relative sea-level is greater than the mean sea level, during neap tide, the opposite occurs. Referring to these deviating sea levels, specific reference lines have to be taken into account when salt marsh probes are investigated.

The MHWST (mean high water spring tide) and the MHWNT (mean high water neap tide). Regarding these two lines every salt marsh can be theoretically classified into different zones. The MHWNT divides the salt marsh into a pioneer zone and into a mid-low marsh zone. The MHWST on the contrary separates a high-mid marsh zone from the high marsh. Beyond the high marsh, the coast is no longer in the tidal range. On the opposing site of the salt marsh, the boundary between the ocean and the salt marsh can be a cliff, varying in height from a few centimeters to over a meter. Additionally to the cliffs, salt pans, tidal channels, creeks and pools can determine the surface of the salt marsh (Radl, 2017). In figure 1 a cross section of a typical salt marsh can be viewed.

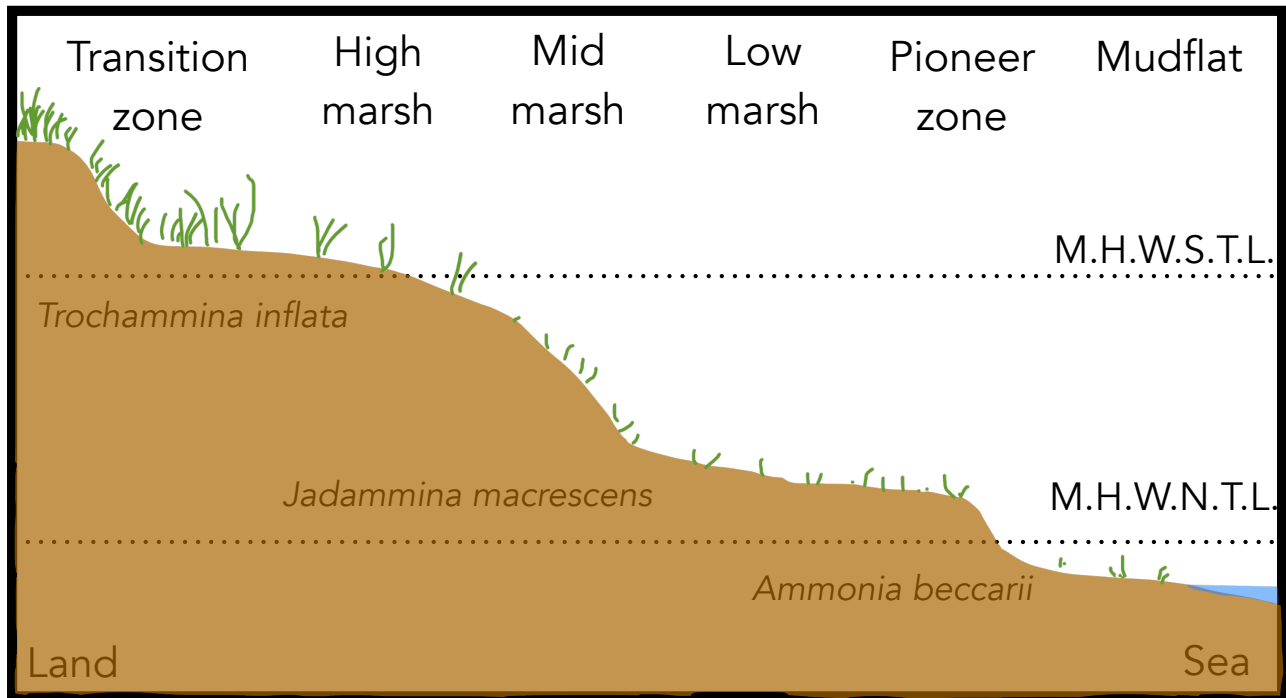


Figure 1: Cross section of a typical salt marsh

The interaction between physical forces and living organisms in tidal salt marshes results in the natural formation of salt-tolerant plant communities into recurring zonation patterns. Abiotic stressors, like wave pressure and salinity for example, additionally lead to a relatively low faunal diversity in salt marshes. Due to increased environmental stress caused by tides, species adapt to specific habitats and are therefore limited to certain zones. These vegetation zonation structures emerge along elevation gradients that are caused by the changing relative sea level. Foraminifera communities and other microorganisms like Ostracodes or Diatoms fluctuate concurrently with plant assemblages (Haslett et al., 2001). In relation to relative sea level changes the adapted species have to migrate on or within the sediment in order to exist within their preferred habitat (Yang et al., 2023; Radl, 2017).

The general consensus in the literature is that the development of a salt marsh is dictated by facilitation succession. This means that the evolution of a salt marsh starts with a mudflat, which turns into a pioneer zone after some time, which becomes a mid-low

marsh and finally grows into a high-mid marsh over time. The development of the salt marsh happens within the MHWST and the MHWNT (Radl, 2017). The driving causes for changes in the evolution of a salt marsh are relative sea level rise or fall, sediment availability and anthropogenic influences. This can result either in accretion or in erosion of the salt marsh (Bouma et al., 2016).

Additionally, the third scenario is called a dynamic equilibrium, characterized by short term fluctuations in salt marsh extent, with no sustained trend of expansion or retreat (Radl, 2017). When sufficient sediment is available, accretion takes place during periods of inundation and the salt marsh can grow vertically and laterally (Bouma et al., 2016). In temperate marshes, typical vertical accretion rates range from 2 to 10 mm per year (Radl, 2017), which historically has exceeded the global mean sea level rise rate of about 1.7 mm per year recorded by tide gauges during the past century (Church et al., 2011).

#### 1.4 Sea level reconstruction

Foraminifera can be a good proxy to reconstruct the evolution of a salt marsh in relation to relative sea-level changes, due to the fact that they can be used as marsh zone indicators (Williams et al., 2021). Foraminifera can be utilized as a proxy because of various reasons. First of all, they have hard carbonate or agglutinated shells that preserve well in the sediment, can resist easily against erosion and are relatively easy to identify due to the extensive research and scientific literature that already exists on this topic (Haslett et al., 2001). Furthermore they have a low analytical cost and only require a relatively small sample size (Hollis et al., 2019). However, more importantly, foraminifera create assemblages that are specific of the different salt marsh zones (Haslett et al., 2001). For example *Trochammina inflata* is an indicator species for the high marsh, *Jadammina macrescens* is primarily found in high-mid marsh areas and *Ammonia beccarii* is the main sign for the pioneer zone and the mid-low marsh environment (Radl, 2017).

Additionally foraminifera shells can also serve as proxies for ecological conditions like temperature and salinity, as the species exhibit preferences for specific habitats characterized by these environmental parameters. A limitation of the method of using foraminiferal assemblages as proxies for sea-level reconstruction is that they can be influenced by multiple biotic and abiotic environmental factors like sediment characteristics and groundwater seepage and not by elevation alone (Gupta, 1999). Moreover, some calcareous foraminifera species are susceptible to postmortem dissolution of their tests in acidic conditions prevalent in high marsh environments, which may prevent their preservation, resulting in their possible absence in the fossil assemblage (Edwards & Horton, 2006).

In this master's thesis a fauna analysis of benthic foraminifera is applied to evaluate the salt marsh development of two opposing channel arms of the Solway Firth estuary on Britain's west coast (McMillan et al., 2011). The study aims to outline and compare the ecological succession of the salt marshes at Nith and Drumburgh.

## 2. Material and methods

### 2.1 Study sites

In 2012 Dr. Michaela Stefanie Radl collected sediment cores and surface samples from different salt marshes in the United Kingdom. In total Dr. Michaela Stefanie Radl collected data from 15 individual study sites. In her doctoral thesis: ‚Meiofauna analyses of salt marsh development with changing sea-levels in the United Kingdom.‘ the study sites are described in further detail (Radl, 2017).

The samples that are used in this master’s thesis were collected by Dr. Michaela Stefanie Radl on the 26th and the 27th of July 2012. A one meter deep sediment core sample and a surface sediment sample of each of the locations Drumburgh and Nith are the foundation for the analysis in this study. The locations of the two sample sites can be viewed in figure 2 and the exact coordinates are shown in table 1.

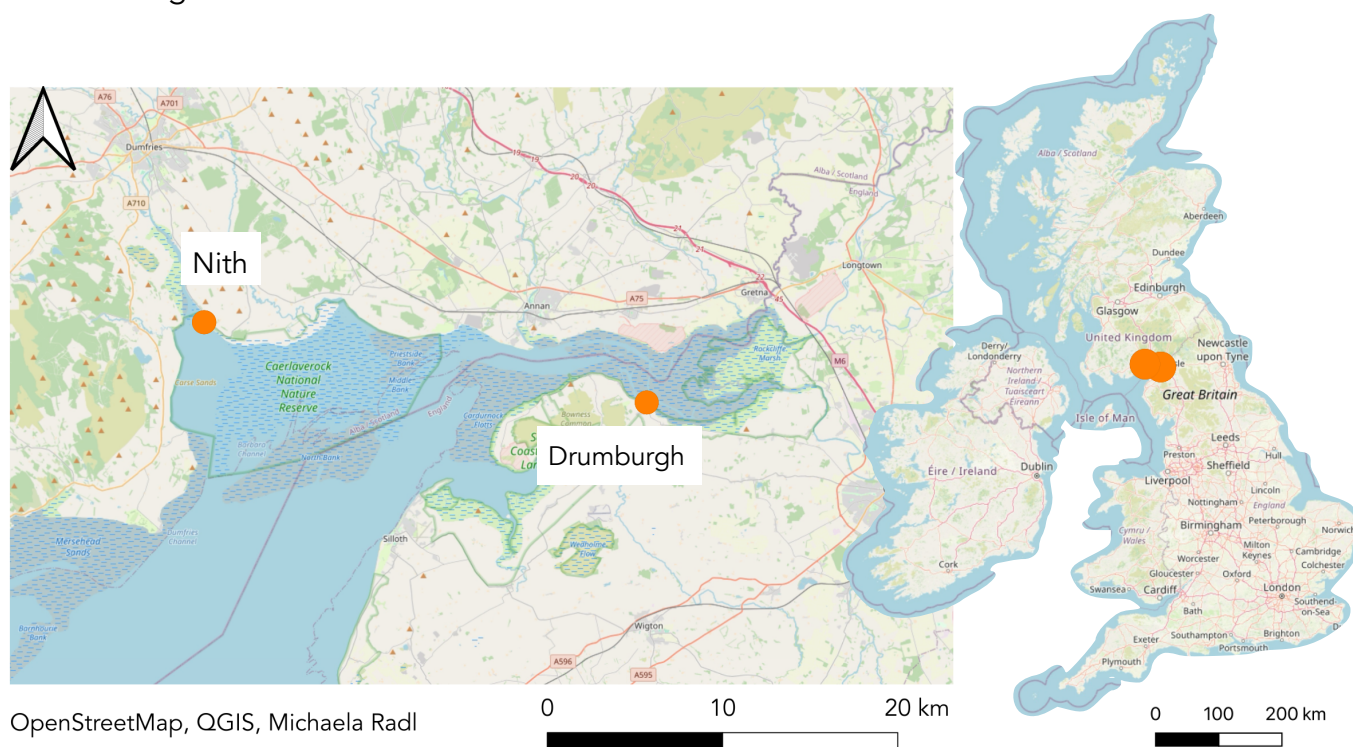


Figure 2: Map of the sample sites

#### 2.1.1 Drumburgh (DR)

The sample site Drumburgh ( $54^{\circ} 56'19.50''$  N,  $3^{\circ} 09'44.60''$  W) is located south of the river Eden, north-west of the name-giving settlement Drumburgh in Cumbria, England. This salt marsh has three different terraces, divided by cliffs. A one meter deep sediment core as well as a surface sample were collected at the upper terrace, the highest of the three terraces of the high marsh. This salt marsh was grazed by cows. The samples were taken on 26.07.2012 (Radl, 2017).

### 2.1.2 Nith (NI)

The sample site Nith (54° 58'47.44"N, 3° 33'26.91"W) is located east of the river Nith, south of the Town Glencaple in Dumfries, England. This salt marsh has two terraces, also divided by cliffs. A one meter deep sediment core as well as a surface sample were collected at the upper terrace of the high marsh. The samples were taken on 27.07.2012 (Radl, 2017).

Table 1: Locations of the samples in Drumburgh (DR) and in Nith (NI)

Sample name	Latitude	Longitude
Surface sample DR	54.938874	-3.1630258
Surface sample NI	54.979879	-3.5570906
Core sample DR	54.938888	-3.1630768
Core sample NI	54.979875	-3.5575332

The reasoning on why the two specific sites Drumburgh and Nith were chosen in this study, is because these two are located at two opposing channel arms. The linear distance between the locations is only 25,71 km (OpenStreetMap, 2025) and they are both located at different ends of the Solway Firth. This shallow estuary is located on the west coast of Great Britain, east of the Irish Sea. Several rivers end in the Solway Firth, for example the rivers Esk and Nith. The area around the Solway Firth is known to have tidal flats, sandbanks and salt marshes, due to the shallow water depth of less than 20m and vast coastal regions found within the intertidal area (McMillan et al., 2011).

### 2.2 Surface and core sediment samples

In Drumburgh and in Nith the sediment cores as well as the surface samples that are used in this thesis were collected on the highest terrace of each salt marsh coastline. The surface samples were taken with a depth of 2cm. In this study the only uppermost 50cm of each one meter deep sediment core were analyzed due to time constraints. To minimize the impact of small scale distribution variations of microfossil species within marsh zones, multiple sub-samples were collected from each zone of the surface samples and combined into a single composite surface sample. Typically, three sub-samples were taken randomly within an area of at least 1 m<sup>2</sup> (Radl, 2017).

Following each sediment sampling, all equipment, including the hand shovel and knife, was thoroughly cleaned to prevent cross-contamination. The two sediment cores were each divided into 10cm intervals and subsequently the collected samples were sealed in clearly labeled plastic bags and then stored at 10 °C in a temperature-controlled room until further analysis. In 2022 the samples were brought to the University of Vienna (Radl, 2017).

## 2.3 Sample preparation and laboratory analysis

At first all of the samples were weighed using a digital scale. Then each of the 10cm intervals of the core sediment samples as well as the two surface sediment samples were split into three roughly equal parts. One third of each sample was taken out of the labeled plastic bag, weighed again and then placed into a glass dish filled halfway with water. This was left to sit for one hour, in order to soften up the hard sediment. Subsequently the pre-soaked part of the samples were wet-sieved in a washbasin using a nested sieve stack with mesh sizes of 1mm, 125  $\mu\text{m}$  and 63  $\mu\text{m}$ . Particles smaller than 63  $\mu\text{m}$  were discarded during the process. Following each sieving process, the sieves were thoroughly cleaned manually and brushed under running water to prevent cross-contamination.

For the 1mm - 125  $\mu\text{m}$  fraction as well as for the 125  $\mu\text{m}$  - 63  $\mu\text{m}$  fraction a new sieving method had to be used, due to the fact that there were too many organic particles in the samples. These high amounts of plant components in the salt marsh samples were responsible for causing agglutination and clumping of the sediment grains including the foraminifera tests. This would result in destruction of the shells, if the microorganisms would have been picked out of the clumps manually. In order to reduce the amount of interfering organic matter in the samples, a special extraction method was utilized. This alternative separation technique, adapted from Radl (2017) was applied to enhance the concentration of microfossils (Radl, 2017).

This separation method involves gentle agitation and decanting. After wet sieving of the 1mm - 125  $\mu\text{m}$  fraction and the 125  $\mu\text{m}$  - 63  $\mu\text{m}$  fraction, the sediment fractions were placed in a glass dish. Water was added until the sediment was fully suspended in water. Thereafter the suspension was manually agitated to mobilize the lighter particles, primarily fine organic debris as well as plant and clay particles, while allowing the heavier mineral grains and foraminiferal tests to settle at the bottom.

Once sedimentation occurred, the container was carefully tilted to decant the supernatant, containing the suspended lighter material, into a secondary container. This decanting step was repeated multiple times, with only partial removal of the floating material during each cycle, followed by the addition of fresh water. The process continued until the supernatant was visually clear, indicating effective removal of most of the fine suspended particles. In the final step, the remaining water was decanted, alongside the heavier organic matter including the majority of the foraminiferal tests, into a secondary container. In such manner all of the samples were divided into the three different particle sizes  $>1\text{mm}$ , 1mm - 125  $\mu\text{m}$  and 125  $\mu\text{m}$  - 63  $\mu\text{m}$ . Then all of the labeled glass dishes were placed in an oven at 60 degrees Celsius for a minimum of 48 hours. Upon complete drying, the samples were weighed and transferred to glass bottles.

For further analysis only the 1mm - 125  $\mu\text{m}$  fraction was utilized. Accordingly, 6 sediment samples, including 5 core sediment samples and 1 surface sediment sample, of each sample site Drumburgh and Nith were analyzed this way in the laboratory. Resulting in 12 analysed sediment samples in total.

Thus, the dried sediment of the 1mm - 125  $\mu\text{m}$  fraction of each sample was sprinkled onto a small dish featuring a grid pattern and a black background to facilitate visualization. Foraminifera tests were picked out of the sediment sample and extracted into a micropaleontological slide with a glass coverslip.

These isolated specimen were then identified accordingly. Each sieved sample was analyzed entirely without splitting it, as only a low number of foraminiferal tests occurred per sample. The stereo microscope which was utilized for the analysis was a binocular lens type LEICA MZ12.

### 2.3.1 Scanning electron microscope imagery (SEM)

Following the picking and the identification of the foraminiferal tests, selected specimen were prepared for imaging using a scanning electron microscope (SEM). Prior to imaging, the specimens were sputter coated with gold under high vacuum to enhance their electrical conductivity and surface resolution using the Bio-Rad Microscience Division SC500 Sputter coater. SEM imaging was conducted at University of Vienna using a Hitachi TM4000 Tabletop Microscope, with technical assistance provided by Matthias Nagy. The instrument was operated under high vacuum conditions at an accelerating voltage of 15 kV, with a working distance of 12.5 mm and a resolution ranging from 120 to 800  $\mu\text{m}$ . Of each of the detected foraminifera species in the samples a SEM image was made. The most abundant and representative foraminifera species were also photographed multiple times in different angles and with special detail images. The SEM images can be viewed in Plate 1, Plate 2 and Plate 3 in chapter 3.5.

## 2.4 Statistic analysis

Firstly, the abundance of the different foraminifera species per sample site as well as the total number of picked foraminifera specimen of each sample site was assessed. Additionally the number of picked foraminifera specimen per sample site per 10 cm interval was evaluated. Subsequently, to compare the samples and conduct statistical analysis, the samples were normed to 1g. Furthermore the not identified specimen with hyaline calcite tests were excluded from the analysis. They could not be identified beyond the foraminiferal level, due to their highly fragmented or broken condition. Additionally the planktonic species were also not taken into account for statistic analysis.

Using the software program called PAST (Paleontological Statistics software package for education and data analysis) the following diversity indices were generated: Taxa\_S, Individuals, Dominance\_D, Shannon\_H, Evenness\_e<sup>H/S</sup>, Fisher\_alpha (Hammer et al., 2001). Each metric assesses biodiversity by focusing on distinct attributes. All biodiversity indices are grounded in species richness, species relative abundance (evenness) or a combination of both, reflecting community heterogeneity (Dias et al., 2023).

The term Taxa\_S focuses on the richness of the sample and stands for the number of species S (Dias et al., 2023).

The Individuals value is the total number of all individuals in the sample, regardless of the species (N).

The Dominance\_D measurement is calculated using the Simpson's index, a biodiversity assessment approach that simultaneously considers the number of species (richness) and their population sizes (abundance). The Simpson's index is evaluated as follows (Bollarapu et al. 2024).

$$D = \sum n(n - 1)/N(N - 1)$$

Equation 1: Simpson's index

The Shannon\_H value stands for the Shannon's diversity index. It is a method for assessing biodiversity that incorporates both species richness and species evenness in its evaluation. The Shannon's diversity index is measured as follows (Bollarapu et al., 2024).

$$H = - \sum P_i \ln P_i$$

Equation 2: Shannon's diversity index

The Evenness\_e<sup>H/S</sup> is also called the Buzas-Gibson evenness. The formula of the Buzas-Gibson evenness reads as follows (Dias et al., 2023).

$$E = e^H/S$$

Equation 3: Buzas-Gibson evenness

The Fisher\_alpha diversity index is primarily derived from species richness. Its formula is shown below (Dias et al. 2023).

$$\alpha = (N(1 - x))/x$$

Equation 4: Fisher alpha diversity index

Additionally a similarity analysis of presence/absence data was carried out also using the software program PAST (Paleontological Statistics software package for education and data analysis). The similarity index Morisita was chosen (Hammer et al., 2001; Barwell et al., 2015).

### 3. Results

Overall 761 specimen of foraminifera from 6 different families and 7 separate genera were found in the 1mm - 125  $\mu\text{m}$  fraction samples. Most of them belong to the orders of: Rotiliida, Lituolida and Miliolida. The classification followed here is based after Murray (1979). The majority of the analysed foraminifera was benthic. The benthic species that were found at the two salt marsh locations are listed and depicted as SEM photographs on Plate 1, Plate 2 and Plate 3 in chapter 3.5. Nonetheless, also several planktonic foraminifera specimen were found in the Nith surface sediment sample. All of the planktonic specimen were excluded from further identification and analysis, as this is a fauna analysis of benthic foraminifera.

#### 3.1 Surface sediment samples

The surface sediment samples of sample location Drumburgh and sample site Nith reveal distinct differences in the foraminiferal composition. The relative foraminifera species distribution of the surface sediment samples of sample location Drumburgh and Nith is displayed in figure 3. At Nith, the benthic foraminifera assemblage contains only two foraminifera species: *Jadammina macrescens* with 2.61 Ind/g (75%) and *Cassidulina* sp. with 0.87 Ind/g (25%). In contrast, the Drumburgh samples show an extreme dominance of *Jadammina macrescens* with 208.51 Ind/g (99.26%) as well as a small presence of *Miliamina fusca* with 1.56 Ind/g (0.74%). Overall, the majority of the foraminiferal assemblage consisted of agglutinated tests (99.26% at DR and 75% at NI).

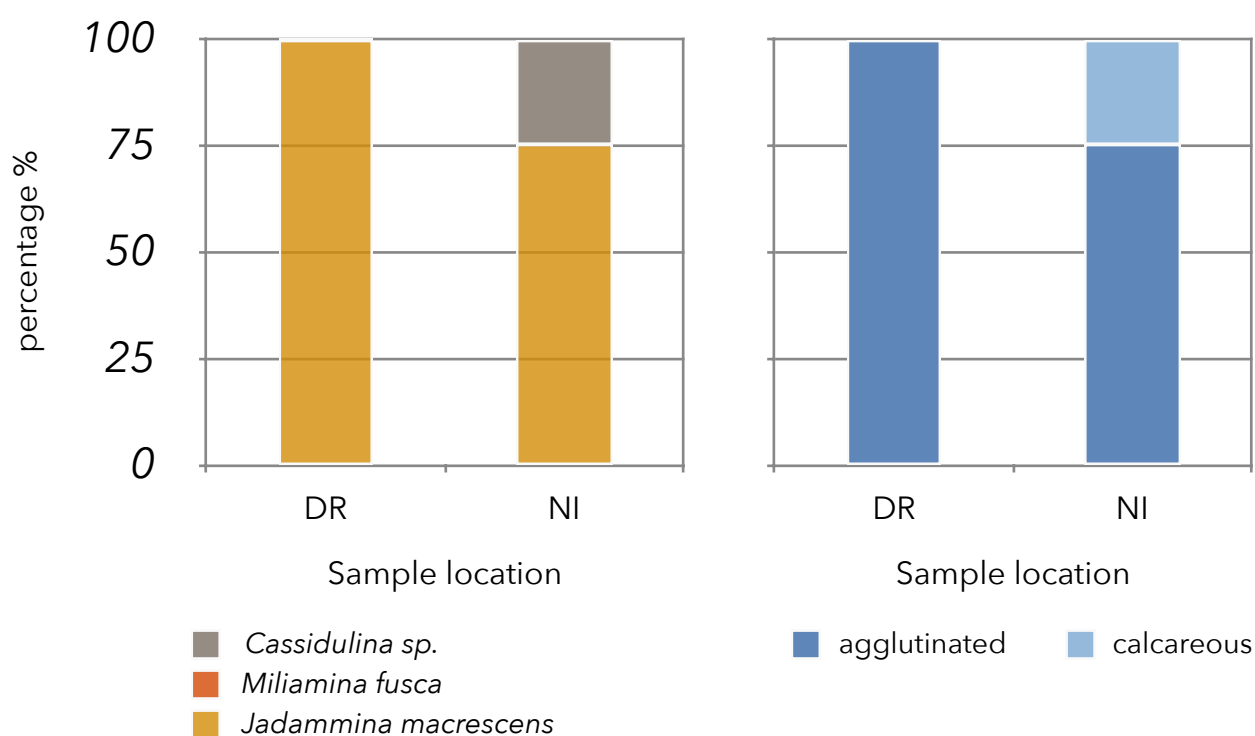


Figure 3: Relative foraminifera species distribution data of the surface sediment samples Drumburgh and Nith and the relative distribution of agglutinated and calcareous species

### 3.2 Sediment core samples

In the sediment core samples at sample location Drumburgh (fig. 4) only the species *Jadammina macrescens* and *Ammonia* sp. were recorded. The assemblage was dominated by *Jadammina macrescens* with values ranging from 1.5 Ind/g in the 0-10cm interval to 2.6 Ind/g in the 20-30cm interval. *Ammonia* sp. only occurred in the shallowest interval of 0-10cm with 0.75 Ind/g. All other taxa were absent and no foraminifera specimen were recorded below 30cm in the 30-40cm and 40-50cm intervals.

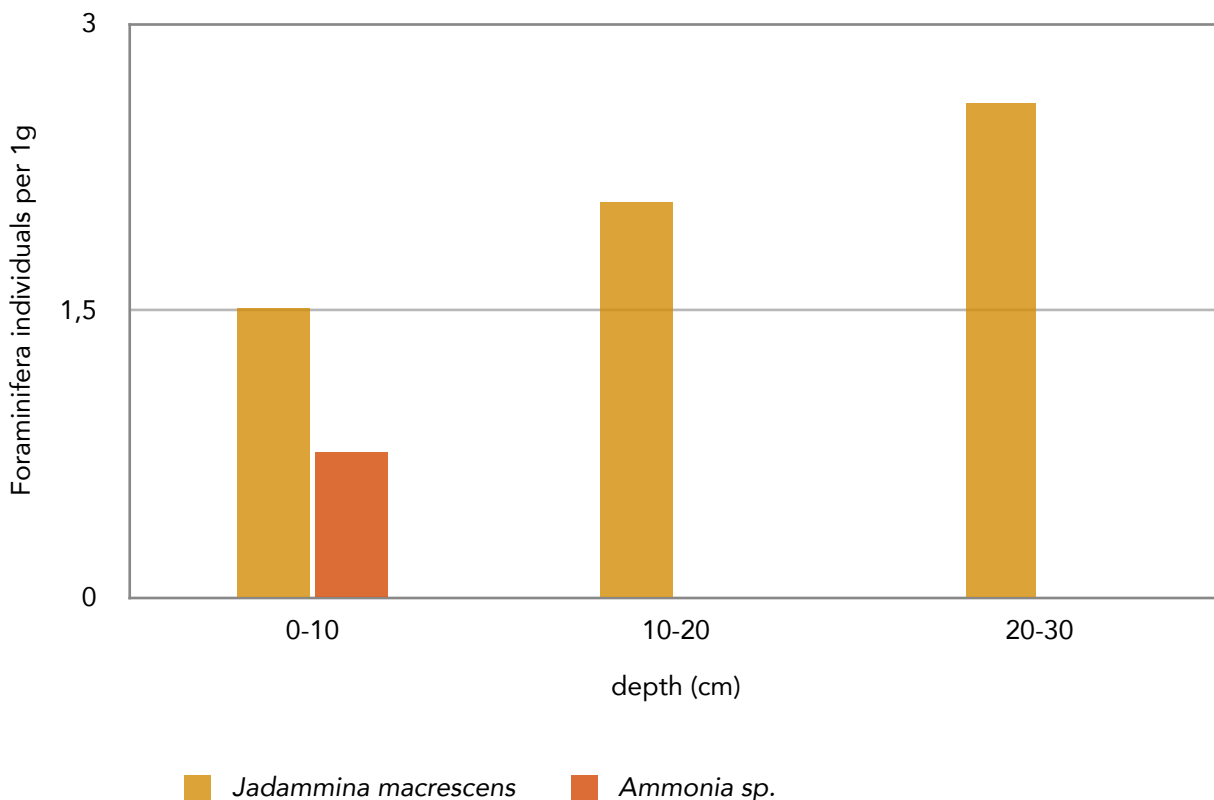


Figure 4: Abundance data of the sediment core Drumburgh (DR) normed to 1 gram (g)

The Nith samples showed a more diverse assemblage than the Drumburgh samples, as well as much higher numbers of specimen. This can be observed in figure 5. In the upper 10 cm, the core was dominated by *Jadammina macrescens* with 27.33 Ind/g and *Trochammina inflata* with 13.2 Ind/g. In the 10-20cm deep interval, the number of *Trochammina inflata* increased to 24.4 Ind/g. Additionally, *Jadammina macrescens* decreased to 5.9 Ind/g. *Haynesina germanica* only occurred in this interval with only 0.84 Ind/g. Between 20cm and 30cm, the abundances of all foraminifera species were low. At 30-40cm *Miliamina fusca* occurred with 15.5 Ind/g. The deepest interval was strongly dominated by *Haplophragmoides wilberti*, even though this species occurred rarely in the upper intervals. At a depth of 40cm, however, it exhibited a distinct peak with 352.6 Ind/g. In the 40-50cm interval *Jadammina macrescens* reached a maximum value of 36.32 Ind/g, as well as *Trochammina inflata* with 55.6 Ind/g and *Miliamina fusca* with 23.5 Ind/g.

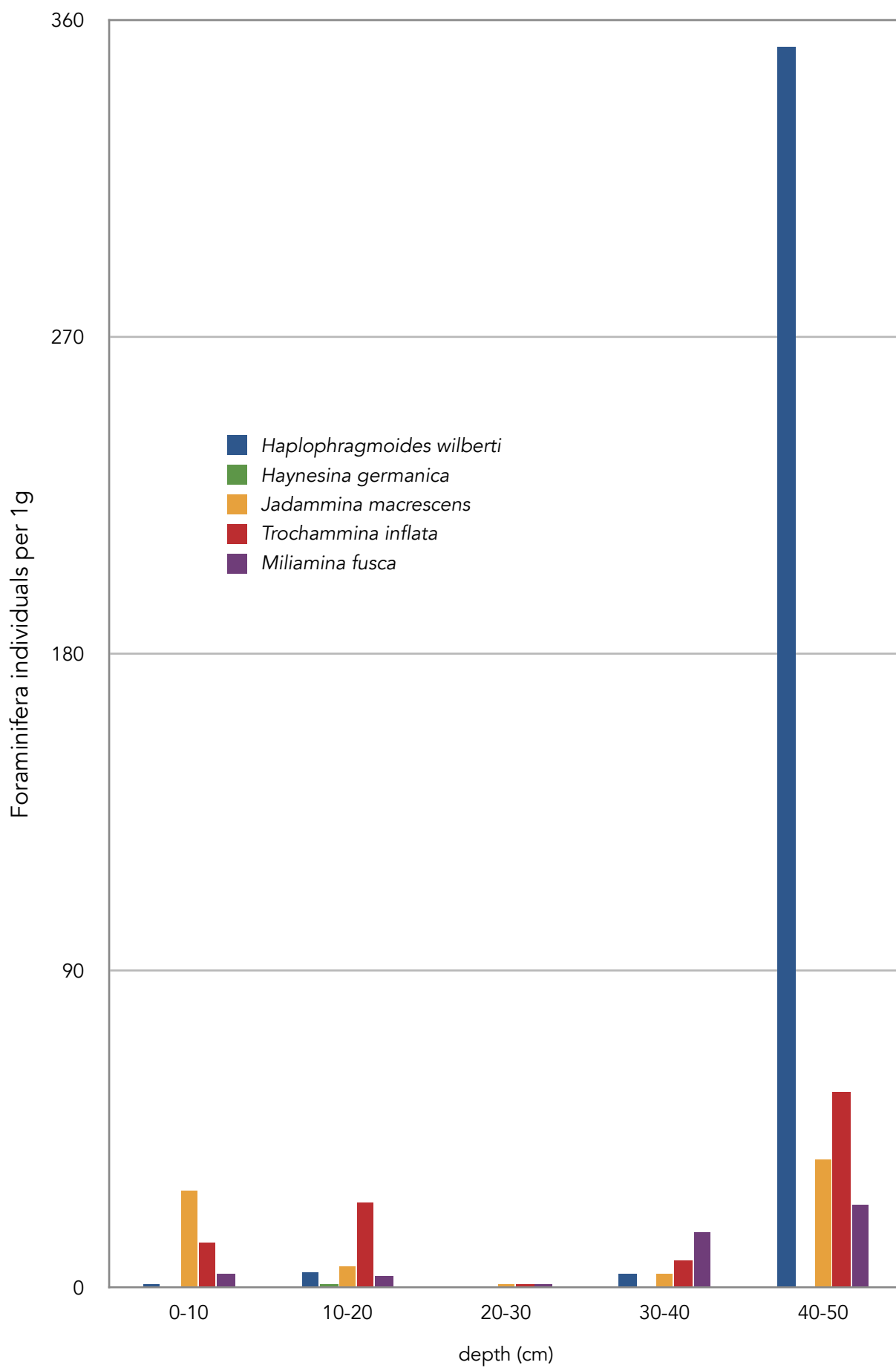


Figure 5: Abundance data of the sediment core Nith (NI) normed to 1 gramm (g)

The benthic foraminiferal assemblages at sample location Drumburgh and Nith show differences in taxonomic composition and in abundance of foraminifera specimen across the sample depth of 0-50cm. The differences in taxonomic composition can be observed in figure 6, where the relative foraminifera species distribution of the sediment cores of sample locations Drumburgh and Nith is displayed. Particularly the dominance of *Jadammina macrescens* at sample location Drumburgh (89.1%) as well as the dominance of *Haplophragmoides wilberti* at sample location Nith (61.7%) can be observed. Additionally the foraminiferal assemblage consisted predominantly of agglutinated tests (89.09% at DR and 99.86% at NI).

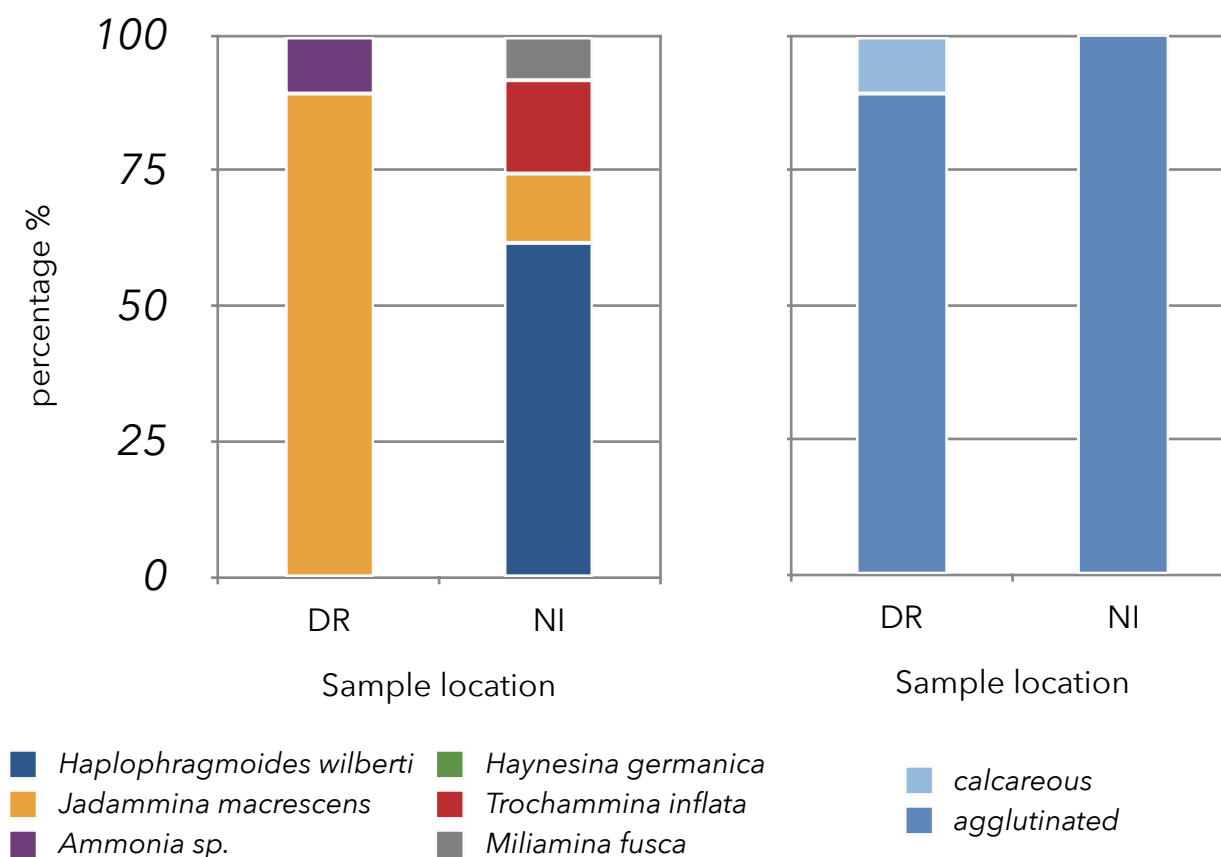


Figure 6: Relative foraminifera species distribution data of the sediment cores Drumburgh (DR) and Nith (NI) and the relative distribution of agglutinated and calcareous species

Overall, the Drumburgh samples are characterized by abundances of the species *Jadammina macrescens* in the shallowest 30cm of the core and by a complete absence of foraminiferal specimen in the deeper intervals. Additionally, the Drumburgh samples depict very low abundances throughout the core compared to the Nith samples. Conversely, the Nith samples are showing a more heterogeneous distribution in the foraminifera assemblage. Nevertheless, they also reveal a very high peak abundance of *Haplophragmoides wilberti* in the deepest interval of the sediment core samples. At sample location Drumburgh only two foraminifera species were found, whereas at sample location Nith five species were detected. *Haynesina germanica* was also observed at sample location Nith, but only accounted for 0.14% of the foraminifera species and is therefore not clearly visible in figure 6.

### 3.3 Diversity indices analysis

The results of the statistical analysis regarding the diversity indices (Taxa S, Shannon\_H, Dominance\_D, Evenness  $e^{H/S}$  and Fisher's alpha) is shown in table 2. These diversity indices show substantial differences between the two sampling locations Drumburgh and Nith in the core samples as well as in the surface samples.

At site Drumburgh, the species richness (Taxa S) values were generally low, with only 1 to 2 taxa recorded in the intervals. In the intervals DR 10-20 and DR 20-30 there is only 1 species present. The corresponding diversity index value of Shannon\_H equaled to 0, reflecting the presence of a monospecific assemblage. This suggests one species dominated the assemblage and there was only a low diversity present in these samples of Drumburgh (Budka et al., 2018; Magurran, 2004; Dias et al., 2023; Bollarapu et al., 2024).

The evenness diversity index (Evenness  $e^{H/S}$ ) and the dominance related measure (Dominance\_D) of samples DR 10-20 and DR 20-30 further confirmed this pattern. The dominance value Dominance\_D and the Evenness  $e^{H/S}$  were 1, which typically indicates perfect evenness, however, when only 1 species is present, these contradicting values are possible. Sample DR 0-10 shows a moderate dominance with 0.56 and a corresponding Shannon diversity of 0.64. Evenness of this sample was relatively high with a value of 0.95, indicating that the two taxa that were found, were represented in nearly equal proportions (Budka et al., 2018; Magurran, 2004; Dias et al., 2023; Bollarapu et al., 2024).

The DR surface sample showed a high dominance value of 0.99 indicating a strongly dominated assemblage. The Shannon\_H measurement of this sample was very low, suggesting a very low diversity. The evenness value was 0.52, showing moderate evenness. Lastly, the Fisher's alpha values of all of the Drumburgh samples were very low, which is expected for species poor assemblages and reflects limited taxonomic richness (Budka et al., 2018; Magurran, 2004; Dias et al., 2023; Bollarapu et al., 2024).

In contrast, sample location Nith exhibited higher foraminiferal diversity and variability with depth. The species richness value (Taxa S) ranged from 3 to 5 in the Nith samples, being consistently higher than the Drumburgh values, showing a richer assemblage. The dominance values, were generally lower at Nith than at Drumburgh.

The lowest measurement of Dominance\_D was 0.33 at 20-30 cm, suggesting a lower dominance of a single species and a more even distribution in the Nith core. Only the dominance value of the 40-50 cm depth showed a slightly higher dominance with a value of 0.59. Compared to the Drumburgh samples, where the Shannon\_H estimate was mostly low, the Nith samples overall had higher Shannon\_H measurements, suggesting a higher diversity. The Shannon\_H value peaked at 1.21 in the 30-40 cm fraction of the Nith samples, indicating an even distribution of species. In the 40-50 cm interval of the Nith core the Shannon\_H estimate exhibited a slightly lower value with 0.82, showing less diversity. The evenness values of the Nith core varied with depth.

In the depth intervals of 0-10 cm, 10-20 cm and 40-50 cm the Evenness  $e^H/S$  was around 0.6, which suggests a moderate evenness. The samples NI 20-30 and NI 30-40 show high evenness values of 1 and 0.84, indicating a community that is very evenly distributed among species and suggesting that all of the species had nearly equal abundance. The Nith surface sample exhibited a higher dominance, lower diversity and higher evenness compared to the Nith core samples. At last, the Fisher's alpha values indicated a low species diversity overall in the Nith core. They ranged from 0.24 (40-50 cm) to 0.36 (10-20 cm), indicating that the higher diversity lays in the upper sediment layers (Budka et al., 2018; Magurran, 2004; Dias et al., 2023; Bollarapu et al., 2024).

Table 2: Results of PAST (Paleontological Statistics software package for education and data analysis) (Hammer et al., 2001). Diversity indices calculated for foraminiferal assemblages from the Drumburgh and Nith sediment cores and surface samples (intervals in cm). Indices include observed richness (Taxa S), diversity (Shannon\_H), dominance (Dominance\_D), evenness (Evenness  $e^H/S$ ) and a richness estimator (Fisher's alpha).

diversity indices	DR 0-10	DR 10-20	DR 20-30	NI 0-10	NI 10-20	NI 20-30	NI 30-40	NI 40-50	DR surface	NI surface
Taxa_S	2	1	1	4	5	3	4	4	2	2
Individuals	2.26	2.07	2.58	45.55	38.72	2.53	31.01	467.95	210.06	3.48
Dominance_D	0.55	1	1	0.45	0.44	0.33	0.34	0.59	0.99	0.63
Shannon_H	0.634	0	0	0.97	1.11	1.10	1.21	0.81	0.04	0.56
Evenness $e^H/S$	0.95	1	1	0.66	0.61	1	0.84	0.56	0.52	0.88
Fisher_alpha	0.17	0.08	0.08	0.28	0.36	0.26	0.29	0.24	0.12	0.16

### 3.4 Presence/absence similarity index Morisita

The results of the similarity analysis of presence/absence data is shown in table 3. The similarity analysis of presence/absence data indicated that the Drumburgh samples were highly similar to each other with peak values of up to 1.0.

On the contrary, the samples from the Nith sample location exhibited strongly varying internal similarity with measurements ranging from 0.178 to 0.862. When comparing the samples from Drumburgh and the samples from Nith with each other, the range of similarity is also very high. Low to high similarity could be observed with minimal values of 0.090 and maximum values of 0.827. The surface layers of Drumburgh and Nith were the most similar to each other, with a measurement of 0.924 (Barwell et al., 2015).

Table 3: Presence/absence similarity values carried out with PAST (Paleontological Statistics software package for education and data analysis), the Morisita index was chosen (Hammer et al., 2001; Barwell et al., 2015)

	DR 0-10	DR 10-20	DR 20-30	NI 0-10	NI 10-20	NI 20-30	NI 30-40	NI 40-50	DR surface	NI surface
DR 0-10	1	0.8571	0.8571	0.7941	0.2037	0.5	0.1853	0.09033	0.8589	0.8471
DR 10-20	0.8571	1	1	0.8265	0.2113	0.5	0.1861	0.0976	0.9999	0.9231
DR 20-30	0.8571	1	1	0.8265	0.2113	0.5	0.1861	0.0976	0.9999	0.9231
NI 0-10	0.7941	0.8265	0.8265	1	0.6356	0.8302	0.4888	0.1959	0.8297	0.8358
NI 10-20	0.2037	0.2113	0.2113	0.6356	1	0.7492	0.5961	0.3355	0.2128	0.2142
NI 20-30	0.5	0.5	0.5	0.8302	0.7492	1	0.8615	0.1780	0.5056	0.5217
NI 30-40	0.1853	0.1861	0.1861	0.4888	0.5961	0.8615	1	0.3398	0.1923	0.1935
NI 40-50	0.0903	0.0976	0.0976	0.1959	0.3355	0.1780	0.3398	1	0.0982	0.0958
DR surface	0.8589	0.9999	0.9999	0.8297	0.2128	0.5056	0.1923	0.0982	1	0.9246
NI surface	0.8471	0.9231	0.9231	0.8358	0.2142	0.5217	0.1935	0.0958	0.9246	1

### 3.5 Analysed benthic Foraminifera

The benthic foraminifera found in the samples included: *Jadammina macrescens*, *Milliammina fusca*, *Haplophragmoides wilberti*, *Trochammina inflata*, *Haynesina germanica*, *Cassidulina* sp. and *Ammonia* sp. All of these foraminifera species are depicted on the following pages in Plate 1, Plate 2 and Plate 3 in SEM photographs.

## Plate 1

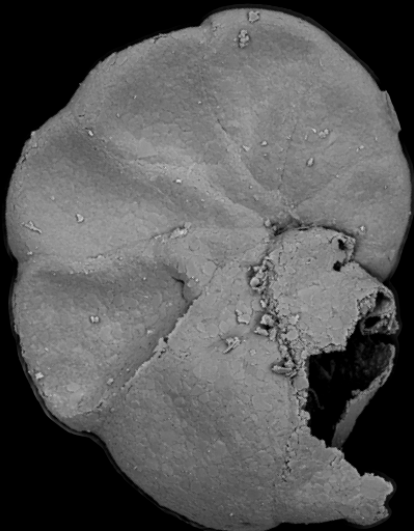
Fig. 1-4: *Jadammina macrescens*

- 1: umbilical view
- 2: umbilical view
- 3: umbilical view
- 4: spiral view

Fig. 5: *Ammonia* sp.

- 5: umbilical view

Plate 1



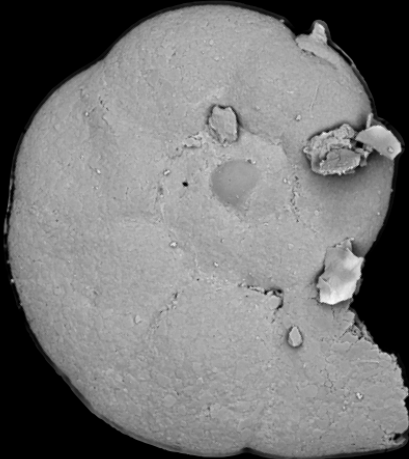
1



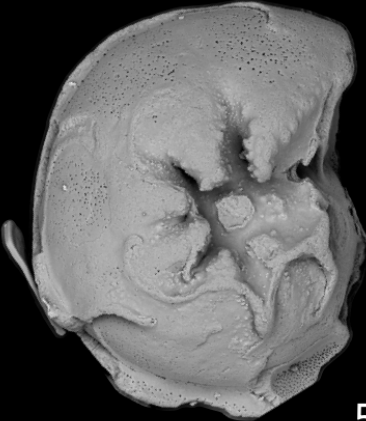
2



3



4



5

..... 200µm

## Plate 2

Fig. 1-2: *Milliammina fusca*

1: lateral view

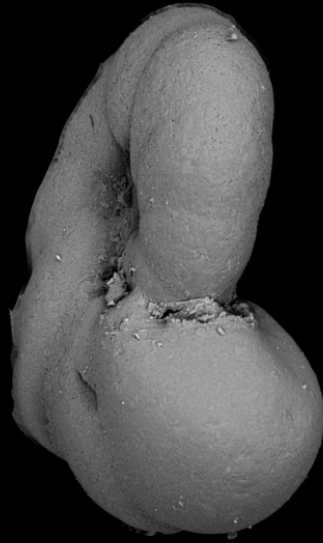
2: lateral view

Fig. 3-4: *Haplophragmoides wilberti*

3: apertural view

4: spiral view

Plate 2



.....  
100µm

## Plate 3

Fig. 1-3: *Trochammina inflata*

1: spiral view

2: umbilical view

3: spiral view

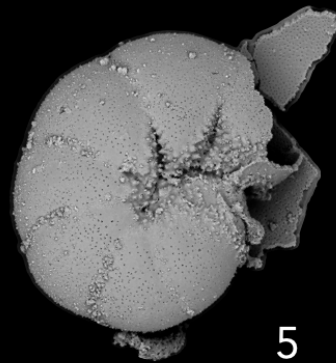
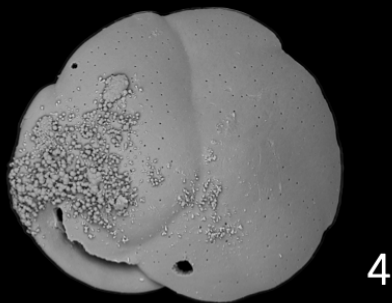
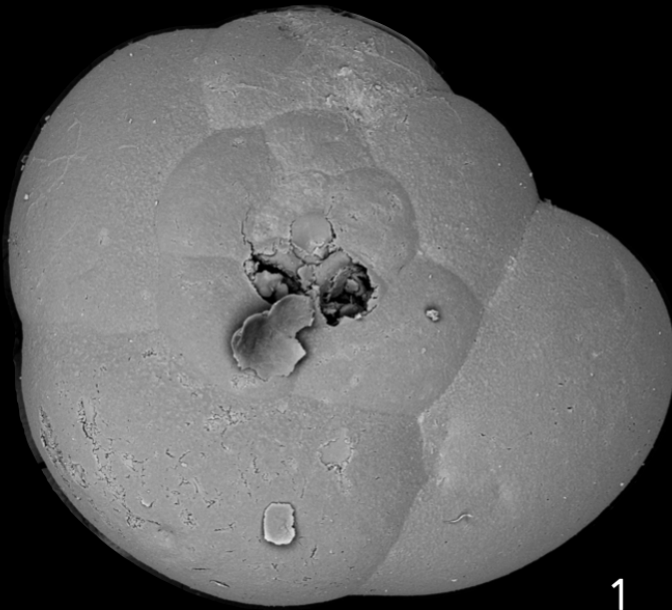
Fig. 4: *Cassidulina* sp.

4: lateral view

Fig. 5: *Haynesina germanica*

5: lateral view

Plate 3



.....  
100µm

***Jadammina macrescens* (Brady, 1870)**

Plate 1, fig. 1-4 (page 17)

This species is an agglutinated foraminifera species (Camacho et al., 2015). It was the most abundant species at both study sites. In the Nith sediment core *Jadammina macrescens* was found in each interval of the 50 centimeters that was analysed. In the surface sample from Drumburgh *Jadammina macrescens* was especially abundant. However, the species was not found in the 30-40cm and the 40-50cm interval of the Drumburgh sediment core.

***Trochammina inflata* (Montagu, 1808)**

Plate 3, fig. 1-3 (page 21)

*Trochammina inflata* is an agglutinated species (Horne & Boomer, 2000; Frenzel et al., 2005). *Trochammina inflata* was collected only at the Nith study site and was not present in the Drumburgh sediment samples at all. *Trochammina inflata* was also not found in the Nith surface sample.

***Haplophragmoides wilberti* (Andersen, 1953)**

Plate 2, fig. 3-4 (page 19)

*Haplophragmoides wilberti* is an agglutinated foraminifera species (Frenzel et al., 2005). This species was only found at the Nith site and was not collected at the Drumburgh salt marsh site. This species occurred in the 0-10 cm, the 10-20 cm, the 30-40 cm and the 40-50 cm fraction of the Nith sediment core. It was most abundant in the 40-50 cm interval of the core sediment sample of Nith.

***Miliammina fusca* (Brady, 1870)**

Plate 2, fig. 1-2 (page 19)

*Miliammina fusca* is an agglutinated foraminifera species (Frenzel et al., 2005). This species was found at both analysed study sites. However, it was only detected in the surface sample and was not present in the sediment core of the Drumburgh site. At the Nith study site *Miliammina fusca* occurred in every fraction of the sediment core, but was not found in the surface sample.

***Ammonia* sp.**

Plate 1, fig. 5 (page 17)

*Ammonia* was only collected with 0.75 individuals per 1 g sample in the 0-10cm interval of the sediment core at the Drumburgh sample site.

***Haynesina germanica* (Ehrenberg, 1840)**

Plate 3, fig. 5 (page 21)

The species *Haynesina germanica* is a calcareous foraminifera (Frenzel et al., 2005). From this species, just 0.84 individuals per 1 g sample was found in all analysed samples. *Haynesina germanica* was detected in the 10-20cm interval of the Nith sediment core.

***Cassidulina* sp. (d'Orbigny, 1826)**

Plate 3, fig. 4 (page 21)

*Cassidulina* sp. occurred, with just 0.87 individuals per 1 g of the samples in the surface sediment sample of the Nith sample site.

## 4. Discussion

### 4.1. Abundance data, biodiversity indices and presence/absence data

In the Drumburgh sediment core, the foraminiferal assemblage is strongly concentrated within the shallowest layers, with all of the observed specimen restricted to the uppermost 30 cm. The highest abundance was recorded in the surface sample at Drumburgh, which contained 210.07 Ind/g, representing 96.82% of the total assemblage. In contrast, only 6.90 Ind/g (3.18%) were recovered from below the surface at this site. The absence of foraminiferal test in the deeper intervals at the Drumburgh site could imply reduced preservation potential or post-depositional dissolution (Chen et al., 2020). Additionally it is also possible, that the foraminifera community may have colonized the site only relatively recently. Consequently no tests would be expected in the deeper and older sediment layers. Alternatively, the absence of foraminifera tests in deeper layers could also be related to reduced oxygen availability or limited food supplies (TROX model) (Fontaine et al. 2002). Environmental stress can also have a significant impact on the foraminiferal assemblage (Blazquez & Usera, 2010). Human-made stressors can influence salt marshes as well and may prevented foraminifera species to occur in those layers. Anthropogenic contaminants, especially heavy metal pollution, as well as organic input like fertilizer, pesticides, industrial or agricultural waste, organic matter enrichment and correlated oxygen depletion can have an impact on foraminiferal assemblages and lead to less divers communities. Additionally, mechanical disturbances resulting from human activities, such as constructional measures, grazing domestic animals or human activities in general can significantly impact benthic environments (Blazquez & Usera, 2010; Parent et al., 2021; El-Kahawy & Mabrouk, 2023). Furthermore dominant species can suppress less competitive species. In this matter a highly dominated assemblage can be formed, where the biodiversity is very low (Pavard et al., 2023).

At salt marsh site Nith, only 3.48 Ind/g were found in the surface sample. However, in the sediment core samples of location Nith, an increase in the abundance of foraminifera individuals with depth could be observed. Especially the deepest analysed 10 cm interval at a depth of 40 cm contained the most specimen with 467.95 Ind/g. This peak in abundance of foraminiferal tests may indicate absence of environmental stressors or improved ecological conditions influencing the foraminiferal distribution. Moreover, this pattern could also be explained by a regression of the salt marsh (Chen et al., 2020; El-Kahawy & Mabrouk, 2023).

When evaluating the statistical analysis regarding the biodiversity indices, the foraminifera assemblages from sample sites Drumburgh and Nith exhibit striking differences in diversity, dominance and species richness. At Drumburgh, the entire sediment core was characterized by extremely low species richness, with only a maximum of two species identified across all depth intervals. Correspondingly, the diversity index Shannon\_H, was 0 or near 0 and the dominance index Dominance\_D reached maximum values of 1, confirming the presence of a monospecific, highly dominated assemblage.

Evenness and richness estimators Fischer's alpha further supported this pattern, with near 0 values, reflecting the lack of taxonomic complexity. These results may suggest environmental stress, disturbance, competitive exclusion by dominant species or poor preservation (Chen et al., 2020; Blazquez & Usera, 2010; Pavard et al., 2023; El-Kahawy & Mabrouk, 2023).

In contrast, the salt marsh samples from Nith exhibited higher taxonomic diversity and more variable foraminiferal assemblages with depth. Species richness ranged from 3 to 5 and corresponding diversity indices increased accordingly. The diversity index Shannon\_H was substantially higher at Nith than at Drumburgh, indicating greater diversity and a more balanced species distribution. The Shannon\_H value reached a peak value of 1.21 at 30-40 cm depth. Lower dominance and moderate species richness at sample location Nith, compared to Drumburgh, suggest a more complex and stable environment. The Fischer's alpha measurements were also slightly higher at site Nith, providing additional evidence for an increase in species diversity. This pattern could, for example, reflect reduced environmental stress or enhanced preservation relative to sample site Drumburgh. These differences between the Drumburgh and the Nith sample location may reflect contrasting ecological regims. Drumburgh showing a lower diversity and a quite homogeneous foraminiferal community, while the Nith sample location supports a richer, more heterogeneous foraminiferal community (Chen et al., 2020; Blazquez & Usera, 2010; El-Kahawy & Mabrouk, 2023).

The similarity analysis of presence/absence data revealed contrasting patterns between the two sample sites. The Drumburgh samples were highly similar, with peak similarity measurements of 1.0, indicating a homogeneous foraminiferal assemblage. Conversely, the Nith samples showed varying values of 0.178 to 0.862, indicating a more heterogeneous assemblage throughout the core. Comparison between the two sites also varied substantially, although the surface samples exhibited notably similarities. Generally, the species composition was more homogeneous within sites than between sites and the composition changed with depth.

Overall, these pattern suggest that Drumburgh maintains a more uniform foraminiferal community, while Nith supports higher heterogeneity, potentially reflecting differences in environmental stability, habitat complexity or sedimentary processes between the two locations (Chen et al., 2020; Blazquez & Usera, 2010; El-Kahawy & Mabrouk, 2023).

When comparing the surface samples to the corresponding sediment core samples, it is apparent that the Drumburgh surface samples have a similar species composition to the sediment core samples, as both exhibit a strong dominance of *Jadammina macrescens*. However, the absolute abundance of foraminifera tests varies significantly between the core samples and the surface samples. In contrast, the Nith surface samples reveal clear differences in species composition to the associated Nith sediment core samples. Potential reasons for the variation in species composition could be bioturbation or post-depositional processes. Additionally, changes in salinity, oxygen, temperature and organic matter flux over time can lead to differences in species composition, as the surface

samples mostly reflect current environmental conditions and the sediment core samples record deposition over a longer period of time (Chen et al., 2020; Fontaine et al. 2002; Pérez-Asensio et al., 2017).

In general, the foraminifera assemblages of the salt marshes Drumburgh and Nith are dominated by agglutinated species that are typical of salt marsh environments (*Jadammina macrescens*, *Trochammina inflata*, *Haplophragmoides wilberti*). The occurrence of *Miliammina fusca*, *Haynesina germanica* and *Ammonia* sp. suggests a marine influence or a low marsh setting (Radl, 2017; Chen et al., 2020; Milker et al., 2015). The only species that are not characteristic for salt marsh environments are *Casidulina* sp. as well as planktonic species. In the Nith surface sediment sample 23.52 planktonic foraminifera specimen were found. These planktonic specimen were not expected as the sample locations around the estuary were only of very shallow water depth. But a minimum depth is necessary for the occurrence of planktonic species (Murray, 1979). They were excluded from further identification and analysis, as they likely represent allochthonous input and are not native to a salt marsh environment (Murray, 1979; Radl, 2017). It is possible that the tests of the planktonic foraminifera specimen were transported and redistributed by oceanic currents, wave dynamics, tidal transport or storm events (Sahoo et al., 2022). Therefore, the occurrence of *Casidulina* sp. and the planktonic foraminifera specimen could support the suggestion of the area being occasionally influenced by marine conditions.

#### 4.2 Comparison to other salt marshes

The foraminiferal assemblage identified in this study is largely consistent with species compositions reported from salt marsh environments in previous research. Most of the reviewed sources describe species like *Miliammina fusca* and calcareous species including *Ammonia* sp. and *Haynesina* sp. as characteristic of tidal flat and low marsh settings (Radl, 2017; Chen et al., 2020; Milker et al., 2015; Saad & Wade, 2017; Horton & Edwards, 2006). Additionally, *Jadammina macrescens* is documented to be primarily found in mid to high marsh settings (Horton & Edwards, 2006). Species like *Trochammina inflata* and *Haplophragmoides* spp. are typically found in high marsh environments (Radl, 2017; Chen et al., 2020; Milker et al., 2015). Horton & Edwards (2006) identified the calcareous foraminiferal assemblage of a salt marsh to generally consist of mainly *Ammonia* spp., *Haynesina germanica* and *Elphidium williamsoni*. Of these taxa, only *Elphidium williamsoni* was absent in the Drumburgh and Nith samples.

The taxonomic diversity of the foraminiferal assemblages in the Drumburgh and Nith salt marshes is low. Most references observed slightly higher species richness than the one recorded in Drumburgh and Nith. For example, Chen et al. (2020) recorded 15 taxa across 54 samples in salt marshes in northern Georgia, USA, while Milker et al. (2015) documented 14 different species across 18 sample sites at Toms Creek marsh in Oregon, USA (Chen et al., 2020; Milker et al., 2015). Saad and Wade (2017) observed five different foraminifera taxa across three sample sites in North Norfolk, England (Saad & Wade, 2017).

However, all of these studies were limited to surface sampling and lack data from sediment cores, which complicates the direct comparison. Observations by Saad and Wade (2017) showed a foraminiferal assemblage that differs notably from those observed in the Drumburgh and Nith salt marshes. Their study identified *Haynesina germanica*, *Ammonia* sp. and *Elphidium williamsoni* as the dominant species. Nevertheless, *Elphidium williamsoni* was entirely absent from both salt marshes in Drumburgh and Nith. Moreover, *Haynesina germanica* and *Ammonia* sp. contributed only a minor proportion to the assemblage recorded at these two sites. However, it is important to note, that the findings by Saad and Wade (2017) represent only the living foraminifera assemblage (Saad & Wade, 2017).

Horton & Edwards (2006) recorded 84 different foraminifera taxa across 236 sampling sites in Great Britain and Ireland. They also took samples of the Nith estuary salt marsh, where they encountered 37 different foraminiferal species. *Jadammina macrescens*, *Haynesina germanica* and *Miliammina fusca* dominated that data. When comparing to the data of this study, it becomes apparent that in particular, *Haplophragmoides wilberti* is absent in the data of Horton & Edwards (Horton & Edwards, 2006).

#### 4.3 Salt marsh development and sea level reconstruction

There are multiple causes for changes in the relative sea level around the coastline of estuaries like the Solway Firth on Britain's west coast. One of them are the global eustatic sea-level changes, which refers to worldwide changes in sea level. Additionally the area of the Solway Firth has been impacted by isostatic sea level change due to the depression of the earth's crust during the glacial loading and also the post glacial tectonic rebound of the land mass after the Last Glacial Maximum. The glacial Isostatic Adjustment has the biggest significance in the western Highlands of Scotland (McMillan et al., 2011; NOAA, 2024c). In the region surrounding the Solway Firth, a relative land uplift of approximately 1mm per year and a relative sea-level fall of circa 1.1mm per year have been reported. More specifically, the northern area of the United Kingdom has been rising gradually since the last glacial period due to post glacial isostatic rebound. As the lithosphere continues to adjust, this leads to compensatory subsidence in the southern part of the United Kingdom, where the land is gradually sinking (Radl, 2017; McMillan et al., 2011; NOAA, 2024c). Therefore theoretically, the reconstructed sea level data of the sample locations Nith and Drumburgh should show the facilitation model, where the salt marsh shifts toward the sea. During this progradation, the zonation of the meiofauna transitions as well as the plant zonation (Radl, 2017). However, it is of course possible that the salt marshes at the sample locations could have developed differently on a local scale.

By examining the vertical succession of the foraminiferal assemblages, representing distinct marsh zones within the sediment core, the reconstruction of the salt marsh development in relation to sea-level change in Nith and in Drumburgh is possible. A progression from high over mid to low salt marsh assemblages with depth suggests a facilitation-driven succession, reflecting landward marsh migration over time. Conversely, if the sediment core displays a sequence from low to mid over high salt marsh assemblage with depth, it indicates marsh development in response to sea-level rise.

Alternatively, if the core is extracted from an area currently classified as high marsh, the assemblage may consistently reflect high marsh conditions throughout, indicating minimal vertical ecological change over time (Radl, 2017).

In order to reconstruct the sea levels at the Nith and the Drumburgh sample site, foraminifera assemblages of the sediment cores were used as indicator fauna for the salt marsh zones (Williams et al., 2021). Most of the reviewed sources describe *Trochammina inflata* and *Haplophragmoides* spp. and occasionally *Jadammina macrescens* as indicator species for high marsh (Radl, 2017; Chen et al., 2020). In contrast, *Miliammina fusca*, *Haynesina germanica* and sometimes *Ammonia* spp. are considered as essentials for low marsh assemblages (Radl, 2017; Chen et al., 2020; Milker et al., 2015). The typical foraminifera species found in high-mid marsh areas supposedly is *Jadammina macrescens*. Some sources also name *Miliammina fusca* when referring to typical high-mid marsh species (Radl, 2017; Chen et al., 2020). *Ammonia beccarii* is an important species for the pioneer zone and the mid-low marsh environment (Radl, 2017).

The foraminiferal assemblages at sample site Drumburgh show signs for the salt marsh indicators that do not all align. In the 0-10 cm interval of the Drumburgh core *Ammonia* sp. was found. This generally suggests a low marsh setting (Chen et al., 2020). But *Ammonia* sp. is also typical for marginal marine environments in general (Murray, 1979). Additionally, it is of course possible, that *Ammonia* sp. was transported by oceanic currents, wave dynamics or storm events (Sahoo et al., 2022). In deeper intervals (10-20 cm and 20-30 cm) of the Drumburgh samples, only *Jadammina macrescens* specimen were found and in the deepest samples (30-40 cm and 40-50 cm) no foraminifera tests were found. *Jadammina macrescens* specimen indicate a high-mid marsh setting (Radl, 2017). This observation supports the assumption that in these samples differential dissolution or high mechanical damage could have occurred, which both could lead to poor preservation. Another possibility is that foraminifera colonized the site only recently, resulting in a lack of tests within older, deeper sediment layers (Frenzel et al. 2005).

Overall the samples of the Drumburgh location primarily show signs of high-mid marsh environments in the upper to mid fragments. This consistent representation of high-mid marsh conditions within the assemblage could imply minimal ecological shifts along the vertical profile and could suggest an equilibrium situation with a stable relative sea level (Radl, 2017).

Due to the nonexistent foraminiferal assemblage in the deeper fragments of the Drumburgh samples, it is however not possible to postulate an accurate development of the salt marsh. The development in the 30-50 cm deep interval cannot be determined without any data.

There are several different possibilities how the development of salt marsh Drumburgh progressed. Possible is a seaward migration of the salt marsh (facilitation succession), which is depicted on the left hand side in figure 7, but also a landwards migration of the salt marsh due to relative sea-level rise, which is shown on the right hand side of figure 7. Both of these two potential salt marsh cross-section profiles can be viewed in figure 7.

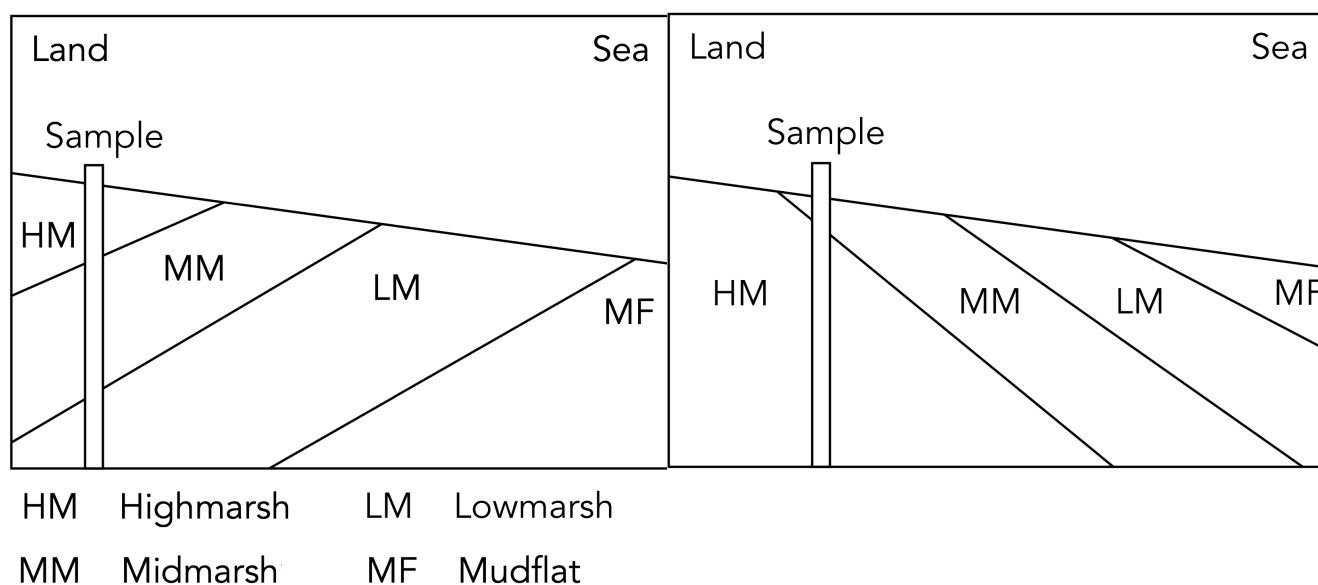


Figure 7: Potential schematic cross-sections of salt marsh Drumburgh

At sample site Nith the foraminiferal assemblages suggest a different succession than at sample location Drumburgh. *Jadammina macrescens* was present in all intervals from 0 to 50 cm depth at the Nith location, with its highest abundance observed in the 0-10 cm depth interval. This species is typical for high-mid marsh settings (Radl, 2017). *Miliamina fusca* was detected from depth 0-10 cm downwards to the 40-50 cm fragment and was increasing with depth. *Miliamina fusca* generally implies a low marsh environment (Radl, 2017). However, in another source, *Miliamina fusca* is stated to occasionally also occur in high-mid marsh environments (Chen et al., 2020). Similar to *Miliamina fusca*, *Trochammina inflata* also occurred from depth 0-10 cm downwards to depth 40-50 cm. *Trochammina inflata* shows its highest abundance in the 10-20 cm interval. This species is described as an indicator species for high marsh settings (Chen et al., 2020; Radl, 2017). *Haynesina germanica*, a species characteristic of low marsh environments (Radl, 2017), was observed in the 10-20 cm sediment interval. The foraminiferal species *Haplophragmoides wilberti* was detected in all of the samples except the 20-30 cm deep sample. This species showed its highest abundance in the deepest fragment of 40-50 cm depth. *Haplophragmoides wilberti* is referred to as a high marsh indicator species (Chen et al., 2020; Radl, 2017).

Overall the samples of the Nith sample location suggests a shift in the foraminiferal assemblages from high to mid to low marsh from bottom to top. This shift in foraminiferal assemblage does not represent the typical seaward migration of the salt marsh called facilitation succession. If the sediment core reveals a stratigraphic transition from low to high marsh assemblages with increasing depth, this pattern reflects salt marsh accretion driven by sea-level rise (Radl, 2017). A possible salt marsh cross-section profile was constructed for Nith as well and can be observed in figure 8 on the left hand side.

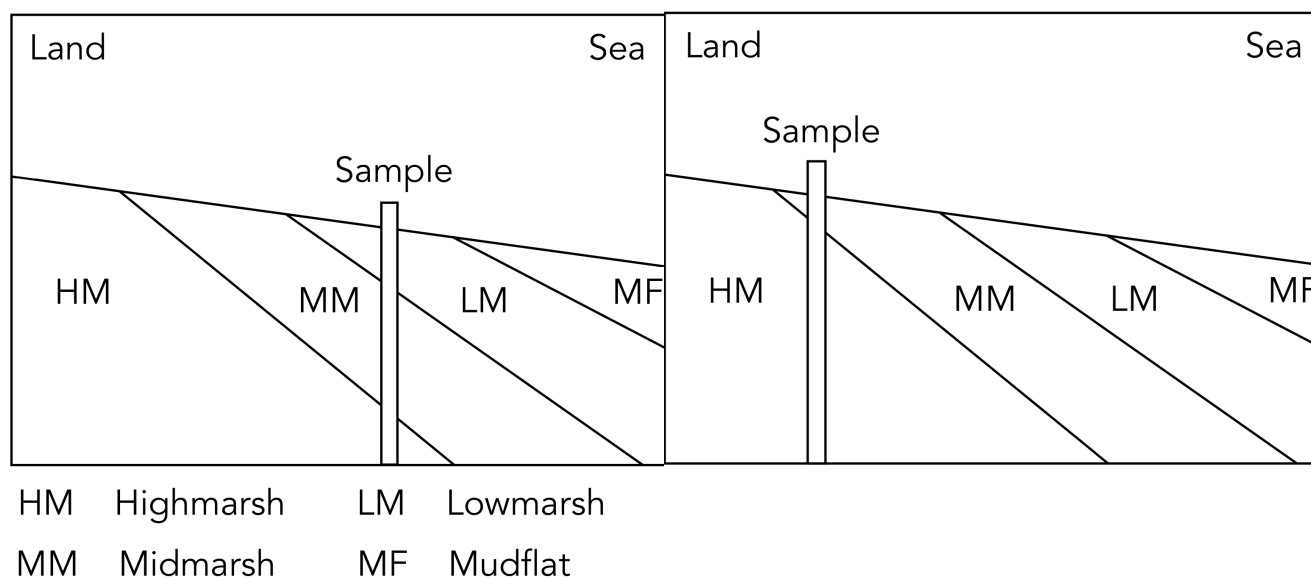


Figure 8: Potential schematic cross-sections of salt marsh Nith

Furthermore, the dominance of agglutinated foraminifera species at both locations (99.7%) suggests mostly high and mid marsh environments, as based on previous studies, calcareous species primarily occur in low marsh and mudflat settings (Radl, 2017). The calcareous foraminiferal species *Haynesina germanica* detected in the 10-20 cm interval of the Nith samples, supports the provided salt marsh cross-section profile presented in figure 8 on the left hand side. However, there is also the possibility, that the development of salt marsh Nith showed a similar progression to Drumburgh, with primarily high marsh to mid marsh environments throughout the core. The potential salt marsh cross-section profile is presented in figure 8 on the right hand side.

#### 4.4 Taphonomic bias, preservation and fragmentation

A very important factor to consider in this study is the taphonomic bias. Some species are better preserved than others. Taphonomic problems and issues are influenced by abiotic and biotic factors, which affect the preservation, the composition and the distribution of fossil remains (Gupta, 1999).

Differential dissolution is where certain foraminiferal tests are more susceptible to dissolution than others. Experimental studies have shown that smaller specimen with less calcite content, dissolve more rapidly than larger and robuster benthic forms. This selective dissolution leads to biased assemblages, with more resistant taxa becoming overrepresented in the fossil record and also leading to a larger average size of the remaining specimens (Nguyen et al., 2009).

Calcium carbonate is highly soluble in cold, brackish water, which limits the fossilization potential of calcareous foraminifera. Their preservation is strongly influenced by sedimentation rates, bioturbation and chemical properties of pore waters within the sediment (Frenzel et al. 2005). Selective dissolution of the calcite shells occurs due to the low, acidic pH of the sediment of a salt marsh. In their study, Fouet et al. observed sediment pore water with moderately acidic characteristics, recording pH values near 6.6 (Radl, 2017; Fouet et al., 2024). Furthermore, differential dissolution of calcareous species can lead to a strong dominance of agglutinated foraminiferal fauna. As the dissolution only affects calcareous species and agglutinated species remain unaffected (Nardelli et al., 2022). The tests of agglutinated species consist of cemented detrital sediment particles in contrast to the calcite shells of calcareous species (Murray, 1979). 790.57 of the 793.04 occurring foraminifera specimen found at sample locations Drumburgh and Nith were agglutinated, which is 99.7%.

Mechanical damage to foraminifera tests of agglutinated and calcareous species frequently takes place during transport, particularly in high-energy environments. Also other abiotic factors like physical reworking through currents or high energy events like storms can have an impact on the preservation and cause breakage and fragmentation of the foraminifera tests, due to collision with sediment particles and other tests. However, also biological activities like burrowing can affect the preservation of benthic foraminiferal shells and may also alter the benthic foraminiferal assemblage through vertical mixing, leading to sediment homogenization (Pérez-Asensio et al., 2017).

When calcareous foraminiferal shells dissolve, the inner organic lining (IOL) often remains and can serve as an indicator of post-depositional dissolution if preserved. In the salt marsh samples from Drumburgh and Nith there were no inner organic linings detected. Given the sample age of 13 years, the possibility of suboptimal storage conditions and the fact, that the material was dried prior to picking, the likelihood of finding an inner organic lining is low. Nevertheless, some uncertainty remains and dissolution cannot be definitely proven (Tyszka et al., 2021).

## 5. Conclusion

This thesis aimed to assess the development of the salt marshes Nith and Drumburgh, using a fauna analysis of benthic foraminifera. The sample sites are situated at two opposing channel arms, located around an estuary called the Solway Firth in the United Kingdom. The goal was to evaluate the species distribution and compare their ecological succession of the salt marshes by examining foraminiferal assemblages as indicators of marsh zones.

The analysis revealed differing foraminifera assemblages at the two sample sites. The Drumburgh samples showed low diversity, a high evenness and a homogeneous foraminiferal community highly dominated by *Jadammina macrescens*. Conversely, the Nith samples indicated a more heterogeneous foraminiferal community with higher species richness and higher taxonomic biodiversity.

Additionally, at the Drumburgh sample site, the foraminiferal assemblage was highly concentrated at the surface. In the deeper intervals of the Drumburgh sediment core sample, no foraminifera tests could be detected. This suggests poor preservation of the microfossil shells, dissolution of the foraminiferal tests is a possible explanation for their lacking. An alternative explanation is that the foraminiferal community colonized the site only relatively recently, which would account for the absence of tests in deeper and stratigraphically older sediment layers (Nguyen et al., 2009; Frenzel et al. 2005).

At sample location Nith an increase in the abundance of foraminifera specimen with depth could be observed. The deepest interval at a depth of 40-50 cm contained 467.95 of the foraminiferal specimen found in the Nith sediment core. The lower dominance at the Nith sample site, compared to Drumburgh, suggest a more complex and stable environment (Blazquez & Usera, 2010; El-Kahawy & Mabrouk, 2023).

The upper to mid foraminiferal assemblage at Drumburgh suggests high-mid marsh conditions suggesting either seaward migration of the salt marsh, succession due to relative sea-level rise, or a relative stable sea-level. The samples from Nith likely exhibit a vertical shift in foraminiferal assemblages from high to mid to low marsh, indicating a progressive salt marsh development driven by relative sea-level rise. However, also a similar progression to the salt marsh development in Drumburgh is considerable for the Nith salt marsh, due to the high amounts of foraminifera specimen, indicating a high-mid marsh environment. Therefore, also succession of the salt marsh due to relative sea-level rise is possible (Radl, 2017).

A limitation of this study is the relatively small number of foraminifera specimen that were included in the analysis. In addition, the lack of foraminifera specimen in the deeper fragments of the Drumburgh sample, complicate the determination of the salt marsh zonation and consequently causes problems in the sea level reconstruction of the Drumburgh salt marsh. Future studies could include a broader geographic area, more sample sites as well as more sediment cores to get a clearer understanding of the sea level development around the Solway Firth.

Overall, this study provides new insights into the succession of two salt marshes in the United Kingdom and suggests differences in their development despite their geographically closeness.

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## 7. Abstract

### 7.1 Abstract english

Salt marshes are dynamic coastal ecosystems that serve as sensitive indicators of sea-level change, sediment dynamics and environmental stress. Foraminiferal assemblages are widely applied as proxies for marsh zonation, yet their comparative use in evaluating succession across opposing estuary arms remains limited. This study applies a benthic foraminiferal analysis to assess the development of the two salt marshes Nith and Drumburgh, located on opposing channel arms of an estuary on Britain's west coast. Foraminiferal assemblages were utilized as a proxy for marsh zone indicators and assemblage data was integrated with biodiversity indices and presence/absence similarity analysis to investigate site-specific patterns of salt marsh development and the environmental factors influencing their divergence.

At salt marsh Drumburgh, the foraminiferal assemblage was restricted to the upper 30 cm of the core, exhibiting high internal similarity and low taxonomic diversity, with no specimen recorded in deeper intervals. In contrast, Nith displayed higher vertical variability, higher diversity values and increased taxonomic richness. Similarity analysis further revealed more heterogeneous assemblages at Nith, whereas Drumburgh remained comparatively uniform.

These results suggest, that Drumburgh represents a more homogeneous and potentially stressed environment, while Nith supports a more diverse and stable assemblage.

## 7.2 Abstrakt Deutsch

Salzwiesen sind dynamische Küstenökosysteme, die als empfindliche Indikatoren für Veränderungen des Meeresspiegels, Sedimentdynamik und Umweltbelastungen dienen. Die Faunenzusammensetzung von Foraminiferen wird häufig als Proxy für die Zonierung von Salzwiesen verwendet. Doch ihr Einsatz zur Untersuchung der Sukzession von Salzwiesen an gegenüberliegenden Ästuarmäandern, ist bislang begrenzt.

In dieser Studie wird die benthische Faunenzusammensetzung von Foraminiferen analysiert, um die Entwicklung der beiden Salzwiesen Nith und Drumburgh zu ermitteln. Die beiden Salzwiesen liegen an gegenüberliegenden Kanälen eines Flussmündungsgebiets an der Westküste Großbritanniens. Die Faunenzusammensetzung von Foraminiferen wurde als Proxy für die Salzwiesen zonen genutzt. Die Faunenzusammensetzung der benthischen Foraminiferen, die Biodiversitätsindizes sowie eine Präsenz-/Abwesenheits-Ähnlichkeitsanalyse wurden kombiniert, um standortspezifische Muster der Salzwiesenentwicklung und die Umweltfaktoren, die ihre Divergenz beeinflussen, zu untersuchen.

In der Salzwiese Drumburgh war die Artenzusammensetzung der Foraminiferen auf die oberen 30 cm des Bohrkerns beschränkt und wies eine hohe interne Ähnlichkeit und geringe taxonomische Vielfalt auf, wobei in tieferen Schichten keine Foraminiferen gefunden wurden. Im Gegensatz dazu zeigte Nith eine höhere vertikale Variabilität, höhere Diversitätswerte und eine größere taxonomische Vielfalt. Die Ähnlichkeitsanalyse ergab außerdem eine heterogenere Faunenzusammensetzung in Nith, während Drumburgh vergleichsweise einheitlich blieb.

Diese Ergebnisse deuten darauf hin, dass Drumburgh eine homogenere und potenziell stärker belastete Umgebung darstellt, während Nith wahrscheinlich eine vielfältigere und stabilere Gemeinschaft beherbergt.

## 8. Appendix

Table 4: Abundance data of the sediment core at sample location Drumburgh (DR) normed to 1 gram (g) (values in Ind/g)

Samples DR with depth	<i>Haplophragma wilberti</i>	<i>Haynesina germanica</i>	<i>Jadammina macrescens</i>	<i>Trochammina inflata</i>	<i>Ammonia</i> sp.	<i>Miliamina fusca</i>	<i>Cassidulina</i> sp.
0-10cm	0	0	1.506024096	0	0.75301204	0	0
10-20cm	0	0	2.066115702	0	0	0	0
20-30cm	0	0	2.577319587	0	0	0	0
30-40cm	0	0	0	0	0	0	0
40-50cm	0	0	0	0	0	0	0

Table 5: Abundance data of the sediment core at sample location Nith (NI) normed to 1 gram (g) (values in Ind/g)

Samples NI with depth	<i>Haplophragma wilberti</i>	<i>Haynesina germanica</i>	<i>Jadammina macrescens</i>	<i>Trochammina inflata</i>	<i>Ammonia</i> sp.	<i>Miliamina fusca</i>	<i>Cassidulina</i> sp.
0-10cm	1.012145748	0	27.32793522	13.1578947	0	4.0485829959	0
10-20cm	4.208754208	0.84175084	5.892255892	24.4107744	0	3.367003367	0
20-30cm	0	0	0.841750841	0.84175084	0	0.8417508417	0
30-40cm	3.875968992	0	3.875968992	7.75193798	0	15.50387596	0
40-50cm	352.5641025	0	36.32478632	55.5555555	0	23.50427350	0

Table 6: Weight of the 125 µm fraction in grams (g) not including the glass bottles (glassbottle = 9.762g)

Depth (cm)	DR (g)	NI (g)
0 (Surface sample)		1.148
0-10	1.928	0.988
10-20	0.968	1.188
20-30	0.388	1.188

Depth (cm)	DR (g)	NI (g)
30-40	0.818	0.258
40-50	0.968	0.468

Table 7: Absolute abundance of foraminifera species

Foraminifera species	DR	NI
<i>Ammonia sp.</i>	1	0
<i>Casidulina sp.</i>	0	1
<i>Haplophragmoides wilberti</i>	0	172
<i>Haynesina germanica</i>	0	1
<i>Jadammina macrescens</i>	406	56
<i>Miliamina fusca</i>	3	20
<i>Trochammina inflata</i>	0	71
Foraminifera with hyaline calcite tests	1	2
<i>Planktonic species</i>	0	27
<b>Total numbers</b>	<b>411</b>	<b>350</b>

Table 8: Abundance data of the surface samples at Nith (NI) and Drumburgh (DR) normed to 1 gramm (g)

Surface samples	<i>Jadammina macrescens</i>	<i>Miliamina fusca</i>	<i>Casidulina sp.</i>
<b>NI</b>	2.61 Ind/g	0 Ind/g	0.87 Ind/g
<b>DR</b>	208.51 Ind/g	1.56 Ind/g	0 Ind/g

Table 9: Absolute weight of the entire samples in grams (g)

depth (cm)	DR	NI
<b>0 (Surface samples)</b>	127.63	73.25
<b>0-10</b>	57.03	55.09
<b>10-20</b>	74.20	71.79
<b>20-30</b>	69.38	78.36

<b>depth (cm)</b>	<b>DR</b>	<b>NI</b>
<b>30-40</b>	12.77	60.57
<b>40-50</b>	31.70	68.90