# Describing scour with sediment characteristics and macroinfaunal assemblages

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# A case study at the Joskär shipwreck

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Tiivistelmä - Referat – Abstract

As water flow encounters an object on the sea floor, its hydrodynamics change. Accelerated currents and vortices develop around the object with changing intensity as a function of distance from its proximity. This leads to erosion and aggradation of sediment, known as scour. Studies focusing on formation processes of scour often involve locating visible scour sites by sonar scanning the geomorphology of the seafloor. However, the effects of scour on macroinfauna and small-scale sediment characteristics are not visible in sonar images.

In this Master's thesis, scour at a shipwreck of a timber-built historic sailing ship, the Joskär shipwreck, was first identified by scanning the study area with side-scan sonar, and by measuring water depth contours around the shipwreck by scuba diving. Sediment samples were then taken inside the area assumed to be under the most pressure from scour. Samples from three separate distances on two transects drawn outwards from the hull of the shipwreck were collected and analysed for sediment grain size, organic content, and species assemblages of macroinfauna. In addition, macrofauna were analysed for individual lengths, number of individuals, diversity index, and functional groups. All samples were collected with a core tube sampler operated by a scuba diver. The methods used in this Master's thesis widen the concept of scour past the sole physical processes observable with sonar to a more holistic level that considers the quality of biological, geological, and chemical characteristics of the benthic environment.

The results of the present Master's thesis show that the quality of the sediment near Joskär shipwreck varies within a relatively small scale. Organic content of the sediment was the most potent descriptor of scour at the study site, exhibiting a consistent decreasing trend as distance to the shipwreck increased on both sampled transects. Sediment grain size became finer as distance to the shipwreck increased. However, compared to grain size, based on visual observations of the sediment samples, shell debris content of the sediment could possibly act as a better measure of presence of scour. The variability of characteristics of macroinfaunal communities as a function of distance from Joskär shipwreck was not a viable tool to describe the presence of scour, as no consistent trends of the variables were observed.

As no control site was included in the study design, the characteristics of the benthic environment inside the scour around Joskär shipwreck could not be compared to the seafloor unaffected by scour. Further research could reveal possible variation between these distinct habitats, and that way produce valuable indicators of scour.

The hypothesis in the present thesis was that macroinfaunal assemblages and sediment characteristics would exhibit variation between the sampling sites as a function of distance from the shipwreck. The observed trends of sediment characteristics validated a part of the hypothesis, showcasing the utility of sediment characteristics in describing scour at Joskär shipwreck. However, a part of the hypothesis was rejected, as no consistent trends of macroinfaunal features were present.

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Veden virtauksesta aiheutuneiden merenpohjan muutosten kuvailu sedimentin ominaisuuksien ja pohjaeläinyhteisöjen avulla – Tapaustutkimus Joskärin hylyllä

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Tiivistelmä - Referat – Abstract

Veden virtauksen kohdatessa merenpohjassa olevan objektin, virtauksen dynamiikka muuttuu. Veden liike kiihtyy, minkä seurauksena merenpohjassa olevan objektin ympärille muodsostuu pyörteitä. Virtausten intensiteetti vaihtelee etäisyyden muuttuessa suhteessa pohjassa olevaan objektiin. Vaihteleva virtauksen intensiteetti aiheuttaa sedimentin eroosiota, mikä havaitaan veden virtauksesta aiheutuneina merenpohjan topologisina muutoksina (engl. scour). Virtausten muokkaamaan merenpohjaan keskittyvät tutkimukset kuvailevat virtausten aikaansaamaa vaikutusaluetta usein ainoastaan kaikuluotaimilla. Veden virtauksen aiheuttamien mutosten vaikutus pohjaeläinyhteisöihin ja pienimittakaavaisiin sedimentin ominaisuuksiin ei kuitenkaan tallennu kaikuluotaimien tuottamiin kuviin merenpohjan geomorfologiasta.

Tässä maisterintutkielmassa Joskärin historiallisen puurunkoisen purjealuksen hylyn ympärillä olevia virtausten aiheuttamia pohjan muutoksia kuvattiin ensin viistokaikuluotaamalla ja määrittämällä merenpohjan syvyys sukeltamalla. Tämän jälkeen sedimenttinäytteitä kerättiin alueelta, jonka oletettiin olevan suurimman virtausten luoman vaikutuksen alaisuudessa. Näytteitä otettiin kolmen eri etäisyyden päästä hylystä, kahden identtisen hylystä poispäin vedetyn linjan varrelta. Näytteistä analysoitiin orgaanisen aineen pitoisuus, sedimentin raekoko, ja pohjaeläinyhteisöjen lajikoostumus. Pohjaeläinyhteisöistä määritettiin lisäksi yksilömäärät, yksilöpituudet, diversiteetti-indeksi, ja funktionaaliset ryhmät. Kaikki näytteet kerättiin putkinoutimella sukeltajan toimesta. Tässä maisterintutkielmassa hyödynnettyjen menetelmien välityksellä käsitys veden virtausten vaikutuksesta merenpohjan ominaisuuksiin laajeni kaikuluotaimen tuottamasta geomorfologisesta tiedosta kokonaisvaltaisemmalle tasolle, jossa otetaan pohjanmuotojen lisäksi huomioon sedimentin biologiset, geologiset ja kemialliset ominaisuudet.

Tämän maisterintutkielman tulokset näyttävät sedimentin ominaisuuksien vaihtelevan Joskärin hylyn ympäristössä suhteellisen pienellä mittakaavalla. Sedimentin orgaanisen aineen pitoisuus oli tehokkain veden virrtausten ja pohjalla olevan objektin aiheuttamien muutosten osoittava ominaisuus Joskärin hylyllä. Sen pitoisuus ilmensi johdonmukaisesti vähenevän kehityssuunnan molemmilla näytteenottolinjoilla etäisyyden hylkyyn kasvaessa. Sedimentin raekoko muuttui hienommaksi kauempana hylystä, mutta sedimenttinäytteiden visuaalisen tarkastelun perusteella sedimentissä olevan kuolleen simpukankuoriaineksen määrä voisi mahdollisesti toimia raekokoa parempana virtausten ja pohjalla olevan objektin aiheuttaman pohjanmuutoksen ilmentäjänä. Pohjaeläinyhteisöjen ominaisuuksien vaihtelu etäisyyden funktiona ei ole toimiva virtausten aiheuttamien muutosten ilmentäjä Joskärin hylyllä, sillä johdonmukaisia vuorovaikutussuhteita pohjaeläinyhteisöjen ominaisuuksien ja hylyn etäisyyden välillä ei paikannettu.

Koska tutkimussuunnitelmaan ei sisällytetty kontrollinäytteitä, Joskärin hylkyä ympäröivän vedenvirtauksen vaikutusalueen ominaisuuksia ei voitu verrata tutkimusalueen ulkopuolisen pohjan ominaisuuksiin. Jatkotutkimuksilla voitaisiin selvittää mahdolliset eroavaisuudet virtausten ja pohjalla olevan objektin vaikutusalueen sedimenttien sekä vaikutusalueen ulkopuolella olevien sedimenttien välillä.

Tämän tutkielman hypoteesina pohjaeläinyhteisöjen sekä sedimentin ominaisuuksien oletettiin vaihtelevan etäisyyden funktiona Joskärin hylystä. Sedimentin ominaisuuksien ilmentämät johdonmukaiset kehityssuunnat suhteessa etäisyyteen hylystä varmistavat osan hypoteesista todeksi, mikä vahvistaa sedimentin ominaisuuksien käyttöarvoa veden virtauksen aiheuttamien muutosten ilmentämisessä Joskärin hylyllä. Osa hypoteesista kuitenkin hylätään, sillä pohjaeläinyhteisöjen ominaisuuksia tutkittaessa johdonmukaisia kehityssuuntia ei löytynyt.

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# 1. Introduction

## 1.1. Scour

An object of artificial or natural origin, lying on the seafloor, enables formation of distinctive environments through physical forcing of water movement over time (Sumer et al., 2001; Quinn, 2006). This phenomenon of object induced change in the surrounding environment is commonly referred to as scouring or scour formation (Caston, 1979; Werner et al., 1979; Quinn, 2006). As water flow encounters an object on the sea floor, its hydrodynamics change. Accelerated currents and vortices develop around the object with changing intensity as a function of distance from its proximity (Sumer et al., 2001; Quinn, 2006) (Figure 1). This variable water flow erodes and aggregates sediment, leaving behind a scour area, distinct from its surrounding seafloor geomorphology. Geomorphological variations within the scour area can include a scour pit that is deeper than the surrounding sediment surface, changes in sediment grain size composition, and aggradation of sediment into elevated sediment deposits and dune-like ripple formations. The phenomenon is relatively dynamic, especially at shallow areas with strong tidal currents and wave action, where the constantly changing physical conditions alter the sea floor (Caston, 1979; Quinn, 2006; Raineault et al., 2013; Fernandez-Montblanc et al., 2016). Deeper areas are less affected by wave action, and formation of a scour is controlled by sedimentation rates and bottom currents (Jönsson et al., 2004; Leino et al., 2011; Webb, 2019).

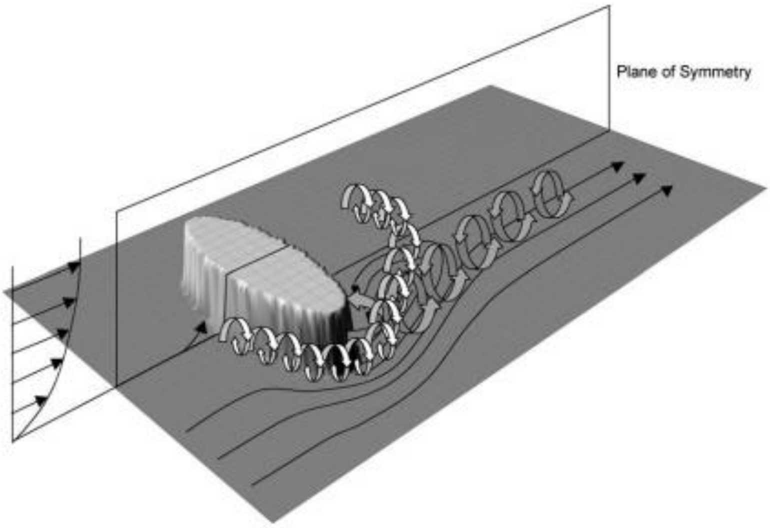

**Figure 1.** A schematic illustration of water movement and sediment scouring taking place in the vicinity of an object on the sea floor. Adapted from Quinn (2006). Black arrows representing the direction of water flow. Light arrows representing vortices developing from the contact of water movement with the object.

The shape and size of the object is one of the factors influencing its surrounding water currents and scour formation (Caston, 1979). Scouring has been observed related to anthropogenic objects, such as piers and anchors of aquatic constructions (Lu et al., 2008; Prendergast & Gavin, 2014), but also to more natural sites, where scour areas form in the vicinity of rocks and boulders (Werner et al., 1979, Hay & Speller, 2005). Previous publications from the field of maritime archaeology have shown interest towards the way physical scouring affects the preservation of historic shipwrecks (Quinn, 2006; Fernández-Montblanc et al., 2016) (Figure 2 A & B). Interdisciplinary studies combining approaches of maritime archaeology and natural sciences aim to reveal scour related relationships between artificial objects and the natural environment on the sea floor (Leino et al., 2011; Ruuskanen et al., 2015).

Studies focusing on scour formation often involve locating visible scour sites by sonar scanning the geomorphology of the seafloor with side-scan sonar and multi beam echo sounders (MBES) (Caston, 1979; Werner et al., 1979; Quinn, 2006; Leino et al., 2011; Raineault et al., 2013; Ruuskanen et al., 2015). These technical instruments draw a visually interpretable image of the seafloor geomorphology that enables locating possible anomalies on the seafloor (Figure 2 A & B). When conditions allow it, divers can be used to confirm the extent of observed physical scour formations based on sonar images (Werner et al., 1979; Fernández-Montblanc et al., 2016). However, the effects of scour are not necessarily visible in sonar images, thus concealing the phenomenon from the human eye. For example, the scale on which scour processes take place in more stable environments is unknown, which calls for more accurate methods and measurements to reveal the less obvious events taking place. It should be considered whether the extent of the effect of an object reaches beyond the physical effects to the geomorphology of the seafloor and alters the biological communities living in it. Furthermore, the extent to which scouring affects processes taking place on a microscopic level, such as the degradation of organic matter by microbial communities, has so far received little attention.

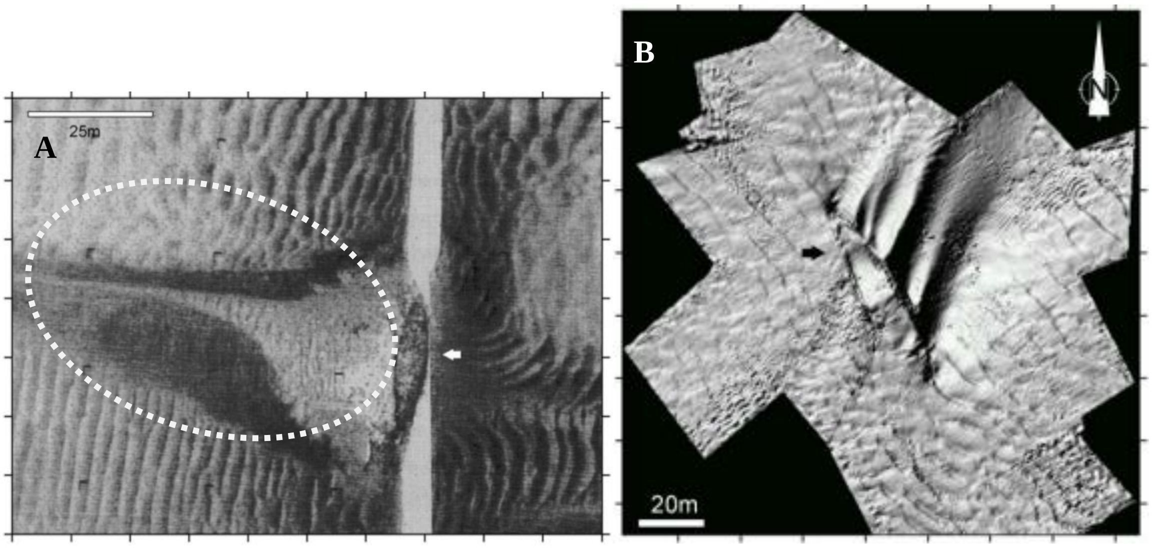

**Figure 2 A & B** (A) Side-scan sonar image of a shipwreck site on a tidal area in Ireland with a visible scour formation. The arrow indicates the position of the shipwreck. A clear anomaly of the geomorphology of the seafloor caused by scour is circled with a dashed line (adapted from Quinn, 2006). (B) A model of a shipwreck site at a shallow tidal region off the coast of Ireland. Black arrow indicates the position of the shipwreck. Sediment has formed elongated ridges on the north side of the wreck (adapted from Quinn, 2006).

## 1.2. Sediment characteristics

Sediment grain size composition and organic content exhibit varying trends as a function of distance from objects on the seafloor (Danovaro et al., 2002; Zalmon et al., 2012; Ruuskanen et al., 2015). In high energy areas, where wave action and currents actively transport sediment, sediment grain size tends to be bigger relative to more stagnant water bodies, where physical forces do not prevent fine sediment from settling (Jönsson et al., 2004).

Caston (1979) and Werner (1979) found that local sediment composition affects scouring, distinguishing formed scour between sandy and gravelly sites. On sandy sites with finer sediment, scour marks identified with sonar technology tend to be shallower and extend further from the object, whereas on gravelly sites with coarser sediment, the marks are shorter and exhibit visible sand plume formation at the edges of the object (Caston, 1979; Quinn, 2006). On seafloors with thin sand cover, Werner et al. (1979) observed scouring generally eroding the top layer of the sediment, leaving behind an area with coarser material, such as gravel, shells, and pebbles. Scouring can also lead to sinking of objects deeper into the sediment. Based on the thickness of the finer sediment layer, the object will eventually stop sinking and stabilise, when coarser bedform is reached (McNinch et al., 2006; Raineault et al., 2013).

In addition, organic content of the sediment, measured as Loss On Ignition (LOI) (Heiri et al., 2001), is connected to prevailing hydrology as organic material generally deposits to low-energy areas (Snelgrove & Butman, 1994). Therefore, by studying the sediment grain size composition and organic content around objects on the seafloor, scour areas can possibly be recognized.

## 1.3. Infauna

Infauna consist of invertebrates encompassing a wide range of taxa inhabiting the second largest biome of the world, marine sediments (Gray & Elliot, 2009). They frequently belong to polychaetes, crustaceans, echinoderms, and molluscs. Infauna can be categorised by their size. Macroinfauna commonly refers to all organisms retained on a 0,5 x 0,5 mm sieve (Anderson et al., 2007; Gray & Elliot, 2009; Zalmon et al., 2012). Exceptions to this classification exists. For example, nematodes and some crustacean species are often classified as meiofauna even if they are larger than 0,5 mm, since a sieve is not a viable tool for their extraction from the sediment (Gray & Elliot, 2009). For juvenile life stages of macroinfauna, a smaller mesh size might be required, since for example in case of *Limecola balthica*, the newly settling individuals are to be extracted with a 0,25 mm mesh sieve, due to their small size (Bonsdorff et al., 1995).

A standardised method for a sufficient sample of macroinfauna in the Baltic Sea by HELCOM's Baltic Monitoring Programme is to use a standard sieve size of 0,5 x 0,5 mm (HELCOM, 2017). Baltic Sea infauna have been classified into functional groups based on their feeding strategies, body size, and motility (Bonsdorff & Blomqvist, 1993). Deposit feeders, predators and suspension feeders all have a distinct influence on the ecosystem and vice versa, the quality of their habitat affects their distribution (Duplisea & Drags, 1999; Coblentz et al., 2015). This type of information is beneficial in ecosystem-based management strategies, where understanding of the functioning of the entire ecosystem is valuable (Aller,1988; Bolam et al., 2002).

The diversity of macroinfaunal assemblages within the Baltic Sea is affected by the young geological age, steep environmental gradients, and strong anthropogenic pressures of the area (Bonsdorff & Pearson, 1999; Leppäkoski et al., 2002; Villnäs & Norkko, 2011; Zettler et al., 2014). Regarding macroinfauna, perhaps the most defining environmental gradient from south to north is the decreasing salinity (Bonsdorff & Pearson, 1999; Villnäs & Norkko, 2011). It is the major environmental factor in preventing marine species from dispersing from the marine-like conditions of the Kattegat and Danish straits to the more brackish water of the northern and eastern Baltic Sea. Therefore, macroinfaunal assemblages show high variation between subregions, exhibiting decreases in diversity and functional groups with decreasing salinity (Bonsdorff & Pearson, 1999; Villnäs & Norkko, 2011).

Anthropogenic impacts such as eutrophication influence the macroinfauna. Eutrophication has caused vast areas of hypoxic bottom conditions to form, changing population dynamics of the macroinfauna, leading to organisms of smaller size and shorter life span (Conley et al., 2009), and wiping out benthic life to the point of local extinction (Villnäs & Norkko, 2011). A consequence of eutrophication is loose lying and decaying algae mats that have become increasingly common in the benthic habitats of the Baltic Sea, causing hypoxia, and affecting the community structures of benthic organisms (Bonsdorff, 1992; Norkko & Bonsdorff, 1996, Ruuskanen et al., 2015).

Benthic invertebrates are used as indicators of the state of the ecosystem. The diversity of the community, the presence/absence of some indicator species, or the occurrence of a certain functional group can reveal possible changes in the environment (Rosenberg et al., 2004; Salas et al., 2006; Villnäs & Norkko, 2011). Pinto et al. (2009) argue that sedentary and long-lived macroinfauna are good indicators of the state of their surrounding environment and the scale of anthropogenic pressure, since benthic areas are under the stress of pollution and oxygen depletion most frequently. Changes happening in the water column are reflected to the zoobenthic communities with varying responses from the diverse assemblage of species. Benthic invertebrates are included in the Marine Strategy Framework Directive (MSFD) of European Union (Directive 2008/56/EC), highlighting the utility of this group of organisms as an indicator of the state of the environment. When determining the ecological state of a benthic habitat, the state of the benthic community is considered.

In addition to responses to anthropogenic pressures, macroinfauna readily respond to habitat quality and the characteristics of the sediment. Distinct infauna in various benthic habitats of Finnish coastal waters are described by for example Blomqvist & Bonsdorff (1986), Aschan (1988), Boström & Bonsdorff (1997) and Kraufvelin et al. (2011). Vertical distribution of macroinfauna is regulated by oxygen concentrations in the sediment since most species of infauna are aerobic and therefore require oxic conditions. This limits their presence to the upper parts of the sediment (Byers & Gabrowski, 2013). On the southern coast of Finland, water depth has been found to be an important determinator of variation within the benthos (Aschan, 1988). Within similar depths however, most variation occurs between shallow habitats, arguably due to the more heterogenous sediment composition that in turn is caused by the stronger pressure from physical forces of wind stress and wave action. Variation in the spatial distribution of macroinfaunal assemblages is common even within relatively small areas, where the relationships of dominating taxa can change drastically between habitats only tens of metres away from each other (Blomqvist & Bonsdorff, 1986).

Prevalent grain size composition and the amount of organic content in the sediment have been linked with the spatial distribution of zoobenthic assemblages (Duplisea & Drags, 1999; Coblentz et al., 2015). Established hydrology influences the way organisms gather their food. Therefore, environments with higher current velocities are often dominated by suspension feeders, such as many bivalves, that gain their nutrition by gathering it from the water column via siphons and other filter feeding apparatuses (Byers & Gabrowski, 2013). Deposit feeders, such as some gastropod and polychaete species, exist commonly in low energy areas, where the amount of organic content in the sediment is bigger as physical forces do not prevent fine sediment from settling (Byers & Gabrowski, 2013). However, the role of a single environmental characteristic in deciding the presence of infauna is discussed (Snelgrove & Butman, 1994).

Few publications have researched the extent of the effect that objects on the seafloor have to their surrounding communities of fauna and flora (Davis, 1982; Ambrose & Anderson, 1990; Barros et al., 2001; Danovaro et al., 2002; Zalmon et al., 2012), and a minority of those publications are regarding the Baltic Sea (Ruuskanen et al., 2015).

## 1.4. Baltic Sea

The bottom topography of the Baltic Sea divides it into several sub basins with restricted water exchange. Height of the sills at the borders of the basins determine the amount of water circulation between them. Water masses deep in the basins remain relatively stagnant, with occasional saltwater pulses causing mixing on the bottom (Leppäranta & Myberg, 2009). Long-term surface current mean velocity flows at around 5 cm $s^{-1}$ (Leppäranta & Myberg, 2009). The dominating winds in the entire Baltic Sea region are westerlies, with average wind speeds ranging seasonally between 5 and 10 m $s^{-1}$ (Leppäranta & Myberg, 2009). Gulf of Finland is the most eastern basin of the Baltic Sea, characterised by a mean depth of 37 meters. The Finnish coast of Gulf of Finland has an inconsistent coastline, with an extensive archipelago and irregular bottom topography (Leppäranta & Myberg, 2009). During late summer and the early autumn months, a thermocline separates warm surface water from bottom water, preventing mixing of the water column and at times, leading to hypoxia (Jilbert et al., 2018). Surface water temperatures during summer vary between 15 and 20 degrees Celsius, and during winter, an ice cover freezes over the Gulf of Finland. Annual sea ice, shallow water column (Leppäranta & Myberg, 2009), and non-existent tides (Rosentau et al., 2017), combined with the anthropogenic impacts of the area, make the Finnish coast of Gulf of Finland an environment of many interconnected physical, chemical, and biological processes.

The Baltic Sea lacks prevalent tides (Rosentau et al., 2017). On deeper basins of the Baltic Sea, the seafloor is mainly affected by relatively steady and unidirectional bottom currents (Jönsson et al., 2004; Leino et al., 2011), whereas shallower areas are more prone to the effect of surface waves and currents induced by wind stress (Jönsson et al., 2004). The extent to which the scouring phenomenon exists in the coastal waters of Finland, and even within the Baltic Sea, remains relatively unstudied (see, e.g., Werner et al., 1979; Leino et al., 2011; Ruuskanen et al., 2015). Nonetheless, the results of these studies are indicative of scour being a prevailing process near objects on the seafloor of the Baltic Sea despite the hydrological conditions being distinct from areas experiencing dynamic tides. However, on sheltered sites, as well as on deep basins, the time scale during which an extensive physical scour formation develops could be relatively long.

The Finnish Heritage Agency has an online inventory of over 2000 underwater archaeological sites from Finnish waters alone (Museovirasto, 2021). Many of the found shipwrecks are relatively well preserved regarding the timber material, with the shipwreck event itself and possible physical forcing from water movement being the sole factors causing deterioration of the ships. This is partly due to the absence of wood-boring shipworms, that cannot sustain themselves in the low salinity waters of the Baltic Sea. In more saline waters, wood-boring fauna accelerate degradation processes in shipwrecks (Florian, 1987; Fors & Björdal, 2013). Another factor possibly inhibiting the degradation processes in some of the Baltic Sea shipwreck sites is anoxia. Without oxygen, biological degradation processes are slower (Fors & Björdal, 2013). On shallower sites however, the physical forcing from wind induced wave action can potentially enhance the degradation processes of timber material (Treu et al., 2019). The extensive sustentation time of timber, and the multitude of shipwreck sites present in the Baltic Sea have possibly enabled the formation of a multitude of scour habitats.

## 1.5. Aim of the study

The present case study aims to describe scour using biological, geological, and chemical characteristics of the sediment in the proximity of a historic shipwreck. The spatial variability of zoobenthic assemblages is taken advantage of, as comparisons between benthos at various distances from the shipwreck are made. Analysis of sediment organic content, and a robust sediment grain size comparison, are also conducted to better understand the characteristics of the habitat that forms next to an object on the seafloor. Sonar technology is used to describe the scour formed at Joskär shipwreck and to ensure the viability of the sampled variables as descriptors of present scour. This approach widens the concept of scour past the sole physical processes observable with sonar to a more holistic level that considers the quality of biological, geological, and chemical characteristics of the benthic environment. To study the effect a centuries old shipwreck has had on its surroundings in a shallow non-tidal area is a novelty in this field of research. This is a case study, and only focuses on the habitat next to Joskär shipwreck.

As scour actively shapes the seafloor by altering the hydrological regime near objects under water, and the intensity of scour varies as a function of distance from the objects, the possible observed variation in the biogeochemical characteristics of the sediment next to Joskär shipwreck could potentially work as describing a scour area. The following hypothesis is tested:

> Sediment characteristics and macroinfaunal assemblages exhibit variation as a function of distance from the Joskär shipwreck.

To test the hypothesis, a sampling design was laid out, and data on biological, geological, and chemical characteristics of the sediment was gathered and analysed with methods of statistical analysis. On the southern coast of Finland, at the shipwreck of Vrouw Maria, the benthos inside of scour was deemed significantly different from the area unaffected by scour (Ruuskanen et al., 2015). Similar effects are assumed to prevail at Joskär shipwreck, and the possible trends are presumed to be caused by scour. Therefore, no control site was included in the design of the present study.

The results of this case study will give new information on processes related to the habitat formed around Joskär shipwreck and are planned to be used as steppingstones for future research in this novel field. To study scour and its effects is valuable in environmental impact assessments of offshore windfarms and other aquatic construction projects, as well as in interdisciplinary projects aiming for the preservation or salvation of historic shipwrecks in the Baltic Sea. Furthermore, understanding scour processes aids in understanding the dynamics in naturally occurring scour sites on bottom types dominated by boulders or other anomalous objects.

# 2. Materials & Methods

## 2.1. Study site

The study site is located at the southern coast of Finland, on the southeast side of Hanko peninsula in approximately 120 meters wide strait between Joskär and Halsholmen islands (ETRS89/WGS84 Lat: 59° 50,6504' Lon: 23° 15,3760'). During winter months, when temperatures remain consistently below freezing, an ice cover separates the water column of the strait from the effects of wind stress. Tidal currents are nearly absent in the region (Leppäranta & Myberg, 2009; Rosentau et al., 2017), distinguishing this study from earlier studies focusing on scour effects in areas dominated by physical effects of tidal currents (Caston, 1979; Quinn, 2006; Raineault et al., 2013; Fernandez-Montblanc et al., 2016).

The strait is sheltered from wind and experiences relatively little wave action. The surface waves are not high enough to reach deep into the water column and cause disturbance on the sediment surface (Webb, 2019). However, based on annual observations made at the study area during active research of personnel of the Tvärminne zoological station, water currents flow through the strait, changing directions towards west and east. In the present study, relatively strong bottom currents compared to other areas of the Finnish coastal waters were experienced during the dives at the shipwreck. The bottom currents were strong enough to force the diver to actively swim against the current to stay still during sampling dives.

Esri, NASA, NGA, NLS, NMA, USGS | Lantmäteriet, National Land Survey of Finland, Esri, HERE, Garmin, METI/NASA, USGS

**Figure 4 A & B.** (A) A map of the Baltic Sea. (B) The location of the study site on the east side of Hanko Peninsula marked with a blue marker. (ETRS89/WGS84 Lat: 59° 50,6504' Lon: 23° 15,3760').

The object studied in the present thesis is a shipwreck of a timber-built historic sailing ship with a length of approximately 30 meters and a width of 7,6 meters (Johansen et al., 2004). The tallest parts of the remaining timber structures reach approximately 3-meter heights from the seafloor. The wreck lies on the bottom at approximately five-meter depth, on the southern side of Joskär island (Figure 4). The longitudinal axis of the shipwreck is in a slight angle towards the shoreline with the stern of the ship located to the southwest from the bow. Pieces of timber belonging to the ship have been scattered on the sediment surface in the proximity of the shipwreck. A 3D-model showcases the condition of the shipwreck (Figure 3). Earlier archaeological studies have approximated that the ship has been built in the 18th century (Johansen et al., 2004).

**Figure 3.** 3D- model of Joskär shipwreck showcasing the condition of the shipwreck. Dimensions not to scale. (Model created by Timo Laaksonen)

The macrobenthos in the vicinity of the study site has been actively studied through decades (Aschan, 1988; Boström, 2002; Rousi et al., 2013; Joensuu et al., 2018). The area hosts a diversity of habitat types from diverse seagrass beds to more barren sandy and muddy seabeds. The different habitats host a variety of macroinfaunal assemblages, with variation of community structures observed not only between habitat types, but also between similar habitats (Boström, 2002; Joensuu et al., 2018).

## 2.2. Sampling design

Before designing the sampling strategy, a pilot study was conducted. The benthic environment around Joskär shipwreck and the bottom quality of the strait was mapped with sonar technology to help in describing the presence of scour with traditional methods. Water depth measurements aiming to locate possible depth contours caused by scour, and visual inspection of the study site were conducted during scuba dives. In addition, suitable sampling device and sediment sampling depth was determined.

The pilot study revealed that not all areas next to the shipwreck would provide suitable area for sediment sampling due to the piles of timber parts of the wreck laying on the sea floor. For the sampling site to be suitable, it had to have enough soft sediment surface to fit three independent replicate sediment samples. In addition, this condition had to be met at three consecutive sampling sites along the sample transects.

Based on the sonar images describing the bottom topography and sediment quality, the strait has a soft sandy bottom and steep shorelines on both sides of the strait (Figure 5 B & C). Deepest parts of the strait reach approximately 10 meters. The area around Joskär shipwreck is characterised by harder substrate than its surrounding areas (Figure 5 C). The shipwreck site is at the shallowest part of the strait, reaching five-meter depths (Figure 5 B).

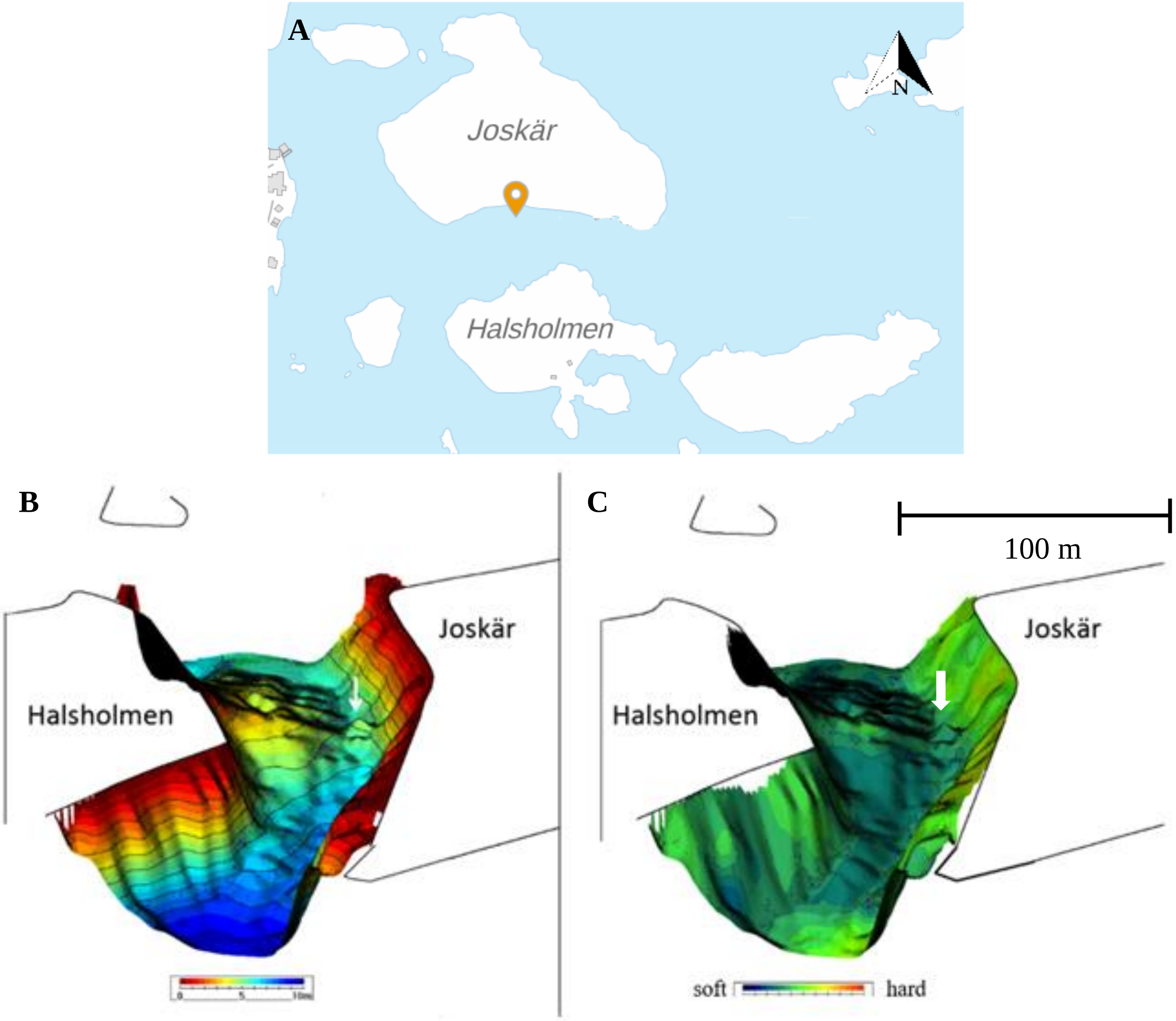

**Figure 5 A, B & C** (A) A map of the strait with the location of the shipwreck marked with a yellow marker. (B) Local geomorphology in the strait between Joskär and Halsholmen islands. Visualisation of depth contour from 0 to 10 meters. (C) Visualisation showing changing bottom quality from relatively softer to harder bottom substrate. The location of the shipwreck in the sonar imagery is marked with white arrows.

In the acquired side-scan sonar image, dune-like sediment ripples can be observed, possibly linked to the presence of the Joskär shipwreck (Figure 6). Water depth measurements at the shipwreck were conducted by scuba diving to obtain numerical depth values and locate possible depth contours formed by scour next to the shipwreck (Figure 6). The area in the vicinity of the wreck was observed to be approximately 0,5 meters deeper compared to the measurements taken further away.

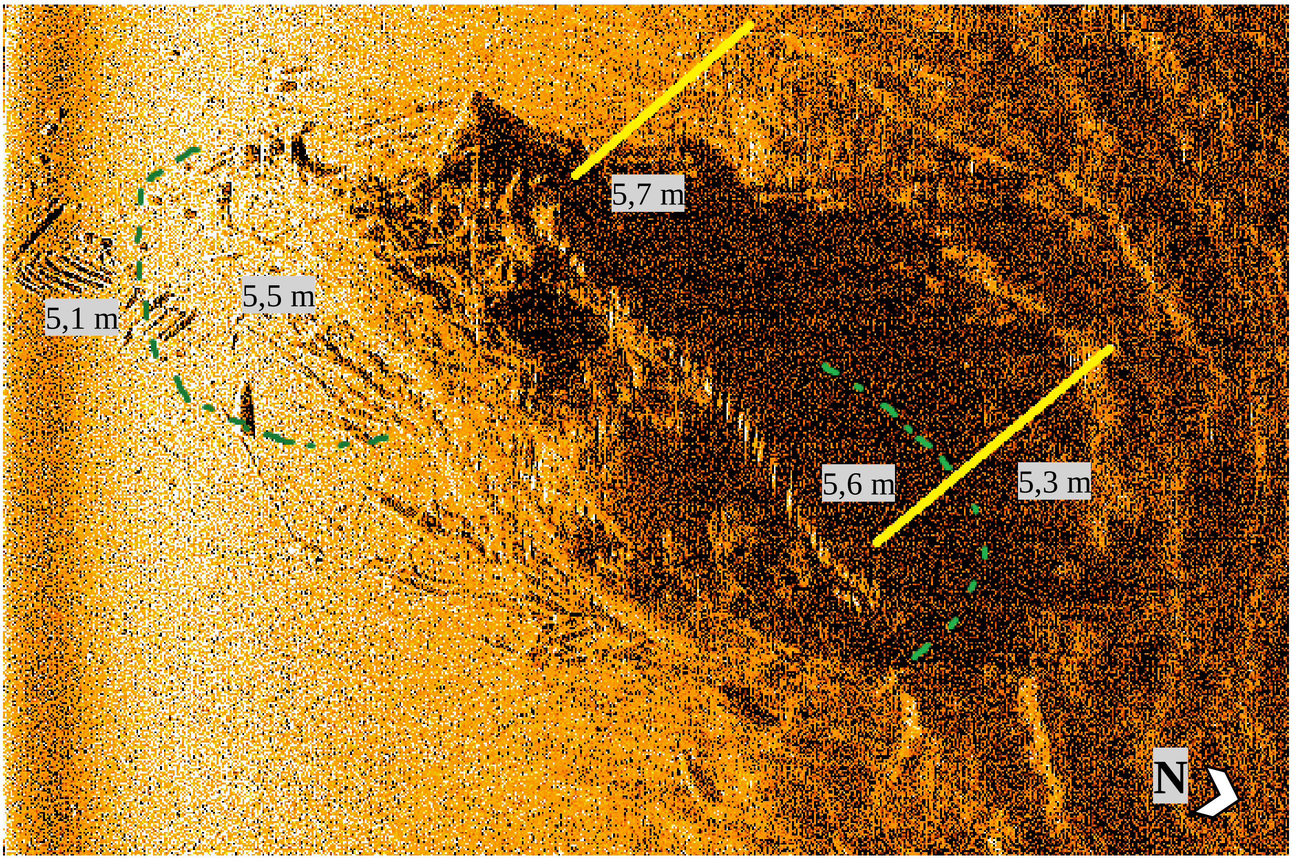

**Figure 6.** Scour at Joskär shipwreck showcased by a side-scan sonar image and manual water depth measurements made during dives. The hull of the shipwreck is approximately 30 meters long. Straight lines represent the approximate location of sampling transects. Dashed lines are approximate locations of measured changing depth contours. The values showcase the approximate depths measured at the locations. Dune-like sediment ripples can be observed on the right-hand side of the image. Image created with side-scan sonar and not in scale.

A 7 cm diameter core tube with a rubber cap on both ends was chosen as the preferred core device. Similar core samplers have been used in sampling of infauna in the nearby regions (Aschan, 1988; Bonsdorff et al., 1995; Boström & Bonsdorff, 1997; Boström, 2002). Due to the variable bottom quality, the core device would not enable consistent sediment sampling after a certain depth threshold was crossed. To ensure a standardised sediment sampling depth at all sites, it was decided that the sampled sediment depth was going to be 5 cm, since this was a depth that the core would penetrate in all present bottom types. The core was marked with depth measures, so that the depth of the sampling could be standardised. The standardised sediment sampling depth produced comparable variables for the analysis of infauna and sediment characteristics and eliminated an error possibly linked to the coring depth of the device. However, the burrowing depth of some organisms extends past the 5 cm depth (Zwarts & Wanink, 1989; Boström & Bonsdorff, 1997; Renz & Forster, 2013). This is considered when interpreting the results.

Sampling design was planned based on the results of the pilot study. Sampling was conducted at three sampling sites along two imaginary parallel transects reaching outwards from the west side of the wreck (Figure 7). Transect one (T1) was drawn from near the stern of the ship, where the conditions on the sediment surface exhibit less variation in the sonar image. Transect two (T2) was drawn so, that it reached from the bow of the ship across the dune like sediment ripples. The sampling sites on each transect were located at three different distances heading away from the hull of the shipwreck: 0,5 meters, 1,5 meters and 13,5 meters. The approximate locations of the sampling sites on the transects were decided based on both visual observation of the study area during pilot dives, and characteristics of scour in sonar images from earlier studies investigating scour at shipwreck sites (Quinn, 2006; Raineault et al., 2013). Three replicate samples were taken at each sampling site, making the total sample count 18. The replicates were taken no less than 15 centimetres away, and no more than 30 centimetres apart from each other to maintain the independency of the samples.

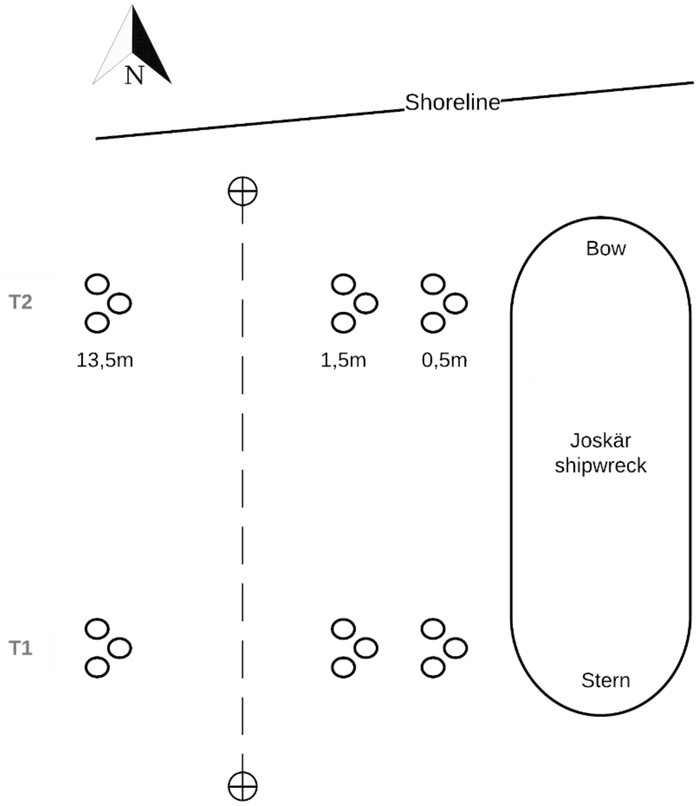

**Figure 7.** A schematic illustration of the sampling design. Dimensions not in scale. Dashed line representing the orientation line. Crossed circles represent the ends of the orientation line. Open circles representing sampling sites with three replicate samples. Transect one (T1) located at the stern of the ship. Transect two (T2) close to the bow of the ship. The distance from the shipwreck in meters marked in the sampling sites of T2.

As both sides of the shipwreck were available for sampling, the sampling sites were first randomised by deciding the side of the shipwreck to be sampled based on the prevailing wind conditions of the planned dive day. The side where the wind pushed the dive boat to was chosen. A tape measurer was set on the sea floor to follow parallel to the side of the wreck at an approximately three-meter distance, to work as an orientation line (Figure 7) to guide the diver, and to provide quantitative measures of the locations of the transects to be chosen.

The locations of the transects were randomised so that a diver would choose the first and second observed suitable location for a 13,5 m long transect, and then check the location of the identified site from the tape measurer at the parallel orientation line. Knowing the locations of the desired sampling sites on the orientation line, a diver would then locate the site during the sampling dives. The 1,5 m sites were sampled first to not disturb a possible organic layer on the sediment surface with e.g., the diver's fins when sampling the 0,5 m distance site. An aluminium rod with length markings was used to identify the sites at 0,5 m and 1,5 m distance from the wreck. For the 13,5 m distances, a tape measurer was used.

The sampling was done by first carefully setting the core tube on the sediment surface, avoiding any turbulence or other disturbance to the upper layer of the sediment. Then the core was pushed into the desired depth of the sediment. The rubber cap was then inserted to the top and the core was carefully lifted out of the sediment. The lower cap was placed to the end of the core after it was entirely out of the sediment, securing the sample inside the core tube. At sampling sites closest to the shipwreck, concretions of loose lying algae covered the sediment surface. Therefore, before pushing the core tube into the sediment, the overlying loose algae was carefully removed to the side, so it would not affect the analysis of sediment characteristics. Care was practiced to not disturb the sediment surface itself. The collected samples were brought to surface after which the sample cores were photographed and emptied into 10-liter buckets that were waiting in the boat. Buckets were labelled to avoid any mix ups and brought to shore for further processing.

Later, the following information was recorded from each replicate core tube sample in a laboratory: For sediment characteristics, the proportion of fine sediment, proportion of coarse sediment, and proportion of organic content in the sediment were analysed. Macroinfauna were first sieved and stored, after which the stored individuals were identified, counted, and measured for their individual lengths.

## 2.3. Sediment characteristics

Sediment was analysed for organic content via loss on ignition (LOI) and for a grain size assessment. Loss on ignition (LOI) is a method of determining total organic content of sediments (Heiri et al., 2001; Veres, 2002). All samples were first sieved through a 0,5 mm mesh sized sieve, to separate the finer and coarser sediment fractions. After sieving, both portions (< 0,5 mm & ≥ 0,5 mm) were separately stored in plastic buckets with seawater in a cool warehouse, to maintain natural temperature and prevent any decaying processes. The separated sediment fractions were given time to settle on the bottom of the bucket for 24 – 48 hours. The finer size fraction especially required some additional time to be settled to the bottom before removing of the excess water was possible. After settling, the clear excess water was carefully removed using a syringe and a pipette. Samples were then stored in sample bags and placed in a 5 °C refrigerator. In the larger grain size fraction of the samples (≥ 0,5 mm), pieces of organic debris were abundant (Figure 8). This floating organic debris, presumably originating from dead vegetation gathered on the sediment surface, was removed from all samples before storage in the sample bags to prevent it from affecting the analysis of sediment organic content (Heiri et al., 2011). Sediment organic content was analysed piror to the grain size classification according to Romano et al. (2017), for the grain size analysis to be independent of the effect of organic matter.

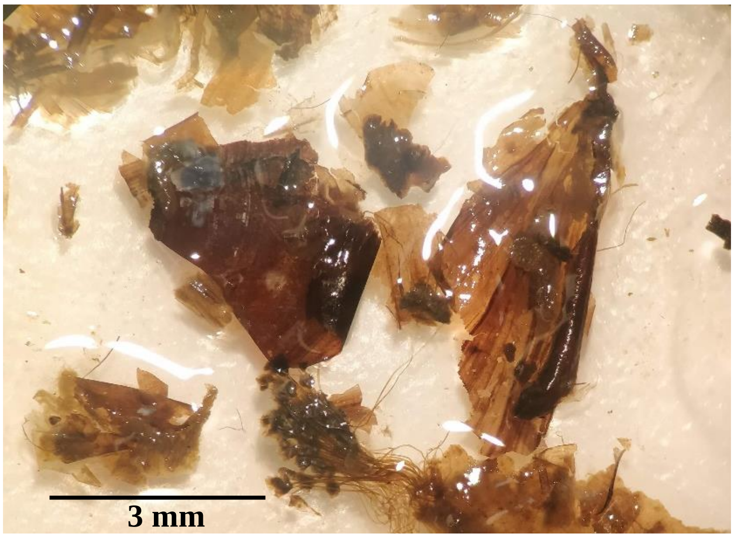

**Figure 8.** A sample of organic debris, that was removed from all samples before analysis.

### 2.3.1. Organic content

Loss on ignition (LOI) was used to estimate the amount of organic content in the sediment samples. First, all remaining excess water was removed from the sample bags with a pipette. To obtain the dry weights, the samples were then placed on tared aluminium cups and set to a drying oven (Heraeus

T12) for 24 h in 105 °C, following the recommendations of Heiri et al. (2001). Prior taring, the aluminium cups were burnt in a 550 °C muffle furnace (Carbolite CFW 1200 & Heraeus MR 170) for a duration of one hour. This was done to remove any excess oils or chemicals that might affect the weighing results later in the process. After the 24 hours, the dried samples were moved to desiccators to cool down. The cool samples were weighed to the accuracy of 0,0001 g (Mettler AE 100). To obtain the ash free dry weights (AFDW), all samples were then set to preheated muffle furnaces (Carbolite CFW 1200 & Heraeus MR 170) for four hours in 550 °C to combust the organic matter (Heiri et al., 2001). After combustion, all samples were again set to cool down in desiccators. Once cool, their weights were recorded to the accuracy of 0,0001 g.

The following equation (1) was used to calculate the LOI (Heiri et al., 2001):

$$\mathrm{LOI550} = ((\mathrm{DW105} - \mathrm{AFDW550})/\mathrm{DW105}) * 100 \qquad \text{(Equation 1)}$$

Where:

DW = dry weight

AFDW = ash free dry weight

This equation (1) presents the amount of organic content as a percentage of the entire sample. The tared weights of the aluminium cups were subtracted prior calculating values of LOI.

### 2.3.2. Grain size

In the present study, a robust grain size fractionation, where sediment was divided into coarser (≥ 0,5 mm) and finer (< 0,5 mm) fractions was conducted. In the commonly used Wentworth sediment classification scale sediment particles larger than 0,5 mm cross the threshold of coarse sand (Wentworth, 1922). In Ambrose & Anderson’s (1990) publication, the coarsest sediment fraction inspected was ≥ 0,5 mm. This coarse fraction was found to exhibit a clear decreasing trend as a function of distance from an artificial reef. This same phenomenon was investigated in the present study, as proportions of coarse and fine sediment fractions as a function of distance from the hull of the shipwreck were inspected. Values of ash free dry weights were used when proportions were calculated, to eliminate the possible effect of organic content on the proportions. (Romano et al., 2017)

## 2.4. Infauna

Macroinfauna (> 0,5 mm) were separated from the samples with a 0,5 mm mesh size sieve prior to the analysis of sediment characteristics (Aschan, 1988; Boström & Bonsdorff, 1997; Anderson et al., 2007). The macroinfauna were picked out from the sample under a 3x dioptre lens. All organisms were stored in 70/30 % ethanol/seawater solution for later analysis. Number of individuals were counted and identified to the lowest possible taxon under a dissecting microscope (LEICA ICC50 HD). Measurements of the length of each individual were recorded to the accuracy of 0,1 mm. Shannon's diversity index was calculated for each replicate sample according to Krebs (2014) (equation 2).

$$H' = -\sum_{i=1}^{R} p_i \ln p_i \qquad \text{(Equation 2)}$$

Where:

Pi = proportion of a taxon of total number of taxa in a sample

R = total number of taxa in a sample

All observed groups of species were assigned to functional groups, representing the feeding behaviour of the organisms (Table 1). The macroinfauna are merely used as tools and descriptors of a present scour. Therefore, the classification of functional groups was adopted from Bonsdorff & Blomqvist's (1993) study conducted in the northern Baltic Sea. *Marenzelleria spp.* was not recorded in that study, therefore information regarding its feeding ecology was gathered from work of Dauer (1981&1997); Miller et al. (1992); Karlson (2011) and Maximov et al. (2011), and so a functional group was assigned.

**Table 1.** Determined functional groups based on organism's feeding strategy (Bonsdorff & Blomqvist, 1993).

| Functional group | Feeding strategy |
|---|---|
| **F** | suspension-feeder |
| **S** | surface detritivore |
| **F/S** | suspension-feeder/surface detritivore |
| **C/S** | carnivore/surface detritivore |
| **C/H** | carnivore/herbivore |
| **S/B** | surface detritivore/burrowing detritivore |

## 2.5. Statistical analysis

Multidimensional scaling without transformations and with a Bray-Curtis dissimilarity metric was used to visualise similarities of species assemblages between all replicate samples.

All measured variables were analysed with a two-way-analysis of variance model, to examine how the two categorical variables, the main effects (transect and sampling distance), influence the sampled response variables. The three replicate samples of each sampling site were pooled, and their mean values compared. The model included an interaction term, which in case of a significant interaction between the transects, would guide towards interpreting the two transects as separate environments. If no interaction was present, the behaviour of the response variable was similar on both transects. From the two-way-analysis of variances it became evident that the two transects behaved differently in most of the analysed response variables. This showed as a significant interaction effect in the summary tables of the two-way-ANOVAs and was backed up by the differences in the physical environment on the transects visualised by the side scan sonar imagery (Figure 6). The transects were thus analysed as distinct environments with a one-way-ANOVA conducted separately for both transects with all response variables.

After conducting analysis of variance, a Tukey's multiple comparison test was conducted to analyse differences between specific sample sites. The parametric ANOVA tests assume heteroscedasticity and normal distribution of the data. Heteroscedasticity was tested with Levene's test. Normality of residuals were tested with Shapiro-Wilk's test. In addition, to ensure the assumptions were met, a visual interpretation of residual versus fits plot and a quantile-quantile plot was done after testing for each response variable. If the assumptions were not met, data was transformed to pass the tests. In some cases where data would not meet the parametric assumptions, a non-parametric Kruskall-Wallis' test and a post hoc Dunn's test were conducted.

All data analysis was done with Microsoft Excel and R. Descriptive statistics of analysed response variables are presented in tables in the results section.

# 3. Results

## 3.1. Sediment characteristics

### 3.1.1. LOI

A one-way-ANOVA and a post hoc Tukey's test was used to study the variation of the proportion of organic material in the sediment between the sampling sites. The proportion data was logit-transformed as suggested by Warton & Hui (2011) to meet the assumptions of the parametric ANOVA tests.

Significant variation of proportion of LOI between sampling sites was observed on both transects (Transect T1: $F$ = 131,4; df = 2; p = 0,00***. Transect T2: $F$ = 96,39; df = 2; p = 0,00***). A post hoc Tukey's test reveals significant differences between all sampling distances on both transects (Table 2). A logarithmic decreasing trend of LOI as a function of distance from the object was observed on both transects (T1: $R^2$ = 0,98. T2: $R^2$ = 0,74) (Figure 9).

**Table 2.** Tukey's multiple comparison of means showcasing the significant difference between the sampling sites on transects T1 and T2.

| **T1** | **p-value** |
|---|---|
| D1,5-D0,5 | 0,01* |
| D13,5-D0,5 | 0,00*** |
| D13,5-D1,5 | 0,00*** |
| | |
| **T2** | **p-value** |
| D1,5-D0,5 | 0,00*** |
| D13,5-D0,5 | 0,00*** |
| D13,5-D1,5 | 0,003** |

**Table 3.** Descriptive statistics of LOI (%) in samples at transect T1 and T2.

| **T1** | **Distance** | **N** | **Mean (%)** | **SD** | **Skew** | **SE** |
|---|---|---|---|---|---|---|
| | **0,5** | 3 | 6,55 | 0,11 | 0 | 0,06 |
| | **1,5** | 3 | 3,97 | 0,37 | 0,34 | 0,21 |
| | **13,5** | 3 | 0,99 | 0,26 | 0,36 | 0,15 |
| **T2** | **0,5** | 3 | 9,33 | 2,18 | -0,23 | 1,26 |
| | **1,5** | 3 | 2,64 | 0,23 | -0,34 | 0,13 |
| | **13,5** | 3 | 1,04 | 0,21 | 0,38 | 0,12 |

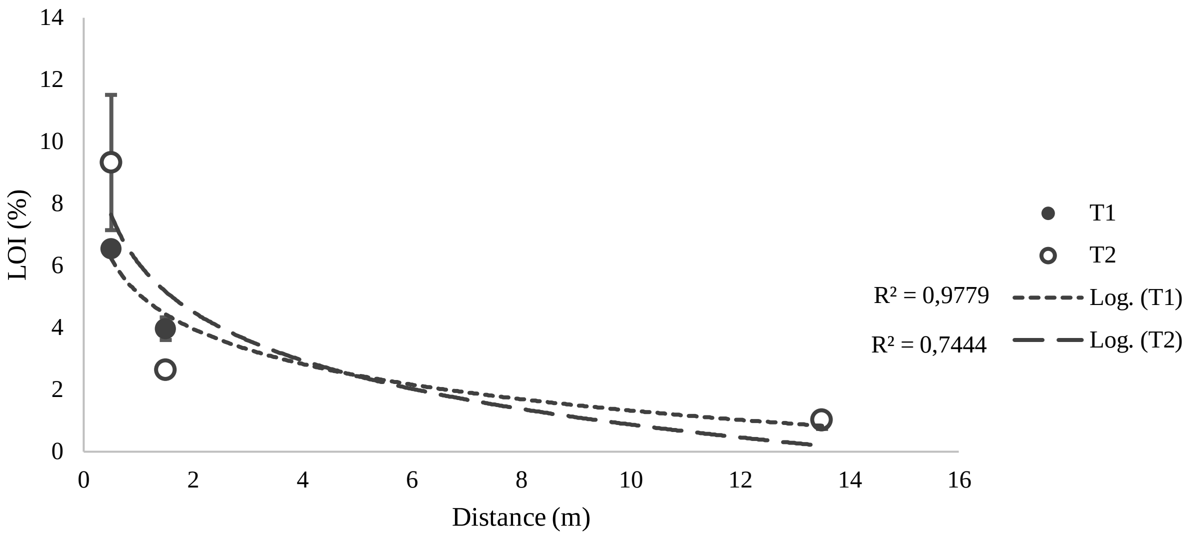

**Figure 9.** Measured LOI (%) values on transects T1 and T2 as a function of distance from the hull of the shipwreck. Mean values of LOI (%) ±SD, N = 3 per sampling site. Decreasing trends visualised with dashed lines (T1: $R^2$ = 0,98. T2: $R^2$ = 0,74).

### 3.1.2. Grain size composition

A one-way-ANOVA and a post hoc Tukey's test was used to study variation of the proportion of coarser sediment when moving further away from the object. The proportion data was logit-transformed as suggested by Warton & Hui (2011) to meet the assumptions of the parametric ANOVA tests.

Significant variation of the proportion of coarser sediment was observed on both transects (T1: $F$ = 343,3; df = 2; p = 0,00***. T2: $F$ = 15,54; df = 2; p = 0,00***). Tukey's post hoc test revealed significant variation between all sampling sites on transect T1. On transect T2, the site at 13,5 m differed significantly from the rest (Table 4). A logarithmic decreasing trend in the proportion of the coarse sediment on T1 can be observed ($R^2$ = 0,99) (Figure 10). The proportion of coarse sediment on T2 decreased when moving from the 0,5 m site to the 1,5 m site but was at its highest on the 13,5 m site, therefore exhibiting no similar trend as observed in T1.

Differences in the grain size composition between the transects were visible, especially on the furthest 13,5 m sampling site (Figure 11 A & B). As the 13,5 m site on transect one was dominated by fine sediment (85 %), the site at the same distance on transect one had a less pronounced fine fraction (38 %). When moving from 0,5 m site to 1,5 m site, the proportion of coarse fraction decreased on both transects. The coarse fraction was larger on the 0,5 m site of transect one (66 %) than on transect two (43 %), but the drop in the proportion was of relatively similar scale on both transects.

**Table 4.** Tukey's multiple comparison of means showcasing the significant difference of coarser sediment fractions between the sampling sites on transects T1 and T2.

| **T1** | **p-value** |
|---|---|
| D1,5-D0,5 | 0,000*** |
| D13,5-D0,5 | 0,000*** |
| D13,5-D1,5 | 0,000*** |
| | |
| **T2** | **p-value** |
| D1,5-D0,5 | 0,16 |
| D13,5-D0,5 | 0,03* |
| D13,5-D1,5 | 0,004** |

**Table 5.** Descriptive statistics of the coarse fraction of the sediment samples on transects T1 and T2.

| | **Distance** | **N** | **Mean** | **SD** | **Skew** | **SE** |
|---|---|---|---|---|---|---|
| **T1** | **0,5** | 3 | 65,66 | 1,02 | -0,38 | 0,59 |
| | **1,5** | 3 | 80,56 | 6,82 | 0,38 | 3,94 |
| | **13,5** | 3 | 14,98 | 1,44 | -0,31 | 0,83 |
| **T2** | **0,5** | 3 | 42,87 | 5,87 | 0,35 | 3,39 |
| | **1,5** | 3 | 31,85 | 9,25 | 0,33 | 5,34 |
| | **13,5** | 3 | 61,71 | 0,82 | 0,38 | 0,47 |

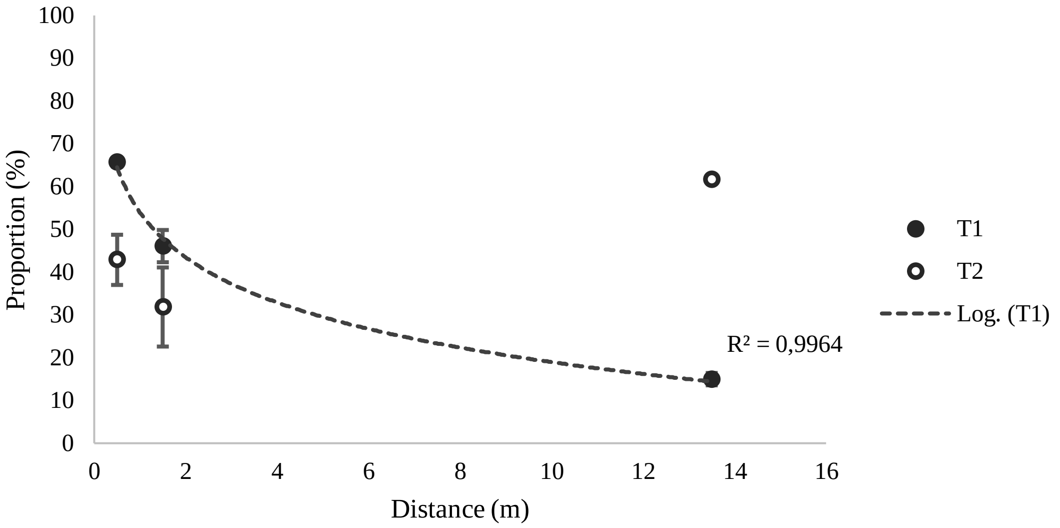

**Figure 10.** Proportion of coarser sediment on transects T1 and T2 as a function of distance from the shipwreck ±SD, N = 3 per sampling site. Decreasing trend of coarse fraction on T1 visualised with a dashed line ($R^2$ = 0,99).

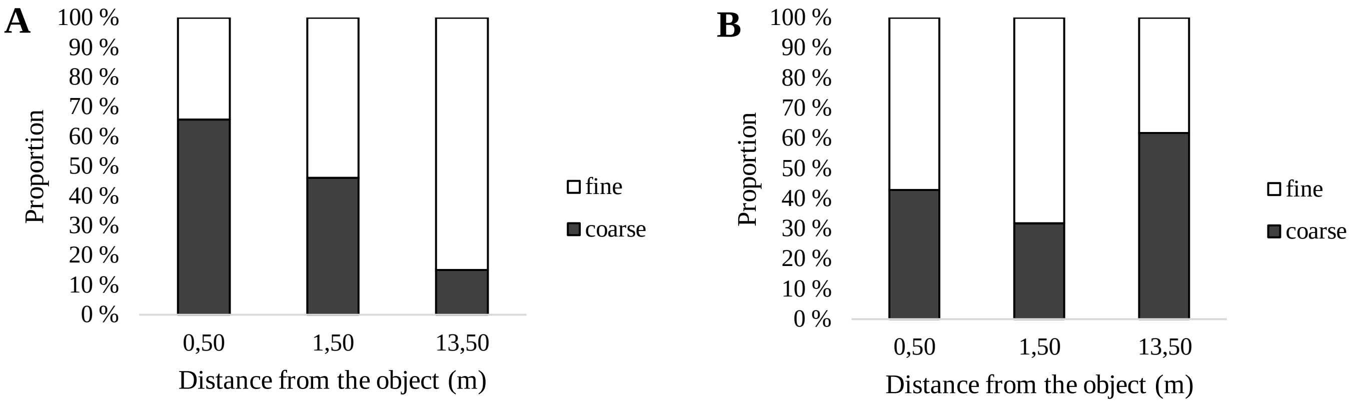

**Figure 11 A & B.** Bar plots showcasing the average proportions of grain size composition on sampling sites (N = 3) on transect T1 (A) and transect T2 (B).

## 3.2. Infauna

### 3.2.1. Community structure

When all samples were pooled, the dominating species at Joskär shipwreck was *Limecola balthica* (total of 219 individuals), with *Hydrobia spp.* on the second place (135 individuals). Together they took up 79 percent of the total number of macroinfauna observed in the samples. *L. balthica* and *Hydrobia spp.* are common inhabitants of the soft sediments of the study region and northern Baltic sea, often representing the dominating groups of species (Boström & Bonsdorff, 1997; Boström et al., 2002; Rousi et al., 2013). The two identified polychaetes, *Hediste diversicolor* (22 individuals) and *Marenzelleria spp.* (20 individuals) came next together with *Mytilus trossulus.* (21 individuals). *Chironomidae spp.* had 14 observed individuals. The remaining groups had presences ranging between one and five individuals and are presented in Table 6.

**Table 6.** All identified taxa and their functional group on sampling sites organised based on taxonomy. Mean number of individuals observed ± SD (N = 3 per sample) and total number of observations in all samples. The line symbol – indicates no observations.

| Taxon, species | Functional group | T1 0,5m | T1 1,5m | T1 13,5m | T2 0,5m | T2 1,5m | T2 13,5m | Total |
|---|---|---|---|---|---|---|---|---|
| **Bivalvia** | | | | | | | | |
| *Limecola balthica* | F/S | 12 ± 4,4 | 18 ± 2 | 9 ± 4 | 10,33 ± 3,5 | 13 ± 1 | 10,67 ± 4,2 | 219 |
| *Mytilus trossulus* | F | 0,67 ± 0,6 | - | - | 4,67 ± 2,1 | 1,33 ± 0,6 | 0,33 ± 0,6 | 21 |
| *Mya arenaria* | F | - | - | - | - | 0,33 ± 0,6 | - | 1 |
| *Cerastoderma glaucum* | F | - | - | - | 0,67 ± 0,6 | 1 ± 1 | - | 5 |
| **Gastropoda** | | | | | | | | |
| *Hydrobia spp.* | S | 3,33 ± 2,5 | 5,67 ± 2,1 | 8,67 ± 5,9 | 18,33 ± 8,7 | 3,67 ± 1,2 | 5,33 ± 2,1 | 135 |
| **Polychaeta** | | | | | | | | |
| *Marenzelleria spp.* | S/B | - | - | 1,33 ± 0,6 | 0,33 ± 0,6 | 0,67 ± 1,2 | 4,33 ± 1,5 | 20 |
| *Hediste diversicolor* | C/S | - | 0,67 ± 0,6 | 0,33 ± 0,6 | 2,67 ± 1,2 | 2,67 ± 2,9 | 1 ± 1 | 22 |
| **Insecta** | | | | | | | | |
| *Chironomidae spp.* | S | 0,67 ± 0,6 | 3 ± 1 | 0,33 ± 0,6 | 0,67 ± 0,6 | - | - | 14 |
| *Trichoptera sp.* | C/H | - | 0,33 ± 0,6 | - | - | - | - | 1 |
| **Isopoda** | | | | | | | | |
| *Saduria entomon* | C/S | 0,33 ± 0,6 | - | - | - | - | - | 1 |
| **Amphipoda** | | | | | | | | |
| *Corophium volutator* | S | - | 0,67 ± 0,6 | - | - | - | - | 2 |
| *Gammarus spp.* | F | - | 0,67 ± 1,2 | - | 0,33 ± 0,6 | - | - | 3 |
| *Monoporeia affinis* | C/S | - | - | - | 0,67 ± 0,6 | - | - | 2 |

To visually interpret similarities of species communities of each replicate sample, multidimensional scaling (MDS) without transformations and with a Bray-Curtis dissimilarity metric was conducted (Figure 12). The Bray-Curtis dissimilarity metric was used as it does not consider the empty values originating from species absences as similarities but focuses on the similarities of present species and their numbers. The mean number of species present at the sampling sites were compared with a one-way-ANOVA and a post hoc Tukey's test. Species data of transect T2 had to be log-transformed to pass the assumptions of the one-way-ANOVA.

In the MDS, present species and the number of individuals within a group of species were considered as the objects of the plot. From the MDS-plot, clear inconsistencies even within the sample replicates can be seen. In the MDS-plot, objects are arranged into a two-dimensional space based on their similarity in terms of observed species and the number of individuals. The objects closer to each other are more alike than those further apart. The sampling sites at 1,5 m distance on both transects seem to follow the same patterns and appear to be relatively similar to each other. Sites at 13,5 m have the most variation between the two transects as well as between sampled replicates. The infaunal assemblages observed at the 0,5 m distance sampling sites are divided into two groups based on the transect, but within replicates, they seem to be relatively similar.

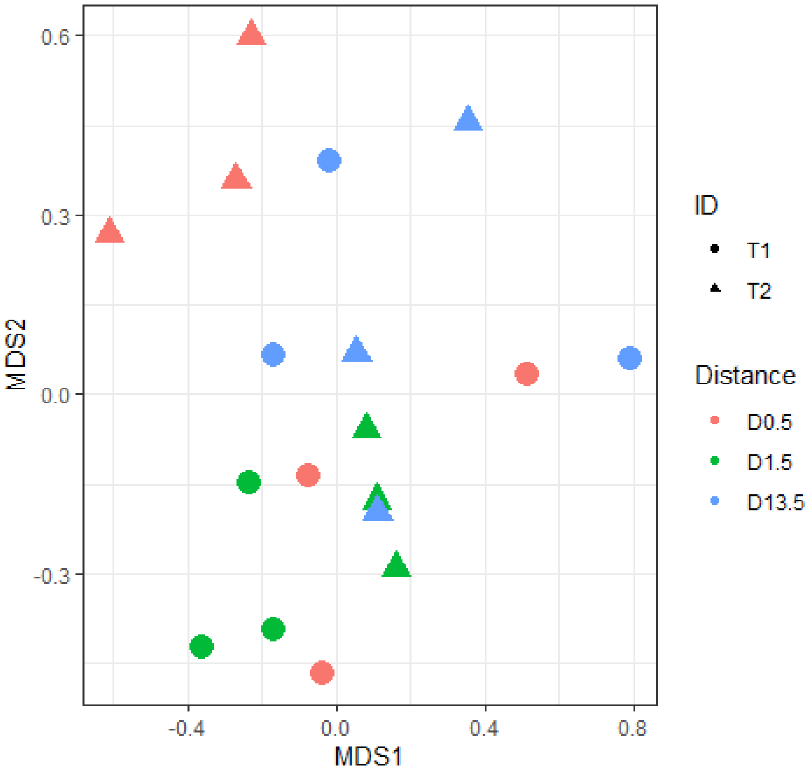

**Figure 12.** MDS- plot illustrating similarities in the species assemblages observed at each sampling site. One object represents one replicate sample. Objects close to each other are more alike than objects further apart. Sampling sites at 1,5 m distance showing the most consistency (green) (stress: 0,10).

On transect two, a one way-analysis of variance presented significant variation of species numbers between the sampling sites (*F* = 5,29; Df = 2; p = 0,05*). Tukey's post hoc test revealed the significant differences being between sites 0,5 m and 13,5 m (Table 7). No significant variation was observed on transect T1 (*F* = 3,2; Df = 2; p = 0,11). Transect T2 exhibited logarithmic decrease in the observed number of species ($R^2$ = 0,96) (Figure 13).

**Table 7.** Results from a Tukey's multiple comparison of means of number of species at sampling sites on transect T2. Significant difference between sites at 0,5 m and 13,5 m.

| **T2** | **p-value** |
|---|---|
| D1,5-D0,5 | 0,33 |
| D13,5-D0,5 | 0,04* |
| D13,5-D1,5 | 0,28 |

**Table 8.** Descriptive statistics of total number of species in samples.

| | Distance | N | Mean | SD | Skew | SE |
|---|---|---|---|---|---|---|
| **T1** | 0,5 | 3 | 3,67 | 0,58 | -0,38 | 0,33 |
| | 1,5 | 3 | 5 | 1 | 0 | 0,58 |
| | 13,5 | 3 | 3,67 | 0,58 | -0,38 | 0,33 |
| **T2** | 0,5 | 3 | 6,67 | 1,15 | 0,38 | 0,67 |
| | 1,5 | 3 | 5,33 | 1,53 | 0,21 | 0,88 |
| | 13,5 | 3 | 4 | 0 | NaN | 0 |

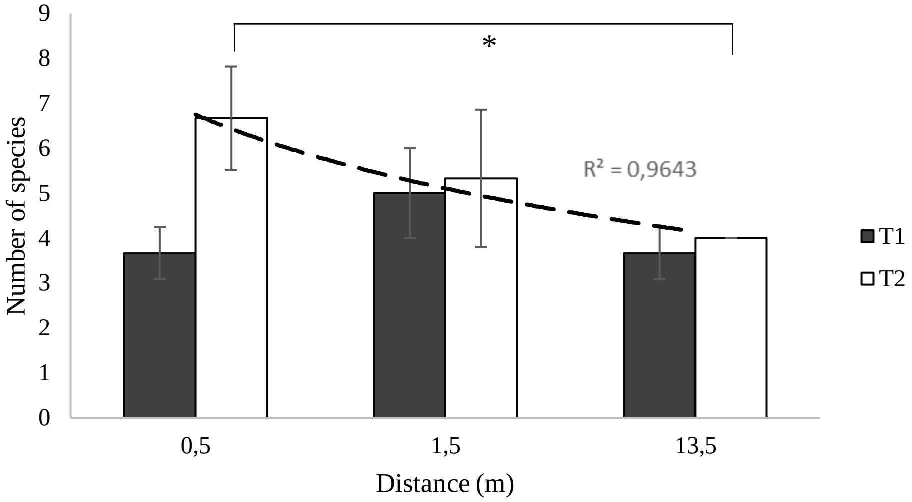

**Figure 13.** A bar plot showcasing the variation in the mean number of species ±SD, N = 3, between sampling sites along transects T1 and T2 as a function of distance from the hull of the shipwreck. Variation on T1 was non-significant. A significant difference was observed between sites T2 0,5 and T2 13,5. Dashed line represents a logarithmic trend of the decrease in mean number of species on transect T2 ($R^2$ = 0,96).

### 3.2.2. Number of Individuals

A one-way-ANOVA for both transects was conducted to investigate variation in the number of individuals observed within groups of species. The dominating groups of species, *Limecola balthica* and *Hydrobia spp.* were analysed. *Marenzelleria spp.* was also included, for it formed a distinct functional group (surface/burrowing detritivore (S/B)).

The lowest number of observations of *L. balthica* was five individuals, and the maximum was 20. However, this variation was not statistically significant on either transect (T1: $F$ = 4,85; Df = 2; p = 0,06. T2: $F$ = 0,62; Df = 2; p = 0,57). No trend as a function of distance from the shipwreck was observed (Figure 14).

**Table 9.** Descriptive statistics of number of individual *Limecola balthica* on transects T1 and T2.

| | Distance | N | Mean | SD | Skew | SE |
|---|---|---|---|---|---|---|
| **T1** | 0,5 | 3 | 12 | 4,36 | -0,36 | 2,52 |
| | 1,5 | 3 | 18 | 2 | 0 | 1,15 |
| | 13,5 | 3 | 9 | 4 | 0 | 2,31 |
| **T2** | 0,5 | 3 | 10,33 | 3,51 | 0,09 | 2,03 |
| | 1,5 | 3 | 13 | 1 | 0 | 0,58 |
| | 13,5 | 3 | 10,67 | 4,16 | -0,29 | 2,4 |

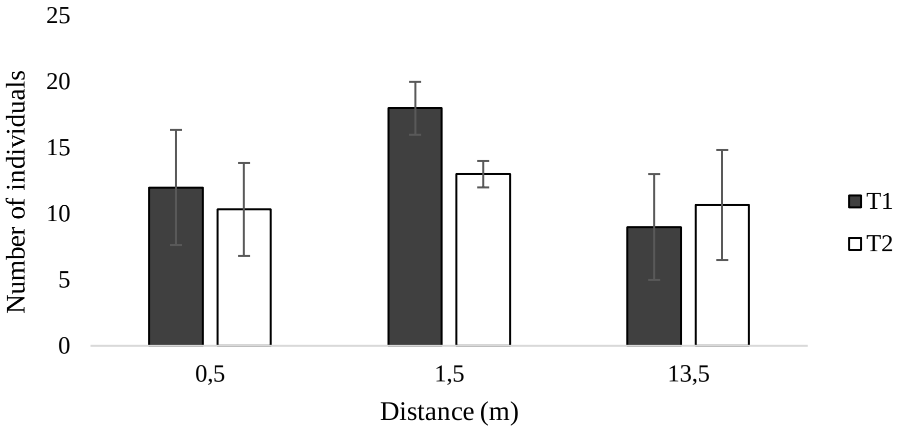

**Figure 14.** Mean number of individual *Limecola.balthica* on transects T1 and T2 ±SD, N = 3, as a function of distance from the hull of the shipwreck.

Observations of *Hydrobia spp.* were relatively constant on the sampling sites, an exception being site at 0,5 m on transect two. This site exhibited high numbers of individuals compared to the rest of the sampling sites. Observations ranged from a minimum one individual to a maximum of 28 individuals per replicate sample. No significant differences were observed on transect T1 ($F$ = 1,43; Df = 2; p = 0,31). Transect T2 showcased significant differences in the abundance of individuals ($F$ = 7,08; Df = 2; p = 0,03*), and a post hoc Tukey's test showcased that the 0,5 m site had significantly more individuals compared to the two further sampling sites (Table 10). No significant trends as a function of distance from the shipwreck were observed (Figure 15).

**Table 10.** Tukey's test on the comparison of number of individual *Hydrobia spp.* on transect T2.

| **T2** | **p-value** |
|---|---|
| D1,5-D0,5 | 0,03* |
| D13,5-D0,5 | 0,05* |
| D13,5-D1,5 | 0,92 |

**Table 11.** Descriptive statistics of sampled individual *Hydrobia spp.* on transects T1 and T2.

| | Distance | N | Mean | SD | Skew | SE |
|---|---|---|---|---|---|---|
| **T1** | 0,5 | 3 | 3,33 | 2,52 | 0,13 | 1,45 |
| | 1,5 | 3 | 5,67 | 2,08 | 0,29 | 1,2 |
| | 13,5 | 3 | 8,67 | 5,86 | -0,34 | 3,38 |
| **T2** | 0,5 | 3 | 18,33 | 8,74 | 0,25 | 5,04 |
| | 1,5 | 3 | 3,67 | 1,15 | 0,38 | 0,67 |
| | 13,5 | 3 | 5,33 | 2,08 | -0,29 | 1,2 |

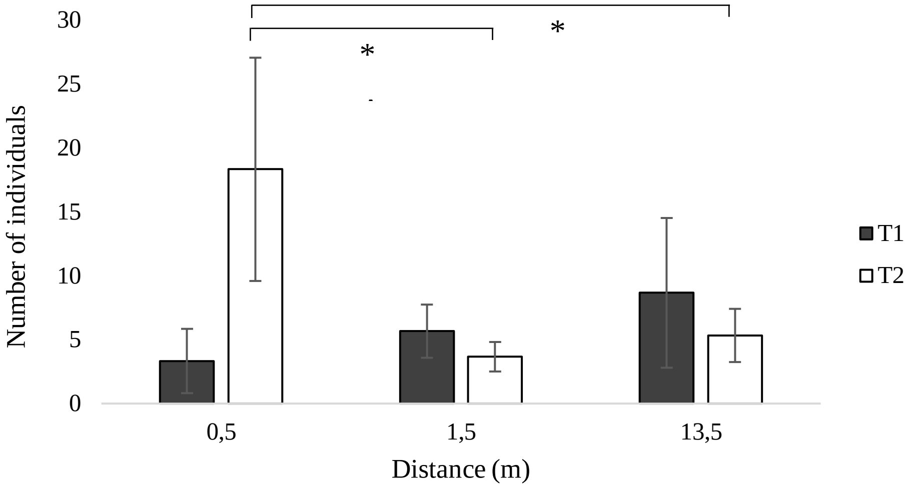

**Figure 15.** Mean number of individual *Hydrobia spp.* on transects T1 and T2 ±SD, N = 3. The site 0,5 m on T2 had significantly more individuals compared to the two other sites on the transect. No significant differences were observed on T1.

*Marenzelleria spp.* was analysed due to it forming a distinct functional group as feeding on detritus both in burrows and on the sediment surface (group S/B). The observations ranged from zero individuals to six individuals, with the higher abundance being at the further sites. Transect one was not analysed, since the only observed individuals of *Marenzelleria spp.* occurred at the 13,5 m site. Transect two was analysed with a one-way-ANOVA ($F$ = 11,08; Df = 2; p = 0,009**). Post hoc Tukey's test for transect T2 showcased the 13,5 m site having significantly higher abundance of *Marenzelleria spp.* compared to the sites closer to the hull of the shipwreck (Table 12). Transect two exhibited exponential increase in the observed number of *Marenzelleria spp.* individuals with increasing distance to the shipwreck ($R^2$ = 0,96) (Figure 16)

**Table 12.** Post hoc Tukey's test for transect T2 comparing the mean number of *Marenzelleria spp.*

| **T2** | **p-value** |
|---|---|
| D1,5-D0,5 | 0,93 |
| D13,5-D0,5 | 0,01* |
| D13,5-D1,5 | 0,02* |

**Table 13.** Descriptive statistics of sampled *Marenzelleria spp.* on transects T1 and T2.

| | **Distance** | **N** | **Mean** | **SD** | **Skew** | **SE** |
|---|---|---|---|---|---|---|
| **T1** | 0,5 | 3 | 0 | 0 | NaN | 0 |
| | 1,5 | 3 | 0 | 0 | NaN | 0 |
| | 13,5 | 3 | 1,33 | 0,58 | 0,38 | 0,33 |
| **T2** | 0,5 | 3 | 0,33 | 0,58 | 0,38 | 0,33 |
| | 1,5 | 3 | 0,67 | 1,15 | 0,38 | 0,67 |
| | 13,5 | 3 | 4,33 | 1,53 | 0,21 | 0,88 |

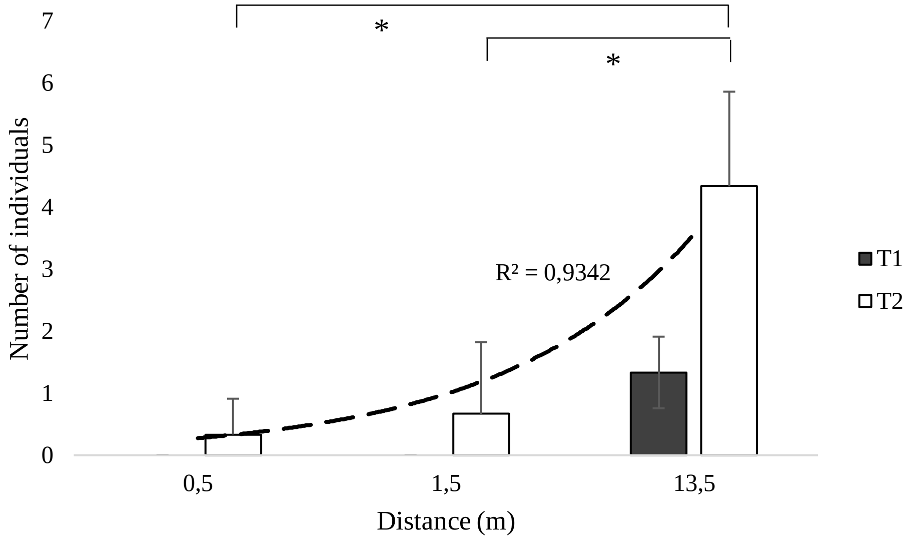

**Figure 16.** Mean number of individual *Marenzelleria spp.* on transects T1 and T2 ±SD, N = 3, as a function of distance from the hull of the shipwreck. The number of individuals was significantly higher at 13,5 m site compared to the two sites closer to the hull of the shipwreck. Exponential trend of *Marenzelleria spp.* individuals on T2 visualised with a dashed line ($R^2$ = 0,96).

### 3.2.3. Individual lengths

To study possible differences in the individual lengths of species as a function of distance from the shipwreck, one-way-ANOVAs for both transects were conducted. To be able to use the length as an indicator of possible variation between the sampling sites, only species present at all sites were analysed, leaving the two dominant species, *Limecola balthica* and *Hydrobia spp.* for the analysis. Length data of *Hydrobia spp.* was log-transformed to meet the assumptions of the tests. In the case of *Limecola balthica*, a Kruskall-Wallis test and a post hoc Dunn’s test on the two sampled transects were conducted, after the assumptions of a parametric ANOVA were not met.

### *Limecola balthica*

The length distribution of the sampled individuals of *L. balthica* exhibited high variation within each sampling site (Figure 17). The range of observed individual lengths was high throughout the replicate samples, reaching a maximum of 18,9 mm at the 1,5 m site on transect T1. Shortest recorded individual in all samples was 1,5 mm and the longest 20,5 mm. Majority of the individuals belonged to the length class of 2,5 mm – 5 mm (Figure 18).

A Kruskall-Wallis test showed no significant differences on transect two (chi-squared = 5,11; Df = 2; p = 0,08), but on transect one, significant differences between the sampling distances were observed (chi-squared = 13,78; Df = 2; p = 0,001**). A post hoc Dunn’s test revealed that the significant difference of individual lengths of *L. balthica* occurred between sites 0,5 m and 1,5 m (Table 14), although the high standard deviation gives reason to be very cautious about the significance of this result. No significant trends as a function of distance from the shipwreck were observed.

**Table 14.** Results from a post hoc Dunn’s test on the comparison of lengths of *Limecola balthica* individuals on transect T1.

| **T1** | **p-value** |
|---|---|
| D0,5 – D1,5 | 0,00*** |
| D0,5 – D13,5 | 0,11 |
| D1,5 – D13,5 | 0,76 |

**Table 15.** Descriptive statistics of sampled individual lengths of *Limecola balthica.*

| | **Distance** | **N** | **Mean (mm)** | **SD** | **Skew** | **SE** |
|---|---|---|---|---|---|---|
| **T1** | 0,5 | 36 | 4,84 | 2,38 | 1,84 | 0,4 |
| | 1,5 | 54 | 3,76 | 3,07 | 3,65 | 0,42 |
| | 13,5 | 27 | 4,82 | 4,34 | 1,98 | 0,84 |
| **T2** | 0,5 | 31 | 6,07 | 4,28 | 0,99 | 0,77 |
| | 1,5 | 39 | 5,79 | 2,23 | 0,28 | 0,36 |
| | 13,5 | 32 | 4,63 | 2,72 | 2,15 | 0,48 |

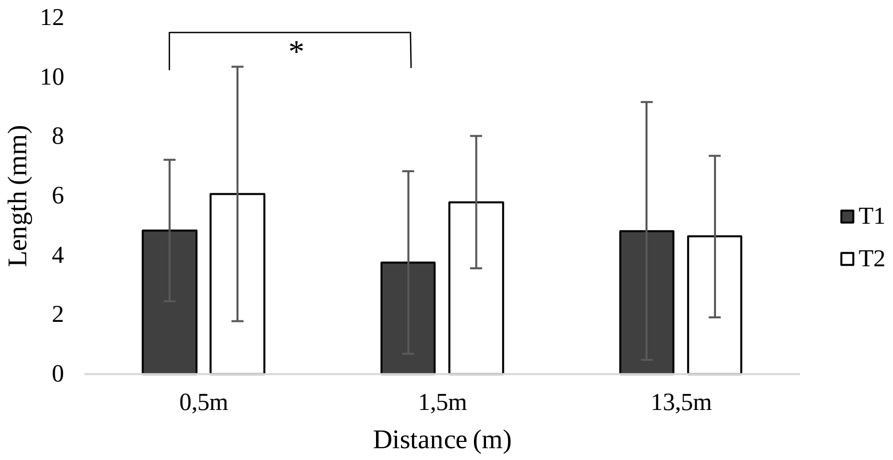

**Figure 17.** Mean lengths of individual *Limecola balthica* ±SD, N = 3, as a function of distance from the shipwreck on transects T1 and T2. High variation in the lengths was observed at all sampling sites.

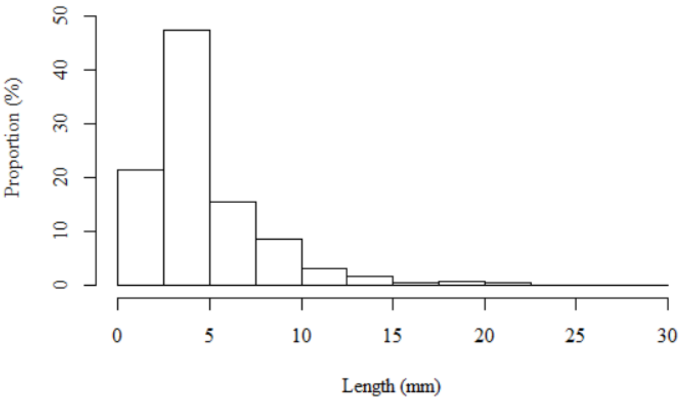

**Figure 18.** Relative proportions of length classes of *Limecola balthicas* at the Joskär shipwreck study site (N = 219). The length class 2,5mm – 5 mm exhibit highest abundance.

### *Hydrobia spp.*

The length distribution of individual *Hydrobia spp.* remained relatively constant between all sampling sites, with lengths measuring a minimum of 3,7 mm and maximum of 4,8 mm. No significant differences in the individual lengths of *Hydorbia spp.* between any sampling sites were observed on either transect (T1: ANOVA *F* = 2,61; Df = 2; p = 0,08. T2: Kruskall-Wallis: chi-squared = 0,93; Df = 2; p = 0,63). No significant trends as a function of distance from the shipwreck were observed (Figure 19).

**Table 16.** Descriptive statistics of sampled individual lengths of *Hydrobia spp.* on transects T1 and T2.

| | Distance | N | Mean (mm) | SD | Skew | SE |
|---|---|---|---|---|---|---|
| **T1** | 0,5 | 10 | 2,84 | 0,59 | 0,48 | 0,19 |
| | 1,5 | 55 | 3,01 | 1,05 | 0,23 | 0,14 |
| | 13,5 | 17 | 2,75 | 0,6 | 0,44 | 0,15 |
| **T2** | 0,5 | 11 | 3,22 | 0,79 | -0,45 | 0,24 |
| | 1,5 | 26 | 2,38 | 0,69 | 0,19 | 0,14 |
| | 13,5 | 16 | 2,86 | 0,9 | 0,01 | 0,23 |

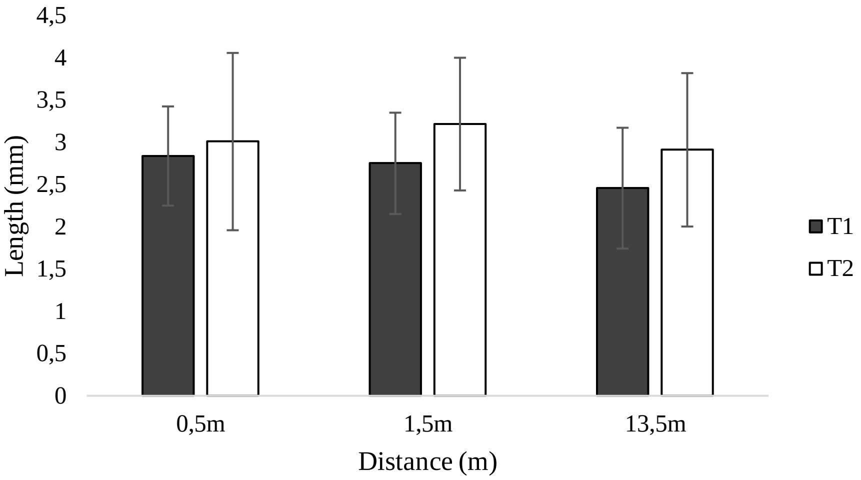

**Figure 19.** Mean lengths of individual *Hydrobia spp.* ±SD, N = 3, as a function of distance from the hull of the shipwreck on transects T1 and T2.

### 3.2.4. Shannon diversity H'

Changes in the species diversity between the sampling sites were analysed to reveal any variation or trends when moving away from the object. Shannon's diversity index was calculated (Equation 2.) for each replicate sample and used as a representative of the prevalent diversity. A one-way-ANOVA test was conducted for both transects.

Lowest value for the diversity index (0,63) was recorded at sampling site 0,5 m on T1. On the contrary, the highest diversity (1,56) was observed at the respective sampling site on T2. The conducted one-way-ANOVAs revealed no significant variation of the diversity index on either of the transects (T1: *F* = 4,65; Df = 2; p = 0,93. T2: *F* = 1,81; Df = 2; p = 0,37). No significant trends as a function of distance from the shipwreck were observed (Figure 20).

**Table 17.** Descriptive statistics of measured Shannon Diversity H' on transects T1 and T2.

| | Distance | N | Mean | SD | Skew | SE |
|---|---|---|---|---|---|---|
| **T1** | 0,5 | 3 | 0,81 | 0,15 | -0,31 | 0,09 |
| | 1,5 | 3 | 1,09 | 0,05 | -0,35 | 0,03 |
| | 13,5 | 3 | 1,01 | 0,13 | 0,31 | 0,07 |
| **T2** | 0,5 | 3 | 1,39 | 0,2 | -0,27 | 0,12 |
| | 1,5 | 3 | 1,21 | 0,16 | 0,22 | 0,09 |
| | 13,5 | 3 | 1,14 | 0,14 | -0,35 | 0,08 |

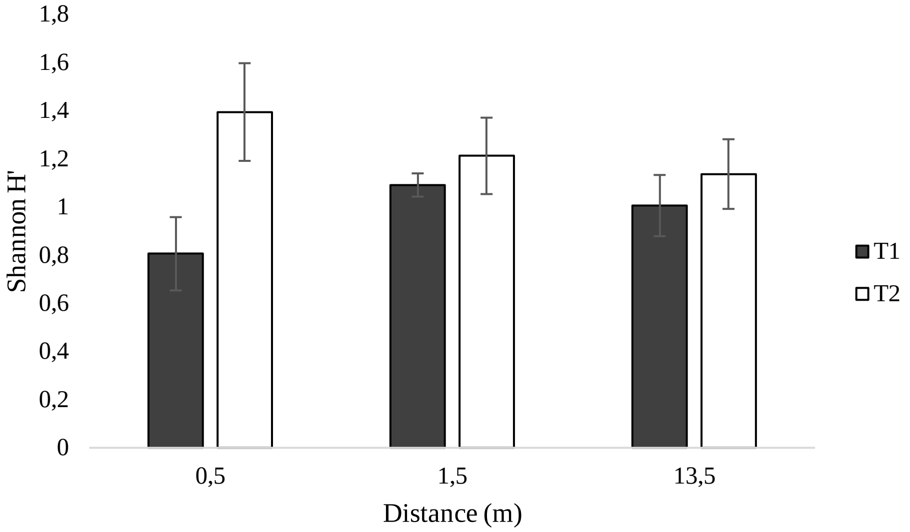

**Figure 20.** Mean values of Shannon's diversity index H' on transects T1 and T2 ±SD, N = 3, as a function of distance from the shipwreck.

### 3.2.5. Functional groups

The classification of functional groups was done based on Bonsdorff & Blomqvist (1993) (Table 1). The relative proportions of all distinct functional groups, the number of functional groups, and the number of individuals within functional groups present at each sampling site were investigated. Observed functional groups were suspension feeders (F), surface detritivores (S), suspension feeder/surface detritivores (F/S), surface/burrowing detritivores (S/B), carnivore/surface detritivores (C/S), and carnivore/herbivores (C/H).

Suspension-feeder/surface detritivore (F/S) was the most abundant functional group on both transects, representing 60 % of all present macroinfauna on average on transect T1 and 44 % on transect T2. Surface detritivores (S) were the second most dominant group, with an average of 32 % representation of the total community on T1 and 30 % on T2. The dominance of these two groups was more profound on T1, where no other functional group reached above 2,6 % representation. On T2 however, suspension feeders (F), carnivore/surface detritivores (C/S) and surface/burrowing detritivores (S/B) all represented 8 – 10 % of the assemblage. One phenomenon that appears to be similar on both transects was the increase in the proportion of surface/burrowing detritivores (S/B) and the decline of suspension feeders (F), as the distance from the hull of the shipwreck increased (Figure 21).

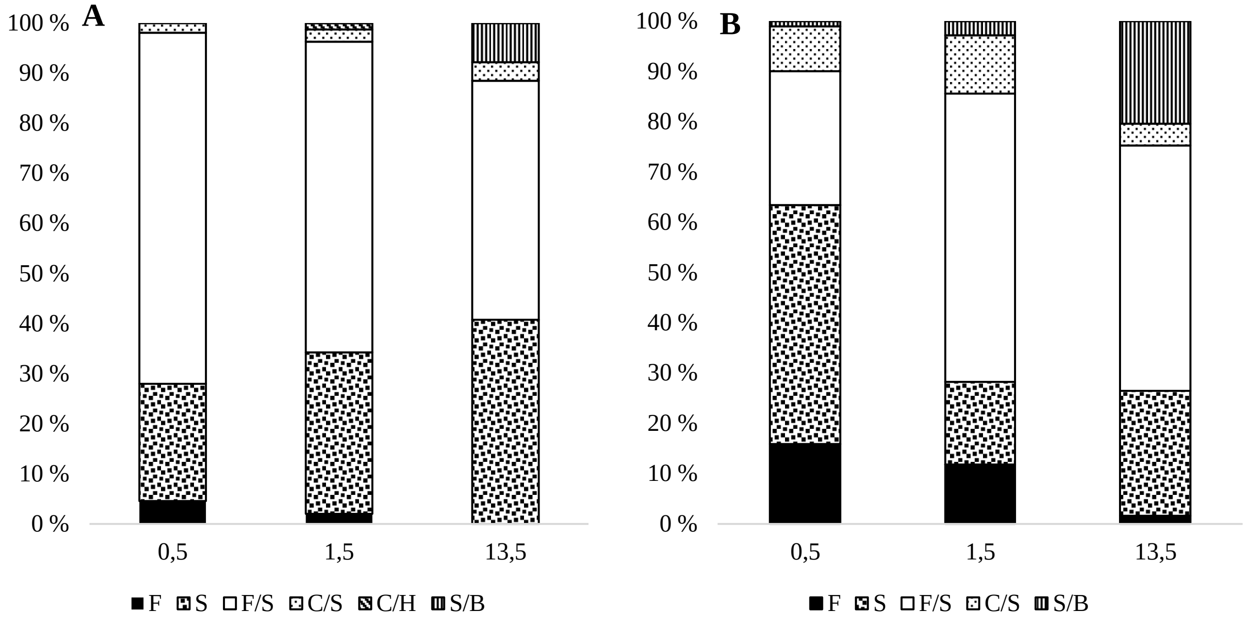

**Figure 21.** Proportions of functional groups on transects T1 (A) and T2 (B) as a function of distance from the hull of the shipwreck. Y-axis = proportion. X-axis = Distance from the hull of the shipwreck (m).

Data was analysed with a one-way-ANOVA and a post hoc Tukey's test. The group C/S on T1 was analysed with a non-parametric Kruskall-Wallis' test, since it did not pass the assumptions of a parametric ANOVA. As the group F/S consists solely of individuals of *L. balthica,* and the group S/B of *Marenzelleria spp.*, they were not separately analysed in this section. Analyses for these variables can be found in the section of analyses done on number of individuals. The group C/H was also left without a separate analysis, since only one individual belonging to this group was found in the entire study.

The results of analyses of groups C/S, F and S are presented here. No significant differences in the number of carnivore/surface detritivore (C/S) were observed (T1: Kruskall-Wallis: chi-squared = 0; Df = 2; p = 1. T2: ANOVA: *F* = 0,18; Df = 2; p = 0,84). The number of individuals belonging to the group suspension feeders (F), exhibited a rather dissimilar distribution on transects T1 and T2. T1 did not exhibit any significant variation (*F* = 0,8; Df = 2; p = 0,49), but T2 showed a significant difference between the sites (*F* = 5,85; Df = 2; p = 0,04*). A post hoc Tukey's test revealed a significant difference between sites 0,5 m and 13,5 m (Table 18). An exponential decreasing trend of number of suspension feeders as a function of distance from the object can be observed on transect two ($R^2$ =

0,93) (Figure 22). Despite the lack of a significant variation on transect one, no suspension feeders were observed at the furthest sampling site, with the only observations being made on sites 0,5 m and 1,5 m. Even without significant variation it speaks for the lack of suspension feeders further away from the shipwreck.

**Table 18.** Results from the post hoc Tukey's test on the comparison of number of suspension feeders (F) on transect T2.

| **T2** | **p-value** |
|---|---|
| D1,5-D0,5 | 0,21 |
| D13,5-D0,5 | 0,03* |
| D13,5-D1,5 | 0,36 |

**Table 19.** Descriptive statistics of number of individual suspension feeders (F) on transects T1 and T2.

| | **Distance** | **N** | **Mean** | **SD** | **Skew** | **SE** |
|---|---|---|---|---|---|---|
| **T1** | 0,5 | 3 | 0,67 | 0,58 | -0,38 | 0,33 |
| | 1,5 | 3 | 0,67 | 1,15 | 0,38 | 0,67 |
| | 13,5 | 3 | 0 | 0 | NaN | 0 |
| **T2** | 0,5 | 3 | 5,67 | 2,89 | 0,38 | 1,67 |
| | 1,5 | 3 | 2,67 | 1,53 | -0,21 | 0,88 |
| | 13,5 | 3 | 0,33 | 0,58 | 0,38 | 0,33 |

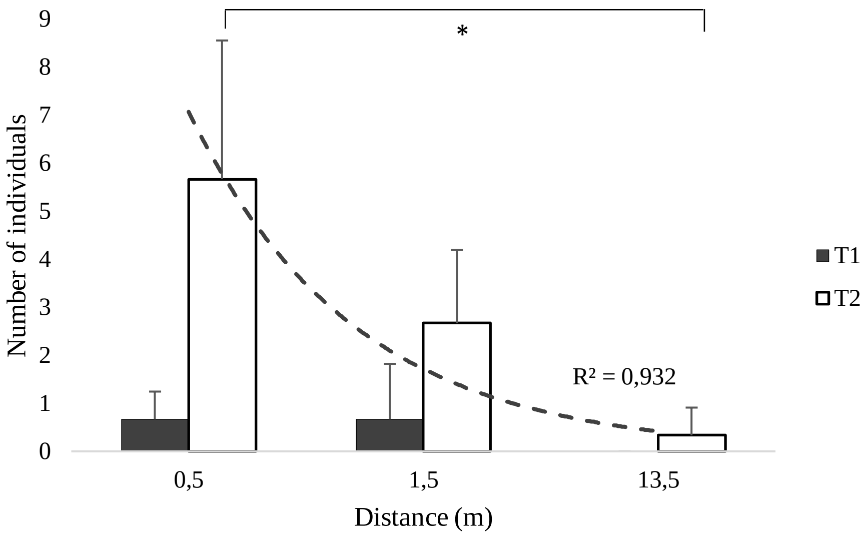

**Figure 22.** Mean number of individual suspensions feeders (F) on transects T1 and T2 ±SD, N = 3, as a function of distance from the hull of the shipwreck. A significant difference was observed between sites 13,5 m and 0,5 m on transect two. Decreasing trend on T2 visualised with a dashed line ($R^2 = 0,93$).

In the analysis of number of surface detritivores (S) on T1 and T2, a one-way-ANOVA on T1 exhibited no significant differences between the sampling sites (*F* = 1,4; Df = 2; p = 0,32). On T2 significant variation existed (*F* = 7,1; Df = 2; p = 0,03*). A post hoc Tukey's test revealed the 0,5 m site of T2 having significantly more individual surface detritivores from the two further sampling sites of the transect (Table 20). No significant trends as a function of distance from the shipwreck were observed (Figure 23).

**Table 20.** Tukey's test on the comparison of mean number of surface detritivores (S) on transect T2.

| **T2** | **p-value** |
|---|---|
| D1,5-D0,5 | 0,03* |
| D13,5-D0,5 | 0,05* |
| D13,5-D1,5 | 0,93 |

**Table 21.** Descriptive statistics of observed surface detritivores (S) on transects T1 and T2.

| | **Distance** | **N** | **Mean** | **SD** | **Skew** | **SE** |
|---|---|---|---|---|---|---|
| **T1** | 0,5 | 3 | 4 | 2,65 | 0,32 | 1,53 |
| | 1,5 | 3 | 8,67 | 2,52 | -0,13 | 1,45 |
| | 13,5 | 3 | 9 | 6,08 | -0,37 | 3,51 |
| **T2** | 0,5 | 3 | 19 | 9,17 | 0,21 | 5,29 |
| | 1,5 | 3 | 3,67 | 1,15 | 0,38 | 0,67 |
| | 13,5 | 3 | 5,33 | 2,08 | -0,29 | 1,2 |

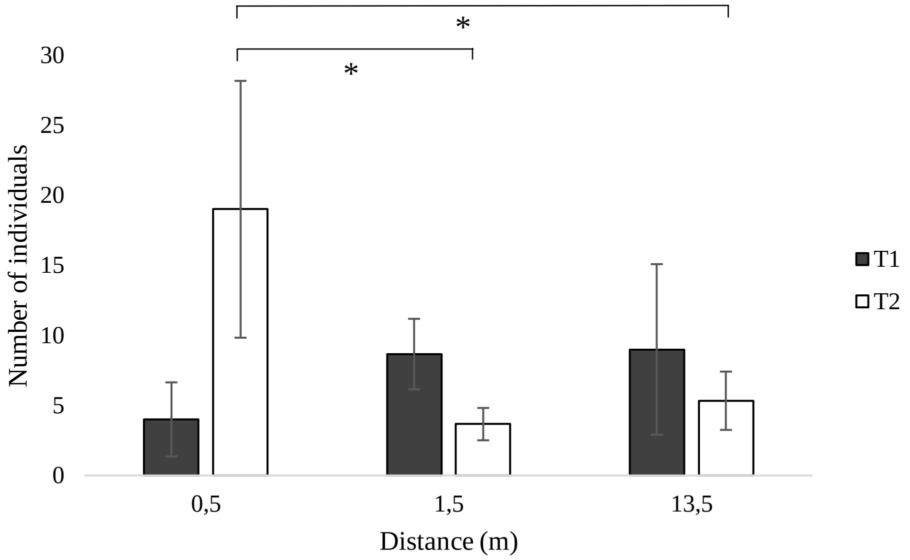

**Figure 23.** Mean number of surface detritivores (S) on transects T1 and T2 ±SD, N = 3, as a function of distance from the hull of the shipwreck. Site 0,5 m on T2 is significantly different from the rest of the transect's sampling sites. No significant variation was observed on T1.

## 3.3. Summary

All analysed variables were compiled into a summary table (Table 22), where the significance levels of one-way-ANOVAs and Kruskall-Wallis tests are displayed together with the possible presence of an interaction effect in the two-way-ANOVA. Observed trends as a function of distance from the shipwreck are also showcased.

|  |  |  | 2-way-ANOVA | ANOVA/Kruskall-Wallis |  | Trend |  |
|---|---|---|---|---|---|---|---|
|  |  |  | Interaction effect | T1 | T2 | T1 | T2 |
| **Sediment characteristics** |  | LOI | * | *** | *** | ⇩ | ⇩ |
|  |  | Grain size | * | *** | ** | ⇩ |  |
| **Macroinfauna** | Community structure | Total species | * | ns | * |  | ⇩ |
|  |  | Shannon's diversity | * | ns | ns |  |  |
|  | Individual lengths | *Limecola balthica* | ns | ns | ns |  |  |
|  |  | *Hydrobia spp.* | ** | ns | * |  |  |
|  | Number of individuals | *Marenzelleria spp.* (S/B) | * |  | ** |  | ⬆ |
|  |  | *Limecola balthica* (F/S) | * | ** | ns |  |  |
|  |  | *Hydrobia spp.* | ns | ns | ns |  |  |
|  | Functional groups | Total functional groups | * | ns | ns |  |  |
|  |  | Suspension feeders (F) | * | ns | * |  | ⇩ |
|  |  | Surface detritivores (S) | ** | ns | * |  |  |
|  |  | Carnivore/surface detritivores (C/S) | ns | ns | ns |  |  |

**Table 22.** Summary table of all analysed variables. Significance codes: < 0,001 ‘***’, < 0,01 ‘**’, < 0,05 ‘*’, ns = non-significant. White arrow = decreasing trend as a function of distance from the shipwreck, black arrow = increasing trend as a function of distance from the shipwreck.

# 4. Discussion

The aim of the present study was to describe scour at Joskär shipwreck by studying sediment characteristics and macroinfaunal assemblages. Scour was first identified with traditional methods by scanning the study area with side-scan sonar, and by measuring depth contours around the shipwreck. Sediment samples were then taken inside the assumed most potent impact area of the shipwreck from three separate distances on two transects drawn outwards from the hull of the shipwreck, and analysed for sediment grain size, organic content, and macroinfaunal features. As scour occurs with changing intensity at different ranges from the object, it was hypothesised that macroinfaunal assemblages and sediment characteristics would exhibit variation between the sampling sites as a function of distance from the shipwreck. If the sediment characteristics alone are inspected, significant trends are observed, which confirms a part of the hypothesis to be valid and showcases the utility of sediment characteristics as descriptors of scour. However, the assemblages of macroinfauna exhibited heterogenous distribution with no significant trends consistent on both transects as a function of distance from the shipwreck. Therefore, trends of the characteristics of macroinfaunal assemblages are not a viable tool to describe scour at Joskär shipwreck. The results of the study are discussed below, together with observations made at the Joskär study site.

Loss on ignition (LOI) is a widely used method of determining total organic content of sediments (Heiri et al., 2001; Veres, 2002). The origins of organic content in the sediment vary, being derived both from terrestrial and marine sources depending on the local conditions (Arndt et al., 2013; Jilbert et al., 2018). As finer sediments are generally organic-rich, and their deposition occurs in areas with relatively low turbulence (Snelgrove & Butman, 1994), organic content can be used as an indicator of scour related hydrological processes.

Organic content of the sediment exhibits a clear decreasing trend as a function of increasing distance from the hull of the shipwreck. Despite the two-way-ANOVA producing an interaction effect, and the sonar scans showcasing the distinct physical characteristics of the area the transects were laid on, significant trends of decreasing organic content in the sediment on both transects when moving further away from the shipwreck are observed (Figure 9). The highest values for LOI were observed in the sampling sites closest to the hull of the shipwreck, with the highest value being 11,2 %. The sampling sites at 13,5 metres exhibited the lowest values, reaching a low of 0,82 %.

The observed values of LOI itself are not necessarily anomalous for the soft bottoms of Tvärminne archipelago. Previous publications have reported values ranging from 17,9 % on muddy to 0,2 % on sandy seafloors (Boström, 2002; Joensuu et al, 2018). In the present study, the measured values closer to the shipwreck are more alike with the muddy sediments of earlier studies, and the further sites represent conditions like the sandier seabeds of the area. What is notable however, is the decreasing trend of organic content on both transects in a relatively small scale. This finding effectively demonstrates scour and the impact the shipwreck has had on its immediate vicinity.

Zalmon et al. (2012) observed a comparable phenomenon on the coast of Rio de Janeiro, where sites closer to an artificial reef exhibited higher organic content compared to the ones further away. In the Mediterranean Sea, Danovaro et al. (2002) captured this same trend on sandy sediments leading away from an artificial reef structure. Visually conducted tentative measurements of organic content at the shipwreck of Vrouw Maria in the Baltic Sea give further support for the universality of this phenomenon (Ruuskanen et al., 2015). However, compared to the present study, the scale of the above-mentioned studies has been orders of magnitude higher, with transects reaching to hundreds of meters from the studied objects, and not all examples of earlier studies of larger scale have captured a similar trend (Davies, 1982; Magro et al., 2017). Perhaps the placement of the closest sampling site too far from the face of the object can explain some instances of not capturing the possible changes taking place. Davies (1982) for example, when investigating changes in the sediment characteristics as a function of distance from an artificial reef, placed the transects so that they started at a four-meter distance from the reef, and found no trend of decreasing organic content. Zalmon et al. (2012) observed a decreasing trend all the way to a 25-meter distance from a reef system, after which at the further sampling sites, the trend ceased to exist.

The importance of inclusion of small-scale sampling at the proximity of the studied object is highlighted, as in the present study a significant difference in the organic fraction is observed already between the two closest sampling sites (0,5 m & 1,5 m). Furthermore, sampling along the observed trends (Figure 9) of organic content would be of high interest to reveal whether the organic content will continue increasing if samples from e.g., 10 cm distance from the wreck are analysed, and whether the decreasing trend holds true all the way to 13,5 meters if samples between the 1,5 m and 13,5 m sites are collected.

The dark colour of the sediment 1-2 cm below the sediment surface at the 0,5 m sampling sites is indicative of anoxic conditions (Figure 24). Iron sulphides produced by diagenetic sulphate reduction give anoxic sediments their distinct dark colour (Morse & Cornwell, 1987). In addition, as the presence of subsurface burrowers, such as *Marenzelleria spp.*, is low close to the shipwreck (Figure 16), their functional properties as providing oxygen and labile compounds to the deeper layers of the sediment are lost, thus possibly slowing degradation rates of organic matter (Norkko, 2012; Bonaglia et al., 2013). The dark sediment together with the high content of organic material indicate that the immediate proximity of the shipwreck is under high rates of deposition of organic matter (Galy et al., 2007; Arndt et al., 2013). However, the sources of the organic material in the present study were not studied and can therefore only be speculated.

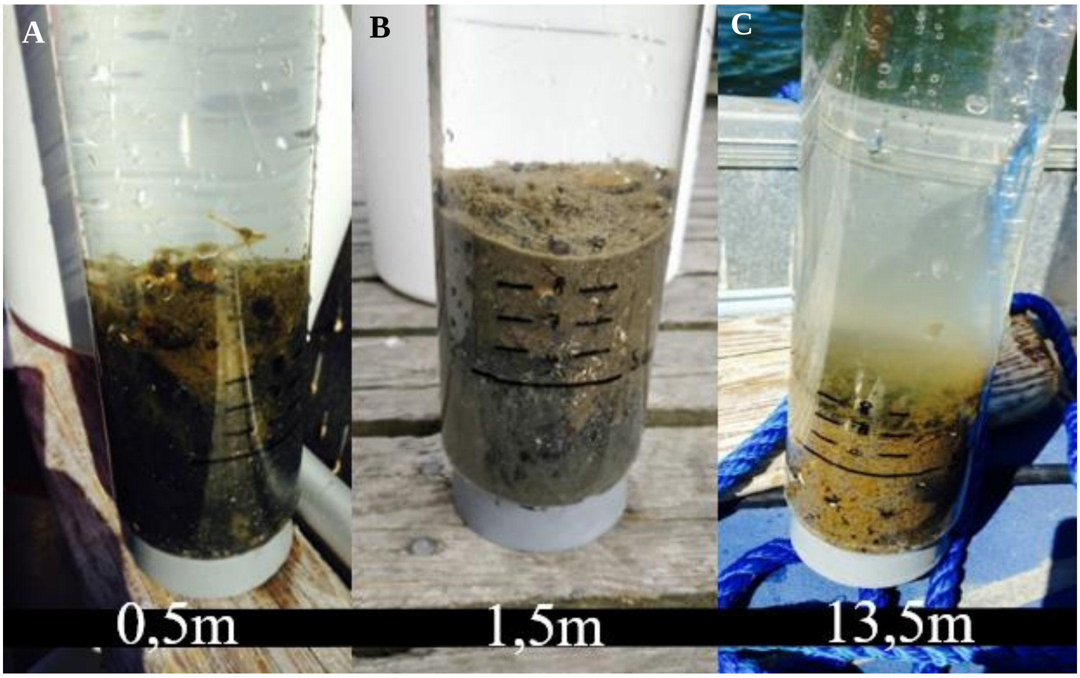

**Figure 24 A, B & C.** Core tube samples from transect T1. Sites at 0,5 m (A) and 1,5 m (B) exhibiting distinct layers, with sediment turning darker as depth of core increases. Site at 13,5 m (C) being a more homogenous, sandy sample.

In previous publications, scouring has been noted to affect the grain size in the vicinity of the studied objects. In some instances, coarse sediment has characterised nearby sediments (Ambrose & Anderson, 1990; Barros et al., 2001; Raineault et al., 2013), and in some, fine sediment has been the dominant size fraction (Ruuskanen et al., 2015). Sediment composition is connected to prevailing hydrological processes that move and aggregate sediment particles (Jönsson et al., 2004). Thus, the way sediment is sorted depends on the local hydrological conditions.

A clear decreasing trend of the fraction of coarse sediment can be observed on transect T1. On transect T2, no trend is observed. As the physical forces of the local hydrology affect sediment granulometry (Jönsson et al., 2004), the unequal sediment composition of the two transects suggests variable hydrological processes next to the shipwreck. The acquired side-scan sonar imagery shows the clear distinction of the sedimentary environment (Figure 6). On T2, dune like sediment ripple formations have developed, whereas T1 exhibits a more homogenous sediment surface. The granulometry of the sediment varies on the crest and the trough of the ripple, with the currents leaving coarser sediment on the crests (Foti & Blondeaux, 1995). The lack of a trend on transect T2 in the dominating grain size fraction could be due to the heterogenous ripple formations along the transect.

The magnitude of the effect on which grain size composition affects the infauna is often debated. In the Baltic Sea for example, Duplisea & Drags (1999) observed no variation in the biomass size spectrum of benthic organisms related to sediment's granulometric properties. Snelgrove & Butman (1994) argue that the effect of grain size is often overstated, and the processes affecting benthic communities are multifaceted. The relationship of sediment infauna and the sediment characteristics is mutual. Infauna actively affect the biogeochemical conditions within the sediment by causing bioturbation and bioirrigation. Already buried material is again exposed to the water column when burrowing infauna lift sediment from the deeper layers back to the surface. The burrowing tunnels enable water to penetrate deeper into the sediment, irrigating anoxic sediment zones with oxic seawater, and enhancing the solute transport otherwise relying solely on diffusion. (Aller & Aller, 1998; Kristensen & Kostka, 2005). The differences in the burrowing and feeding strategies of functional groups create a mosaic of sediment layers and burrows (Aller, 1988). In areas of diverse macrobenthic assemblages, degradation of organic material is faster, and microbial communities within the sediment are more active (Aller & Aller, 1998; Sun et al., 1999). In the region of the present study, in Tvärminne archipelago, Joensuu et al. (2018) presented the erosional properties of sediments being modified by the prevailing benthic infaunal assemblages.

Zoobenthic assemblages of the sampling sites reflect the heterogeneity of the habitat next to Joskär shipwreck. Nearly all analysed zoobenthic response variables (8 of 11) exhibited an interaction effect in the initial two-way-ANOVAs, showcasing a different distribution of zoobenthos as a function of distance from the shipwreck on transects T1 and T2. The variables with no interaction effect, showed no significant variation. The distinction of the transects was not necessarily surprising, after the visual inspection of the sonar images and the drawn MDS-plot revealed varying sea floor geomorphology and contrasting species assemblages of the sampling sites (see Figure 6 & 12). Sporadic distribution occurred through individual lengths, functional groups, and numbers of individuals. Most analysed zoobenthic variables exhibited no significant trends as a function of distance from the shipwreck, and little significant variation between the sampling sites was observed. This is partly due to the high standard deviation of the measured parameters (see e.g., Figure 17). The high standard deviation could indicate that the sample sizes were not large enough (3 replicates per sampling site) to effectively demonstrate the nature of the zoobenthic populations. It could also be that the sampling method was not thorough enough to capture a large enough representation of the local macroinfaunal community. In earlier publications, where infauna has been sampled along transects drawn away from an object on the sea floor, three replicates per sampling site has yielded relatively low standard deviations of observations (Fabi et al., 2002; Ruuskanen et al., 2015). In these publications, sampling methods used have been different.

Observed number of species varied between three and eight species per replicate sample. Previous studies have consistently reported higher numbers of species from the soft sediments on the coast of Finland, with species numbers ranging from 10 to over 20 species (Blomqvist & Bonsdorff, 1986; Boström & Bonsdorff, 1997; Perus & Bonsdorff, 2004; Rousi et al., 2013). An exemption is the shipwreck of Vrouw Maria, and its adjacent scour area, where the species numbers appear to be like the ones of the present study (Ruuskanen et al., 2015). Perhaps the altered hydrological conditions and their effects near the shipwreck prevent the recruitment and sustenance of diverse zoobenthic assemblages. The measured Shannon's diversity index exhibited relatively low values, with even the highest observed value (H' = 1,39) being like the lowest values of previous studies on the coast of Finland (Blomqvist & Bonsdorff, 1986; Boström & Bonsdorff, 1997). It can also be deliberated, whether the proximity of the shipwreck is under heavier predation pressure. Contradicting effects of reef associated fish predation near objects on the seafloor exists, with some reporting weakened benthic communities (Davies, 1982; Zalmon et al., 2012), and some with evidence of no effect (Ambrose & Anderson, 1990). The sampling methods in the above compared studies vary, and it is possible that some of the variation in the measured macroinfaunal community variables is derived from the sampling methods used in the present study.

Blomqvist & Bonsdorff (1986) argue that the patchiness of zoobenthic assemblages is a function of habitat structure, an argument that helps explain the varying zoobenthos at Joskär shipwreck, as the habitat is characterised by a mosaic of pieces of loose timber and distinct sediment formations. In general, transect T1 exhibited less variation of zoobenthos than transect T2. In fact, on T1 the only significant differences were observed between the mean number of *Marenzelleria spp.*, and the mean lengths of *L. balthicas*. However, the length data exhibited such high standard deviations, that no conclusions from that should be drawn. On T2 number of species was significantly higher in the proximity of the shipwreck. The 0,5 m site on T2 was also the most diverse site in terms of Shannon's diversity index. Significantly higher numbers of surface detritivores were also noted on that site, due to the large amount of *Hydrobia spp.* in the replicate samples. The high number of *Hydrobia spp.,* the high organic content of the sediment, and the present decaying algae at the 0,5 m site, is consistent with the observations of Norkko et al. (2000), who noticed *Hydrobia spp.* thriving in similar conditions. *Hydrobia spp.* are also known to take advantage of circumstances, where other organisms have decreased their abundance due to stress, and where organic deposits are plentiful (Norkko &

Bonsdorff, 1996). However, the high numbers of the present study (max ~7000 ind $m^{-2}$) do not match the richest *Hydrobia spp.* assemblages recorded outside of scour areas in coastal Finland, where numbers of *Hydrobia spp.* reach numbers as high as 25 000 ind $m^{-2}$, although those numbers have been acquired with different sampling methods (Norkko & Bonsdorff, 1996).

Despite the rather sporadic distribution of zoobenthos, some trends as a function of distance from the hull of the shipwreck were observed. *Marenzelleria spp.* exhibited a significant increasing trend, as distance to the hull of the shipwreck was increased. A significant trend was observed on transect T2. On transect T1 the only observations were made on the 13,5-meter sampling site. It can only be deliberated, why in an otherwise heterogenous environment, *Marenzelleria spp.* showcase relatively explicit behaviour. As a deposit feeder, *Marenzelleria spp.* would likely benefit from the high organic content of the sediments closer to the hull of the shipwreck (Snelgrove & Butman, 1994). *Marenzelleria spp.* feed on organic deposits (Karlson, 2011) and are known to opportunistically utilise available niches (Norkko et al., 2012). In addition, other deposit feeding polychaetes have been observed preferring sediments with higher organic content (Ramey & Bodnar, 2008). The effect of fish predation could be one control causing the absence of *Marenzelleria spp.* in the proximity of the shipwreck, although Norkko et al. (2012) and Karlson et al. (2011) do propose that the pressure from predation would not necessarily be a concern for them, due to their ability to dig deep burrows. *Marenzelleria spp.* are known to burrow past 10 centimetres of the sediment column up to depths of 30 centimetres (Zettler et al., 1997; Quintana et al., 2007; Norkko et al., 2012). The burrowing depth could also have affected the observed presence of *Marenzelleria spp.* at the sampling sites, since the sediment cores were pushed into a depth of 5cm, therefore unable to capture possible individuals in the deeper layers of the sediment. However, it is unlikely that deeper cores would have provided different results, since the presence of *Marenzelleria spp.* has been observed to be most profound in the upper 7 centimetres of the sediment column (Quintana et al., 2007; Norkko et al., 2012).

One possible explanation could be that conditions close to the shipwreck are too turbulent for the populations of *Marenzelleria spp.* to sustain themselves. Miller et al. (1991) noticed that a species belonging to the same genus (*Marenzelleria jonesi*) was unable to use its feeding apparatuses when current velocities were increased over a certain threshold. The substantial amount of organic content and shell debris in the sediments closer to the shipwreck, however, speak against prevailing strong hydrological forces since the material is not actively transported away from the area.

Another trend was the decrease of suspension feeders as a function of distance from the shipwreck. The mean number of individuals on transect T2 dropped exponentially, with the 0,5 m site having significantly more individuals compared to the site at 13,5 m. The mean number of suspension feeders at 1,5 meters on T2 does fit the exponential trend, but due to a relatively high standard deviation, it does not differ significantly from the 0,5 m and 13,5 m sites. At the 13,5 m sites on T1 and T2, suspension feeders were nearly absent. Only one individual was observed. Despite the lack of a significant variation on transect one, no suspension feeders were observed at the furthest sampling site, the only observations being on sites 0,5 m and 1,5 m. Even without the significant result it speaks for the lack of suspension feeders further away from the shipwreck.

The functional group of suspension feeders consisted of *Mytilus trossulus, Mya arenaria, Cerastoderma glaucum,* and *Gammarus spp.*, *M. trossulus* dominating the group with a relative proportion of 70 percent. The dominance of *M. trossulus* readily explains the observed trend of higher numbers closer to the hull of the shipwreck. *M. trossulus* does not necessarily belong to infauna but is a macrobenthic bivalve that requires a substrate to attach on (Seed & Suchanek, 1992). Previous studies investigating infauna include them in their analyses, which rationalizes their consideration in the present study as well (Boström & Bonsdorff, 1997; Perus & Bonsdorff, 2004). Their disappearance at the furthest sampling sites can be explained with the lack of substrate to attach on. The individuals identified in the sediment at the proximity of the shipwreck in the present study were probably fallen off the surface of the shipwreck that had abundant assemblages of *M. trossulus.* inhabiting it. The size of *M. trossulus* varied from 2,9 mm to 39 mm. A size range this wide is indicative of a relatively stable population, where new individuals are recruited among the assemblage of *M. trossulus* with many age classes (Kautsky, 1982; Seed & Suchanek, 1992).

In the present study, the observed groups *Chironomidae spp.* and *Trichoptera spp.* are freshwater insects, which in their seasonal life cycle, after their larval stage, will emerge from the water column (Paasivirta, 1975; Raunio & Paasivirta, 2008). Therefore, for the accurate replication of this study, the sampling must be conducted during the larvae stage of these organisms. *Oligochaeta spp.* were also abundant in the samples (80 individuals) but had to be excluded from further analysis due to the uncertainty rising from the sieving method not being a suitable method for the sampling of this group of species. However, *Oligochaeta spp.* have been commonly observed in earlier publications from the region (Aschan et al., 1988: Boström et al., 2002; Rousi et al., 2013) In the present study, small individuals of *Oligochaeta spp.*, likely classified as meiofauna (< 0,5 mm), were observed to tangle up to the used 0,5 mm sieve, thus rendering the counted number of individuals in a sample less reliable.

The distinct distribution of zoobenthic variables on transects T1 and T2 guide future studies to have a baseline of treating each transect as a distinct environment. Therefore, it should be ensured that the number of replicates within each site alone is large enough to enable reliable statistical analysis of the parameters, and so possibly avoid problems related to high standard deviations of observations. For now, the results do not present enough confirmation for the use of trends of macroinfauna as a function of distance from an object as indicators of a present scour.

Before the present study, studies at the shipwreck of Vrouw Maria by Leino et al. (2011) and Ruuskanen et al. (2015) were the only publications regarding scour and its effects on the adjacent benthic environment in the Finnish coastal waters. The geomorphology and hydrological conditions of the study site in the present study and of the area where Vrouw Maria lies are distinct. However, as these sites are the only studied shipwreck scour-sites on the coast of Finland, their comparison is of interest.

Vrouw Maria lies in a 41-meter-deep, bowl-like basin (Leino et al.,2011), whereas the depth of the water column at Joskär shipwreck ranges between three and five meters. According to Leino et al. (2011), relatively steady and unidirectional bottom currents with a mean velocity of 3 cm $s^{-1}$ dominate the environment at the shipwreck of Vrouw Maria. Current velocities were not recorded in the present study, but a qualitative assessment of bottom currents at the sampling sites during dives revealed prevalent bottom currents with varying velocities. Furthermore, the observed ripple formations in the side-scan sonar image indicate of physical forces of water currents present at the study site (Amos et al., 2017), and the deeper pit around the shipwreck (Figure 6) indicate the effect of scour having either buried the shipwreck itself or aggregated sediment around it; a phenomenon that in other published studies is known to be caused by accelerated water currents (Quinn, 2006; Raineault et al., 2013). The narrow strait between the islands, and the shallow water column of the coastal area could expose Joskär shipwreck to more dynamic and turbulent hydrological conditions compared to the ones Vrouw Maria experiences lying on the deep basin (Jönsson et al., 2004; Leino et al., 2011).

In terms of zoobenthos of these distinct shipwreck sites, the relatively steady conditions at Vrouw Maria have enabled *Limecola balthica* to develop rather constant populations, where the variation in individual lengths and population sizes between sampled replicates is low, even with a replicate sample size of three and the distance between replicates as high as 10 meters (Ruuskanen et al., 2015). The same cannot be said from the data of the present study. High variation in the number of individual *L. balthica* and their lengths, as well as other studied zoobenthic variables, prevailed in almost all replicate samples, even though the replicates were acquired from as little as 15 cm from each other. Furthermore, the mean length of *L. balthica* in the publication of Ruuskanen et al. (2015) was approximately 10 mm, whereas in the present study *L. balthica* mean lengths varied from 3 mm to 6 mm, with most individuals being in the length class between 2,5 mm and 5 mm (Figure 18). The shell length is indicative of the age of the bivalve (Gusev, 2012), and the food availability in the habitat of the organism affects its growth rate (Hummel, 1985). Thus, if the environmental conditions at Joskär shipwreck are dynamic, perhaps they prevent the formation of stable populations, therefore exhibiting smaller and younger individual *L. balthica* compared to the individuals at the shipwreck of Vrouw Maria (Ruuskanen et al., 2015).

The study period of the present thesis considers only a length of under a month, and the extent of the seasonal dynamics of sediment deposition and water movement at Joskär shipwreck are not known. Previous publications have shown scour sites to be dynamic environments, where sediment is in erratic movement and changes in the distribution of sediment occur on a seasonal basis (Quinn & Boland, 2010; Fernandez-Montblanc et al., 2016). Temporal measurements of water currents and sediment deposition would help in understanding the extent of turbulence that occurs at Joskär shipwreck, and at other non-tidal and relatively sheltered scour sites. If the sediment at Joskär shipwreck is under constant pressure from dynamic water currents, it only makes sense that stable and homogenous zoobenthic assemblages do not develop. For now, the effect of hydrodynamics on the macrobenthos around Joskär shipwreck can only be speculated, as no control site was included in the study design.

The results of the present study suggest that the relationship of a shipwreck and the surrounding benthic environment extends past the physical alterations of geomorphology of the seafloor, as changes on a small scale in the characteristics of the sediment were observed. Abundant organic material and the dark colour of the sediment at 0,5 m distance from the shipwreck indicate reduced sediment conditions with low oxygen availability. From an archaeological standpoint this might help further understand processes related to the preservation of timber-built shipwrecks on the coast of Finland.

The collected sediment samples were anomalously rich with shell debris. All shell material was included in the size fractionating of the sediments. Earlier studies investigating geological characteristics of sediment in proximity of objects on the sea floor, although sparse, have paid little attention to the abundance of shell material within the sediment. However, some studies have made observations of shell material accumulating in the proximity of the objects studied (Werner et al., 1979; Ambrose & Anderson, 1990, Barros et al., 2001). These observations have not prompted any further analysis on the matter, although Barros et al. (2001) concluded the reason for the coarser sediments in the vicinity of a rocky reef being caused by abundant shell debris. The results of the sediment analysis give the impression that similar phenomenon exists at Joskär shipwreck, where the coarse fraction of the sediment close to the shipwreck is dominated by shelly debris (Figure 25). The 0,5 m sites on T1 and T2 seem to consist mostly of shells of *Mytilus trossulus*, probably originating from the population attached to the surfaces of the shipwreck (Figure 25 A & D). Already at 1,5 m sites however, many shell pieces originating from other species, such as *Mya arenaria* and *Limecola balthica* can be observed, possibly brought in by water currents (Figure 25 B & E). The sampling sites at 13,5 m are bare of shell material (Figure 25 C & F).

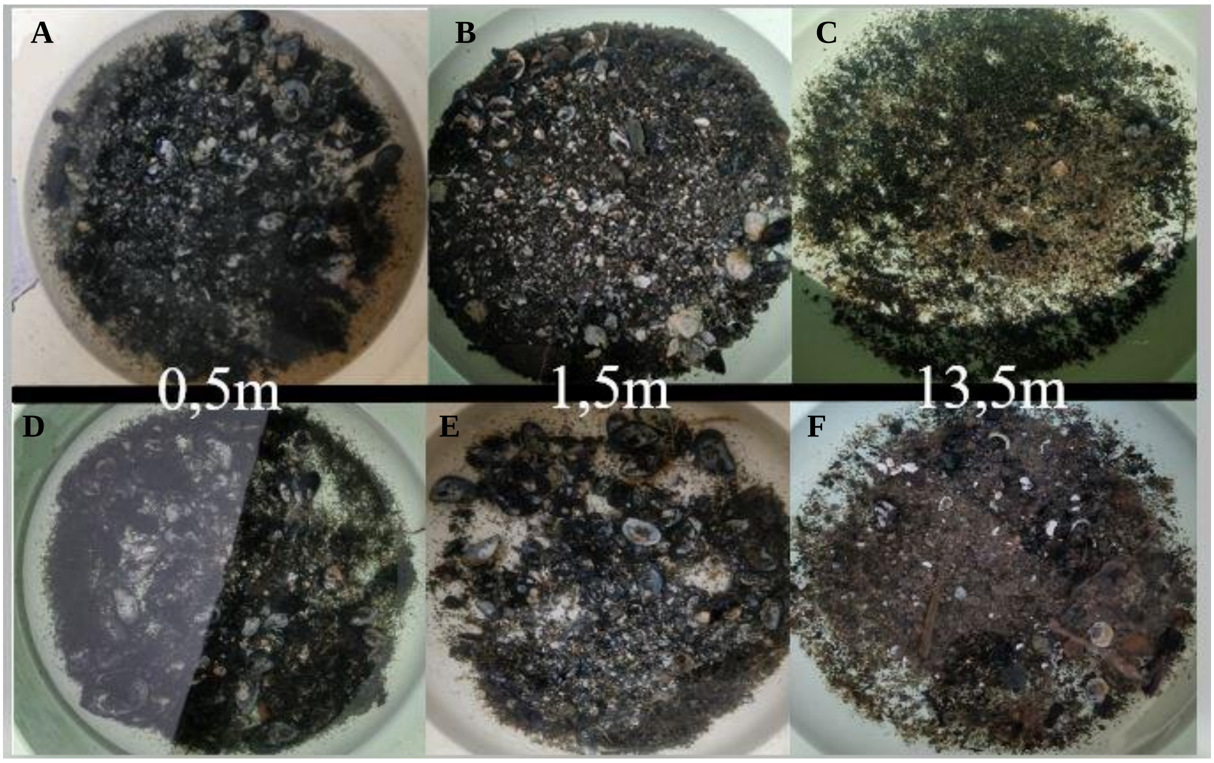

**Figure 25 A, B, C, D, E & F.** Images visualising the decreasing trend of shell material in the coarse sediment sample fractions as a function of distance from the shipwreck. (A, B & C) Coarse fraction on sites of transects T1. (D, E & F) Coarse fraction on transect T2. One replicate of from each site is shown. The dark, almost black material in the images consists of relatively large particles of organic debris later removed from all samples.

The acquired photographs of the coarse fractions of the samples work well at showcasing the decrease of coarse shell material in the samples as a function of distance from the shipwreck. However, it is impossible to visually tell how much of the fine sediment fraction is shell material. An analysis of shell content of the sediment would provide interesting information on the formation process of scour at Joskär shipwreck and could possibly help explain some of the trends observed with the zoobenthic variables. One method to estimate shell content could be to analyse the calcium carbonate ($CaCO_3$) content of sediments, as instructed by Heiri et al. (2001).

# 5. Conclusions

In this Master’s thesis, using the Joskär shipwreck as a case example of a scour habitat, I demonstrated how the effect of scour alters more than just the physical shape of the seabed. By measuring the organic content of the sediment, I was able to show how the organic fraction decreases as a function of distance from Joskär shipwreck. Dominating sediment grain size fraction exhibits a trend towards finer grained sediment as distance to the Joskär shipwreck increases. However, compared to the grain size composition, based on visual observations of the quality of the sediment, shell debris content of the sediment could possibly be a more viable tool to describe the scour at Joskär shipwreck. Based on the results of the present thesis, trends of characteristics of macroinfaunal assemblages as a function of distance from the shipwreck do not work as describing a present scour. However, as no control site was included in the study design, possible divergences of the macroinfaunal communities inside the Joskär scour from the communities outside of its impact area are not known. Further studies could reveal possible dissimilarities of the macroinfauna of these distinct habitats, and that way produce valuable measures of scour.

To conclude, the presence of scour at Joskär shipwreck can be confirmed based on the results of the sediment analysis. Results from the traditional methods of identifying scour with sonar technology confirm this finding, as the physical characteristics of the habitat reflect those of earlier publications regarding scour.

# 6. Acknowledgements

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