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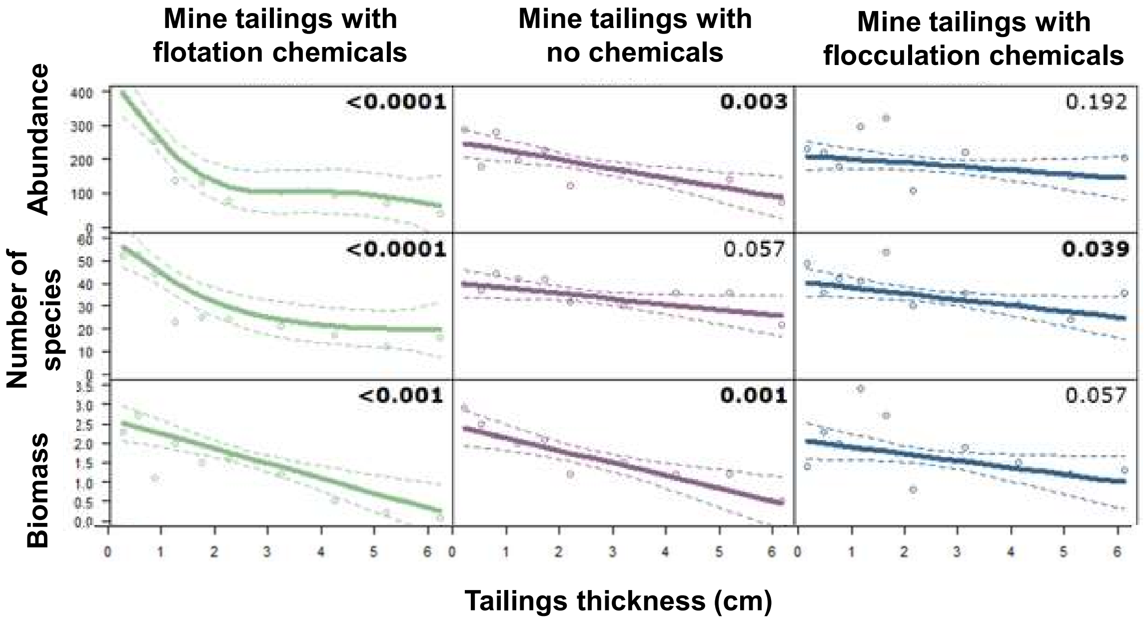
Research highlights:

1) Dose and response of 3 types of mine tailings studied in a soft-bottom mesocosm
2) Apparent effect threshold at 2 cm layer thickness
3) All tailings affected the fauna through more factors than hypersedimentation
4) Most severe effects of fine grained $CaCO_3$ with remnants of flotation chemicals
5) Indications were found on *in situ* biodegradation of flotation chemicals


Mine tailings with flotation chemicals
Mine tailings with no chemicals
Mine tailings with flocculation chemicals
Abundance
Number of species
Biomass
<0.0001
0.003
0.192
<0.0001
0.057
0.039
<0.001
0.001
0.057
400
300
200
100
0
60
50
40
30
20
10
0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
Tailings thickness (cm)

Effects of submarine mine tailings on macrobenthic community structure and ecosystem processes

Hilde C. Trannum[1]*, Hege Gundersen[1], Carlos Escudero[1], Joachim T. Johansen[1], Morten T. Schaanning[1]

[1] Norwegian Institute for Water Research, Gaustadalléen 21, NO-0349 Oslo, Norway

*Corresponding author: hilde.trannum@niva.no, phone +47 90595603

Abstract

A mesocosm experiment with intact benthic communities was conducted to evaluate the effects of mine tailings on benthic community structure and biogeochemical processes. Two types of tailings were supplied from process plants using flotation and flocculation chemicals, while a third type was absent of added chemicals. All tailings impacted the sediment community at thin layers, and through more mechanisms than merely hypersedimentation. In general, the strongest impact was observed in a very fine-grained tailings containing flotation chemicals. The second strongest occurred in tailings with no process chemicals. The tailings with flocculation chemicals initiated the weakest response. Fluxes of oxygen, nitrate and ammonium provided some indications on biodegradation of organic phases. Release of phosphate and silicate decreased with increasing layer thickness of all three tailings. A threshold level of 2 cm was identified both for faunal responses and for fluxes of phosphate and silicate. The particular impact mechanisms should receive more attention in future studies in order to minimize the environmental risk associated with tailings disposal.

Keywords: Mine tailings, sea deposits, benthos, mesocosm experiment

1 Introduction

The mining sector is growing in parallel with societal demands for minerals (Ramirez-Llodra et al., 2015). Historically, the mining industry has been a vital economic driver, and the industry remains necessary for the global economy as it contributes jobs, social benefits, infrastructure, wealth, and the vast array of goods that are part of everyday modern life (Hudson-Edwards, 2016). At the same time, the mining activity produces large volumes of unwanted waste and profitless materials (including rock, sediment, tailings, metallurgical wastes, dusts, ash, and processing chemicals) that are found at or near mine sites in virtually every country in the world (Lottermoser, 2010). Traditionally, tailings have been stored in land dams, and only 0.6% of industrial-sized mines deposit the tailings in the marine environment (Vogt, 2013). However, the lack of land availability, potential risk of dam failure, and complex topography in coastal areas result in increasing interest of disposal into marine systems. In Norway, several mines are located in rugged terrain making land-based tailing storage unsuitable. Since these mines are also situated close to fjords, sea disposal has been practiced in Norway (Ramirez-Llodra et al., 2015). Currently, Norwegian tailing discharges are taking place in Frænfjorden (Omya Hustadmarmor, western Norway), Ranfjorden (Rana Gruber, northern Norway) and at Stjernøy (Sibelco, Arctic region), and new deposits have been granted permits in Førdefjorden (Nordic mining, western Norway) and Repparfjorden (Nussir, Arctic region).

The sedimentation caused by mine wastes into the marine environment may be huge; up to several million tons of tailings per year with an accumulated layer up to tens of meters thick (Ramirez-Llodra et al., 2015). Thus, the soft bottom fauna is the ecosystem compartment which will be most severely affected by such discharges. In the most extreme cases of hyper-sedimentation, most benthic fauna can disappear and large areas may be barren (Ramirez-

Llodra et al., 2015). In less impacted areas, such as in transitional zones outside the main deposit area, the community may still be impoverished and dominated by opportunistic species (Brooks et al., 2015). The effects may be significant also in time. After cessation of the mining activity, the initial colonization may be fast, but the reestablishment of a faunal community similar to the original state may take several decades (Burd, 2002; Josefson et al., 2008; Olsgard and Hasle, 1993), or probably never happen in cases where the bathymetry has been severely modified.

In addition to hyper-sedimentation, the tailings may have toxic effects caused by metals in the waste and added process chemicals. Flocculation chemicals are used in the thickener to recover fresh water, and may also be added to the tailings pipe to increase the formation of flocs and thus to inhibit large scale dispersal of fine tailings (Skei and Syvitski, 2013). Magnafloc is one of the flocculants commonly used by the mining industry. The active agent in Magnafloc is polyacrylamide, which exists in several tens of polymers, both anionic and cationic. The different polymers have been shown to exhibit varying toxicity (Liber et al., 2005), but in general these substances are not considered highly toxic (Berge et al., 2012). Flotation chemicals are used to separate ore minerals from gangue minerals. There are essentially three types of flotation chemicals; skimmers (facilitates the formation of air bubbles), collectors (adsorb to the surface and make hydrophilic particles hydrophobic), and regulatory substances (added to get full effect of skimmers and collectors) (Skei, 2010). Generally, flotation chemicals have been of more concern than flocculation chemicals, and toxic effects have been observed in bioassay tests (Berge et al., 2010).

It is important to minimize the risk associated with the mining discharges, and the industry needs to find the least environmentally harmful solutions. While monitoring provides important information on the *in situ* conditions in the vicinity of each discharge, a more thorough comparison between various tailings is needed for more accurate determination of dose response relationships and impact mechanisms. Further, in the actual sea deposit a highly impoverished fauna is expected and widely accepted, but in the transition zones where deposition rates are lower, the effects can vary between different tailings. Effects of thin layers have also been pointed out as a research-need regarding predictive modelling of the extension of the impacted seabed area (Skei, 2010). Thus, the aim of the present study was:

1) To investigate the response of biogeochemical fluxes and macrofauna community structure to sedimentation of thin layers of mine tailings
2) To identify dose response relationships suitable for prediction of environmental impacts based on particle spreading
3) To compare effects of three types of tailings currently discharged to sea deposits in Norway

A controlled mesocosm setup with intact benthic communities was used to address these research questions. The set-up has been used in several previous experiments (Berge et al., 1986; Trannum et al., 2010; Näslund et al., 2012), and the effects provoked in manipulated communities resemble the effects occurring in a natural seabed. Benthic community structure and functional variables measured as biogeochemical fluxes were used as the main response variables.

2 Materials and methods

2.1 Test materials

The experiment included three types of tailings:

1) Without process chemicals (delivered from Sibelco Nordic AS, denoted S);
2) With flocculation chemicals (delivered from Sydvaranger Gruve AS, denoted V);

3) With flotation chemicals (delivered from Omya Hustadmarmor AS, denoted H).

The Sibelco mine is located in Stjernsundet in Finnmark, the northernmost county of Norway. Mining activities started up in 1961. The product (nepheline-feldspar concentrate) is separated from the nepheline syenite rock, and the tailings arise from a process involving crushing, drying, milling, sieving and magnetic separation. The ore does not contain base metals above natural levels, and is dominated by feldspar, amphibole, nepheline, calcite, pyroxene, hornblende, biotite sphene and magnetite (Geis, 1979; Berge et al., 1993; Norwegian Mineral Industry, 2014). About 45% of the tailings particles are <63 μm and 15% <20 μm (Norwegian Mineral Industry, 2014). The tailings are discharged in the surface water of a bay, approximately 1 km wide and 50 m deep. Outside the bay the water depth exceeds 400 m.

Sydvaranger Gruve is an iron ore mine, also located in Finnmark. The ore is taconite, a magnetite ore interlayered with quartz. The latest production period lasted from 2009 to 2015, and processing during this period was similar to the previous production period which was terminated in 1997. The tailings contain gangue minerals such as quartz (about 75%), amphiboles and feldspars, and metals in the tailings are not elevated (Norwegian Mining Industry, 2014). According to Norwegian Mineral Industry (2014) about 80% of the tailing particles are < 63 μm, but analyses reported below showed that our samples had less than 55% in this fraction. The flocculation chemical Magnafloc (composed of polyDADMAC and polyacrylamide) is added to the tailings. When active, the discharge was located at ~30 m depth in Bøkfjorden, with a final deposition depth of approximately 220 m (Ramirez-Llodra et al., 2015).

Omya Hustadmarmor AS is located in Frænfjorden in Møre- and Romsdal County, western Norway, and receives marble mainly from an open pit mine in Brønnøy, Nordland county.

The marble is ground, washed and sieved at the production plant. Liquid marble is the final product, which is used in the production of paper, either as filler or as coating. The discharge consists of 40–50% calcium carbonate, and other minerals are quartz, feldspar, mica and small amounts of iron sulfide. The tailings are very fine-grained; 20 % > 63 µm, 40 % > 20 µm and 70 % > 4 µm (Arnstein Amundsen, Omya Hustadmarmor, pers.comm.). The tailings do not contain elevated levels of metals (Farkas et al., 2017), but both flocculation chemicals (anionic polyacrylamide) and cationic flotation chemicals have been used in the process. In October 2014, before sampling of source tailings for this study, the previously used flotation chemical (Lilaflot 1596) was substituted with FLOT 2015[1].

2.2 Experimental set-up

The experiment was performed on sediment communities collected in box-core liners and maintained in a mesocosm laboratory. On 11th -12th March 2015, 30 core liners fitted to a 0.09 m^2 KC-Denmark^{TM} box corer were used to collect test communities in the Oslofjord (110-116 m depth, 59°38.574N / 10°37.728E) with the vessel “RV Trygve Braarud”. Within eight hours the core liners were transferred to the mesocosm setup. The setup resembles the conditions at the fjord sampling locations as the mesocosm is kept relatively cool and dim and is supplied with unfiltered fjord water with temperature of 6-10 °C from 60 m depth in the fjord outside the mesocosm facility (Berge et al., 1986). This water was distributed to each liner via a common header tank and a multichannel peristaltic pump which maintained stable flows of 10 ml min^{-1}. Gentle stirring with submerged aquarium pumps ensured a well-mixed, non-stratified overlying water in all liners. In spite of the most careful handling throughout sampling and transfer from seabed to mesocosm, it is generally assumed that the communities will experience some stress during this process. Therefore, the test communities

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[1] FLOT2015 is a fictitious name used for reasons of confidentiality.

were allowed to adapt to the experimental environment for eight weeks before addition of tailings.

After acclimatization, the tailings were added in ten nominal layer thicknesses from 0 (control) to 6 cm (0, 0.3, 0.6, 1, 1.5, 2, 3, 4, 5 and 6 cm). This range of layer thicknesses was expected to provide a gradient from no to clear responses, and was chosen based on previously reported dose-response studies on sedimentation of mineral particles (Smit et al., 2008; Näslund et al., 2012; Trannum et al., 2010). The PNEC-value for burial is 6.3 mm, which represents the level where a maximum 5% of the species are affected (Smit et al., 2008). At increasing levels, more and more species will theoretically be affected. From this, we assumed that burial effects to some extent would be evident for all materials at doses exceeding 6.3 mm, and this level was therefore placed in the lower scale of the doses. Thickness intervals were intensified at the lower end of the scale where it was assumed that the changes were largest.

The amount of tailings required to obtain a given layer thickness will depend on particle compaction and pore water volume, and may change slightly during the course of the experiment. The doses were therefore determined by weight based on simple pilot experiments on weight/volume relationship obtained by sedimentation of the tailings in glass beakers with seawater. One quarter of the dose was added each week during a period of four weeks. The dry Sibelco material was sprinkled just above the water surface. The two other materials were saturated with water when delivered to our laboratory. These materials were diluted with seawater to appropriate slurries and poured evenly and gently out in the liner water. After addition of test materials, the water circulation and flow were stopped for one day to allow the particles to settle. However, despite this measure, a small amount of the fine fraction (<1% of the added material) may have remained in suspension until being washed away on restart of the peristaltic pump. Similar processes will probably cause larger loss of fine fractions at real subsea deposit sites.

The liners were named H0 to H6, S0 to S6 and V0 to V6 (i.e. letters denoting mine, Hustadmarmor (H), Sibelco (S) and Sydvaranger (V) and number denoting layer thickness). The experiment lasted for 4.5 months after the first addition. This timeline is in accordance with previous experiments (e.g. Trannum et al., 2010), and is needed to ensure that not only acute mortality is measured, but also more time-lagged and chronical effects on the benthic community.

2.3 Sampling and analyses

Fluxes of oxygen and micronutrient species across the sediment-water interface were determined from the concentration change in the water flowing through each liner.

Oxygen concentration was measured with a Clark-type oxygen electrode in liner water and header tank. Water samples for phosphate (PO_4), nitrate including nitrite ($NO_{3/2}$), ammonium (NH_4) and silicate (SiO_4) were collected from each liner and the header tank. Samples were stored in the dark at 4 ºC until analysis using automated spectrophotometric methods modified after Grasshoff (1983). Nitrite was not determined separately, so the concentrations and fluxes given for nitrate actually represent nitrate + nitrite.

The fluxes (J_{tot}) were calculated based on the following equation:

$$J_{\mathrm{tot}} = \frac{(C_i - C_o) \times Q}{\mathrm{A}}$$

where C_i = concentration in header tank, C_0 = concentration in liner-water, Q = flow of water through the liner (measured gravimetrically) and A = liner area. A more comprehensive description of flux calculations can be found in Trannum et al. (2010).

At the end of the experiment, total organic carbon (TOC) (0-1 cm) and sediment fine fraction (0-5 cm) samples were taken from each liner with a small hand-held corer (d=4 cm). Then, the sediments in the liners were washed through a 1 mm sieve with circular holes for retrieval of macrofauna. The rest-material was preserved with 10% buffered formalin and later transferred to 75-80% ethanol. The organisms were identified to species or lowest possible taxonomic level. Biomass (wet weight) was determined for the main taxonomic groups.

The fine fractions (< 0.063 mm) of tailings and sediments were determined gravimetrically after separation from the coarser fractions by wet sieving. TOC and TN were analyzed with a Carlo Erba element analyzer based on chromatographic detection of CO_2 and N_2 gases, respectively, after oxygen had been removed. More detailed data on each tailings can be found in Norwegian Mining Industry (2014) and Ramirez-Llodra et al (2015).

Morphological and local chemical information about the tailings were obtained by performing Scanning Electron Microscopy - Energy Dispersive X-Ray (SEM-EDX) analysis using an Hitachi S-3000N Electron Microscope with EDX Bruker Esprit 1.8.

2.4 Data analyses

Abundance (N), taxa richness (S), Margalef's species richness (d) (Margalef, 1958), Shannon–Wiener diversity index H' ($\log_2$) (Shannon and Weaver, 1963), and the biotic index AMBI (AZTI Marine Biotic Index) (Borja et al., 2000) were calculated for each sample. Each taxon was classified into feeding type; suspension feeder (SF), surface deposit feeder (SDF), subsurface deposit feeder (DF), deep deposit feeder (DDF), carnivore/omnivore (CO), dissolved matter/symbionts (DMS), large detritus/scraper/grazer, scavenger and parasite/commensal. Species within the three last groups were rare (<12 individuals pr. box) and were thus omitted from statistical analyses. In addition, taxa with unknown or other feeding groups were omitted (14 taxa, mainly belonging to a high taxonomic level, which made trait classification impossible). As some species can have different feeding modes, each species was scored (from 0 to 3) according to its affinity to the value category for each property, using the ‘fuzzy coding’ procedure (Chevenet et al., 1994). The abundances were then weighted and normalized to obtain a sample/feeding-traits matrix. The taxon classification is based on a traits database held by the Norwegian Institute for Water Research (NIVA) where information has been compiled from a broad selection of literature on natural history and life functions and by consulting experts, see Oug et al (2012).

In order to investigate the faunal response to increasing thickness of the three materials, Generalized Additive Models (GAMs, Zuur et al., 2009) were conducted in R (version 3.3.2, R Core Team, 2016), using the *mgcv* library (Wood, 2011). This method was chosen to allow for non-linear (curvilinear or asymptotical) trends in the response, and to visually identify possible thresholds. This procedure automatically estimates the optimal wiggliness of the model through estimated degrees of freedom (edf); the higher the edf, the more ups and downs are allowed in the model. Macrofaunal indices (N, S, d, H’, AMBI, biomass) and feeding groups (SF, SDF, DF, DDF, CO, DMS) were analyzed separately using tailing thickness (interval) and mine (Hustadmarmor, Sibelco and Sydvaranger) and their interaction as predictors. The interaction term was included to check if the three stations responded differently to the manipulations. No further (co)variables were included. Also candidate models without the interaction term were tested, and the difference in Akaike Information Criteria values (ΔAIC) was used to select the best amongst the two candidate models.

To test for possible thresholds in responses to layer thickness, multiple Generalized Linear Models (GLMs) were performed in the R *stats* library where mean values of the responses for thickness levels below vs. above (or equal to) potential thresholds (10, 15, 20, 30, 40 and 50 mm) were compared. This resulted in 18 comparisons for each of the 17 different response variables. Since multiple testing on a single dataset increases the chance of getting significant results (Dunn, 1961); the critical p value (α=0.05) should be Bonferroni corrected by dividing α with the number of comparisons made on the same dataset (i.e. 18) to interpret the p values directly. However, for comparison reasons, this is not necessary.

Oxygen and nutrient fluxes (O_2, NH_4, NO_x, PO_4, SiO_4) were treated statistically using various platforms in JMP®v.11. Of approximately 500 flux measurements, 16 were excluded after identification as outliers presumably resulting from erroneous measurements. Such errors result from occasional breakage of worn tubes at the roller heads of the peristaltic pump or other anomalous disturbance of the steady state concentrations in liner water, on which accurate flux measurements are crucially dependent. In the PCA (Principal Component Analyses), complete set of flux data are required for each liner. Thus, in the PCA data subset of 300 fluxes, 18 missing fluxes from 12 liners were replaced with dummies taken as the average flux of the two liners with adjacent layer thickness of same type of tailings.

Similarity in faunal community structure was visualized with MDS-ordination, based on Bray-Curtis similarity measure (Bray and Curtis, 1957) and fourth-root transformed data. The Index of Multivariate Dispersion (Warwick and Clarke, 1993) was used as a measures of rank dissimilarity among boxes within each tailings group. These analyses were performed with the PRIMER software package ver. 6.

3 Results

3.1 Sediment properties

The natural sediment (0 cm layer) had a fine fraction of 51-58% and a TOC-content of 13-17 µg/mg (Table 1). The added Hustadmarmor tailings had a fine fraction as high as 97%, compared to Sibelco and Sydvaranger tailings of 41 and 40%, respectively (Table 1). The latter two had TOC-content below the detection limit of 1 µg/mg, as compared to 6.4 µg/mg for Hustadmarmor. The analysis of TOC is based on removal of inorganic carbon by acid treatment to dissolve carbonate carbon. Incomplete removal of carbonates may occur due to inadequate doses of acid used in samples with exceptional high concentrations of inorganic carbon. This is known to occur with analyses of samples with high contents of shell debris. Similarly, incomplete removal of inorganic carbon may have applied to the Hustadmarmor samples, and the true concentration of TOC in this material remains unclear.

Total nitrogen (TN) was measured in the tailings only, and was less than the detection limit of 1 µg/mg in all three materials.

The element composition (Table 2) showed that tailings from Hustadmarmor contained calcium (Ca) as the main metal with just traces of magnesium (Mg). The high carbon and oxygen content was consistent with the presence of calcium carbonate ($CaCO_3$). Tailings from Sibelco exhibited a high concentration of silicon (Si) with relevant traces of iron (Fe). The presence of residual amounts of potassium (K) and Ca in the tailing supports the evidence of a nepheline-syenite mineral. Sydvaranger tailings were rich in Fe and in silicon (Si), consistent with the abundance of the magnetite interlayered with quartz that forms the taconite ore.

The SEM-pictures showed the presence of edged triangular and rectangular shapes of the particles for all three tailings (Figure 1). From the three tailings observed, Sydvaranger and Sibelco in particular showed the presence of particles with cleavage in two directions, which could result in elongated cleavage fragments. The pictures recorded at the highest magnification showed particles formed by surface-parallel structures and clear exfoliation joints that could lead to the formation of smaller prismatic particles.

3.2 Visual observations

A foam was formed when mixing the Hustadmarmor material with seawater. This foam remained visible in the liners for some days after the addition and was interpreted as a result of the flotation chemicals present in this material.

In liner S0.6 and H5, one individual of the large burrowing crustacean *Calocarides coronatus* was present from the start. It survived throughout the experiment in S0.6, but died between the third and fourth addition in H5.

Due to the light color of both the Hustadmarmor and Sibelco material, it was easy to observe holes, tracks and burrows of the organisms on the sediment surface. One month after the last addition, there was clearly less faunal activity on the surface of the sediment in the liners with the highest loads for both materials compared to the liners with lower loads.

3.3 Flux measurements

3.3.1 Time trends

Fluxes of oxygen were measured in all liners on two occasions before the first addition of tailings and three occasions after (Table 3). Nutrient fluxes were measured in five randomly selected liners on May 4th (before the first addition), and again on June 8th after the last addition. Nutrient fluxes were also measured in all liners on the two last occasions.

On March 25th, shortly after the transfer from field to mesocosm, the mean flux of oxygen in the three boxes selected for control was 473 µmol m^{-2} h^{-1}. A major decrease to 322 µmol m^{-2} h^{-1} occurred before the first addition, but further variations were small and not significant. Also, the variation between the liners tended to decrease throughout the experiment. Thus, the addition of tailings appeared not to have any clear effect on fluxes of oxygen other than smoothing out inherent differences between the liners.

Similar to oxygen, both fluxes and flux variability of ammonium, phosphate and silicate decreased after the first measurements, but due to the lack of observations on March 25th it was not clear whether the initial decline resulted from maintenance in the mesocosm or from the addition of tailings. The fluxes of nitrate shifted from a mean release during the first series to a consistent uptake in the five selected liners after tailings were added. However, significant differences ($p<0.05$) between fluxes before and after addition of tailings were found for phosphate only. Similar to oxygen fluxes, nutrient flux variations between liners tended to be smaller after addition of tailings.

3.3.2 Effect of layer thickness

Linear regression analyses of fluxes vs. tailing layer thickness showed no significant effect ($p>0.05$) of any tailings on fluxes of oxygen and ammonium (Figure 2). Increased layer thickness of Sibelco tailings provided a significant decrease in the uptake of nitrate ($p<0.05$), although the correlation coefficient (R^2) of 0.29 reflected the high scatter of these data. All tailings types did however, provide a shift from a negative flux (i.e. release from sediment to water) towards less negative or positive (uptake from water to sediment) flux of phosphate and silicate with $0.22<R^2<0.76$. Hustadmarmor and Sydvaranger tailings showed better fits to the linear model than Sibelco tailings. In order to elucidate possible non-linear relationships, a flexible Kernel smoothing was applied for all significant linear relationships between fluxes and layer thickness (grey lines in Figure 2). For fluxes of phosphate and silicate in the liners treated with Hustadmarmor, the smoothed profiles revealed a steeper change in the 0-2 cm range than in the 2-6 cm range. In the liners treated with Sibelco tailings, the Kernel smoothing indicated that most of the flux-change occurred at layer thickness larger than 2 cm. This also seemed to be the case for the flux of nitrate.

3.3.3 Principal component analyses

A Principal Component Analyses (PCA) was run for the fluxes of nutrients and oxygen determined in all liners on Aug.12th and Sep. 7th. As shown in Figure 3, the two first components could account for respectively 50.1% and 24.3% of the variations in the fluxes. The symbols in the left-hand diagram, which represent the projected flux pattern in each liner, revealed a shift from lower left for thin layers (blue symbols) towards upper right for thicker layers (red symbols). Thus, the low left cluster represents all liners with 0-15 mm layer thickness. In addition, V20 and S40 were positioned near origo at the periphery of the 0-15 mm cluster. The vector plot in the right-hand diagram showed that this separation was primarily caused by higher fluxes of phosphate and silicate in samples with thicker layers (i.e. ≥ 20 mm). In this context, higher flux indicates less negative or less release from sediment to water.

The PCA analyses also showed that the vectors for fluxes of oxygen and nitrogen nutrients were directed almost perpendicular to the flux vectors for phosphate and silicate. Thus, the axes following the diagonal from lower right to upper left corresponds to a gradient from low sediment uptake of oxygen and nitrate and low release of ammonium low right, towards higher uptake of oxygen and nitrate and higher release of ammonium up left. Such a shift might be expected to follow from death and decay of organisms, but the absence of any clustering for tailings type indicated that the three types of tailings tested here did not differ clearly with regard to effects on fluxes of oxygen and nutrients.

3.3.4 Factor analyses

A factorial model of the flux measurements was run using the Fit model platform in JMP®11 (Table 4). Layer thickness was modelled as a continuous factor. The model was run treating date as a separate factor and all two-ways interactions were included.

The results showed a significant effect of date on all fluxes except phosphate and a significant Date * Layer interaction for nitrate (Table 4). This resulted from the general decreasing trends described above, but for nitrate the decrease was primarily observed in thick layer treatments. Nitrate also showed significant effects of layer thickness, treatment and layer * treatment interactions. These effects resulted from a decreasing uptake of nitrate with increasing layer thickness, and a stronger decrease in Sibelco tailings compared with the other two treatments.

The very clear effects of layer thickness ($p<0.0001$) on the fluxes of phosphate and silicate were consistent with the general shift from negative flux (release from sediment to water) towards less negative or positive flux (uptake) in thicker layers, also revealed in the PCA analyses (Figure 3).

The significant interaction between tailing type and layer thickness found for ammonium fluxes was not very strong ($p=0.048$), and probably related to the slightly elevated release of ammonium observed at high layer thickness of Sydvaranger tailings in particular on Aug. 12th.

3.4 Macrofauna

In total, 151 taxa and 5 540 individuals were counted in the mesocosm liners. Overall, the bivalves *Thyasira equalis, Mendicula ferriginosa, Adontorhina similis*, *Nucula* sp. juv. and *Abra nitida* and the annelids *Heteromastus filiformis* and *Paramphinome jeffreysii* and nemerteans were the most abundant taxa (Supplement 1). The number of taxa (S) per liner ranged from 12 to 54, abundance (N) ranged from 38 to 398 and biomass (with echinoids and other large organisms excluded) ranged from 0.14 g to 3.38 g. H' spanned from 2.61 to 4.70, AMBI from 1.68 to 3.14 and d from 2.59 to 9.19.

The results from the GAM of the macrofaunal responses are presented in Figure 4. For Hustadmarmor, all endpoints responded strongly (< 0.001) to tailing thickness. For Sibelco, a significant response was observed for abundance, biomass and AMBI ($p \leq 0.015$), and a trend was detected also for the number of taxa ($p = 0.057$). For Sydvaranger, significant relationships were found for number of taxa, AMBI and d ($p \leq 0.039$), but also biomass was close to being significant ($p = 0.057$). For AMBI in Sydvaranger, the selected model was curvilinear with two maxima at approximately 2 and 6 cm with an estimated degree of freedom (edf) of 4.3 for the smoothing factor. All other edf's were < 2.2 except of abundance, AMBI and taxa richness for Hustadmarmor with edf's of 3.3, 2.6, and 2.5 respectively (Figure 4). When comparing candidate models with and without interaction, only abundance ($\Delta AIC = 5.4$) was sufficiently better including the interaction, whereas the two candidate models of AMBI performed equally good ($\Delta AIC = 0.7$). For comparable reasons, all models shown in Figure 4 include the interaction term.

All feeding groups except for carnivore/omnivore (CO) showed a significant response of the Hustadmarmor treatment (Figure 5). For Sibelco, the response was significant for species utilizing dissolved matter or symbionts as the main nutrient source (DMS) as well as for deposit feeders (DF) and deep deposit feeders (DDF). For Sydvaranger, the response was significant only for surface deposit feeders (SDF), but approaching significant for suspension feeders (SF).

MDS-ordination of macrofauna is presented in Figure 6. A very clear gradient in the Hustadmarmor treatment was evident in the liners with 0 and 0.3 cm tailings addition to the left and then towards right liners with increasing layer thickness. There was also a tendency that the liners with the highest doses of Sibelco material were placed along the same axis. No similar trend was evident for the Sydvaranger tailings. The multivariate dispersion index was 0.66 for Sydvaranger, 0.96 for Sibelco and 1.38 for Hustadmarmor, showing that the tailings initiated different degree of multivariate variability within each group.

3.5 Tests for thresholds

Tests for possible thresholds in responses to layer thickness for the three groups of response parameters are presented in Table 5. To interpret the p values directly, the tests should be Bonferroni corrected, and thus, the critical value for a statistical significant result is 0.0028 instead of 0.05. For the macrofauna indices N, S, biomass and H' (except Sibelco), a clear threshold was found at 2 cm depth for all tailing types. This was especially obvious for Hustadmarmor, which showed a clear flattening response at 2 cm for N and S (Figure 4). A threshold of approximately 2 cm also seemed to be the case for d, although less clear for Sibelco (Figure 4). AMBI showed an apparent threshold at 5 cm for Hustadmarmor, at 3 cm for Sibelco and between 2 and 4 cm for Sydvaranger, probably caused by the bi-modal GAM curve (Figure 4).

A general pattern was found for Hustadmarmor for most feeding groups, where layers as thin as 1 or 1.5 cm caused a sudden drop in the number of individuals (Figure 5 and Table 5). Sibelco or Sydvaranger, however, had the most significant thresholds closer to 2 or 3 cm, but sometimes also at 5 cm (DMS, Sydvaranger).

Although no obvious threshold was visible for the biogeochemical fluxes in Figure 2, some thresholds stand out as more plausible than others in the comparative threshold tests. Both silicate and phosphate had the most significant thresholds at approximately 2 cm for all tailing types. For the rest of the nutrient responses (nitrate, ammonium and oxygen) thresholds were not investigated, since these variables did not respond significantly to layer thickness (Figure 2), except nitrate for Sibelco which had the most significant threshold at 3 cm.

4 Discussion

The overall aim of this study was to investigate how soft bottom communities respond to increasing layer thicknesses of mine tailings and whether the response varies according to tailing type. Benthic macrofaunal community structure and functional parameters measured as biogeochemical fluxes were used as response variables.

4.1 Biogeochemical fluxes

4.1.1 Pre-treatment variations and general comments

Considering the small variations in concentrations of oxygen and nutrients in the source water from 60 m depth, the fluxes measured here reflect variations in pore water concentrations, which are driven by the metabolic activity of organisms living in the sediment and modified by physical processes such as diffusion and bioturbation and chemical processes such as precipitation, adsorption and desorption (Di Toro, 2001; Zehnder and Stumm, 1988). As observed in field investigations in the outer Oslofjord (Olsgard et al., 2008) and other coastal areas (Devol and Christensen, 1993; Hall et al., 1996), fluxes of oxygen and often nitrate were directed into the sediments, while ammonium, silicate and often phosphate were released from the sediments to the overlying water. For silicate, nitrate and ammonium the fluxes determined before addition of cuttings were within the range observed in March 2002 in an area a few km south of our box-core sampling area (Olsgard et al., 2008). Our release of 7.86 µmol phosphate m^{-2} h^{-1} was higher than those observed in the field investigation, but Näslund et al (2012) reported similarly high release of phosphate from Oslofjord control sediments.

The major decrease of the oxygen uptake occurred before any addition of tailings. In previous experiments, a similar decrease of SOC has been observed during the first weeks after transfer from fjord to mesocosm. Trannum et al. (2011) observed an increase followed by a rapid decrease from 800 to 400 µmol m^{-2} h^{-1} after addition of fresh algae to Oslofjord sediments. The decrease has been related to decay of the most labile fractions of organic carbon introduced from seasonal sedimentation of phytoplankton blooms in combination with no active feeding and low input of natural food items via the water exchange system (Berge et al., 1986).

After addition of tailings on May 4th, the fluxes did not change significantly. The fact that the variability tended to decrease with time may result partly from the decline of the overall metabolism in sediments depleted in labile organic matter and partly from the addition of mine tailings with low TOC. Both factors will contribute to reducing the variability between the liners.

As the tailings are inorganic, they will not themselves cause degradation, but may influence the fluxes through other mechanisms. However, the tailings from Hustadmarmor and Sydvaranger had been treated with various types of organic chemicals, and bacteria capable of utilizing this source of organic carbon, may be present.

4.1.2 Phosphate and silicate

The release of phosphate and silicate decreased with increasing layer thickness in all three types of tailings (Figure 2), with the factor analyses showing significant effects at $p<0.0001$ for both fluxes (Table 4). Silicate was released from the sediments in all treatments, but the flux of phosphate shifted from release to a small uptake in liners with the thickest layers. Phosphate is known to adsorb on mineral phases such as iron oxides (Mortimer, 1971), therefore, the shift from release in liners with thin layers to uptake in liners with thick layers was most likely explained by high abundancies of anionic adsorption sites on the freshly grinded mineral materials. In this respect, no differences were found between the three types of tailings.

The release of silicate decreased with increasing layer thickness. Pore waters are frequently undersaturated with silicate and dissolution of silicate minerals will sustain a mineralogenic flux component which is independent of metabolic activity (Di Toro, 2001). In areas such as the Oslofjord, with regular sedimentation of phytoplankton from spring blooms (e.g. diatoms with silica skeletons), the release of silicates will also have a significant biogenic component (Devol and Christensen, 1993; Hall et al., 1996). This biogenic component will disappear when the Oslofjord sediment is increasingly covered with mine tailings, whereas dissolution of silicates present in the mine tailings may increase the mineralogenic flux component, which may differ between the different types of tailings. An ANOVA comparison (JMP®v.11) of the flux of silicate from the thickest layers (5 and 6 cm) showed a significantly lower release from Hustadmarmor (4.7 µmol m^{-2} h^{-1}) compared to Sydvaranger and Sibelco (12.9 and 15.8 µmol m^{-2} h^{-1} respectively). This difference was consistent with the element composition observed with SEM-EDX (Table 2) which showed a much smaller content of silicon in Hustadmarmor (0.2 %) compared to Sydvaranger (11.9%) and Sibelco

(6.1 %). Thus, in the two latter materials, the decrease of the biogenic release appeared to be partially compensated by an increased dissolution of silicate minerals.

4.1.3 Threshold at 15-20 mm

The PCA analyses for the fluxes (Figure 4) revealed two clusters separated primarily due to more positive fluxes (lower release) of phosphate and silicate in liners with tailings layers ≥ 2 cm. This indicated a threshold depth where major change of these fluxes occurred. The threshold at 2 cm also appeared as minimum p-values in Table 5, but was to a large extent masked by large scatter in the flux vs. layer thickness plots in Figure 2. If the tailings are considered relatively inert with low bacterial activity, the nutrients are produced or consumed primarily in the sediments beneath the tailings and the tailings layers represent diffusive barriers, which will reduce the exchange with the overlying water dependent on particle size and bioturbation. Thus, a layer with smaller particles and less bioturbation will reduce the exchange more than a similarly thick layer with coarser particles and more bioturbation. Disregarding one anomalous flux of silicate (H3 on Aug.12th), the release of phosphate and silicate decreased primarily within the 0-2 cm range of Hustadmarmor tailings. In Sibelco and Sydvaranger, however, the release of these nutrients decreased more steadily across the whole range of layers tested. Also, the significant change of nitrate uptake in Sibelco appeared to decrease steadily across the entire range of layer thicknesses. Fine fractions were clearly more abundant in Hustadmarmor (97%<63 µm) than in Sibelco (41%<63 µm) and Sydvaranger (40%<63 µm) (Table 1), but also the stronger depletion of macrofauna in Hustadmarmor suggests that bioturbation may be an important factor sustaining the fluxes of nutrients through the tailings layers. A gradient in bioturbation activity was supported by the visual observations during the experiment (chapter 3.2).

4.1.4 Oxygen, nitrate and ammonium fluxes

Oxygen, nitrate and ammonium fluxes are mainly controlled by microbial processes driven by the degradation of organic matter. Labile organic matter is primarily present in the sediments transferred from the fjord location. In addition, some mortality during addition of tailings (May 4th – June 8th) may have contributed to increase the reservoir of degradable organic matter in all treatments in the beginning of the experimental period. Thus, the significant decrease of the fluxes of oxygen, ammonium, nitrate and silicate between Aug. 12th and Sept. 7th (Table 4) most likely resulted from burn-out of initial reservoirs of natural organic matter.

Remnants of organic chemicals were only present in the tailings from Hustadmarmor and Sydvaranger, and indications on degradation might be sought in differences between the three treatments. The factor analyses (Table 4) provided significant effects on nitrate fluxes of both treatment, layer thickness and treatment * layer interactions. The interaction results from the fact that the consumption of nitrate decreased with increasing layer thickness in Sibelco treatments without chemicals, but not in the two treatments with remnant chemicals (Figure 2). A similar trend, though not statistically significant, was observed for O_2. This might be explained by degradation of process chemicals, which maintains higher consumption of the electron acceptors nitrate and oxygen in the thick layers of Hustadmarmor and Sydvaranger tailings.

Also, field investigations have revealed some indications on biodegradation of organic matter, possibly remnant chemicals, in the sea deposit at Hustadmarmor. Thus, blackening of the sediments indicating sulfate reduction and precipitation of ferrous sulfides has been documented on SPI-photos (Schaanning et al., 2009), and odor of H_2S has been noted during grab sampling in the area (Trannum, pers. com.). These observations might result from biodegradation of authigenic organic matter and does not necessarily indicate degradation of remnant chemicals. Interestingly, however, high abundancies of the bivalve genus *Thyasira* have recently been found near the tailings discharge point in Frænfjorden (Trannum et al., *in prep.*). Because this bivalve genus is known to benefit from a symbiotic relationship to anaerobic bacteria involved in sulfur cycling, their proliferation close to the discharge point supports the idea that these tailings contain remnant chemicals exploitable by specialist organisms.

4.2 Faunal effects

4.2.1 Faunal responses

Both the univariate and multivariate analyses revealed unequivocal responses of the tailings. From the MDS-ordination (Figure 6) and the index of multivariate dispersion, it was evident that the species composition was most altered by Hustadmarmor as these boxes showed the largest spreading, less by Sibelco and least by Sydvaranger. Further, both the number of taxa, number of individuals and biomass as well as the univariate indices responded significantly to the tailings at a significance level lower than 0.001 for Hustadmarmor (Figure 4). For Sibelco, the response was significant for abundance, biomass and AMBI, and almost significant for the number of taxa. For Sydvaranger the response was significant for the number of taxa, AMBI and d and almost significant for biomass. AMBI, however, showed a curved response, which is difficult to explain. To conclude, the Hustadmarmor tailings initiated the most severe response, followed by Sibelco, while the Sydvaranger tailings gave the weakest response.

The pattern described above with strongest effects of Hustadmarmor and weakest effects of Sydvaranger also applied to the faunal feeding groups (Figure 5). The Sydvaranger treatment initiated only one significant response in this respect; on surface deposit feeders (SDF). The response of this group was also significant for Hustadmarmor, but notably not for Sibelco. This group has been found to be relatively sensitive towards various kinds of disturbances (Gaston et al., 1998; Nunesa et al., 2008; Roth and Wilson, 1998; Trannum, 2000), and the lack of response towards the Sibelco-tailings was in that regard unexpected. Since surface deposit feeders are known to select food particles based upon characteristics such as size, texture, specific gravity and organic coatings (Guieb et al., 2004; Mahon and Dauer, 2005), they may have actively avoided the Sibelco-particles due to surface properties like shape and sharpness. In the mesocosm, the inflowing water was unfiltered and contained some particulate organic matter, which the surface deposit feeders may have utilized as an alternative food source. A similar, although weaker, response, which may have the same explanation, was observed for suspension feeders (SF); the effect was significant for Hustadmarmor, and close to significant for Sydvaranger, but not for Sibelco. However, for SF, it is important to note that the organisms were only exposed to the tailings during the time of actual addition of materials, and thus a weaker response could be expected.

On the other hand, for species feeding on particles beneath the sediment surface; deposit feeders (DF) and deep deposit feeders (DDF), a different pattern occurred (Figure 5). The response was significant for Hustadmarmor and Sibelco, but not for Sydvaranger. As the added layer was up to 6 cm, most of the organisms in these feeding groups were permanently exposed to the tailings. These species will be heavily exposed by ingestion of tailing particles and may suffer from both physical effects and potential desorption of chemicals and uptake through the gut. The response in Hustadmarmor corresponds very well with field monitoring of this discharge, where species living deeper in the sediment decreased, and mobile species living on or near the surface dominated (Brooks et al., 2015). In general, deposit feeders are assumed relatively tolerant to pollution (Gaston et al., 1998; Nunesa et al., 2008; Pearson and Rosenberg, 1978; Roth and Wilson, 1998). However, in that context pollution frequently means organic enrichment, and it is important to note that the present disturbance represents deposition of particles with a very low nutritional value.

Similarly, the group assigned as “dissolved matter/symbionts” (DMS) was significantly affected by the Hustadmarmor and Sibelco materials, but not Sydvaranger (Figure 5). This group is mainly composed of bivalves belonging to the genus *Thyasira*, and includes *Thyasira equalis*, which was overall the most abundant species in the experiment. These bivalve species host chemoautotrophic symbiotic bacteria, which they use as a nutrient source (Dando and Spiro, 1993). They are often found in organic enriched sediments (Dando et al., 2004; Keuning et al., 2011), and are thus often considered relatively tolerant. They have also been found near to the tailings discharge in Frænfjorden (Trannum et al., *in prep.*). The interpretation of the nutrient fluxes (chapter 4.1.4) indicated elevated bacterial activity in the Hustadmarmor material, although this may have evolved too late in the experiment to save the symbiotic bivalves from starvation.

Carnivore/omnivores (CO) were least impacted, with no significant responses (Figure 5). This group will not be directly exposed to the tailings via the food, and the group has also generally been considered to be tolerant towards disturbances (Oug et al., 1998; Pearson, 2001; Pearson and Rosenberg, 1978). Of course, as the prey items disappear, also this group will be affected, and this mechanisms may explain the tendency for less CO with increasing layer thickness in Hustadmarmor, supported by a p-value of <0.1.

The findings described above on the faunal impacts were supported by the visual observations during the experiment (see chapter 3.2). It was clearly less faunal activity on the surface of the sediments in the liners with highest loads of Hustadmarmor and Sibelco compared to the liners with lower doses. Further, the large burrowing crustacean *C. coronatus* survived throughout the experiment in box S0.6, but died between the third and fourth addition in box H5. This may have been a random occurrence and cannot for certain be attributed to the higher load of tailings present in H5. Nevertheless, there were indications that several organisms did not succeed in resuming their normal activity after the addition of high doses of Hustadmarmor and Sibelco tailings.

4.2.2 Impact mechanisms

The present study was designed to compare effects of different "bulk" tailings, not to investigate the particular impact mechanisms affecting the fauna. However, it is worth discussing which impact mechanisms that may have been involved. Of these, hypersedimentation is the most obvious stressor. This factor is common for all three tailings. From this, it follows that hypersedimentation cannot explain more than what was found for the least harmful Sydvaranger tailings. In a previous mesocosm-experiment, layers up to 24 mm of natural test sediment did not affect benthic communities (Trannum et al., 2010), and only very minor effects of sedimentation of natural particles were observed in previous studies (Bellchambers and Richardson, 1995; Jackson and James, 1979; Maurer et al., 1982; Smith and Rule, 2001). Thus, the sedimentation component of faunal effects was probably not very severe, but still present. In general, species in muddy, stable sediments have a poorer ability to cope with sediment burial compared to species in sandier habitats where sediment movement is more naturally frequent (Hinchey et al. 2006). Furthermore, the additions were repeated four times. Such repeated deposition may initiate more severe responses than single instances (Bolam et al., 2006; Lohrer et al., 2004), following from the fact that the rate of disturbance is the product of frequency and extent of disturbance events (Miller, 1982; Svensson et al., 2009).

Starvation due to low nutrient content in the tailings is another stressor. Tailings are in general assumed to be low in organic content (Blackwood, 2007; Burd et al., 2000), and a reduced nutritional value could typically be expected (Shimmield et al., 2010). Indeed, total nitrogen (TN) was less than the detection limit of 1 µg/mg in all three materials. This was also the case for total organic carbon (TOC) in the Sibelco- and Sydvaranger materials. As mentioned in chapter 3.1, the higher TOC content in the Hustadmarmor liners (Table 1) probably also reflects inorganic carbon (Table 2). In the Sibelco- and Sydvaranger liner-sediments the TOC-level was highly reduced with increasing layer-thickness (Table 1). At thicknesses exceeding 3 cm, the TOC-level in the uppermost sediment was below the detection limit. Thus nutrient depletion may have been involved in the faunal impacts.

The more severe response in the Sibelco-tailings, with no added process chemicals, compared to the Sydvaranger-tailings was very interesting. A recent toxicity assessment performed on the same three tailings also showed that Sibelco had a larger effect on the development of the oyster embryo as well as on shell growth of juvenile oysters than the other materials (Brooks et al. *in prep.*). The concentration of metal ions known to be present in some tailings could potentially have been responsible for the differences in toxic response between the tailings. However, the metal concentrations were low in all three tailings and chemical analysis of the pore waters did not reveal any causal relationship between toxic response and metal concentrations (Brooks et al. *in prep.*).

Particle properties like altered particle shape and angularity is another possible explanation for the response of the Sibelco tailings. In general, tailings consist of mechanically crushed rock that have relatively sharp-edged grains compared to natural sediments, which are rounded from the natural grinding over geological time (Kvassnes and Iversen, 2013). This may create additional risks for the fauna (Olsgard and Hasle, 1993). In the SEM-EDX analysis, edged triangular and rectangular shaped particles were evident for all three tailings (Figure 1). Notably, for the Sibelco-tailings, it was also evident that some particles exfoliated into elongated prismatic cleavage fragments, and that the tailings had a very rough surface. In fish, needle shaped particles have proven to be more harmful to gills than other tissues (Jacobsen et al., 1987), and Lake and Hinch (1999) found that highly angular particles caused a larger stress-response in juvenile coho salmon than spherical particles. Farkas et al. (2017) have previously observed edged shapes in Hustadmarmor tailings, and they further observed surface attachment and ingestion of these particles by the zooplankton *Calanaus finmarchicus*. Thus, particle angularity effects may have been responsible for at least some of the impacts of the Sibelco-tailings.

Toxicity of added process chemicals is an impact mechanism that should be considered for Hustadmarmor and Sydvaranger. Notably, the Sydvaranger tailings containing flocculation chemicals were less harmful than Hustadmarmor containing flotation chemicals. This finding is consistent with toxicity tests on *Skeletonema* and *Arenicola* (Berge et al., 2012) and also with tests on reproduction of the copepod *Tisbe battagliai* and growth of small turbot (*Scopthalmus maximus*) performed with the Sydvaranger tailings (Berge et al., 2014). Furthermore, relatively low toxicity of the Sydvaranger tailings compared to Hustadmarmor and Sibelco was also observed in the sediment contact bioassays measuring growth effects of juvenile oysters and survival of *Corophium* sp (Brooks et al., *in prep*), which accords well with the present study. Indeed, as effects of the Sydvaranger-tailings in general were less severe than for the Sibelco-tailings, a toxicity-response of this material seems to be marginal.

In contrast, chemical toxicity of the Hustadmarmor tailings could partly explain the more severe responses observed for this material. Both flocculation and flotation chemicals are used in the processes, and the different effects compared to Sydvaranger as mentioned above, points to the flotation chemical as the most harmful component. The flotation reagent currently employed at Hustadmarmor belongs to the family of cationic tensioactive-type substances (foamers). The foaming is due to the presence of esterquats. The use of this family of substances instead of alkyl quaternary ammonium compounds (such as Lilaflot® 1596, previously used at Hustadmarmor), changes the environmental impact, since the ester bond of esterquats is a labile point that leads to the fast hydrolysis of the product. Nevertheless, a more severe impact on the benthic community was found for Hustadmarmor than for the other tailings, and toxicity tests on *Corophium* sp. confirmed a toxic response of Hustadmarmor (Brooks et al., *in prep.*).

Also of importance, the Hustadmarmor tailings were much more fine-grained than both the original sediment and the Sibelco and Sydvaranger tailings (Table 1), which may have contributed to the more severe effects of this material. Highly fine-grained particles may lead to suffocation and clogging of feeding and respiratory organs, and the fact that suspension feeders were significantly affected only by the Hustadmarmor-treatment supports such impact mechanisms. To speculate, such clogging could intensify effects of chemical toxicity and particle sharpness. Further, highly fine-grained tailings can reduce subsurface oxygen penetration and exchange of nutrients across the sediment water interface (Ramirez-Llodra et al., 2015). Näslund (2012) showed that an increasedclay size fraction in a similar material (crushed marble) caused oxygen penetration to be reduced from 4.0 to 2.6 mm. Tailings deposition may typically also reduce sediment heterogeneity (Morello et al., 2016), which restricts the niche availability and leads to low faunal diversity (Gray, 1974).

4.2.3 Field relevance

Extensive field monitoring has been carried out for all three mines, and are summarized in Ramirez-Llodra (2015). In the very vicinity of the Hustadmarmor outfall, the species richness and abundance have been extremely low throughout the monitoring period (Brooks et al., 2015), which concurs well with the present experiment. There is a distinct change in benthic community structure at intermediate distance (0.5-1.5 km) from the outfall (Brooks et al., 2015). The stations beyond the boundary of the deposit achieve “good” status according to the Water Framework Classification system (DNV, 2014). Monitoring has also showed that outside the Sibelco-outfall, the amount of organic carbon is low and the fauna highly depleted with low species richness and abundance inside the bay (Trannum and Vögele, 2001), which again accords well with the present experiment. Outside the bay, the fauna did not seem to be disturbed. The Sydvaranger mine has not had a continuous production, and the impacts have therefore varied with time. In the last monitoring in 2011, an area up to 6 km from the outfall was influenced by the tailings (Berge et al., 2012). The sediment at the stations reaching out to 1.7 km from the outfall, were almost entirely composed of tailings. More distant stations showed good faunal conditions. Thus, all three mines initiate strong faunal effects in areas where deposition rates are high. This is expected and widely accepted. However, in the transition zones, where deposition rates are lower, the effects on the benthic communities may depend on the type of tailings deposited, which is demonstrated by the present study

Here, we have shown that a layer thickness of 2 cm appeared to represent a threshold level above which all tailings types had adverse effects both on nutrient fluxes and faunal parameters (Table 5). There was also a clear ranking between the three tailings showing generally few effects of Sydvaranger tailings with flocculation chemicals, quite clear effects of Sibelco tailings without any chemicals, and very frequent effects of Hustadmarmor which was fine grained and with remnants of flotation chemicals.

The present setup represents a fairly realistic multi-species experiment. Nonetheless, it needs to be noted that in contrast to a field situation, recruitment of more tolerant species is very restricted. Thus, only mortality is measured. Furthermore, the system is run with a limited water-exchange in order to monitor sediment-water fluxes accurately. The responses measured in the present experiment are therefore considered to represent a worst-case scenario, and are more suitable to compare effects of different types of tailings than to predict absolute effects.

4.3 Conclusion

The following main conclusions can be drawn from this study:

- Mine tailings affected soft bottom communities at thin layers (scale of cm)
- Approximately 2 cm layer thickness was found to represent a threshold level which altered fauna and nutrient fluxes in all types of tailings.
- Indications on *in situ* biodegradation of chemicals were found in tailings where process chemicals had been used.
- The tailings impacted the fauna through more factors than merely hypersedimentation.
- In terms of their environmental impact the tailings tested were ranked Hustadmarmor>Sibelco>Sydvaranger.
- The particular impact mechanisms should receive more attention in future research.

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Table captions

Table 1. Total organic carbon (TOC, µg/mg) and sediment fine fraction (%<63 um) of all liners at the end of the experiment and of the added materials.

Table 2. SEM-EDX analyses of element abundancies (%) in the tailings from Hustadmarmor (H), Sydvaranger (V) and Sibelco (S).

Table 3. Fluxes of O_2 and nutrients before and after addition of mine tailings. Only the nutrient fluxes determined in 5 randomly selected liners before addition of tailings are displayed in this table. Mean flux ± one standard deviation. Unit = $\mu mol\ m^{-2}\ h^{-1}$.

Table 4. Effects of time, tailing type and layer thickness on fluxes of O_2 and nutrients. All data are from the dates 12.08. and 7.09. Significant effects ($p<0.05$) are highlighted. Calculations performed using the Fit model platform in JMP®11. Missing values were replaced by mean flux in two liners with adjacent thicknesses.

Table 5. Threshold tests for the three response groups: macrofaunal indices, number of individuals in feeding groups and biogeochemical fluxes. p-values are shown for each GLM performed where the observations are divided into groups below and above (or equal to) the given threshold values of thickness layer. Separate sets of six threshold tests are performed for each response and each of the three mines Hustadmarmor (H), Sibelco (S) and Sydvaranger (V). For each set of tests (i.e. for each response and mine group) the cell values are colored using a palette ranging from the lowest (dark green) to the highest (dark red) p-value within the set. The coloring is done to aid in identifying a potential threshold where a further response to thickness layer is less obvious.

Figure captions

Figure 1. SEM pictures acquired at two magnifications of tailings from a) Hustadsmarmor, b) Sibelco and c) Sydvaranger.

Figure 2. Variation with layer thickness of fluxes (F) of O_2 and nutrients determined in core liners Aug.12th (circles) and Sep.7th (crosses) 2015. Mine tailings from Hustadmarmor (left), Sibelco (middle) and Sydvaranger (right). The plots show linear regression line (black) and confidence intervals (dotted). The grey line is a local smoother (Kernel, linear tricube). In cases when slopes were significantly different from zero (linear regression $p<0.05$), the correlation coefficients (R^2) for the straight and smoothed line are given in the respective diagram. Scales on y-axis are identical for each substance and shown only on the left-hand plots. Units are μmol m^{-2} h^{-1}.

Figure 3. Principal Component Analyses (PCA) for fluxes of O_2 and nutrients in core samples determined towards the end of the experiment (12.08 and 07.09.). Table up left shows the relative contribution from five components determined. Left-hand plot shows the position of each sample projected on the plane of the two first components which accounted for 68.4% of the total variance. Tailings type (H, S, V) are shown by symbol shape (in legend) and increasing layer thickness is indicated by a continuous change of color from blue (0 cm) to red for (60 cm). Right-hand-plot shows the vector for each parameter (direction and strength).

Figure 4. Predicted curves based on GAMs of univariate macrofaunal responses to tailing thickness (p-values are shown in upper right corner of each curve). Note that the seemingly opposite effect of AMBI compared to the other indices, is due to the opposite scale of this index. N=number of individuals, S=number of species, Biomass=g w weight $0.09m^{-2}$, H'=Shannon-Wiener diversity index, AMBI= AZTI Marine Biotic Index, d= Margalef's species richness¸ y-axis is the unit pr. response parameter.

Figure 5. Predicted curves based on GAMs of macrofaunal feeding groups responses to tailing thickness (p-values are shown in upper right corner of each curve). SF=suspension feeder, SDF=surface deposit feeder, DMS=dissolved matter/symbionts, DF=subsurface deposit feeder, DDF=deep deposit feeder, CO=carnivore/omnivore; y-axis is number pr. group.

Figure 6. MDS-ordination of macrofauna in the experimental liners (H=Hustadmarmor, V=Sydvaranger, S=Sibelco, numbers denote layer thickness in cm).

Table 1.

	Hustadmarmor		**Sibelco**		**Sydvaranger**	
cm layer	TOC	Fine fraction	TOC	Fine fraction	TOC	Fine fraction
0	17.2	58	13	51	13.5	55
0.3	13.7	82	7.5	68	13.4	66
0.6	12	58	13.1	63	11.3	57
1	10.7	77	<1.0	40	13	54
1.5	11.1	67	6.7	50	5.7	43
2	11.6	91	6.3	48	2.4	52
3	10.9	96	1.5	45	<1.0	38
4	39.7	98	<1.0	40	<1.0	53
5	13.4	96	<1.0	45	<1.0	55
6	27.1	97	<1.0	41	<1.0	45
Added material	6.4	97	<1.0	41	<1.0	40

Table 2.

Element	**Hustadmarmor**	**Sydvaranger**	**Sibelco**
C	34.99	14.45	47.20
O	53.59	43.10	42.19
Mg	0.20	1.29	0,85
Al	-	1.06	0.74
Si	0.21	11.92	6.12
K	-	-	0.20
Ca	11.02	0.66	0.84
Fe	-	27.53	1.86

Table 3.

		O_2	**NH_4**	**NO_3**	**PO_4**	**SiO_4**
Treatment:	0 mm	3-60 mm	3-50 mm			
No. liners:	3	22-27	5 (H40, S3, S50, V3, V40)			
Mar. 25th	473 ± 123	528 ± 134	-	-	-	-
May 4th	322 ± 133	393 ± 165	-26 ± 34	-1.8 ± 15	-7.86 ± 2.53	-34 ± 39
June 8th	389 ± 69	386 ± 126	-11 ± 5.8	12 ± 10	0.12 ± 1.34	-17 ± 17
Aug. 12th	375 ± 26	391 ± 71	-3.2 ± 1.3	15 ± 4.0	-0.22 ± 1.17	-20 ± 11
Sep. 7th	340 ± 55	330 ± 61	-1.7 ± 1.1	3.1 ± 6.6	-0.68 ± 1.22	-18 ± 14

Table 4.

		O_2	**NH_4**	**NO_3**	**PO_4**	**SiO_4**
Whole model R2		0.34	0.48	0.73	0.59	0.59
Source	DF	Effect (p)				
Treatment (H, S, V)	2	0.1782	0.2588	**0.0003**	0.0543	0.3177
Layer (mm)	1	0.2188	0.3987	**0.0022**	**<0.0001**	**<0.0001**
Date (12.8 and 7.9.)	1	**0.0002**	**<0.0001**	**<0.0001**	0.8656	**0.0130**
Layer * Treatment	2	0.0873	**0.0448**	**0.0021**	0.4164	0.0608
Layer * date	1	0.6875	0.9820	**0.0059**	0.0652	0.1305
Treatment * Date	2	0.4018	0.0854	0.9646	0.7723	0.9959
		Mean flux (µmol m^{-2} h^{-1})				
	H	381	-3.70	14.9	-0.39	-23.7
	S	347	-2.80	10.3	-0.42	-27.0
	V	357	-3.99	10.3	-0.89	-22.5
	12. aug.	392	-5.45	17.1	-0.58	-27.6
	7. sep.	331	-1.54	6.5	-0.55	-21.2

Table 5.

Macrofaunal indices

	N			S			Biomass			H'			AMBI			d		
Threshold	H	S	V	H	S	V	H	S	V	H	S	V	H	S	V	H	S	V
10	0.9804	0.0304	0.9804	0.3344	0.2058	0.3344	0.9037	0.0109	0.9037	0.2709	0.7539	0.2709	0.0579	0.2818	0.0579	0.2397	0.4662	0.2397
15	0.4128	0.0285	0.4128	0.2603	0.0669	0.2603	0.1729	0.0066	0.1729	0.1364	0.3136	0.1364	0.2415	0.3556	0.2415	0.2557	0.1660	0.2557
20	0.0420	0.0039	0.0420	0.0100	0.0086	0.0100	0.0281	0.0008	0.0281	0.0479	0.1215	0.0479	0.5129	0.1004	0.5129	0.0150	0.0444	0.0150
30	0.3743	0.0396	0.3743	0.0722	0.0388	0.0722	0.2359	0.0139	0.2359	0.1364	0.0864	0.1364	0.8432	0.0062	0.8432	0.0452	0.0931	0.0452
40	0.2805	0.0423	0.2805	0.0772	0.1478	0.0772	0.1855	0.0186	0.1855	0.1779	0.1469	0.1779	0.5447	0.0170	0.5447	0.0565	0.3732	0.0565
50	0.4553	0.0921	0.4553	0.1761	0.0918	0.1761	0.2465	0.0485	0.2465	0.2010	0.0253	0.2010	0.0931	0.0719	0.0931	0.1431	0.1687	0.1431

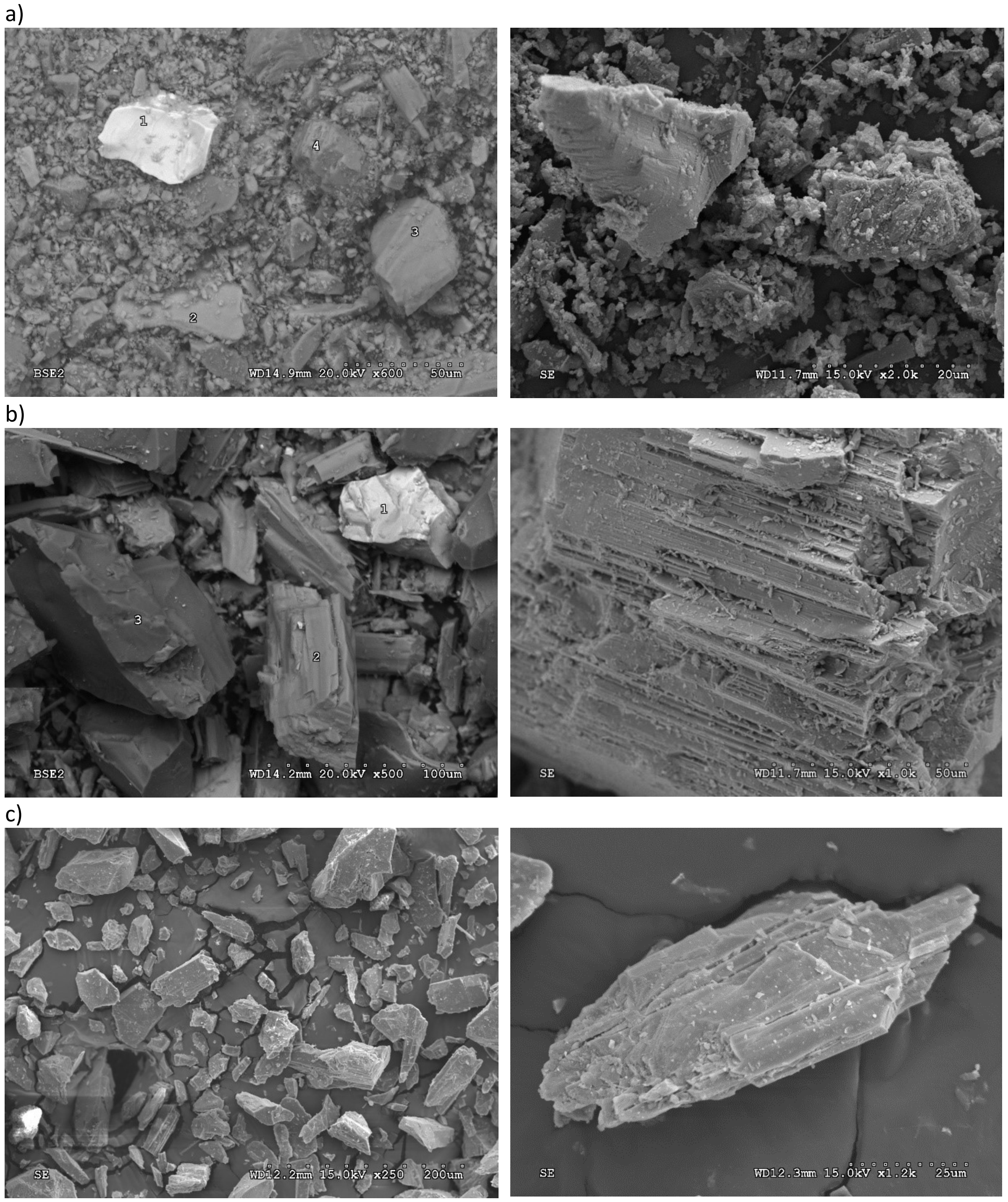
Feeding groups

	SF			SDF			DMS			DF			DDF			CO		
Threshold	H	S	V	H	S	V	H	S	V	H	S	V	H	S	V	H	S	V
10	0.0025	0.1145	0.5347	0.0009	0.1134	0.6796	0.0006	0.0495	0.2657	0.0010	0.0303	0.7700	0.0014	0.0397	0.4398	0.0060	0.7447	0.2651
15	0.0393	0.3030	0.2244	0.0161	0.1449	0.0704	0.0005	0.0137	0.3309	0.0026	0.0366	0.8691	0.0033	0.0111	0.7797	0.1091	0.6619	0.5245
20	0.1163	0.0652	0.0081	0.0327	0.0110	0.0083	0.0012	0.0014	0.3709	0.0051	0.0033	0.5415	0.0129	0.0018	0.3658	0.2431	0.9823	0.5658
30	0.1753	0.2818	0.0935	0.0538	0.0559	0.0485	0.0244	0.0024	0.9695	0.0562	0.0356	0.6306	0.1107	0.0434	0.8312	0.2785	0.8788	0.8967
40	0.2505	0.5039	0.1556	0.1536	0.1703	0.2015	0.0525	0.0005	0.3888	0.1054	0.0158	0.8685	0.1767	0.0163	0.5543	0.1824	0.7913	0.6972
50	0.3779	0.5131	0.2884	0.2535	0.3600	0.4485	0.1603	0.0092	0.1967	0.1676	0.0622	0.8286	0.1983	0.0871	0.9750	0.1259	0.9862	0.9141

Biogeochemical fluxes

	Si			PO4			Nox			NH4			O2		
Threshold	H	S	V	H	S	V	H	S	V	H	S	V	H	S	V
10	0.0003	0.5976	0.0018	0.0014	0.4392	0.0020	0.7136	0.1654	0.6761	0.8960	0.6383	0.5749	0.4879	0.8257	0.4189
15	0.0000	0.0490	0.0002	0.0003	0.1535	0.0009	0.8390	0.0300	0.3726	0.7690	0.7353	0.5728	0.5403	0.0551	0.8213
20	0.0000	0.0052	0.0000	0.0000	0.0004	0.0002	0.7039	0.0346	0.1796	0.6921	0.5229	0.4503	0.3112	0.0884	0.7251
30	0.0009	0.1002	0.0001	0.0002	0.0149	0.0002	0.7507	0.0083	0.2943	0.9805	0.9573	0.2911	0.7214	0.1247	0.9955
40	0.0002	0.2590	0.0039	0.0002	0.0298	0.0150	0.3954	0.0304	0.4083	0.4135	0.6963	0.1964	0.7214	0.2145	0.9150
50	0.0083	0.0800	0.0695	0.0133	0.0116	0.0021	0.9133	0.0841	0.4339	0.4324	0.3611	0.0713	0.9399	0.0795	0.8801

Figure 1.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BSE2
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SE
WD11.7mm 15.0kV x1.0k 50um
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Figure 2.

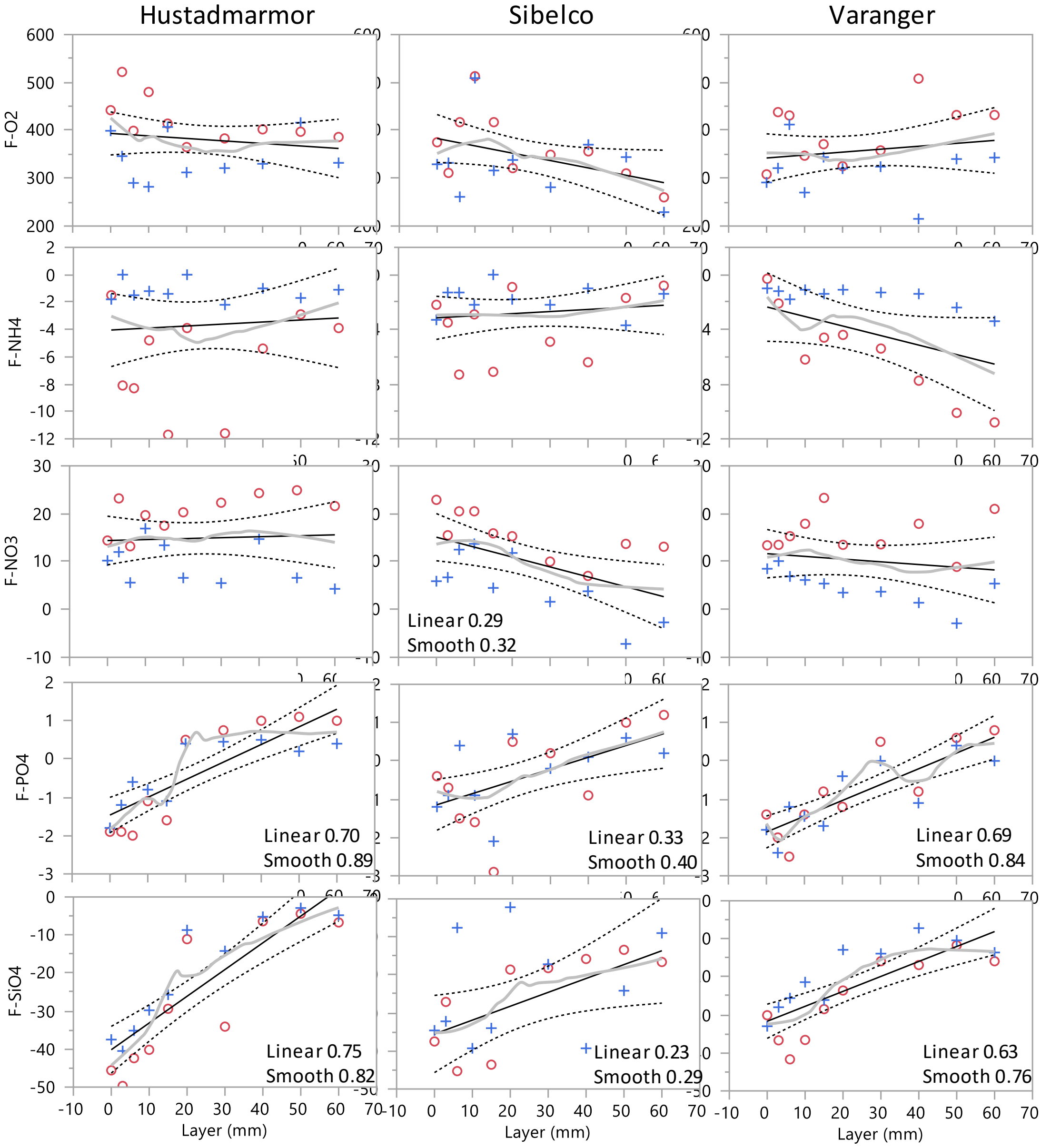
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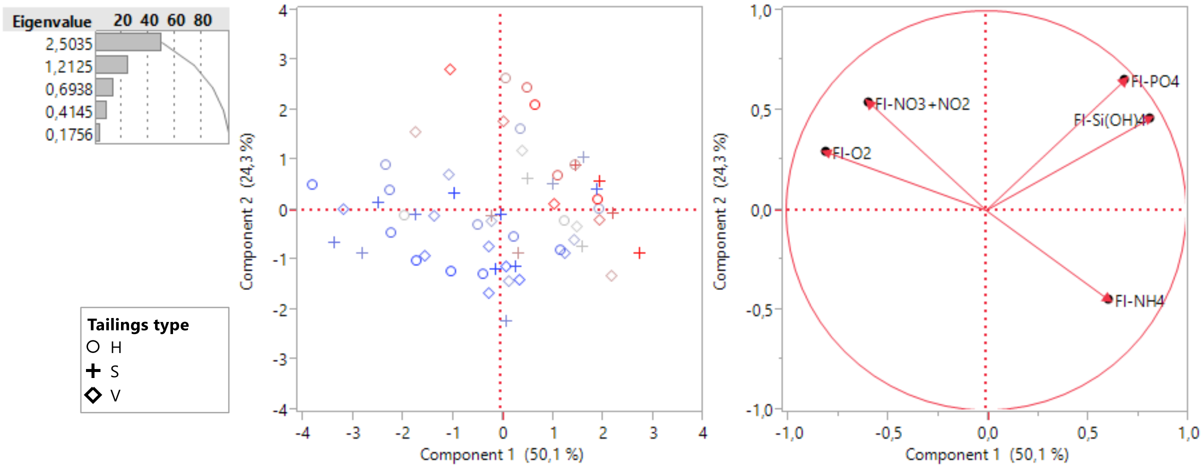
Figure 3.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Component 1 (50,1 %)
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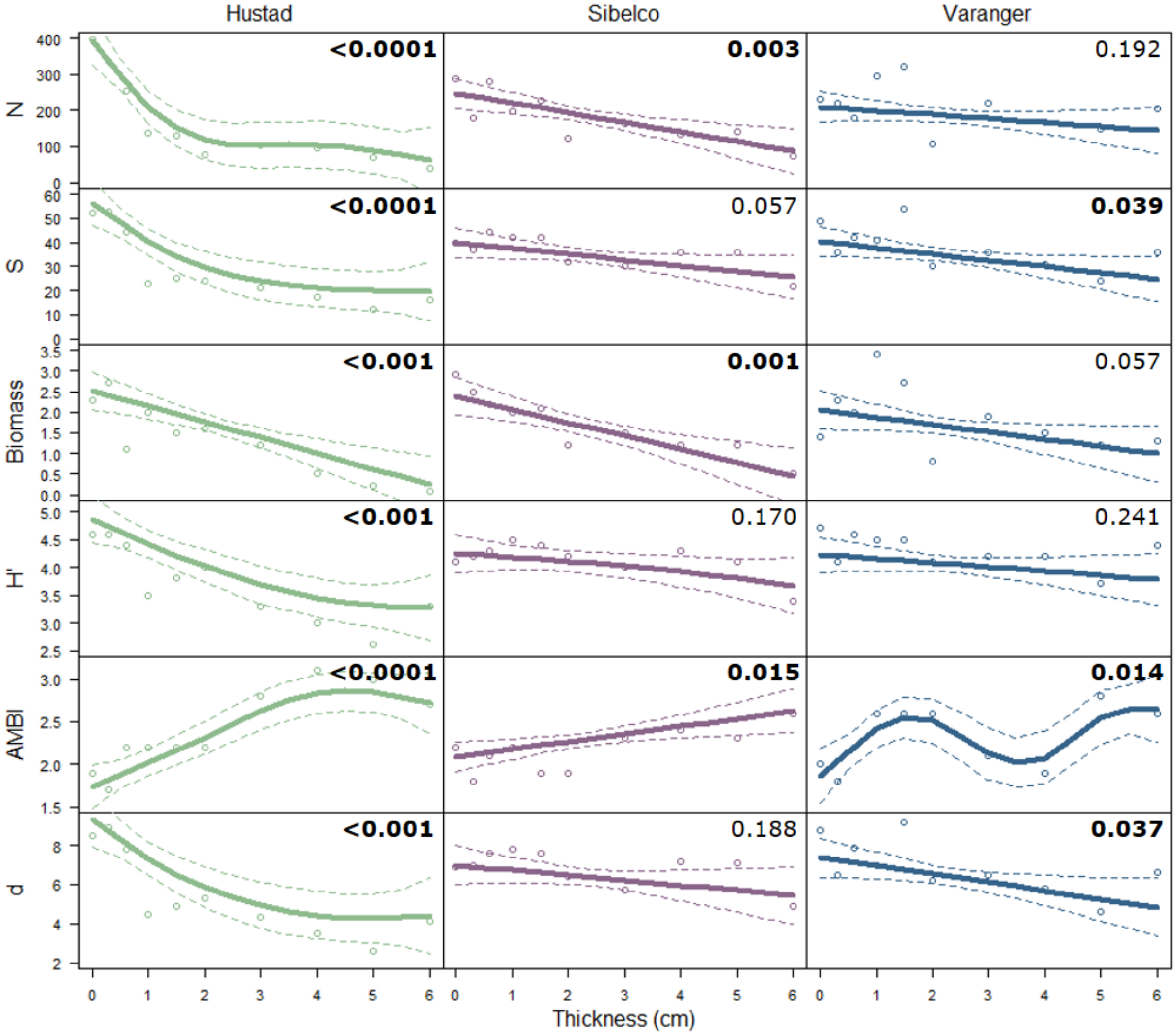
Figure 4.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1.5
1.0
0.5
0.0
5.0
4.5
4.0
3.5
3.0
2.5
3.0
2.5
2.0
1.5
8
6
4
2
0
1
2
3
4
5
6
Thickness (cm)

Figure 5.

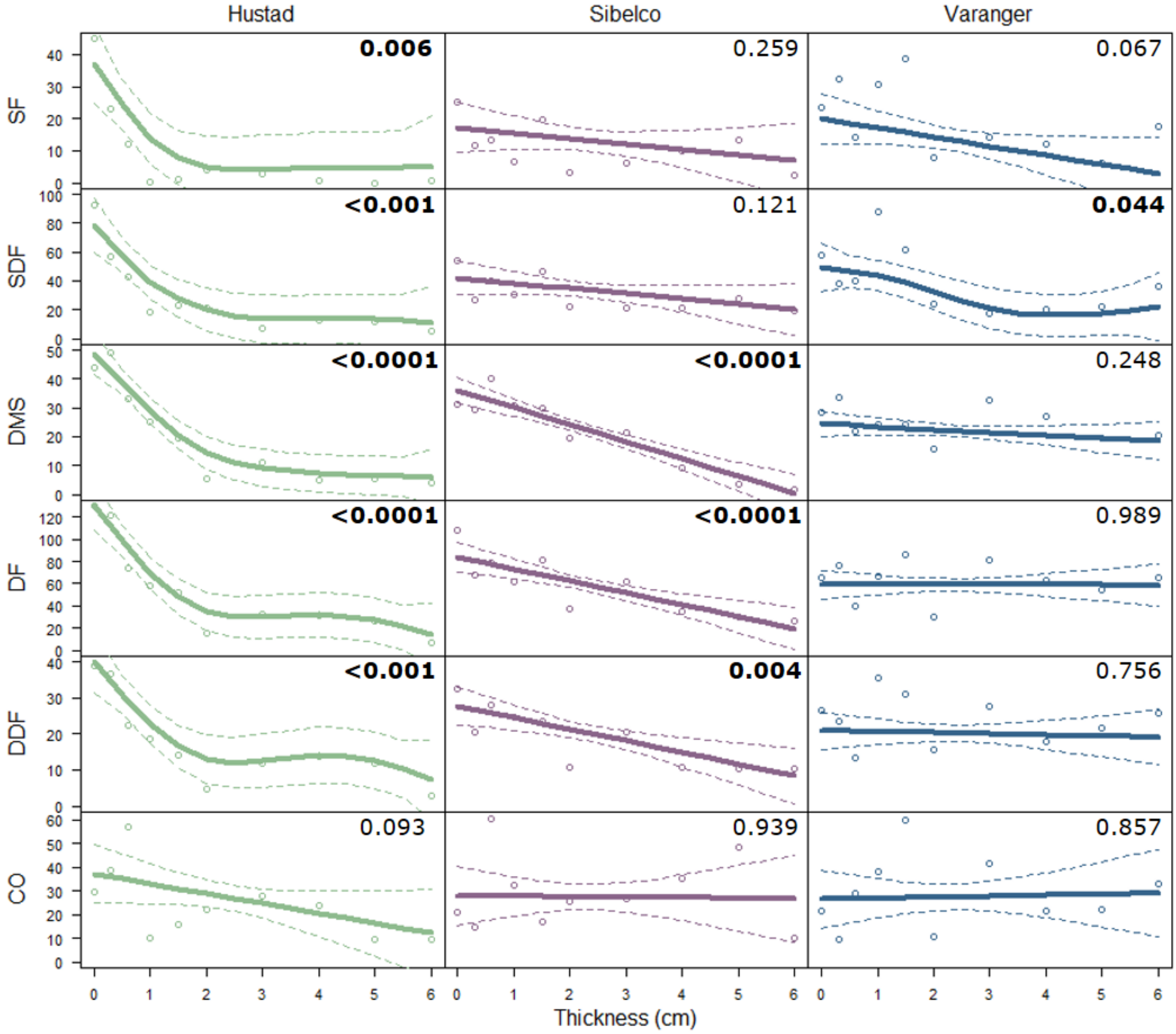
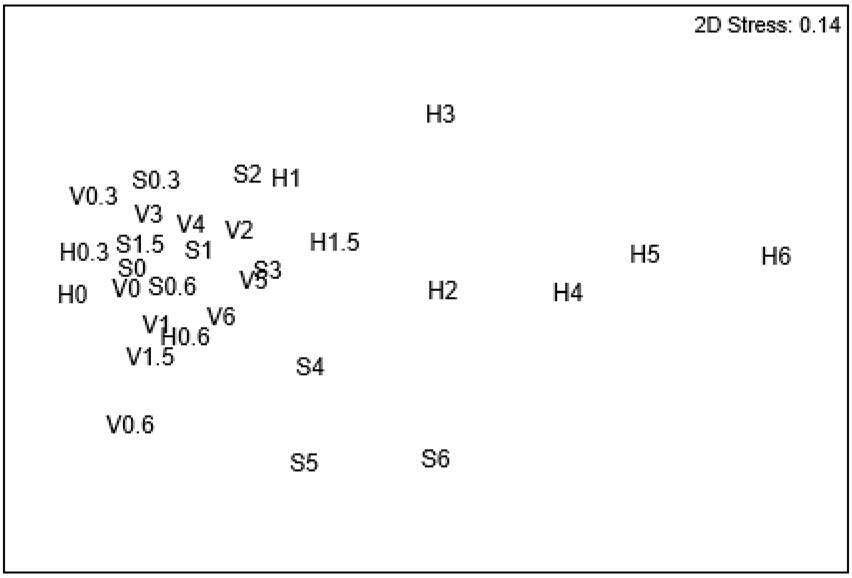

Hustad
Sibelco
Varanger
SF
SDF
DMS
DF
DDF
CO
0.006
0.259
0.067
<0.001
0.121
0.044
<0.0001
<0.0001
0.248
<0.0001
<0.0001
0.989
<0.001
0.004
0.756
0.093
0.939
0.857
0 10 20 30 40
0 20 40 60 80 100
0 10 20 30 40 50
0 20 40 60 80 100 120
0 10 20 30 40
0 10 20 30 40 50 60
0 1 2 3 4 5 6
Thickness (cm)

Figure 6.


2D Stress: 0.14
H3
S0.3
S2
H1
V0.3
V3
V4
V2
H1.5
H0.3
S1.5
S1
H5
H6
S0
V5
S3
H0
V0
S0.6
H2
H4
V6
V1
H0.6
V1.5
S4
V0.6
S5
S6

Supplementary material

Species list mesocosm experiment		H0	H0.3	H0.6	H1	H1.5	H2	H3	H4	H5	H6	S0	S0.3	S0.6	S1	S1.5	S2	S3	S4	S5	S6	V0	V0.3	V0.6	V1	V1.5	V2	V3	V4	V5	V6
ANTHOZOA	Paraedwardsia arenaria		1		1	1	1							1		1	1		1				1	2	1	1					1
PLATYHELMINTHES	Platyhelminthes indet												1																		
NEMERTEA	Nemertea indet	10	8	23		3	10	10	10	2	1	6	1	28	14	2	7	3	20	37	3	6		16	15	27	5	23	7	16	21
POLYCHAETA	Polychaeta										2																				
POLYCHAETA	Paramphinome jeffreysii	14	14	25	8	11	13	22	20	11	12	2	8	21	6	6	5	21	14	2	6	2	5	4	15	18	2	7	12	5	8
POLYCHAETA	Aphrodita aculeata																				1							1			
POLYCHAETA	Gattyana cirrhosa	1										3				1	1					2	1					1			
POLYCHAETA	Harmothoe sp.																									1					
POLYCHAETA	Polynoidae indet																		1						1						
POLYCHAETA	Neoleanira tetragona	3	1	1	1	1						2	2	1	1	3	1	1	1	2	1	3	1	3	1	2	1	3	1	1	1
POLYCHAETA	Pholoe baltica					2											2			1					1						
POLYCHAETA	Pholoe pallida	2	12	6	2		1					2	2	9	5	2	5	6	2	2	1	4	1	3	6	5	1	5	5	1	2
POLYCHAETA	Gyptis rosea																									1					
POLYCHAETA	Nereimyra punctata										1													2							
POLYCHAETA	Glyphohesione klatti	1																													
POLYCHAETA	Pilargis sp.		1																1	1											
POLYCHAETA	Exogone (Exogone) verugera		1	2	1	1	2														1	1	1	1			1	2			2
POLYCHAETA	Ceratocephale loveni	3	3	7		1						2	4	6	10	1	6	1		1		5	1	2	6	6	1	4	1	1	
POLYCHAETA	Nereididae				1																										
POLYCHAETA	Aglaophamus pulcher		1																												
POLYCHAETA	Nephtys ciliata						1																								
POLYCHAETA	Nephtys sp.																					1									
POLYCHAETA	Glycera unicornis							1				1			1					1							1				
POLYCHAETA	Goniada maculata											1								1						1					
POLYCHAETA	Onuphidae indet												1																		
POLYCHAETA	Paradiopatra quadricuspis																		1							2					1
POLYCHAETA	Abyssoninoe hibernica	1						1														1									1
POLYCHAETA	Lumbrineridae indet													1																	
POLYCHAETA	Phylo norvegicus	1																1													
POLYCHAETA	Levinsenia gracilis	9	5	6	2	1	3	1	2	2	2	2	1	1	3	1	5	3		1	4	5		7	6	3	1		2		5
POLYCHAETA	Paradoneis armata														1																
POLYCHAETA	Paradoneis eliasoni		2											1																	
POLYCHAETA	Paradoneis lyra	3	1	2		2									3				1	2					1			1			2
POLYCHAETA	Prionospio cirrifera							1	1			1			1				2	2				1	20	11	2		1		5
POLYCHAETA	Prionospio dubia	2		1									2			1															
POLYCHAETA	Prionospio fallax																									1					
POLYCHAETA	Pseudopolydora paucibranchiata		1										1	3					4	2	1	1				1		2			2
POLYCHAETA	Spiophanes kroyeri	28	6	8			2					5	5	2	5	7	2					11	3	3	13	9	8	4	2	8	5
POLYCHAETA	Spiochaetopterus typicus		1									1																			
POLYCHAETA	Aphelochaeta sp.							1																1			1	1			
POLYCHAETA	Chaetozone setosa	7	4	7	2	7	1		1			4		7	1	9	3	6	2	3	1	4		6	13	8	4	1	1	9	8
POLYCHAETA	Tharyx killariensis	4			1										2									1	6						
POLYCHAETA	Brada villosa	2	1											2		4	1	1	1			1	2		2						
POLYCHAETA	Diplocirrus glaucus	2	1	1	1				4	1		1	1		1				1	1	2	1							1		
POLYCHAETA	Pherusa falcata		1	1			1						2			2						1				7					
POLYCHAETA	Ophelina norvegica	2		1								1										2	1	2							
POLYCHAETA	Capitella capitata																1														
POLYCHAETA	Heteromastus filiformis	24	19	16	18	12	6	18	33	28	2	38	10	19	13	25	4	30	20	26	29	18	14	5	18	49	12	19	10	30	26
POLYCHAETA	Heteromastus sp.														1																
POLYCHAETA	Mediomastus fragilis		2			1		1					1	2											6						
POLYCHAETA	Notomastus latericeus																					1									
POLYCHAETA	Chirimia biceps biceps		1																						2						
POLYCHAETA	Euclymene droebachiensis															1															
POLYCHAETA	Euclymeninae indet	7	2									4	1		4							4	2		14		4	5	1	2	6
POLYCHAETA	Lumbriclymene sp.																									1					
POLYCHAETA	Maldane sarsi																									1					
POLYCHAETA	Maldanidae indet		1																			1									
POLYCHAETA	Praxillura longissima																									1					1
POLYCHAETA	Rhodine loveni		1										1																		
POLYCHAETA	Galathowenia oculata			1												1		1	1					1		1			3	1	1
POLYCHAETA	Owenia sp.						1		1			1														1					
POLYCHAETA	Amphictene auricoma	2												1								1									
POLYCHAETA	Lagis koreni													1																	
POLYCHAETA	Anobothrus gracilis																					1									
POLYCHAETA	Melinna cristata												1																		
POLYCHAETA	Sosane wahrbergi																					1									
POLYCHAETA	Amaeana trilobata												1																		
POLYCHAETA	Paramphitrite tetrabranchia																					1									
POLYCHAETA	Terebellidae indet																1														
POLYCHAETA	Terebellides stroemii	6	6	5								7	1	2	2	1						3		5	6	1	2		1		
POLYCHAETA	Trichobranchus roseus														2					1	1										
POLYCHAETA	Chone duneri																							1							
POLYCHAETA	Chone sp.	2	6				3					1	2		1	1	2		1	2	1	2		1		9		3		2	4
POLYCHAETA	Euchone papillosa	1	2	1									3			1		1					3			2	1			1	
POLYCHAETA	Euchone southerni							1																	1						
POLYCHAETA	Euchone sp.		1											1					2			1									
POLYCHAETA	Fabricia stellaris																							2							
POLYCHAETA	Jasmineira candela	1	7										1			1		2	1				3	1	1	3					
POLYCHAETA	Sabella pavonina															2								1	1						
POLYCHAETA	Sabellidae indet																		1						1			1			
OLIGOCHAETA	Oligochaeta indet	2		1		1	1		1				1		1					1				1	1	1					1
OPISTOBRANCHIA	Nudibranchia indet	2									1			1							1		2				1				
OPISTOBRANCHIA	Retusa sp.		2	1				1								2	1	1								2					
OPISTOBRANCHIA	Philine sp.			3								3		1			1									1					
CAUDOFOVEATA	Caudofoveata indet	3		3		1			1	1	1			1				2	3	2		4	2		3	2		1		1	
BIVALVIA	Bivalvia indet				1							8												18					2		
BIVALVIA	Ennucula tenuis	1			2							4	5		6	2	4	3	1				2	2	1	1	2	4			1
BIVALVIA	Nucula sp.																							2					3		
BIVALVIA	Nucula sp. juvenil	31	24	15	13	10	2	8	1			33	13	15	4	13	5	2	3	2	1	8	16		8	6	1	22	13	9	7
BIVALVIA	Nucula sulcata	3	17	5	3	4	1		1			11	6	1	4	10	2	10	9	3	2	6	4	3	11	6	3	3	5	5	8
BIVALVIA	Nucula tumidula	1	8		1	8						1	4	1	3	1		2				2	2			5		3	1		5
BIVALVIA	Yoldiella lucida		1										1		1								1								
BIVALVIA	Yoldiella philippiana																												1		
BIVALVIA	Yoldiella propinqua	14		1										5	1	7						2	7		1	7		4	3	1	3
BIVALVIA	Yoldiella sp.																												1		
BIVALVIA	Bathyarca pectunculoides	1																													
BIVALVIA	Limatula subauriculata	1	1	1								2				1							3								
BIVALVIA	Delectopecten vitreus			1																4		1		1							
BIVALVIA	Palliolum incomparabile	1																													
BIVALVIA	Adontorhina similis	16	33	3	10	4	3	5				6	26	25	21	7	6	12	3	3		11	13	4	8	2	5	19	24	11	12
BIVALVIA	Axinulus croulinensis	1	2												2		1						1	1		1	1	2			
BIVALVIA	Mendicula ferruginosa	25	19	12	13	8	2	1				15	8	22	15	15	13	19	7	4	4	16	22	19	5	7	5	14	14	7	9
BIVALVIA	Thyasira equalis	65	64	54	40	36	9	22	10	13	8	57	40	51	37	49	27	20	11	1		41	45	17	45	50	28	45	27	29	29
BIVALVIA	Thyasira flexuosa	1																										1			
BIVALVIA	Thyasira obsoleta		3												2			1					1						2		
BIVALVIA	Thyasira sarsii		1	2					2		2																	1			1
BIVALVIA	Thyasira sp.			1																											
BIVALVIA	Thyasiridae indet			10																		1		14						1	
BIVALVIA	Kurtiella bidentata															1															
BIVALVIA	Montacuta substriata														1																

BIVALVIA	Tellimya tenella					2								4																	
BIVALVIA	Astarte sp.			1																		1					1				
BIVALVIA	Parvicardium minimum																					1				1		2			1
BIVALVIA	Abra nitida	25										32	1	6	4	3			1			17	25	11	31	31	3	4	8		14
BIVALVIA	Kelliella miliaris	15	4	5			1	4			1	3	9	2	3	10	1	6	3	8	2	11	20		1	7	2	9	9	3	3
BIVALVIA	Thracia sp.															1															
BIVALVIA	Tropidomya abbreviata		4									2		3		4		1					3	1		2		1			
PYCNOGONIDA	Pycnogonum litorale																						1								
OSTRACODA	Philomedes (Philomedes) lilljeborgi						1	1				1		1			2	1			1		1	1				1			
OSTRACODA	Macrocypris minna			1												1	1														
CUMACEA	Eudorella emarginata		1	1				1																							
CUMACEA	Eudorella sp.		1																												
CUMACEA	Eudorella truncatula	1																													
CUMACEA	Diastylis cornuta													1						1						1					
CUMACEA	Diastyloides biplicatus	1																													
TANAIDACEA	Tanaidacea indet																					2				1					
ISOPODA	Isopoda indet							1						1																	
ISOPODA	Gnathia maxillaris									1																					
ISOPODA	Janira maculosa	6	1					1		1	1	2		2	1	3	1		1	5		1				2		1			3
AMPHIPODA	Amphipoda indet																								1						
AMPHIPODA	Eriopisa elongata	3	8	4		9	7		6	7	1	7	3	5	6	8	10	2	1	1		6	3	3	9	3	1		2		
AMPHIPODA	Harpinia crenulata		2	2																						1					
AMPHIPODA	Harpinia pectinata									1	1					1															
AMPHIPODA	Harpinia sp.	3																													
AMPHIPODA	Jassa										1								1						1	1					
DECAPODA	Calocarides coronatus														1																
DECAPODA	Paguridae								1																						
SIPUNCULIDA	Golfingiidae indet	3	2	4	1								1									1									1
SIPUNCULIDA	Nephasoma sp.	26	11	4								2		8		5		1		6			2	1	2	1			5		
SIPUNCULIDA	Onchnesoma steenstrupii steenstrupii	2		1	3	3	6		1	2	1	2		1	3			2	2	6	4	5		3	2	3				1	3
SIPUNCULIDA	Phascolion strombus strombus						1							1																	
ASTEROIDEA	Asteroidea juvenil																			1											
OPHIUROIDEA	Ophiuroidea juvenil		1											2					6	2	1	1		1		1	1	1			2
OPHIUROIDEA	Amphiura chiajei																1														
OPHIUROIDEA	Amphilepis norvegica	7	13	4	10	1		1				9	6	9	1	10	1	3	2	2	7	8	5	6	7	1	5		1	3	
ECHINOIDEA	Brisaster fragilis														1																
ECHINOIDEA	Brissopsis lyrifera				1	1								1						1											
CHAETOGNATHA	Chaetognatha indet																													1	
ASCIDIACEA	Molgula sp.											1			1																
HEMICHORDATA	Hemichordata			1																											
PISCES	Myxine glutinosa																		1												