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Review

New insights into submarine tailing disposal for a reduced environmental footprint: Lessons learnt from Norwegian fjords

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A R T I C L E I N F O

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A B S T R A C T

Submarine tailing disposal (STD) in fjords from land-based mines is common practice in Norway and takes place in other regions worldwide. We synthesize the results of a multidisciplinary programme on environmental impacts of STDs in Norwegian fjords, providing new knowledge that can be applied to assess and mitigate impact of tailing disposal globally, both for submarine and deep-sea activities. Detailed geological seafloor mapping provided data on natural sedimentation to monitor depositional processes on the seafloor. Modelling and analytical techniques were used to assess the behaviour of tailing particles and process-chemicals in the environment, providing novel tools for monitoring. Toxicity tests showed biological impacts on test species due to particulate and chemical exposure. Hypersedimentation mesocosm and field experiments showed a varying response on the benthos, allowing to determine the transition zone in the STD impact area. Recolonisation studies indicate that full community recovery and normalisation of metal leakage rates may take several decades due to bioturbation and slow burial of sulfidic tailings. The results are synthesised to provide guidelines for the development of best available techniques for STDs.

1. Introduction

Global demands for mineral resources are rapidly increasing, not only to sustain traditional uses but also for the development of new, green energy technology such as wind turbines or electric car batteries (Vogt, 2013; Dold, 2014a). Discussions based on robust scientific and engineering knowledge need to take place to find the necessary balance between exploration for and exploitation of known and new resources, the development of new technologies and recycling of existing resources. However, the United Nations Environment Programme (UNEP) has predicted that the amount of minerals, ores, fossil fuels and biomass consumed globally per year could triple between current day and 2050 (IRP, 2020). Mining activities produce large amounts of waste, and the environmentally sound management of such waste, at all stages of mining (production, closure and post-closure), is one of the major issues faced by the mining industry, and a major concern for civil society. Mining waste includes rocks from overburden and tailings representing the waste produced after the target mineral has been extracted from the ore, and may account for a high proportion of the extracted ore (e.g. up to 99% for copper and 99.99% for gold (MMSD, 2002)). Tailings usually

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comprise a fine-particle slurry that can contain potentially toxic components such as trace metals and organic chemicals from flocculation and flotation processes. The tailings particles have different shapes and sizes and highly variable mineral composition. Most mines world-wide dispose tailings in land-based dams. However, in certain locations, dams can be prone to environmental or physical stress (e.g. seismicity, heavy precipitation, complex topography). In such cases, submarine tailings disposal (STD) or deep-sea tailings disposal (DSTD) have been prioritised as tailing management approaches (reviewed in Reichelt-Brushett, 2012; Dold, 2014a; Ramirez-Llodra et al., 2015; Vare et al., 2018). In Norway, fjords are often selected as mine tailing disposal sites because many mineral ores are located adjacent to the coast, and, as natural sedimentation basins, it has been stated that they can provide equal or less environmental impact compared to tailings disposal sites on land (Norwegian Environment Agency, 2019).

STD management is a major source of conflict between the mining industry and local and national stakeholders. If mining is to continue and prosper in Norway, it must rely on techniques and procedures that ensure that the environmental impacts are reduced to an absolute minimum, and that ecosystems are given the best chance to recover as quickly as possible following the closure of processing plants and finalization of tailings disposal in fjords. The processes used for STDs have evolved and improved during the 50 years of tailing disposal and over 30 years of monitoring active and closed sites in Norwegian fjords. However, there remained important knowledge gaps in all phases of the process, including physical, geological, chemical and biological aspects (Reichelt-Brushett, 2012; Vare et al., 2018). In the water column, a better understanding of physical oceanography and tailings characteristics is necessary to better delimit the spread of tailings and potential post-depositional re-mobilisation (e.g. re-suspension, slope failures). Containment of the tailings on the seafloor and potential post-depositional effects are directly linked to the morphology and sedimentological characteristics of the seafloor, which needs to be mapped at high resolution (Baeten et al., 2020). In terms of chemistry, a better understanding of the tailings' composition and of the behaviour and transformation of added flocculants and/or flotation chemicals in the processing plant and the environment is essential to better assess potential toxicity impacts (Dold, 2014b; Hauton et al., 2017). In terms of biology, robust baseline studies need to be conducted, both in the approved impact area and adjacent areas that may be affected indirectly (e.g. plume re-suspension, dispersion of process chemicals) (Hughes et al., 2015). These baselines should include the understanding of functional diversity, ecosystem function and the services these functions provide to society (e.g. nutrient re-generation on the seafloor or the presence of structuring communities such as corals that provide habitat for other species, including commercial ones; Armstrong et al., 2012) and how tailings may impact these functions. Identifying thresholds and indicators to evaluate serious harm will contribute to developing sound legislation (Josefson et al., 2008; Mengerink et al., 2014). Assessing the long-term fate of tailings and process chemicals, and their long-term effect on the ecosystem, is necessary to understand recovery potential (Schaanning et al., 2019). Major gaps here include the understanding of early life history for many species, and their dispersal potential (Kline and Stekoll, 2001; Hilário et al., 2015). Finally, it is important to consider cumulative impacts with other stressors and industries, such as fisheries, waste, or stressors linked to climate change (Ramirez-Llodra et al., 2011).

To address these knowledge gaps, the NYKOS programme (New Knowledge on Sea Deposits) conducted multidisciplinary scientific investigations (Fig. 1, studies described in Section 2) and multi-stakeholder discussions with industry and authorities over five years (2014–2019), with the aim to increase significantly the knowledge base around the impact of STDs on the marine environment. The overall goal was to facilitate the development of new or improved environmentally-sound criteria and monitoring technologies that would allow for a more sustainable mining industry in Norway.

This paper synthesizes the main results obtained from a multidisciplinary study on the processes and effects of STDs in fjords. It highlights novel mapping, analytical, modelling and monitoring methods and provides new knowledge that will support guidelines for best available technologies and improved management in Norway and internationally.

2. The study framework

To develop new knowledge on the processes and effects of submarine tailing disposal in fjords, four main goals were addressed: 1) improve knowledge on tailings characteristics and associated chemicals prior to deposition in the marine environment; 2) use high-definition marine geological mapping as a basis to improve the location and monitoring of STDs; 3) develop innovative oceanographic modelling to assess the distribution and dynamics of tailing particles in the marine environment in order to improve impact predictions and response; and 4) improve understanding of the effects of mine tailings and associated trace metals and process chemicals on marine benthic ecosystems.

Scientific studies addressing geology, physical oceanography, physical and geochemical modelling, environmental chemistry, ecotoxicology and biology were conducted in five fjords that are, or have been, subjected to mine tailing disposal in Norway (Fig. 2; Table 1).

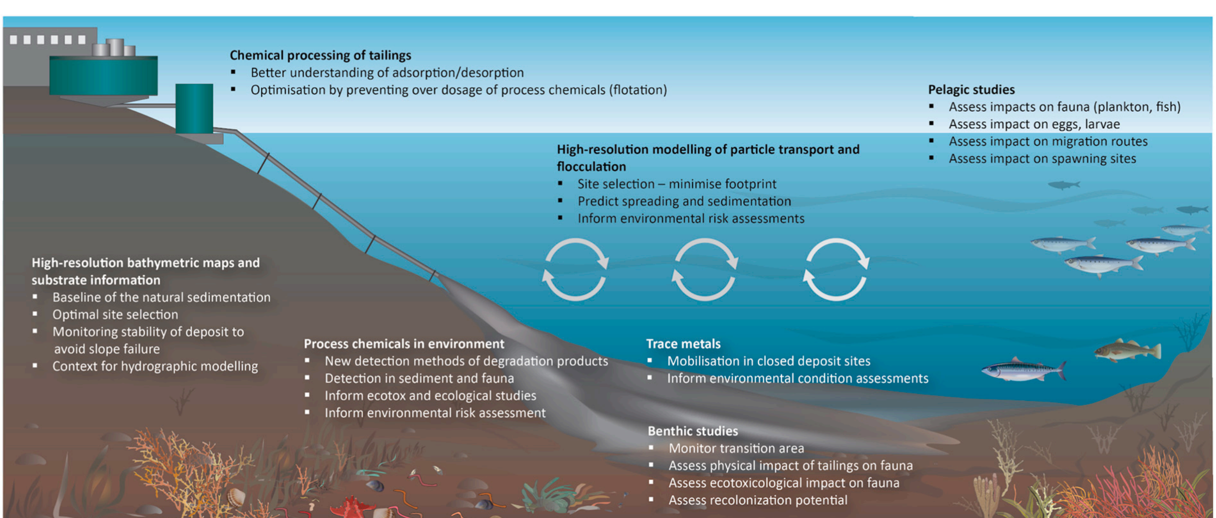

Fig. 1. Schematic diagram showing a submarine tailing disposal in a fjord and the main processes studied during the NYKOS project (excluding pelagic studies).

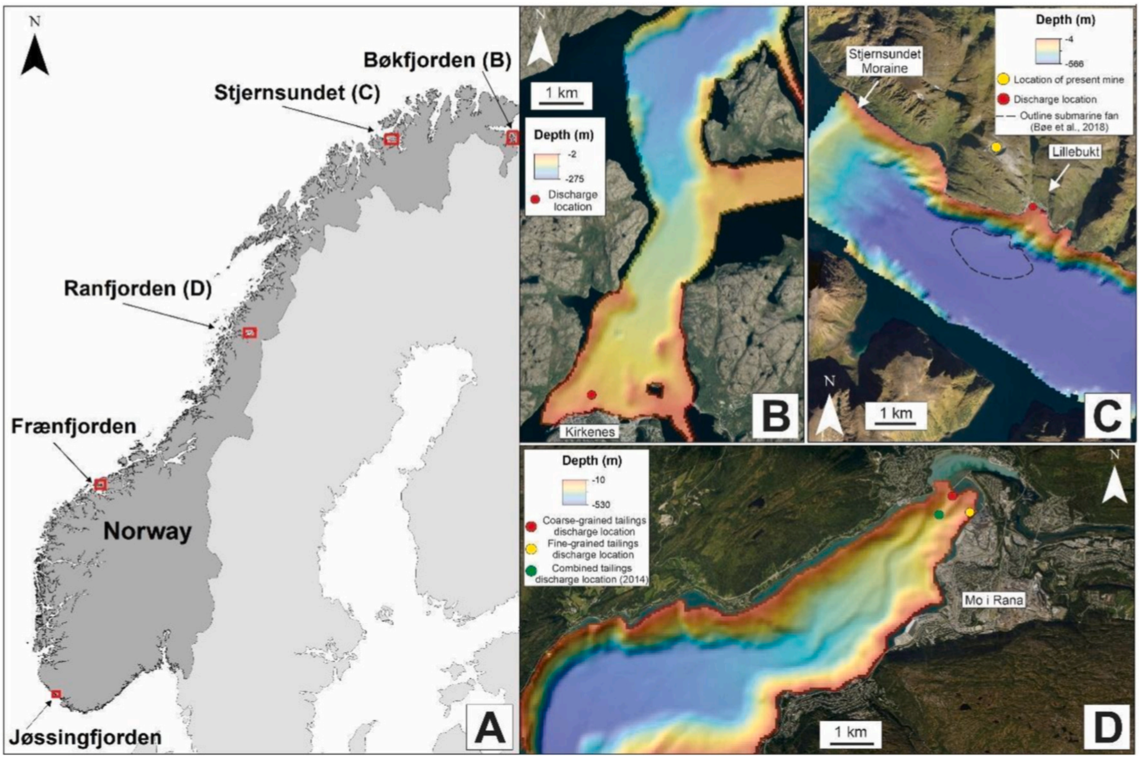

Fig. 2. Location of the different study areas (A) and multibeam bathymetry data in Bøkfjorden (B), Stjernsundet (C), where the outline of a submarine fan is indicated (Bøe et al., 2018) and Ranfjorden (D). The discharge locations are indicated in B, C and D.

Table 1
Brief description of the STDs in each of the fjords considered in the NYKOS programme. Additional details can be found in Ramirez-Llodra et al., 2015 and references therein. N/A: not applicable – old deposit.

Fjord name	Frænfjorden	Stjernsundet	Ranfjorden	Bøkfjorden	Jøssingfjord
Location (county)	Møre og Romsdal	Troms og Finnmark	Nordland	Troms og Finnmark	Rogaland
Mine/plant	Omya Hustadmarmor AS	Sibelco Nordic Stjernøy AS	Rana Gruber AS	Sydvaranger mining AS	Titania AS
Commodity	Calcite marble for calcium carbonate	Nepheline syenite	Iron oxides	Iron oxide	Iron titanium oxide
Separation process	Reverse flotation	Magnetic separation	Magnetic separation	Magnetic separation	Magnetic and gravimetric separation, acid leaching, flotation, and reverse flotation
Added chemicals	Flotation chemicals	None	None	Flocculation chemicals	Flotation and flocculation chemicals
STD time frame	1982–present	1961–present	1964–present	1974–1998 2009–2015	1960–84 (Jøssingfjord) 1984–1994 (Dyngadjupet)
Tailings permit tonnes/yr	700,000	300,000	3,000,000	4,000,000	3,600,000 in landfill
Pipe outflow distance from shore (m)	Flexible. Approx 500	<50	ca. 2000	450	N/A
Pipe outflow depth (m)	20	Tidal zone	127	28	N/A
Final deposition depth (m)	Minimum 30	ca. 450	530	230	N/A

The major characteristics of these fjords are described in Table 1, while additional details on past and current submarine mine tailings in Norway have been described in Kvassnes and Iversen (2013) and Ramirez-Llodra et al. (2015). The fjords included in this study are:

1. Frænfjorden in Western Norway, which since 1982 has received calcium carbonate tailings from a marble production plant, discharged at 20 m depth and deposited in the fjord basin at 40–70 m depth (Figs. 2, 4; Trannum et al., 2019; Baeten et al., 2020, Nepstad et al., 2020).
2. Stjernsundet in Arctic Norway, which since 1961 has received silicate-mineral tailings discharged near the water surface from a nepheline syenite processing plant (Fig. 2; Bøe et al., 2018).
3. Ranfjorden in Northern Norway has received iron ore (hematite and magnetite) processing tailings consisting mainly of quartz since 1964, initially with two disposal pipes for the coarse and fine fractions, which was changed to a single discharge pipe in 2014, disposing at 127 m depth (Fig. 2; Golmen and Norli, 2013).
4. Bøkfjorden in Arctic Norway has received fine-grained tailings consisting mostly of quartz and amphibole from an iron ore processing plant during two mining operations in 1910–1997 and 2009–2015 (Fig. 2; Kvassnes and Iversen, 2013).
5. Jøssingfjorden in southern Norway has received silicate-mineral tailings with small amounts of ilmenite, magnetite and sulfides, from an ilmenite mine, between 1960 and 1984. Between 1984 and 1994 the tailings were disposed of in Dyngadjupet outside the fjord

threshold. Currently, the deposit takes place in a landfill, which is estimated to be full by 2026.

A series of studies analyses were conducted in the different fjords between 2015 and 2019. The approaches for each study are described in Section 3, and the detailed methodologies are presented in the papers published in the framework of the NYKOS programme. Frænfjorden was the area most comprehensively studied (Table 2), with analyses including bathymetry, geology, oceanography, environmental chemistry, ecotoxicology and biology using in situ and mesocosm experiments, as well as different modelling techniques. Also, this fjord had the longest and largest available data series of macrofauna, extending from 1993 to 2010 (Brooks et al., 2015a) and 2015 to 2018 (this study). Thus, Frænfjorden and the Hustadmarmor production plant located in this fjord were chosen as a study site to model the spatio-temporal distribution of sediment-dwelling macrofauna.

3. New knowledge to address current environmental challenges of STDs

Several environmental challenges associated with mine tailings have been addressed in the present study. The effects considered range from the spreading and distribution of tailings and chemicals in the marine environment, to effects at the organism and community levels. In the sections below, we provide a short overview of the issues addressed, the studies conducted to assess those challenges, and how the results may contribute to the development of best available techniques and the reduction of environmental impact from STDs.

3.1. The role of physical oceanography

The transport and fate of tailings discharged into the sea is a key part of determining potential impact on the marine environment. Ocean currents and wind, combined with physical properties of the discharge such as particle size, govern this transport. In order to minimize environmental impacts, the transport pathways must be understood. In the NYKOS project, we have used numerical models to study the transport and fate of discharged tailing particulates from an STD in Frænfjorden (Fig. 4). Ocean currents and turbulence were provided by the three-dimensional coupled ocean-ecosystem model SINMOD (Slagstad and McClimans, 2005), in a 32 m horizontal resolution setup. The Lagrangian particle model DREAM (Rye et al., 2004) was used to predict the spreading, concentrations and sedimentation of mine tailings, forced by the three-dimensional current field from the ocean model, and accounting for the effects of vertical mixing, particle settling and flocculation (Nepstad et al., 2020). Being a relatively shallow fjord, Frænfjorden circulation is influenced by wind-waves, and the Weather Research and Forecast (WRF) model was used to provide wind forcing (Skamarock et al., 2008).

A field study in Frænfjorden was also performed, where suspended tailing particles and particle aggregates (flocs) were quantified using a combination of instruments in order to cover a large range of particle sizes. This included a LISST-100X and a silhouette camera (SilCam) system (Davies et al., 2017) mounted on a profiling frame. The SilCam enabled direct imaging of particles larger than around 50 μm (Davies and Nepstad, 2017), which allowed shapes to be determined, and provided indications of floc composition (Fig. 3). In addition, measurements of currents with Doppler profiling instruments were taken. Determining particle and floc sizes are crucial for predicting their settling speed, and thus their transport and influence area, which in turn can be tied to environmental impact and risk. Such knowledge, combined with numerical models, can be used to assess different discharge scenarios and help select the best upstream discharge designs for a minimal footprint.

3.2. Geological mapping and monitoring of the seafloor

Disposal of tailings causes disturbance of the seafloor environment, but the dispersal, distribution, and stability of disposed materials are

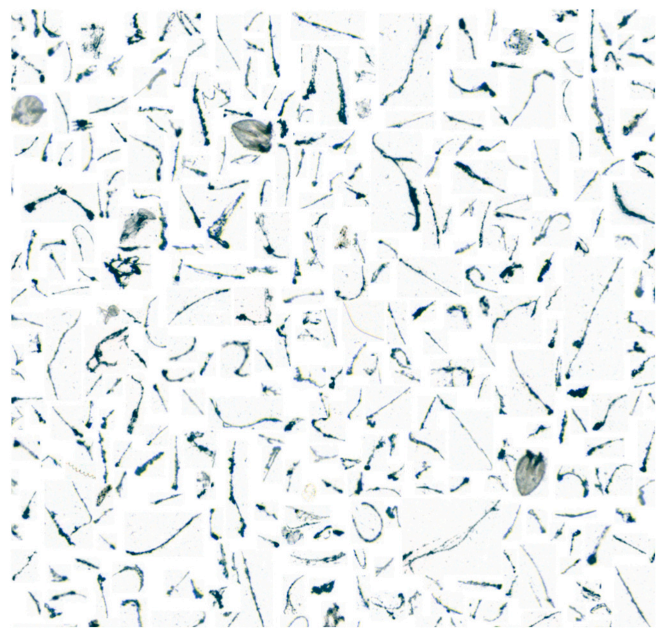

Fig. 3. Montage of randomly selected particles with diameter greater than 360 μm from SilCam images taken in Frænfjorden. See Davies and Nepstad (2017) for details.

Table 2
Summary of analyses conducted in the different fjords, indicating the papers where the results have been published.

	Bathymetric and geological surveys	Oceanographic measurements and modelling	Environmental chemistry and biogeochemical modelling	Ecotoxicology	Benthic ecosystems (faunal responses & recolonisation)	Mesocosm experiments
Frænfjorden	Baeten et al., 2020	Nepstad et al., 2020; Davies and Nepstad, 2017	Ibragimova and Kleiv, 2018a, 2018b; Brooks et al., 2019; Trannum et al., 2018a	Brooks et al., 2018, 2019	Trannum et al., 2019; Trannum et al., 2020; This study	Trannum et al., 2018a, 2019
Stjernsundet	Bøe et al., 2018		Trannum et al., 2018a; Schaanning et al., 2020	Schaanning et al., 2020; Brooks et al., 2019	Schaanning et al., 2020; Trannum et al., 2020	Trannum et al., 2018a; Schaanning et al., 2020
Ranfjorden	Haugen, 2018; Figenschau, 2018					
Bøkfjorden	Ladstein, 2018; Figenschau, 2018		Trannum et al., 2018a	Brooks et al., 2015b; Brooks et al., 2019	Trannum et al., 2020	Trannum et al., 2018a
Jøssingfjord			Pakhomova et al., 2021; Yakushev et al., 2017; Schaanning et al., 2019		Trannum et al. (2018c); Schaanning et al., 2019	Trannum and Schaanning, 2017

ultimately linked to the natural physical processes operating in the water column and on the seafloor. Detailed seafloor geological maps are required to study the natural sedimentation, provide a status of the present situation, and allow reliable predictions of the fate of submarine tailings to be made (Fig. 4). Modern multibeam echosounder technology allows to obtain high-resolution bathymetry and backscatter datasets, which, combined with the results of seafloor sediment characterization (seabed samples) and visual observations (video footages of seafloor) can be used to produce detailed, full spatial coverage geological maps. Such maps provide information on sediment dynamics and can outline areas where erosion or accumulation processes from STDs are prevailing. The maps also help to uncover areas that can be sensitive to slope failures (Baeten et al., 2020).

The geological datasets obtained from the studied fjords Bøkfjorden, Stjernsundet, Ranfjorden and Frænfjorden (Figs. 2, 4) have been used to map the extent of the tailings on the seafloor, clearly distinct from natural sediments, and to assess processes governing their dispersal as suspended particles, slope failures and bedload forming migrating sand waves (e.g. Bøe et al., 2018; Baeten et al., 2020). Comparison of several bathymetric datasets demonstrated the usefulness of repeated surveys to evaluate the accumulation dynamics. Studies of sediment cores from Ranfjorden demonstrated that tailings in some areas have effectively capped seafloor sediments significantly contaminated by PAHs (Polycyclic Hydrocarbons) and thereby isolated the toxic compounds from the environment. Pockmarks are formed in the seafloor along the edge of the tailings visible on the sub-bottom profiler data in Frænfjorden. This is due to the loading of tailings that cause a compaction regime in natural sediments and tailings themselves triggering fluid expulsion (Baeten et al., 2020). Given the crucial importance of a variety of geological processes operating on the seafloor, optimal selection of the disposal site as well as the assessment of the stability of tailings is tightly linked to the results of geological mapping/monitoring that needs to be undertaken during both planning and operational phases of submarine disposal.

3.3. Dynamics of process chemicals

Froth flotation is widely employed for the concentration of ores and has become one of the most important techniques for mineral processing in mining industries. This technique works based on surface chemistry and facilitates a separation of fine mineral particles according to their hydrophobicity. This separation process disperses small bubbles of gas, generally air, inside a flotation tank, also referred to as a flotation cell. The tank contains the finely ground minerals suspended in an aqueous medium, a suspension referred to as the pulp. Surfactants (collectors) are added to the pulp to selectively enhance the hydrophobicity of the valuable minerals (in the case of direct flotation) or of the gangue minerals (reverse flotation). The particles that have gained hydrophobicity on the surface attach to the gas bubbles and overflow through the top of the flotation cell. Additional reagents are used to obtain a stable froth and to enhance and control the selectivity and reactivity of the collector (i.e. pH regulators, activators and depressants).

Surfactants are among the most widely employed collectors in mineral industries (Shah et al., 1991; Fuerstenau and Pradip, 2019; Pattanaik and Venugopal, 2019). These chemicals, once disposed into the marine environment, may undergo biotic and abiotic transformations to yield a set of chemical species that might substantially differ from the structure of the parent compound. Untangling the chemistry of this

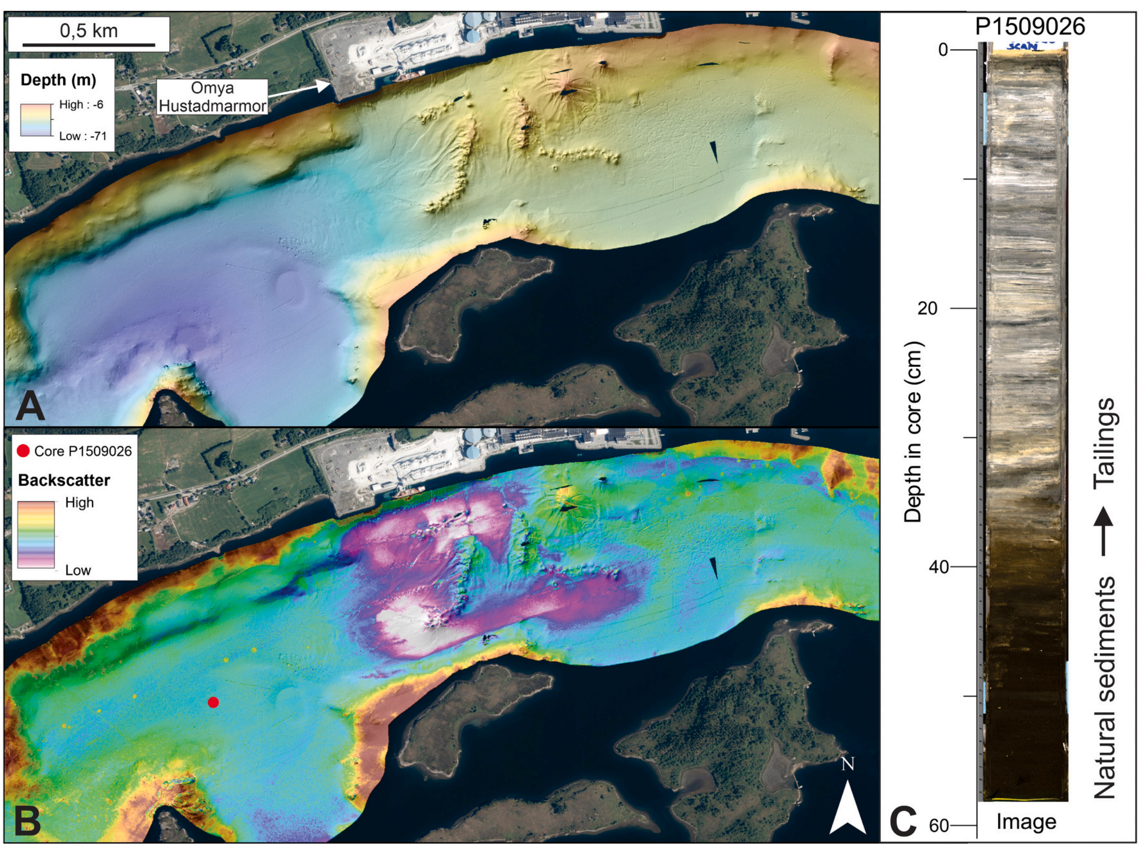

Fig. 4. Multibeam echosounder data collected in 2016 from the inner part of Frænfjorden. A: Depth-colored shaded-relief bathymetry showing the chain of tailings cones tracking the dynamics of the discharge pipe. B: Backscatter data draped on shaded relief bathymetry. Low backscatter indicates fine grained sediments, especially abundant around the discharge location. C: Sediment core P1509026 (red point in B) taken in the distal part of the STD shows the change from the dark brown natural sediments at the base of the core to the white greyish tailings on top. From Baeten et al. (2020). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

transformation and ascertaining the risk of these products becomes of paramount importance to the implementation of safe STD practices. In addition, flocculation chemicals such as polymers of acrylamide are frequently used to recycle process water, but environmental concern is less for these chemicals than many of the flotation chemicals. Hence, the focus in this project was on flotation chemicals and, in particular, on those used for reverse flotation that yield high percentage loss of chemicals to the environment.

3.3.1. State and mobility of chemicals in the processing plant

The physicochemical properties of the tailing's materials are governed by the preceding comminution and separation processes. Novel approaches in dewatering and flocculation, as well as the recycling of process-water and process-chemicals provide potential for improving this phase in the tailing management system. These different processes are established unit operations, but they are not necessarily optimized for the reactions and interactions that take place in a system where fresh process water meets sea water. By investigating the desorption characteristics of the adsorbed collectors, important information regarding their mobility can be obtained, providing valuable information for environmental impact assessments. In addition, such knowledge could facilitate improved solutions for chemical recycling or immobilisation and, thereby, reducing environmental impact.

Adsorption/desorption experiments were conducted to investigate the kinetics and degree of desorption of flotation collectors when the tailings are mixed with sea water prior to discharge. The bulk of the work was performed on FLOT2015 (flotation reagent based on esterquats formulation), in combination with feed and tailings from Hustadmarmor (Table 1). Adsorption experiments were used to study the coverage of collector molecules on the particle surfaces (i.e. monolayer vs. multilayer adsorption) as a function of collector concentration. The extent of adsorption and desorption were determined by measuring the resulting collector concentration in solution. As part of this work, a rapid, robust, sensitive and low-cost UV-spectrophotometric method for quantitative analysis of the FLOT2015 collectors prior to discharge in the environment was developed and validated (Ibragimova and Kleiv, 2018a, 2018b).

The results from the adsorption/desorption experiments showed that flotation chemicals desorb to a lesser extent than expected when mixed with seawater provided that the chemical dosage during conditioning/flotation is less than that required for multilayer adsorption. This seems to be true not only for the collectors that are chemically adsorbed, but also when physical/electrostatic adsorption is the main mechanism. Desorption of flotation collectors was highly affected by the duration of exposure to seawater and the initial concentration of chemicals. In the case of the amine/calcite marble-system found at Hustadmarmor, the results indicated that less than 4% of the adsorbed FLOT2015 was desorbed when the initial concentration was equal to the industrial dosage. At concentration levels higher than those required for efficient flotation multilayer adsorption was present, and significant desorption occurred (Ibragimova and Kleiv, 2018b). From a processing point of view, monolayer adsorption of collectors is usually all that is required to achieve effective flotation. Multilayer adsorption would be counterproductive as it could reduce the selectivity of the separation as well as representing an unnecessary additional cost. Hence, monitoring and optimizing the collector concentration during the flotation process would both enhance the overall performance of the plant and reduce the environmental impact of the resulting tailings.

3.3.2. Assessment of transformation products of flotation chemicals in the environment

The flotation chemicals used in STDs are usually supplied as technical products and contain a very complex mixture of different chemical structures. This complexity provides an extra challenge to the analytical process of environmental samples and to the exploration of fate and behaviour after discharge. Additionally, these substances, once disposed of in water bodies, may undergo biotic and abiotic processes that lead to the production of a series of transformation products (TPs). Developing a robust analytical method to qualify and quantify the TPs of process chemicals in the environment is essential to understand the fate and potential effect of such chemicals on the recipient environment, including the fauna.

A novel analytical procedure based on Solid-Liquid extraction using acidified organic solvents followed by separation through Ultra High Performance Liquid Chromatography (UPLC) and coupled to High Resolution Mass Spectrometry (HRMS) was developed for the cationic flotation collector (FLOT2015) discharged in Frænfjorden from Hustadmarmor (Table 1). One transformation product, methyl triethanol ammonium (MTA), was identified and found in the fjord samples (Brooks et al., 2018). The TP was employed as a tracer for tracking the occurrence of the flotation chemical in the fjord. With this technique, we were able to quantify, for the first time, the MTA in sediments, pore water and faunal samples (holothurians and blue mussels) collected at various distances from the discharge outlet (Brooks et al., 2018). The concentration of flotation chemicals studied in Frænfjorden showed a general decreasing trend along the fjord, from the outlet of the tailings discharge pipe to the outer fjord (Fig. 4). A similar decreasing concentration of chemicals was observed with depth in the first 10 cm of sediment. Analyses of pore water extracted from the sediments showed that the chemicals are partially desorbing from the mineral particles after their discharge in sea water. The chemical may undergo hydrolytic cleavage to leave the ester and amino groups (MTA) more available than the mother compounds for further degradation, uptake in biota or dilution in pore water and surrounding seawater. Concentrations of MTA in the range of a few mg/kg dry sediment and in the range of μg/L in the pore water were observed in all the sampled locations and depths.

The tracing of technical products – based on complex mixtures – and their transformation products in the environment has rarely been possible in the past due to the lack of commercially available reference standards and the appropriate analytical tools for this purpose. Nowadays, the use of advanced analytical techniques, mostly based on UPLC-HRMS, shows a great potential to address the challenges and fill the knowledge gaps associated with STDs, ensuring a safer discharge and acting as an eventual early-warning system. The process analytical chemistry (PAC) is the science of making measurements to monitor large-scale chemical processes, obtaining quantitative and qualitative information about a chemical process. Here PAC has made use of the analysis of TPs of target chemicals as unique characterization of STDs. This procedure allows tailoring the analytical measurements for every chemical process. The methodology developed in this study has revealed a large potential to develop advanced monitoring strategies and to deeply understand how process chemicals in mine tailings migrate and transform in the marine environment. These techniques are ready to be implemented in routine monitoring and control programs of sites affected by STDs. Close cooperation with mining industries and the chemical companies producing these compounds becomes of vital importance to fine-tune the analytical methodologies and to establish the list of suspected chemical structures that need to be assessed in the environment and biota.

3.4. Leakage from metal sulfides

In Norway, a major sulfide-containing STD is derived from the titanium oxide production at Jøssingfjorden (Table 1). Also, copper production at Repparfjorden, North of Norway (Sternal et al., 2017), will eventually generate sulfide-containing tailings (not included in Table 1 as production has not yet started). Leaching of trace metals is a major environmental concern, which, however, can be reduced by storing the tailings in environments where oxygen is not available (Arnesen et al., 1997; Dold, 2014a). Leaching involves transformation of sulfides to more soluble and more bioavailable forms, which will increase the risk of toxic effects (Simpson and Spadaro, 2016).

3.4.1. In situ measurements of copper and nickel fluxes

In the framework of NYKOS, trace metals were measured in Titania tailings, and box core samples were collected along a gradient, from offshore reference locations to the inner part of the old deposit sites in the Jøssingfjorden area (Table 1). The cores were transferred to a benthic mesocosm where they were kept undisturbed for observations. Mobility of metals was measured as concentrations in extracted pore water, fluxes to overlying water, as well as uptake in DGT probes (Diffusive Gradients in Thin films) and in the gastropod *Hinia reticulata* (experimental details in Schaanning et al., 2019).

The range of concentrations and release fluxes for Cu and Ni (Table 3) showed that metal concentrations in the deep deposit layers (data from Gravdal, 2013) were similar to or higher than in the tailings supplied for the NYKOS project, whereas the maximum concentrations found in the 0–1 cm top layer were depleted or diluted compared to the tailings and more so for Ni than for Cu. Higher mobility and loss of Ni than Cu was consistent with higher pore water concentrations and fluxes of Ni at the old deposit sites. This showed that dissolution of metals contributed significantly to the general decrease of metal concentrations resulting from dilution of the tailings by mixing with new, unpolluted sediments. The bioaccumulation in gastropods did not reflect the availability of the metals indicated by pore water concentrations and fluxes. The very low Ni:Cu ratios in the soft tissues of this organism (Table 3), revealed preferential accumulation of Cu, probably as result of active regulation of metal levels in this organism (Ruus et al., 2005). Compared to Environmental Quality Standards (EQS) for Norway and other European countries, the concentrations of Cu and Ni both in tailings and deep STD-layers exceeded the Maximum Admissible Concentration (MAC-EQS) of 271 μg Ni and 84 μg Cu g^{-1} dry sediment (Norwegian Classification Guidance, 2018). These observations are apparently in conflict with the “good” to “very good” status reported from biological monitoring alone (ref. Section 3.5). Within the top 0–1 cm layer, concentrations were still, 20 years after the deposition was ended, elevated compared to background levels. This was concluded to be maintained by upwards mixing of old tailings driven by bioturbators, which were particularly abundant in Dyngadypet.

Microelectrode measurements showed that O_2 penetration was limited to the upper 10 mm of the sediments. The fluxes of Ni and Cu will decrease with time due to natural sedimentation, which provides dilution and burial of the sulfide tailings, but as noted above, the decrease is slowed down by bioturbation. The burial rate can be enhanced by covering the STD with a few centimeters of clean material (sand, silt, clay). Our studies show that the added cap must be sufficiently thick to prevent potential bioturbators from mediating contact between tailings and O_2 from the overlying seawater. Currently, leaching from the Titania land deposit releases approximately 800 kg Ni y^{-1}, which is a nuisance to downstream limnic environments, and opposed to the sea deposit this release flux is likely to escalate over the years (Koski, 2012; Dold, 2014b).

Table 3
Ranges of copper (Cu) and nickel (Ni) concentrations determined in Titania tailings, deep cores and box core samples collected along a gradient from remote offshore locations to the inner part of Jøssingfjorden. The gastropods (*Hinia reticulata*) were analysed after four weeks exposure in cores maintained in a benthic mesocosm.

	Ni	Cu	Ni:Cu
Titania tailings (μg g^{-1})	220–370	120–180	1.8–2.1
Sediment, 10–100 cm (μg g^{-1})[a]	250–570	120–310	1.8-2.5
Sediment, 0–1 cm (μg g^{-1})	17–210	19–160	0.7–1.3
Pore water, 0–1 cm (μg/L)	4–77	4–28	1.1–5.9
Release flux (μg m^{-2} h^{-1})	0.5–25	0.2–3.5	1.7–9.1
Gastropods (μg g^{-1})	2.6–6.3	31–52	0.06–0.15

[a] Data from deep cores reported in Gravdal, 2013.

3.4.2. Biogeochemical modelling of metal fluxes

Because of the complexity of factors controlling the transformation of metals at the sediment water interface, the development of novel biogeochemical models provides useful tools for a better understanding of the processes involved. Using nickel (Ni) in tailings from Jøssingfjorden as a case study, a 1D benthic-pelagic coupled biogeochemical model, BROM (Yakushev et al., 2017), supplemented by a Ni module was developed (Pakhomova et al., 2021). The model aimed to simulate the cycling of Ni in the water column, the Benthic Boundary Layer (BBL), and upper sediments (distributions, fluxes, rate of processes) and its reaction to the dumping of the Ni containing tailing. The biogeochemical module BROM considers interconnected transformations of chemical species (N, P, Si, C, O, S, Mn, Fe). Organic matter (OM) dynamics include parameterizations of OM production (via photosynthesis and chemosynthesis) and OM decay. To provide a detailed representation of changing redox conditions, OM in BROM is mineralized by several different electron acceptors and dissolved oxygen is consumed during both mineralization of OM and oxidation of various reduced compounds. Transformations of variables are considered both in the water column and in the upper sediment layer, as well as exchange with the atmosphere for gases (e.g. O_2, CO_2). The Ni module considers Ni species transformations interconnected with other chemical compounds involved in the Ni cycle: O_2, S, Fe, Mn, dissolved and particulate OM and biota (Pakhomova et al., 2021).

Modelling redox-dependent changes is a convenient way of studying Ni fate under variable redox conditions. In this study, the BROM model was optimized using field data collected in Jøssingfjorden (Table 1). The model allowed simulation of the principal features of distributions and seasonal variability of biogeochemical parameters and Ni compounds for the period before deposition (1950–1960), during the intensive deposition (1960–1984) and recovery period after cessation of the intensive deposition (1984–2020) (Fig. 5). Based on these simulations, it was possible to calculate an interannual variability of benthic fluxes of total dissolved Ni, which demonstrated that even after cessation of the deposition, the Ni flux remained high for several years. Therefore, the model allows to numerically predict processes of the Ni transformation (i.e. concentrations, benthic fluxes) in the planning scenarios of the waste deposition allowing to develop measures to minimize impact.

3.5. Effects of STDs on biota

The disposal of mine tailings in the marine environment may impact the ecosystems through several mechanisms, such as hypersedimentation, toxicity of metals or process chemicals, changes in the substrate and submarine topography, sediment plumes, and higher turbidity (reviewed in Shimmield et al., 2010; Ramirez-Llodra et al., 2015). As the deposition of tailings into the marine environment can amount to several million tons per year (Table 1), the benthic sessile and soft bottom fauna are the ecosystem components that are expected to be most affected by tailings disposal (Ramirez-Llodra et al., 2015; Trannum et al., 2018a). Ideally, the environmental effects of tailings deposition should be as limited as possible in space and time and be contained within the approved impact area by the authorities issuing the STD permit. Within the authorised STD area, profound effects are expected and accepted, but a central question concerns the effects in the transition zone, i.e. the zone from the STD to the adjacent non-impacted area (Trannum et al., 2018a). Although several environmental monitoring studies in fjords subjected to mine tailing disposal have been conducted previously (Ramirez-Llodra et al., 2015), no systematic comparison on the effect of different tailing types has been done until now. Previous reviews have identified the need for additional knowledge on benthic community composition and functioning to better understand the impacts of tailing accumulation on the benthic fauna, as well as the colonization and recovery potential (Ramirez-Llodra et al., 2015; Vare et al., 2018). Also, a better understanding of the lethal and sub-lethal effects of metals and chemicals have been identified as an important knowledge

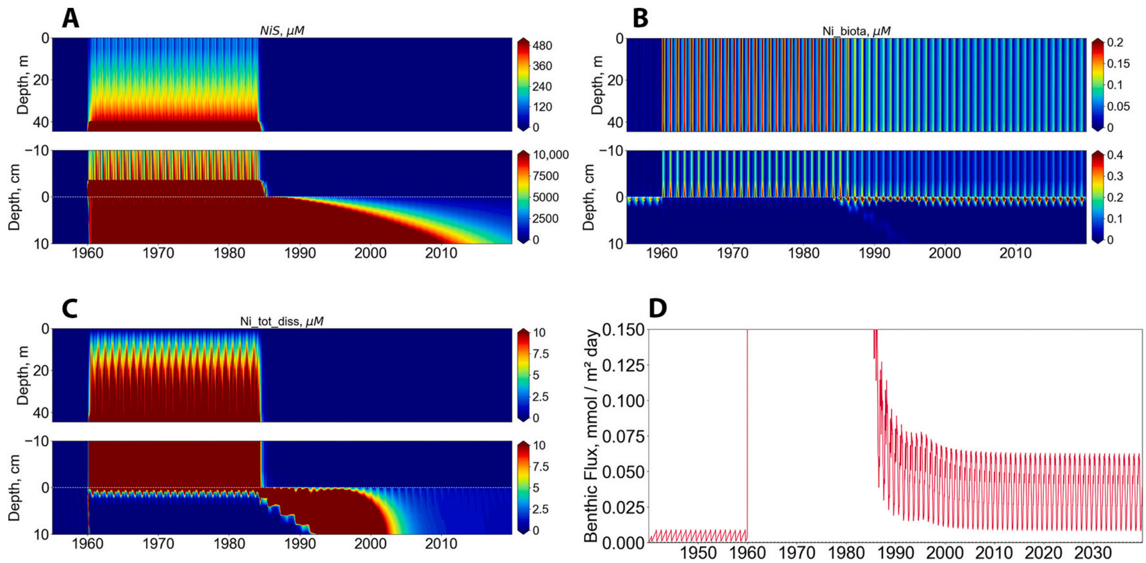

Fig. 5. Modelled interannual variability of concentrations NiS (A), Ni accumulated by biota (B), total dissolved Ni (C) and benthic flux of total dissolved Ni at the sediment water interface (SWI) before (1950–1960) during (1960–1984) and after (1984–2020) the intensive tailing deposition (D). Upper panels in the plots A-C show variability in the water column (from 0 m to 43 m) and the low panels show variability at the SWI interface (in 5 cm in the water above the sediment and 5 cm in the sediment).

gap to current STD assessments (Ramirez-Llodra et al., 2015).

In the following sections we describe the main results of a series of analyses and experiments within the NYKOS project that addressed these knowledge gaps using a range of approaches and novel methods to analyze 1) ecotoxicity of single species in the lab and in the field; 2) quantify impact thresholds of hypersedimentation to benthic fauna in the transition zone; 3) assess status of the benthic ecosystem in a post deposition site; and 4) assess recolonisation potential using field experiments. Finally, all the abiotic and biological data collected in Frænfjorden in relation to the Hustadmarmor STD, including historical and new data, were used to develop a geospatial model for predictions of spatiotemporal variation in benthic diversity within an STD.

3.5.1. Ecotoxicological responses to mine tailings

To assess the toxic potential of tailings, a range of ecotoxicity assessments were performed using mine tailings from three Norwegian mines: Sibelco (no chemicals added), Sydvaranger (flocculation chemicals added) and Omya Hustadmarmor (flotation chemicals added) (Brooks et al., 2019) (Table 1). The mining companies supplied the tailings representing the material at the time immediately prior to discharge to sea. Ecotoxicity assessments were performed on: 1) the overlying water extracted from the mine tailings; 2) the transformation/dissolution waters obtained from the mine tailings; and 3) whole sediment assessment using a suite of marine organism groups including the microalga *Skeletonema pseudocostatum*, the copepod *Tisbe battagliai* and oyster embryos. In addition, the biological effects of tailings on mussels were analysed in situ on three moorings with transplanted mussels deployed in Frænfjorden. Here, mussels were placed out in the fjord for six weeks at known distances from the discharge outlet. Chemical concentrations and a suite of biological effects markers were then measured (Brooks et al., 2018).

The effects of the dissolved concentrations of metals from the three mine tailings showed that the tailings from Sibelco resulted in the highest toxicity followed by Sydvaranger and Hustadmarmor (Brooks et al., 2019). Toxic responses were observed in both oyster embryo development and growth inhibition of the marine algae. Process chemicals were not used at Sibelco and the toxicity was most likely due to the combined effects of elevated concentrations of metals such as Al (100 μg/L), Mn (325 μg/L) and Ba (140 μg/L). The impact of mine tailing particles from the sediment contact assays revealed a different response between the three mine tailings, with Hustadmarmor showing the largest effects on the survival of the amphipod *Corophium* sp. The fine and round particles of Hustadmarmor tailings, which may interfere with the respiratory and/or feeding organs of the organism (Brooks et al., 2019), were considered to be a contributing factor.

In the field investigation with mussels, significant biological responses were observed 1500 m downstream from the Hustadmarmor discharge outlet in Frænfjorden (Brooks et al., 2018). The biological responses observed included a reduction in the general fitness of the mussel as well as increased stress markers and genotoxic responses. Similar, but milder biological responses were observed in mussels 2000 m from the outlet compared to reference mussels. The biological responses observed were believed to be caused by exposure to the suspended particles from the mine tailings discharge within the fjord. Concentrations of methyl triethanol ammonium (MTA), a chemical marker for the esterquat-based flotation chemical FLOT2015 used at Hustadmarmor (Section 3.3.2), was detected in whole mussels up to 2000 m from the discharge outlet. This confirmed exposure of the mussels to the mine tailing discharge and linked tailing exposure (including metal concentrations) with the biological effects observed. However, assessing the contribution of the flotation chemical to the observed toxicity in the mussels within the fjord was not possible to determine. In addition, MTA concentrations were also measured in holothurians collected from the seafloor, approximately 1500 m downstream from the Hustadmarmor discharge outlet. However, holothurians are mobile benthic fauna that could have transited over the STD impact area. High concentrations of Cr and Ni were measured also in the tissue of these holothurians, at levels of pollution where biological impacts would be expected based on guidelines from the Norwegian authorities (Molvær et al., 1997). With respect to flocculation chemicals, there have been less indications of toxic effects in marine organisms. Laboratory studies on the tailings from Sydvaranger, where the flocculation chemical Magnafloc has been used, did indicate some toxicity, but no correlation was found between flocculant concentration and observed toxic responses (Brooks et al., 2019).

When it comes to metals, the EQS-values of Cu and Ni were exceeded in the tailings supplied from Titania as well as in the sediments collected from Jøssingfjorden and Dyngadypet (Section 3.4.1). For the tailings supplied from Nussir, the EQS for Cu only was exceeded. In laboratory exposures with Sibelco tailings, the combined toxicity of metals Al, Mn and Ba were attributed to the observed toxicity of the developing oyster larvae (Brooks et al., 2019).

3.5.2. Spatial response of benthic fauna to an STD

The constant deposition of tailings, i.e. hypersedimentation, is one of the most apparent effects of tailings deposition, particularly for sessile organisms. Nevertheless, deposition areas completely barren of fauna do not seem to be common. Understanding the potential avoidance behaviour of mobile benthic megafauna (>1 cm) and the gradient-effect of tailings on the benthic macro-infauna (>0.5 cm) are essential to assess and monitor the spatial scale of the STD on the seafloor. To investigate the response of these fauna components to an active STD, a field study was conducted in Frænfjorden (Table 1). Faunal samples collected with a 0.1 m^2 Van Veen grab and an Agassiz trawl were used to calculate structural and functional diversity and assess community structure and functional trait analyses along a gradient from the tailings outflow to the area outside of the approved STD (Trannum et al., 2019). A gradient of decreased species richness and biodiversity for both infauna and epifauna was observed from the outfall of the discharge pipe to the non-impacted area (Trannum et al., 2019). In addition, the total abundance of infauna increased in the most impacted area due to dominance of opportunistic species. This response resembled the classical disturbance model described by Pearson and Rosenberg (1978). On the other hand, the epifauna was reduced and represented by a few scattered specimens only. This could be explained by the high motility of large detritivores (e.g. holothurians) that move away from an area where there is no food supply, or by a high sensitivity of certain species towards the tailings. The infauna in Frænfjorden has been monitored regularly from 1993 in relation to the Hustadmarmor STD (Brooks et al., 2015a). A notable finding was that the infaunal biodiversity at the most impacted station (i.e. closest to the outfall) had increased considerably from 2013 to 2016, and it was suggested that this was a result of the replacement of the process chemical Lilaflot by the less environmentally-harmful chemical FLOT2015 in 2014 (Trannum et al., 2019).

The functional diversity of the infauna varied less than the species diversity along the fjord gradient, which indicated that there were relatively many different functions (low redundancy) represented among the species present (Trannum et al., 2019). For the epifauna, an interesting finding was that the functional diversity not fully paralleled the structural diversity. This can imply that preserving biodiversity quantified with traditional biodiversity indices will not necessarily result in the preservation of ecosystem functioning. If functional diversity is reduced by the decline of a specific functional group, certain resources or ecosystem services could potentially be lost (Tillin et al., 2006). A reduction in functional diversity can diminish the buffering capacity of benthic ecosystems and increase the susceptibility of the system to other stressors (McGovern et al., 2020). The functional responses to tailing deposition included an increase in mobile carnivore and omnivore species as well as species utilising symbiotic bacteria, while deposit and suspension feeders and sessile and tube-living taxa decreased (Trannum et al., 2019).

3.5.3. Impact thresholds of the STD transition zone on the benthic ecosystem

All STDs have an authorised deposit area on the seafloor, where major impacts are expected on the benthic fauna. However, in the transition zone from the impacted to the unimpacted area, the effects are assumed to vary according to the particular tailing type discharged. Thus, in this zone, there is a potential for reducing the ecological footprint. To better understand the thresholds and processes that define the STD transition zone, a mesocosm experiment was conducted with thin layers of mine tailings (Trannum et al., 2018a). The same three tailings used for the ecotoxicological tests (Section 3.5.1), including tailings from Sibelco with no chemicals added, Sydvaranger with flocculation chemicals and Omya Hustadmarmor with flocculation and flotation chemicals added (Table 1), were added at 10 different thicknesses (from 0 to 6 cm) to benthic communities collected with box-cores and acclimatized in the mesocosm set up (methodological details are available in Trannum et al., 2018a) (Fig. 6). Sediment oxygen consumption and nutrient fluxes were determined several times during the experiment. At the end of the experiment, environmental variables (total organic carbon (TOC) and sediment fine fraction (<0.063 mm)) and biological variables (biomass, abundance, species richness and selected diversity indices) were determined and each taxon was classified into feeding type.

In the mesocosm experiment, all three tailings had significant negative effects on the fauna (Trannum et al., 2018a). In general, the strongest faunal impact was observed for the tailings from Hustadmarmor, which was fine-grained and contained flotation chemicals. Here, there was a significant effect on total abundance, species richness, biomass and diversity indices. The second strongest occurred in tailings with no process chemicals (Sibelco), while the weakest impact was found on the communities subjected to the tailings with flocculation chemicals (Sydvaranger). Deposit feeders (both surface and deep deposit feeders), which are directly exposed to tailings particles, were found to be more vulnerable than carnivorous and omnivorous species (Trannum et al., 2018a).

A smaller mesocosm-experiment was conducted with sulfide-containing tailings, provided from the Titania processing plant (Trannum and Schaanning, 2017) and from a test-operation at Nussir (Hilde Trannum, pers. obs.), following the same methodology as above, but with a layer thickness of 2 cm only. Process chemicals were not added in the tailings provided from Nussir. After exposure to the tailings, both treatments had fewer species and individuals than the control, although the difference was only significant for the number of individuals in the Titania-treatments (Trannum and Schaanning, 2017). The two dominating species in the controls (a subsurface deposit feeding and a suspension feeding bivalve) were reduced by as much as 90% in the Titania-treatment and by over 50% in the Nussir-treatment. The results showed that also sulfide-containing tailings affected the fauna.

Although some species will survive hypersedimentation, the species composition of a community affected by a STD will reflect the sedimentation stress, with a domination of tolerant species (Ramirez-Llodra et al., 2015; Trannum et al., 2019). Olsgard and Hasle (1993) stated that sedimentation of mine tailings of 3–4 cm y^{-1} clearly affected the infauna, while sedimentation of 1 mm y^{-1} did not result in any observable effects. This is in line with the present study, where effects were documented at layers exceeding 2 cm for all tailings in the mesocosm setup (Trannum and Schaanning, 2017; Trannum et al., 2019). On the other hand, in an experimental setup including macro- and meiofauna, bacteria and functional parameters, significant responses occurred from 1 mm tailings added but still, no effects were observed for the macrofaunal composition, not even at the maximum layer of 2 cm (Mevenkamp et al., 2017). Thus, it seems likely that effects on macrofauna can be expected from approximately 2 cm layer thickness, possibly related to inhibited exchange of nutrients by reduced irrigation at higher layer thicknesses. The apparent effect threshold at 2 cm layer thickness was supported by the correlation between sedimentation rate and biodiversity obtained from the NYKOS field study (Section 3.5.4).

3.5.4. Mapping the transition zone area

The analysis of spatiotemporal variation in benthic diversity (Section 3.5.3) could not be fully integrated with the model predictions of spatially resolved sedimentation rates in Frænfjorden (Nepstad et al., 2020). However, by combining the latter with the impact thresholds determined from the benthic community level studies (layer thickness, Section 3.5.3), a map of the STD influence zones was made (Fig. 7).

The thresholds used for the color categories here include the general 2 cm thresholds of tailings effect (orange, see also Section 3.5.3), but with an additional category (yellow) accounting for effects observed at lower values in Frænfjorden specifically, using a previously reported PNEC (Predicted No Effect Concentration) value of 0.63 cm (Smit et al.,

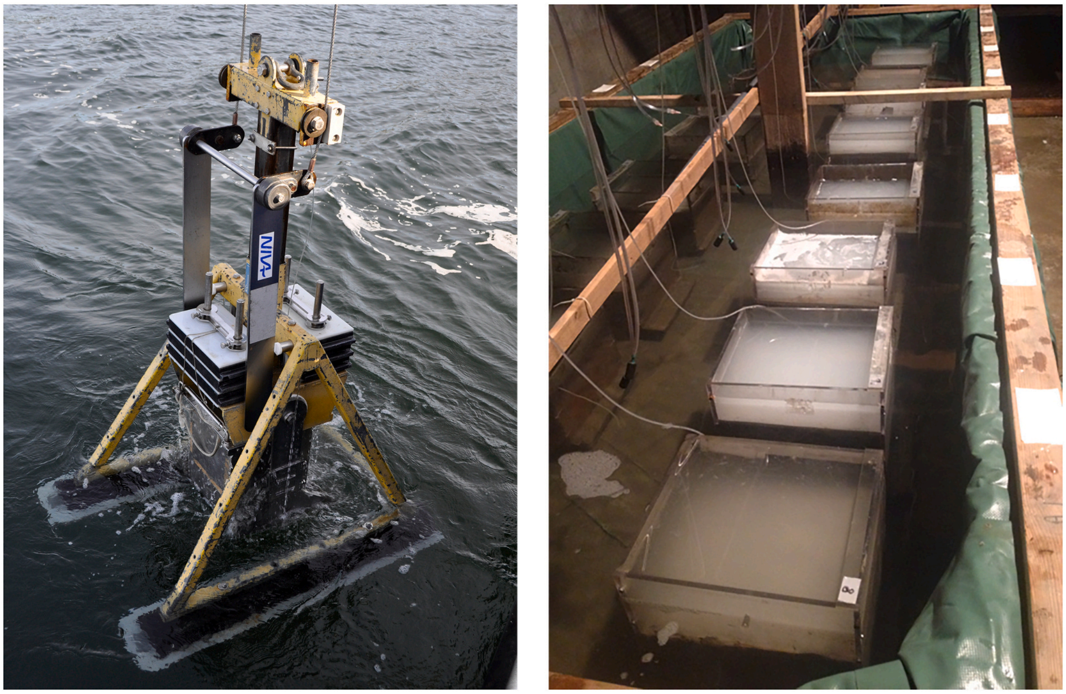

Fig. 6. Collection of sediment cores (left) and the mesocosm setup just after addition of test tailings (right).

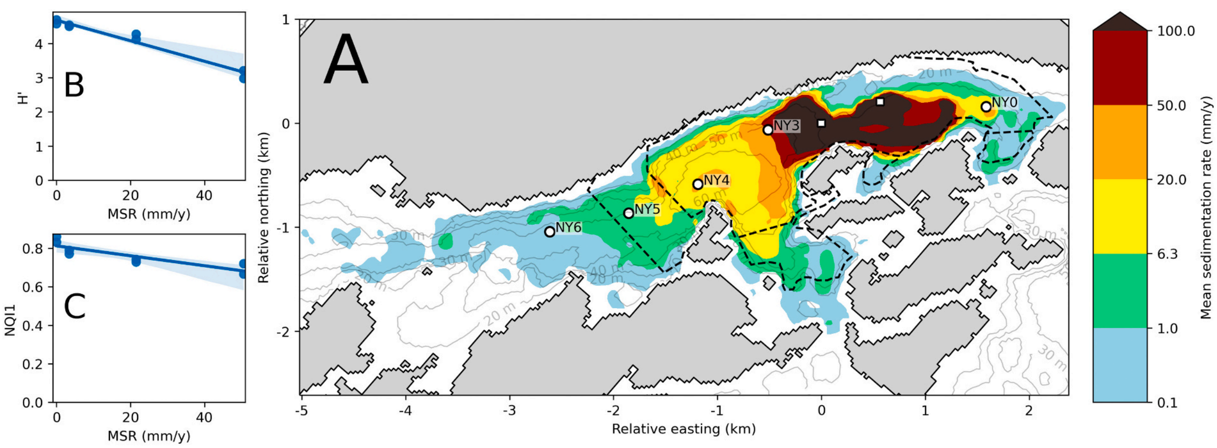

Fig. 7. Predictions of sedimentation rates in Frænfjorden from the particle spreading model, categorized from low (blue) to high (black) rates (A). The inner STD area and transition zone are indicated by the dashed black lines. Discharge points are indicated by the two white squares, while the white circles indicate sampling stations. Coordinates are given relative to the westernmost discharge point. The inset figures (B and C) show correlations between measured ecological indices in Frænfjorden and mean yearly sedimentation rates (MSR) predicted by the spreading model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2008). Below this value, we may expect a lower environmental risk for the benthic biota, corresponding to areas of green and blue in the figure. These regions are found in the transition zone of the STD, delineated by dashed black lines in the figure, and extend somewhat further outwards from there, in particular on the western side of the STD. We also observe a correlation between the model sedimentation rate and the two biodiversity indices H′ and NQI1, shown in Fig. 7A and B, respectively. Despite few data points, there is a clear negative correlation between the sedimentation rate and biodiversity, as also found in the spatiotemporal analysis in Section 3.5.3, which was based on distance to the discharge point as a proxy for sedimentation rate. It should be noted that the threshold value was derived based on 2 cm over a few weeks, compared with the model prediction based on an annual sedimentation rate, so quantitative comparisons should be used with caution and there is some uncertainty regarding the effect of lower sustained sedimentation rates over longer time periods (years). A fine-tuning of the scale should thus be performed in future modelling. In future applications, extension of this work to also incorporate associated chemicals would provide a more general risk assessment tool for the industry, similar to the Environmental Impact Factor (EIF) method used for discharges of drill cuttings (Singsaas et al., 2008).

3.5.5. Sediment composition and particle morphology

Sediment composition, primarily particle size and organic content, is often considered the most important structuring variable for soft bottom communities (Oug, 1998; Ellingsen, 2002; Gray and Elliott, 2009; Trannum et al., 2018b). Within the STD impacted area, the substrate will be totally replaced by the tailings, usually finer and sharper than the natural sediment and deprived of organic carbon. The changes may result in profound effects on the benthic communities. Also, the altered grain size composition represents a more or less constant change at the seabed, where natural sedimentation is the only mechanism that will slowly return the sediments to a composition closer to the natural status after the cessation of the discharge.

In Frænfjorden, a decrease in benthic biodiversity with increasing proportion of fine tailings has been observed (Brooks et al., 2015a). Also, the spatio-temporal analysis in this study showed that the diversity increased by distance to point source, indicating a negative impact of the tailings (Section 3.5.3). A homogenous sediment is another typical characteristic of mine tailings (Morello et al., 2016). A decrease in sediment heterogeneity has been documented in Frænfjorden (Trannum et al., 2019), which potentially may reduce available niches and, in turn, benthic biodiversity (Gray, 1974; Etter and Grassle, 1992). A more homogenous sediment can also reduce sediment oxygen penetration (Näslund et al., 2012).

In addition to grain size, particle shape is a key variable to assess environmental impacts. As mine tailings consist of mechanically crushed rock, they can often be relatively sharp-edged compared to natural sediments, which are rounded from the natural grinding over geological times (Kvassnes and Iversen, 2013). The sharpness of such tailing particles is considered to represent an additional risk to the benthic fauna, particularly for deposit and filter feeders (Olsgard and Hasle, 1993). To assess differences in shape of particles, three tailings received for experimental purposes from the production plants Sibelco, Sydvaranger and Hustadmarmor (Table 1) were subjected to chemical and morphological analysis with a Scanning Electron Microscopy - Energy Dispersive X-Ray spectroscopy (SEM-EDX) (Trannum et al., 2018a; Brooks et al., 2019). Edged-shaped particles were observed for all three tailings, with the tailing particles from Sibelco exfoliating into elongated prismatic cleavage fragments with very rough surfaces (Trannum et al., 2018a). This is suggested as one of the explanations for the adverse effects of this material on the fauna found in the different ecotoxicological and thin-layer exposure experiments (Brooks et al., 2019; Trannum et al., 2018a), as these tailings have no added process chemicals. Literature on the effects of edged-shaped particles on benthic invertebrates is scarce, but highly edged particles have been found to initiate a larger stress-response than spherical particles in juvenile coho salmon (Lake and Hinch, 1999). In the ecotoxicological experiment (Section 3.5.1), the particles of Hustadmarmor were speculated to have interfered with the respiratory and/or feeding organs of the organism, thus intensifying the toxicity (Brooks et al., 2019). In addition, ingestion of sharp-edged mine tailings by a copepod was considered to have contributed to adverse effects in a test with Hustadmarmor-tailings (Farkas et al., 2017). Damaging respiratory and feeding structures can perhaps be intensified if the particles are sharp-edged. It can also be speculated that particle sharpness can lead to epithelial injury, which again can increase the risk of uptake and toxic effects of metals or chemicals. In addition, sediment composition and particle morphology are factors that are expected to influence the recolonization potential (Section 3.5.7; Trannum et al., 2020). Sweetman et al. (2020) suggested that the non-marine physical structure of the tailing particles with great angularity was the main responsible factor for the observed delayed recovery of a community in a colonization experiment in the intertidal zone, with a larger importance than an altered nutrient content.

Further investigations on the interaction of particles with respect to size and shape on feeding and respiratory structures of different marine organisms are needed to better understand the different potential effects of particle characteristics on fauna. This information would help to improve current management practices where the discharge of the most harmful types of tailing in the sea can be restricted.

3.5.6. *Mapping spatiotemporal variation in benthic diversity within an STD*

Assessing variations in benthic communities along a spatial gradient from the outflow of the tailings to the non-impacted area and over several years provides a valuable tool to understand the mid-term effect of the tailings on the ecosystem. This can inform adaptive management to help reduce the environmental impact. To map such spatiotemporal variation in benthic diversity through a period of tailing disposal from the Hustadmarmor STD (Table 1), we used an extensive dataset from Frænfjorden (Trannum et al., 2019). Faunal species data from the period 1993–2015 available from previous monitoring studies (Brooks et al., 2015a) and from the current study (Trannum et al., 2019; Section 3.5.3) were used to calculate four indices of faunal diversity and community structure used as biological quality elements for Norwegian coastal waters in the EU Water Framework Directive (Norwegian Classification Guidance, 2018). These indices included the Shannon-Wiener diversity index H' (Shannon and Weaver, 1949), Hurlberts' Diversity Index ES_{100} (Hurlbert, 1971), the sensitivity index "Indicator Species Index" ISI_{2012} (Rygg and Norling, 2013) and the Norwegian Quality Index NQI1 (Rygg and Norling, 2013). The indices were analysed against distance to discharge outlet of the tailing outflow in Generalized Linear Models in R (version 3.5.2, R Core Team, 2018) and spatial mapping using ArcGIS 10.4 (ESRI, 2011). Bathymetry, slope, curvature and wave exposure (all at a 25 m resolution) were also included in the modelling to improve predictive power. Year of sampling was included in the models to test for temporal effects.

The R analyses revealed that all indices, although NQI1 not significantly, increased by distance from the tailings outflow, indicating that both diversity and sensitive species are most likely negatively affected by the tailings (Fig. 8).

The proportion of sensitive species in the sediments, represented by NQI1 and ISI_{2012}, also increased over time (dynamic figures available online: NQI1 (https://figshare.com/articles/media/predNQI_animation_gif/8088542/1) and ISI_{2012} (https://figshare.com/articles/media/predISI_animation_gif/8088509/1)). This increase of sensitive species suggests improved conditions in the area over time, possibly related to the substitution of the flotation chemical Lilaflot by the less environmentally harmful FLOT2015 in 2014 (see also Section 3.5.2). It is important to be aware that the fauna and data subject to this study were not sampled specifically to answer questions of spatiotemporal nature and, therefore, not perfectly balanced in time and space. Thus, we must be careful to draw conclusions about causative relationships between the STD activity and responses in the benthic fauna community. However, the benthic community analyses presented in Section 3.5 (Trannum et al., 2019) indeed support that there is an effect of tailings on community structure and function, which also accords with a previously published study in Frænfjorden (Brooks et al., 2015a). The benthic infaunal community in Frænfjorden has been monitored in relation to the Hustadmarmor STD since 1993. Despite not being fully balanced in space and time, this dataset represented an opportunity to assess if species composition were affected by the tailings discharge, and if the faunal response changed over time. The GIS modelling and map outputs provide an integrative view of the Frænfjorden system and show that long-term standardized data from different disciplines is crucial to investigate any spatiotemporal dynamics in benthic community assemblages. The outputs of such models can contribute to management decisions, including adaptive management as conditions change.

3.5.7. *Post-closure recolonisation*

After a mine closes down, the tailings can prevail in the deposited area for long periods. Depending on the natural sedimentation rate and bioturbation by resident fauna that may redistribute tailings from deeper sediment layers and upwards (Schaanning et al., 2019), such phase may eventually last as long as several decades. During this time, metals and chemicals will be made available constantly for uptake by the benthic fauna as well as dispersing into overlying water. Capping, i.e. covering seabed sediments with a layer of clean sand or clay, is a common method to reduce the risk associated with contaminants from harbour and industrial activities (Förstner and Apitz, 2007), and might in certain cases be considered applicable also for STDs. The thickness of the cap may range from about 40 cm, which is generally considered sufficient to reduce contact between the contaminants and the benthic

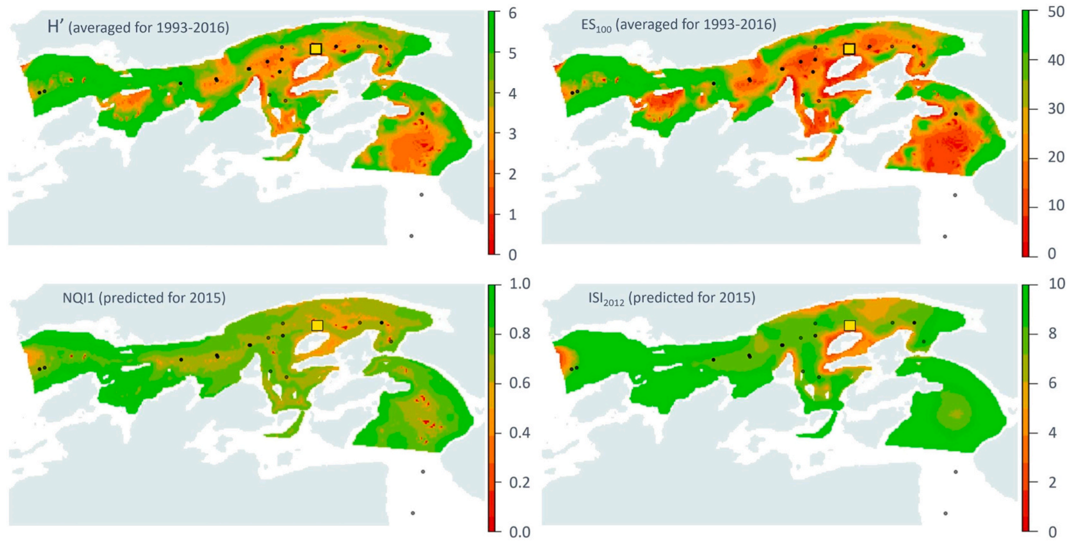

Fig. 8. Predicted maps based on GLM analysis of fauna community indices' responses to geophysical variables (bathymetry, slope, curvature and wave exposure) and distance from the discharge outlet (yellow square). Black dots show the position of fauna stations, whereof many have been visited on several occasions in the period 1993–2015. The two sensitivity indices (NQI1 and ISI_{2012}) are predicted for the last year in the series (2015) and show relatively high values, as the analyses revealed an improvement through the monitoring period. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

fauna, to a few centimeters assisted by natural burial processes (i.e. enhanced natural remediation). Required cap thickness can be considerably reduced by the addition of sorbents such as activated carbon, organoclay, zero-valent iron and others (Olsta et al., 2006; Näslund et al., 2012; Schaanning et al., 2021). A prerequisite for a successful capping measure is that the deposit is complete and ready for final closure. To our knowledge, most post closure STDs are left unattended to recover through natural processes. A key component of the recovery of an ecosystem following natural or anthropogenic disturbance is the potential for recolonisation of the impacted area by local or regional fauna (Cowen and Sponaugle, 2009; Hilário et al., 2015). However, data on population connectivity potential and recolonisation processes is scarce for most species in areas affected by STDs (Kline and Stekoll, 2001; Ramirez-Llodra et al., 2015; Trannum et al., 2020). To contribute new knowledge to the processes driving recolonisation of STD-impacted areas, a mesocosm experiment and a field-based study were conducted within the NYKOS programme and the results are summarised below.

The effect of thin layers of mine tailings on the recolonisation of the benthic macrofauna were assessed with a colonization experiment in the Oslo fjord. The setup used a frame with eight boxes containing defaunated sediments covered by 2 cm of tailings (the same as used in the mesocosm experiment; Section 3.5.3) and a control (no added tailings) (Trannum et al., 2020). The benthic community in the boxes was analysed after 6 and 12 months. All sediments capped with thin layers of tailings showed a rapid colonization with a high number of species within half a year, as high as the control. A rapid initial colonization has also been observed after cessation of deposition in tailings-affected fjords (Olsgard and Hasle, 1993; Kline and Stekoll, 2001; Burd, 2002). Still, there were differences among treatments particularly with regards to the faunal composition within the trays (Trannum et al., 2020). Sediments treated with tailings from Hustadmarmor (i.e. fine-grained particles with flotation chemicals) showed a significantly lower number of colonizing individuals than the control and the other tailing treatments throughout the one-year experiment. Particularly tube-building annelids had a lower recruitment success in the tailings-treatments, probably caused by substrate-differences between the tailings and control sediment. The lower colonization of this group was, to some extent, compensated for by increased colonization of other taxonomic groups, and mollusks in particular. Also, the Sibelco-tailings (i.e. particles with no added process chemicals) showed a lower colonization than the control and Sydvaranger-tailings (i.e. particles with flocculation chemicals) after the first six months, but similar numbers after twelve months. In general, there were larger differences in faunal abundance between the controls and tailings after six than twelve months, probably due to natural sedimentation throughout the experiment as well as mixing of the thin tailings layer with the sediment underneath by bioturbation (Trannum et al., 2020). Although a rapid initial colonization was observed for all tailings, it is important to note that the communities were in a relatively early successional phase, and that long-lived species which require stable habitat conditions were not present (Trannum et al., 2020). Furthermore, the scale was small both with regard to the tailings layer thickness (representing the transition zone) and the sediment area subject to colonization. Thus, the results cannot be directly transferred to a situation where an entire STD impacted area needs to be recolonized. In particular, the altered sediment composition will persist for a very long time. Grain size can be an important settlement cue for larvae, and especially tube-building species may exhibit more sediment-specific preferences during settlement (see Trannum et al., 2019 and references therein), and it has been shown to lead to different colonization patterns (Trannum et al., 2011; Kanaya, 2014). Although additional studies over large spatio-temporal scales are needed, small-scale recolonisation studies such as the one conducted in the NYKOS project contribute to understanding the processes driving recolonisation and can inform the development of best practices for the closure and post-closure of STD operations (Ramirez-Llodra et al., 2015; Vare et al., 2018; Trannum et al., 2020).

To assess the long-term recovery of an area impacted by an STD after cessation of activities at a scale of decades, a field study addressed recovery of metal concentrations and benthic macrofauna in Jøssingfjorden and Dyngadypet (Trannum et al., 2018c; Schaanning et al., 2019; Table 1). The innermost station in the fjord, situated in the older deposit (1960–1984), has been monitored since 1983. These studies showed that, initially, the fauna was very highly disturbed with only three macrofaunal species recorded (Olsgard and Hasle, 1993). In 1985, just one year after relocation of the discharge, the ecological condition improved markedly. In 2015, i.e. 30 years after the closure, the soft bottom fauna obtained the level of “good” (class II) condition, according to the benthic indices used in the Water Framework Directive (WFD) monitoring system for Norwegian coastal waters (Norwegian Classification Guidance, 2018), but the condition was close to "moderate" (class III). In 2018, the fauna was well within the class "good", i.e. with signs of prevailing improvement (Trannum et al., 2018c). Nevertheless, concentrations of Cu and Ni exceeded MAC-EQS levels (Schaanning et al., 2019) and disturbance effects were recorded, such as the occurrence of tolerant species and high dominance of single species. The new deposition site in Dyngadypet, where tailings were deposited from 1984 to 1994, was not monitored before 2015. Also here, pollution-tolerant species were then recorded, and this station showed signs of disturbance, even though it fell in the "good" (class II) condition (Trannum et al., 2018c; Schaanning et al., 2019). It is important to be aware that the ecological classification system within the WFD is mainly developed to detect effects of increased nutrient loading and, in our opinion, it does not reflect well other disturbance factors like hyper-sedimentation. It is therefore important to develop specific monitoring indices for the classification of ecological status that consider the particular stressors and ecological responses of the ecosystem being studied. Black ilmenite particles were observed on all stations except the reference station, and some benthic organisms were discolored or had the particles visible in their tube. When the faunal data were related to the environmental variables, tailings-induced factors such as particle size and copper were identified as significant variables for the faunal composition, in addition to depth, i.e. showing a long-lasting effect of the tailings.

The conclusion from our studies of recovery, as well as from other studies (Ramirez-Llodra et al., 2015; Schaanning et al., 2019; Trannum et al., 2020), is that initial colonization is fast and occurs within 1–2 years, but that it may take up to several decades before the faunal composition and concentrations of metals and other persistent chemicals have returned to their original state. A thorough baseline study prior to the start of tailing discharges is thus essential to understand the response of the community during tailing discharge and its recovery after cessation of activities. In order to obtain a more complete understanding of recovery, biological studies must be accompanied by chemical analyses of harmful substances potentially present within the bioturbated surface sediments.

4. Proposed pathways to minimize environmental footprint from STDs

4.1. Best available techniques framework

Based on our study and published data, we have created a conceptual model (Fig. 1) of a generic STD, from which to assess areas that would benefit from clearly defined best available techniques (BATs).

Best Available Techniques (BATs) are defined in article 2 (11) of the EU Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control as: "*the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole*" (Box 1).

EU BATs can be legally binding (e.g. BATs based on IED/IPPC Directive) or non-legally binding (e.g. BATs based on other directives, such as the Extractive Waste Directive). The role and proper use of BATs for extractive mineral waste is explained in the Extractive Waste Directive (2006/21/EC) and the revised Best Available Techniques Reference Document for the Management of Waste from Extractive Industries (MWEI BREF, Garbarino et al., 2018). The MWEI BREF provides a non-legally binding reference «toolbox» for management of waste from the extractive industry. This document, and in particular the BAT conclusions, should help and support decision makers to ensure that the necessary techniques are implemented to reduce, as far as possible, adverse effects of waste disposal to the environment or human health. However, the MWEI BREF is mostly based on waste management on land and does not consider per se the disposal of tailings in the marine environment.

In the particular case of STDs, defining clear BAT guidelines by the relevant authorities based on sound scientific data is essential to develop robust waste management measures. This is particularly important in the marine environment, where knowledge is more limited than on land and where processes taking place in the environment during the disposal and post-closure are more difficult to monitor, and impact more difficult to remediate. These BAT guidelines should be used for baseline studies and the evaluations of new permit applications (initial environmental impact assessment), as well as for monitoring ongoing operations and assessing post-closure recovery of the ecosystem. The STD conceptual model illustrated in Fig. 1 includes processes in the processing plant prior to the discharge, and processes taking place in the recipient environments (pelagic and benthic). Using this model, we discuss several areas that would benefit from clearly defined BATs for submarine tailing disposal (Fig. 9; Table 4). These priorities apply mostly to STDs in Norwegian fjords, but they can inform also BAT guidelines for most STDs, as well as to many aspects relevant to Deep-Sea Tailing Disposal (DSTD) (Hughes et al., 2015; Vare et al., 2018).

4.2. BAT recommendations for STDs.

4.2.1. Processing plant

Understanding tailings properties (Table 4), including shape, size, mineralogy and chemical substances and reactivity, is essential to understand the changes of such particles in the environment and potential impacts on the fauna. Indeed, the results obtained within the NYKOS project point to varying responses between tailing types, which also illustrate that the final effect on the ecosystem is modulated not only by the tailing deposition rate, but also by the specific tailings characteristics (Trannum et al., 2018a; Brooks et al., 2019; Trannum et al., 2020).

An appropriate and well-designed system for tailings handling and discharge (i.e. the infrastructure of the tailings disposal) is thus a prerequisite for good operation (Table 4). The description of these systems represents critical information when developing guidelines. Adequate flow dynamics in pipes (i.e. the optimal plume velocity, the optimal ratio

Box 1
BAT terms and definitions (EU Directive 96/61/EC).

Best shall mean most effective in achieving a high general level of protection of the environment as a whole.
Available techniques shall mean those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator.
Techniques shall include both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned.

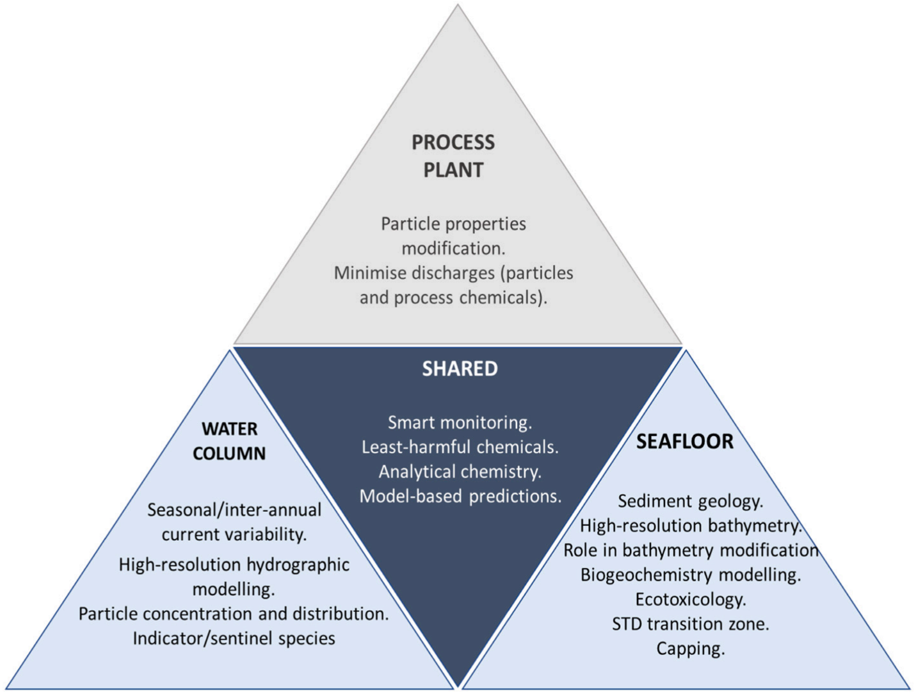

Fig. 9. Key areas proposed for the development of BATs for submarine tailing disposal operations.

of fresh water, saline water and solids) are essential to obtain a plume density higher than the density of the receiving sea water. The outfall should be designed to create a homogenous density current that follows the bottom topography to limit the influence on the bottom water quality and reduce the occurrence of shear plumes (Morello et al., 2016). Additionally, an infrastructure which removes air from the plume is critical to avoid fine particles being transported upwards in the water column.

A careful selection of the least harmful chemicals and optimization of the tailings by preventing over-dosage of process chemicals, and flotation chemicals in particular, is essential to minimize impact in the recipient pelagic and benthic environments. The ability of detecting and quantifying process chemicals prior to their discharge in the fjord (Table 4) can help prevent over dosage of flotation collectors, and simple test protocols could be integrated in BATs. However, such tests must be adapted to the mineral/collector-system in question. Accelerated breakdown of adsorbed or dissolved collector molecules prior to discharge of the tailings could offer an additional opportunity to lower the environmental impact of the flotation chemicals.

4.2.2. *Water column*

Understanding the processes that shape patterns of particle transport (both of natural particles and from tailings) is important for several phases of an STD. A wide range of sizes, shapes and concentrations of suspended particles can be measured in situ using laser-based instruments (e.g. LISST) in combination with camera systems such as the SilCam (Davies et al., 2017). This can help uncover underlying physical processes such as flocculation and transport driving the ultimate fate of discharged STD particles (Davies and Nepstad, 2017). High-resolution modelling of particle transport (Table 4) will allow for an accurate selection of the impact area. It will also highlight potential sporadic events, such as re-suspension, deep-water exchange and particle dispersal during storms, or specific particle transport related to detailed topography of the seafloor (e.g. transient turbidity currents) that may affect the water column and its ecosystem (Findikakis and Law, 1998; Vare et al., 2018; Spearman et al., 2020). Understanding the dispersal of natural particles, for example from river outflows, will provide basic information from which to differentiate between natural and STD particle processes.

In addition, analytical methods to better understand the transformation, transport and accumulation of process chemicals once they enter the seawater environment are essential to assess the potential ecotoxicological effects in the ecosystem (Table 4). Ultra-High Resolution Chromatography coupled to High Resolution Mass Spectrometry tools such as Orbitrap(r) technology are excellent tools to follow the transformation processes that the chemicals undergo in the recipient water bodies (Brooks et al., 2018). The residence time of the tailings in the water column is small compared to the residence time in sediments. In contrast to fast flocculation/deflocculation processes, adsorption/desorption of flotation chemicals and dissolution of metal sulfides are generally slow processes and likely to be more important in the sediment-porewater system than in the water column.

The dispersal of tailings in the water column can potentially have effects on the phytoplankton and zooplankton communities, through increased turbidity, toxicity of chemicals and/or damage from particles (Reinardy et al., 2019; Farkas et al., 2017). The pelagic macro- and megafauna, including fish, can also be affected, and migration routes or spawning areas can be altered. Understanding the effects of tailing particles on the distribution of pelagic populations (Table 4), particularly in relation to feeding or spawning grounds, is essential. In addition, assessing the effects of tailings on the early life-history phases (larvae, juveniles) of organisms - both pelagic and benthic - is particularly important to assess potential sub-lethal effects in the population, as well as on recolonisation potential (Ramirez-Llodra, 2002; Ramirez-Llodra et al., 2015).

4.2.3. *Seafloor*

The seafloor is the main recipient of the tailings and its associated process chemicals. The time the tailing particles spend in the water column will depend on the particles size and hydrographic conditions, ranging from minutes to days, but even months or years as is the case for the very fine particles of gold-processing tailings. Once the tailings have settled on the seafloor, the time they spend within the bioturbated surface layer of the STD will be on a scale of months to decades. The main impacts of an STD are the spreading of particles, potentially toxic compounds and smothering of the benthic infauna (Dold, 2014a;

Table 4
Proposed components for the development of concrete best available techniques (BAT) for submarine tailing disposal.

BAT component	Impact to be minimized by proposed BAT	Area for BAT	Phase for BAT implementation
Flow dynamics in discharge pipe	Development of shear plumes	Processing plant	Planning & design
	Size of impact area		Operational
High resolution bathymetry	Size of impact area	Seafloor	Planning & design
	Risk of slope failure		Operational
	Risk of damaging tailings pipe		
Seabed sediment mapping	Size of impact area Risk of slope failures	Seafloor	Planning & design
High-resolution modelling of particle transport in the water column	Particle spreading (sedimentation and particle concentration)	Water column	Planning & design
	Size of impact area	Seafloor	Operational
Mesocosm experiments on hypersedimentation	Negative effects on fauna	Seafloor	Planning & design
	Size of impact area		
Spatio-temporal distribution of benthic macro- and megafauna	Impact on fauna	Seafloor	Planning & design
	Presence of vulnerable ecosystems (e.g. corals)		Operational
	Obstacles to recolonisation		Post-closure
Spatio-temporal distribution of pelagic macro- and megafauna	Impact on fauna	Water column	Planning & design Operational Post-closure
Early-life history patterns of key species	Negative impact on spawning grounds, reproduction and recolonisation	Water column Seafloor	Planning & design
Population connectivity	Obstacles to recolonisation	Water column Seafloor	Planning & design Operational
Functional Trait Analyses	Negative impact on community/ ecosystem functions	Water column Seafloor	Planning & design
Characterization of tailings particles, including ecotoxicological tests	Negative impact on fauna/flora due to particle characteristics (size, shape, chemistry, mineralogy)	Processing plant Water column Seafloor	Planning & design Operational Post-closure
Ecotoxicology	Negative impact on fauna and flora (lethal and sublethal effects)	Water column Seafloor	Planning & design Operational Post-closure
Dissolution and release of bioavailable species (e.g. metal ions or complexes)	Toxicity on fauna due to high metal concentrations in sediment and pore water.	Water column Seafloor	Planning & design Operational
Seafloor redox conditions	Negative impact due to oxidative dissolution of minerals	Seafloor	Planning & design Operational Post-closure
Biogeochemical flux modelling	Negative impact due to fluxes of dissolved minerals	Seafloor	Planning & design
Quantification, dynamics, modification and effects of process chemicals (including transformation compounds)	Process chemicals dispersal in water column, and accumulation in sediment & fauna	Processing plant Water column Seafloor	Planning & design Operational
Capping	Release of trace metals	Seafloor	Post closure

Ramirez-Llodra et al., 2015; Vare et al., 2018), and thus the affected area should be contained within the permit area. It is therefore important to ensure, prior to the start of the STD activity, that the impact area is well delimited and its development during the STD activity and after the cessation of the activity is regularly monitored. High-resolution bathymetry and seabed sediment maps (marine base maps), together with high-resolution seasonal hydrographic modelling, provide information for different phases of an active STD (Baeten et al., 2020; Nepstad et al., 2020) (Table 4). During planning, such data will allow for an accurate selection of the deposition and impact area based on robust baseline data. This will minimize geohazards such as submarine landslides or turbidity currents. It will also provide the necessary seafloor topographic detail for the development of high-resolution modelling of particle transport in the water column. During the lifetime of the STD, regular monitoring will provide information on the dynamics of tailings deposition in different areas, allowing optimal positioning of the disposal pipe.

In order to assess potential impacts during tailing disposal, and recovery of the system post-closure, a thorough environmental baseline study is necessary prior to any discharge (Table 4). This study should include abiotic (sediment characterization, hydrography, bathymetry, geochemistry) and biotic compartments (faunal composition, community structure and ecosystem functions). Functional analyses are not normally included in standard surveys. However, benthic organisms play a key role in several essential ecosystem functions that support important ecosystem services, such as nutrient cycling, carbon turnover and secondary production including nutrient supply for commercial species, as well as transport and fate of pollutants (Harman et al., 2019). Thus, understanding ecosystem functions is extremely important and should be included in baselines studies for STD permits (Trannum et al., 2019), similarly to recommendations made for seabed mining (Montserrat et al., 2019). Novel technologies and methods are also being developed that will provide cost- and time-effective tools to conduct baseline studies and monitoring. For example, the development of autonomous underwater vehicles is rapidly increasing our capacity of data gathering in the marine environment (Vasilijević et al., 2017). Similarly, the development of molecular analyses, including environmental DNA, provide excellent tools to complement physical sampling for community characterization (Ruppert et al., 2019).

Understanding the effect of thin layers of tailing on the benthic fauna (Table 4) is important to assess the extent of the impact area and identify the transition zone between the deposit and the natural environment. Mesocosm studies are efficient in providing essential information on the effects of the tailings at the benthic ecosystem level. A recent study has shown that the most fine-grained material in tailings, which is the material that will disperse the furthest in the water column, has the most profound effect on the infauna, clearly indicating the need to minimize the spreading of this tailing fraction into the receiving water bodies (Näslund et al., 2012; Davies and Nepstad, 2017; Trannum et al., 2018a).

Chemical reactivity of the tailings is another important issue to consider. The bulk of the tailings is non-reactive rock material. Sulfide minerals will be stable after burial to depths below the oxic surface. However, near the sediment surface, dissolution and release of more bioavailable species such as metal ions or complexes will occur and enhance metal fluxes significantly above background levels, potentially resulting in metal concentrations in pore water exceeding environmental quality standards (EQS). The fraction released will depend on the rate of mineral oxidation reactions and the residence time of the tailings within the oxic environment. Such oxidative dissolution is hindered in natural anoxic basins. Hence, if available, such basins should be preferred for disposal of tailings rich in sulfide minerals. Given the redox dependence on chemical stability of tailings, the seafloor redox conditions of the disposal area need to be accounted for in the STD management. Pollutant seafloor fluxes can be predicted with mathematical models (Pakhomova et al., 2021). These models will analyze how the pollutants interact with environmental variables (redox conditions, presence of organic matter, bioturbation and bio-irrigation) and simulate the distributions and fluxes of all the modelled parameters. Therefore, modelling can help to plan STD regimes (amount, timing and frequency of dumping) and potential consequences for the environment. Post-depositional release of trace metals by oxidation of sulfide minerals can be reduced by capping to avoid exposure of sulfide tailings to oxygen from the overlying water (Schaanning et al., 2019). Such capping, when conducted with appropriate material, will also minimize effects related to particle properties (Sweetman et al., 2020) as well as process chemicals. In fjords, silt and clay will be more similar to autochthonous material and hence more appropriate for capping than coarser, sandy materials.

Like in the water column, analytical methods are essential to evaluate the transport, adsorption/desorption and transformation of process chemicals and metals on the seafloor and fauna. In addition, these analyses will help explain ecotoxicity as well as to identify sub-lethal effects that may, potentially, affect population maintenance in the long term (Brooks et al., 2018). The same analytical methodology described in Section 4.2.2 for analytical methods in the water column is suitable to address these advanced characterization challenges on the seafloor and biota.

Because tailing particles often have a different size and shape than the natural sediment, characterizing both the tailings and natural sediment (shape, size and mineralogy of particles, organic matter and sediment heterogeneity) is necessary prior to upstart of deposition (Table 4). Further, understanding sediment composition in the impact area and its evolution (in time and space) as STD activities cease and the area is covered with natural sediments, is important to predict recolonization success and ecological recovery potential (Table 4). In addition, to assess recolonization potential, it is essential to have a robust understanding of the early life-history variables of the fauna and to assess population connectivity with adjacent communities that would provide the necessary offspring/dispersing juveniles or adults to recolonize the impacted area after the cessation of the tailing discharge.

5. Forward look

Submarine tailing disposal is the preferred tailing management system in Norway, with seven currently active STDs in fjords (Ramirez-Llodra et al., 2015) and two new permits awarded in 2018–2019. In addition, even though there are major knowledge gaps in understanding the composition and functioning of many deep-sea ecosystems, interest for deep-sea tailing disposal (DSTDs) is increasing in several countries (Vare et al., 2018). Therefore, there is a need for robust national and international regulations for the disposal of mine tailings in the marine environment, including fjords, coastal areas and the deep sea (reviewed in Ramirez-Llodra et al., 2015). The UN GESAMP is a Group of Experts on the Scientific Aspects of Marine Environmental Protection that provides independent scientific advice to the UN system on marine environmental protection aspects. The GESAMP working group #42 (Impacts of Wastes and Other Matter in the Marine Environment from Mining Operations Including Marine Mineral Mining) provides independent advice on potential environmental impact from land-based and marine-minerals mining, including tailing disposal in the marine environment. A report is being prepared by this working group, which will inform the IMO (International Maritime Organisation) in the context of the London Convention/London Protocol on the Prevention of Marine Pollution by Dumping of Waste and Other Matter (IMO, 2012). In addition, a group of international experts has started working towards a document that will provide guidelines for best available practices and techniques for submarine and deep-sea tailing disposal (Ramirez-Llodra, pers. com.). Nevertheless, to date, no general best available techniques and practices exist for disposing of mine tailings in the marine environment (neither shallow nor deep). In Europe, the EU MWEI BREF mostly assesses land-based solutions and does not include specific BATs for submarine disposal of tailings, even though this tailing management system has been used in several countries (e.g. Norway, France, UK, Greece) for decades (Ramirez-Llodra et al., 2015). Legislation will also be modulated by societal's acceptance or opposition to tailings from land-based mines being disposed in the ocean. And such acceptance/opposition will be driven by society's understanding of the potential impacts of STDs on ecosystem services (i.e. the ecosystem functions that have a benefit to us humans, such as biomass production for fisheries, aquaculture, tourism). STDs are heavily debated in Norway and other nations that dispose tailings from land-based mines in the marine environment. Social impacts, threats and values need to be fully recognized in the decision-making process (reviewed in Ramirez-Llodra et al., 2015; Reichelt-Brushett, 2012; Vare et al., 2018).

Here, we recommend that the authorities of countries with ongoing or planned STDs or DSTDs initiate a process of defining a set of overarching guidelines that will ensure that environmental impacts of mine tailing disposal in the marine environment are minimized and the long-term sustainability of the ecosystem functions and services guaranteed (Reichelt-Brushett, 2012; Vare et al., 2018). The guidelines should include specific information for baseline studies, environmental impact assessments, monitoring during operations, closing plans and post-closure monitoring. The guidelines should be developed in collaboration with the scientific community and industry, to ensure that they are based on robust scientific knowledge and the latest analytical tools and methods available. Lastly, the guidelines should follow an adaptive management system, allowing for adjustment as new knowledge and new techniques become available. For instance, the current monitoring in Norway is based on the quality elements set by the Water Framework Directive. Such monitoring should be more adapted to the specific discharge, and also include other effect indicators than what is measured in standardized monitoring programs. For instance, as the epifauna was more vulnerable than the infauna in the field study, monitoring of this ecosystem component would be in accordance with the precautionary principle (Trannum et al., 2019). Furthermore, it is recommended to also consider functional approaches to assess the effects of tailings in the ecosystem and the services it provides. Regarding chemical aspects, to be able to detect effects on fauna, appropriate biomarkers should be considered. This is particularly important for chemicals without any EQS-values (environmental quality standard) in sediment or biota, like most process chemicals. Close cooperation with mining industries and the producers of process chemicals is of high importance to fine-tune the analytical methodologies and to establish the list of suspected chemical compounds structures to be further tracked in the environment. Sensitive chemical analyses of trace metals and production chemicals potentially present in sediment samples are the most accurate methods for mapping the impact area of the STD and validation of applied models for particle transport.

Monitoring capacity and accuracy are greatly and rapidly developing in parallel to technological developments such as autonomous underwater vehicles, molecular methods and modelling. A wealth of guidelines and criteria are already available from similar actives, in land-based tailings management, deep-sea tailings disposal in Papua New Guinea and Indonesia (Shimmield et al., 2010; Hughes et al., 2015; Vare et al., 2018) and the currently developing regulations for deep-sea mining (Jones et al., 2019; Durden et al., 2018). Although each marine environment will have unique characteristics to consider (e.g. depth, hydrodynamics, geochemical variables, faunal biodiversity and biomass), knowledge exchange among experts with different backgrounds can greatly improve the current management of tailings disposal at sea.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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