PAME-workshop 2023

# Marine Tailing Disposal: The Norwegian Experience

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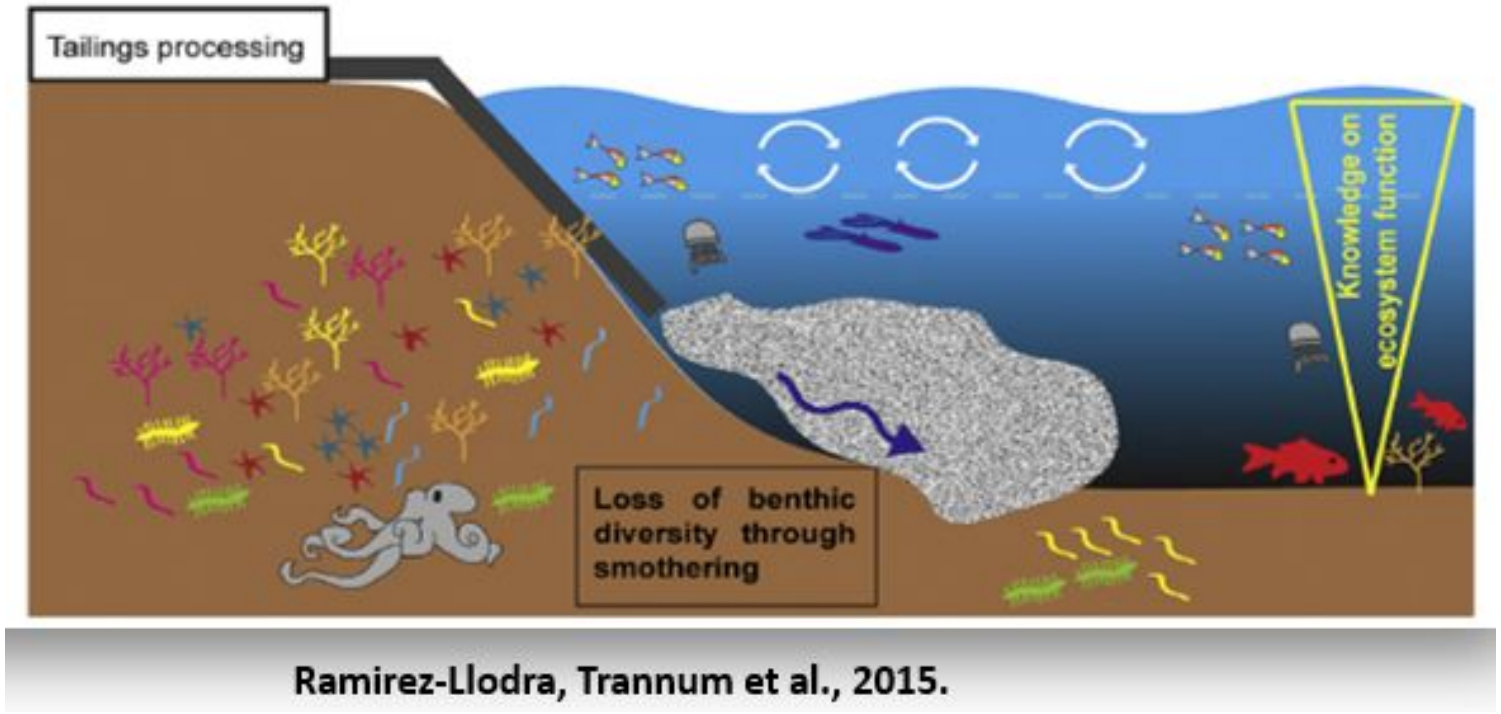
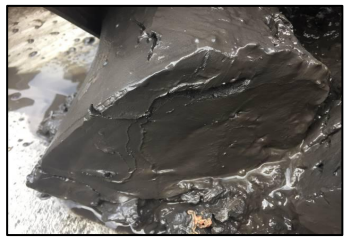
Norsk institutt for vannforskning

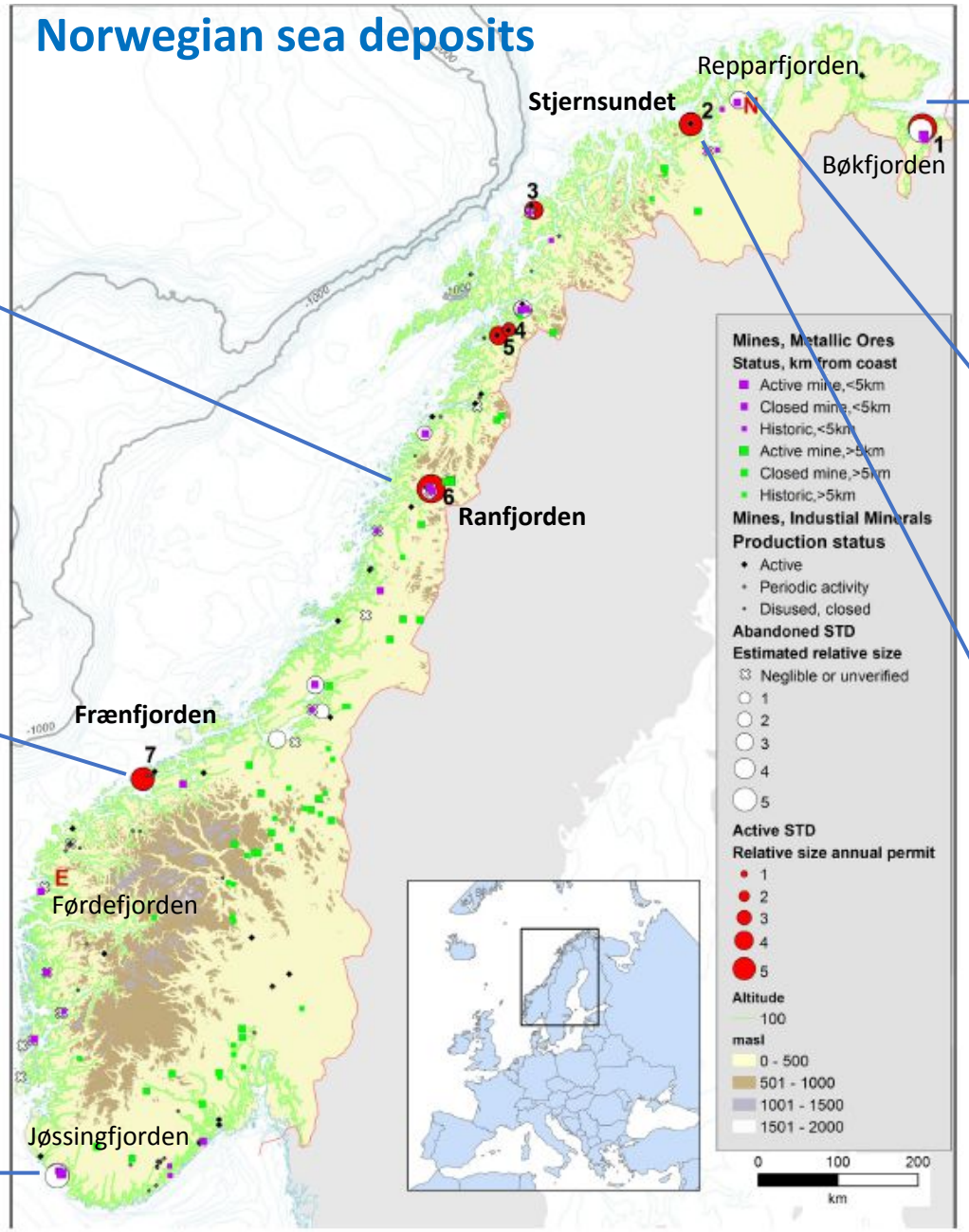
# Submarine tailings disposal (STD)

- Disposal of tailings in the sea
- In Norway, fjords are often selected as disposal sites because
  - Many mineral ores are located adjacent to the coast
  - Natural sedimentation basins
- Magnitude up to order of million tons/year!
- Mine tailings
  - Particles of chrushed stone
  - Minerals and metals
  - Process chemicals



# Norwegian sea deposits






*Ramirez-Llodra, Trannum et al., 2015. Mar. Poll. Bull.*

# Controversial!

Foto: Vidar Ruud


(namdalsavisa.no)


HOW TO KILL A FJORD: Torulf Olsen vil gjøre alt i sin makt for å bevare Repparfjorden ren og frisk. Stivt ulydighet er ikke noe han utelukker. Foto: Nina Hansen

Fjorden forever

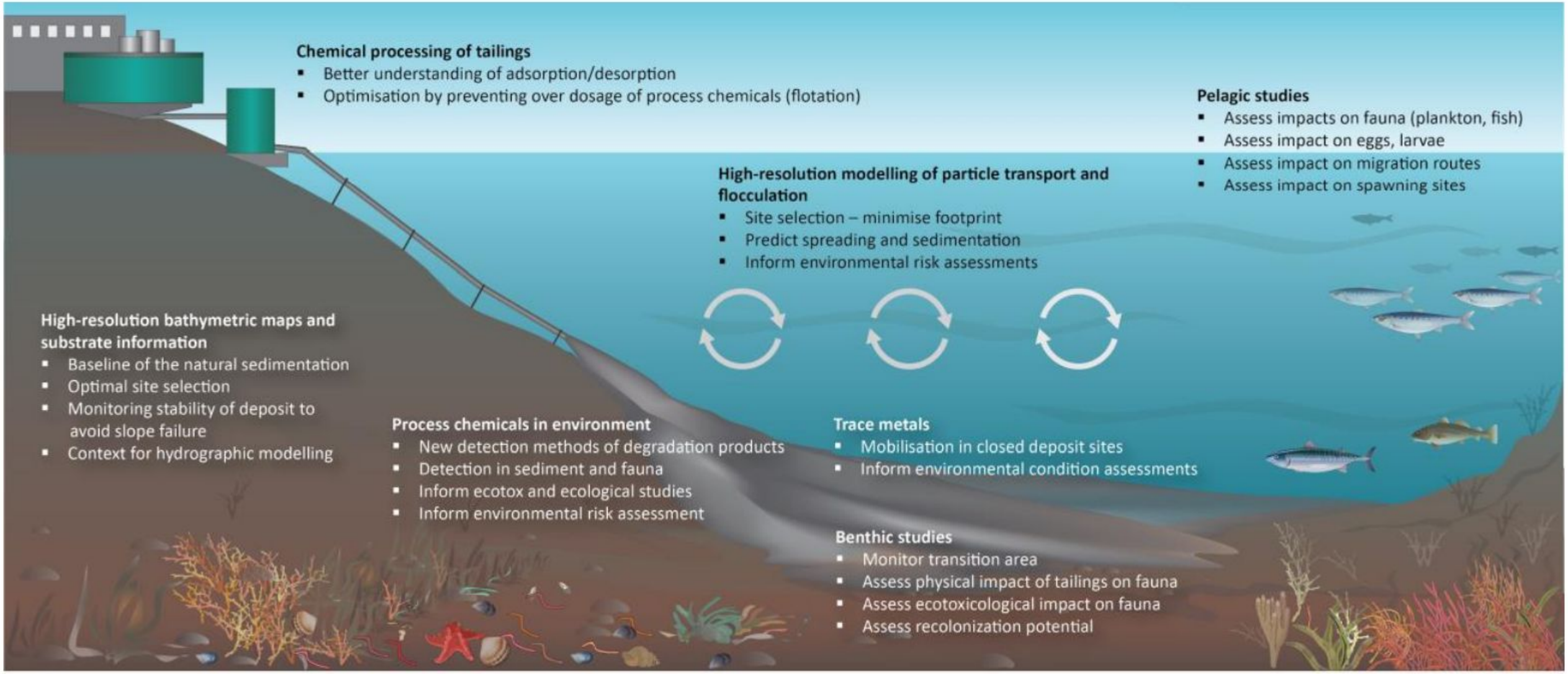
## - De skal ikke få drepe fjorden vår. Ikke faen

Motstanden mot sjødeponiet i Repparfjorden vokser, også internasjonalt. Torulf Olsen vil kjempe til siste pust, mens politikere på Sametinget har knyttet bånd med aksjonister fra Standing Rock.

Demonstrantene i Repparfjorden i Finnmark lar seg ikke true av trusler om verken søksmål eller politi.
FOTO: JONAS LØKEN ESTENSTAD / NRK


(dagsavisen.no)

# Study framework of the research project NYKOS

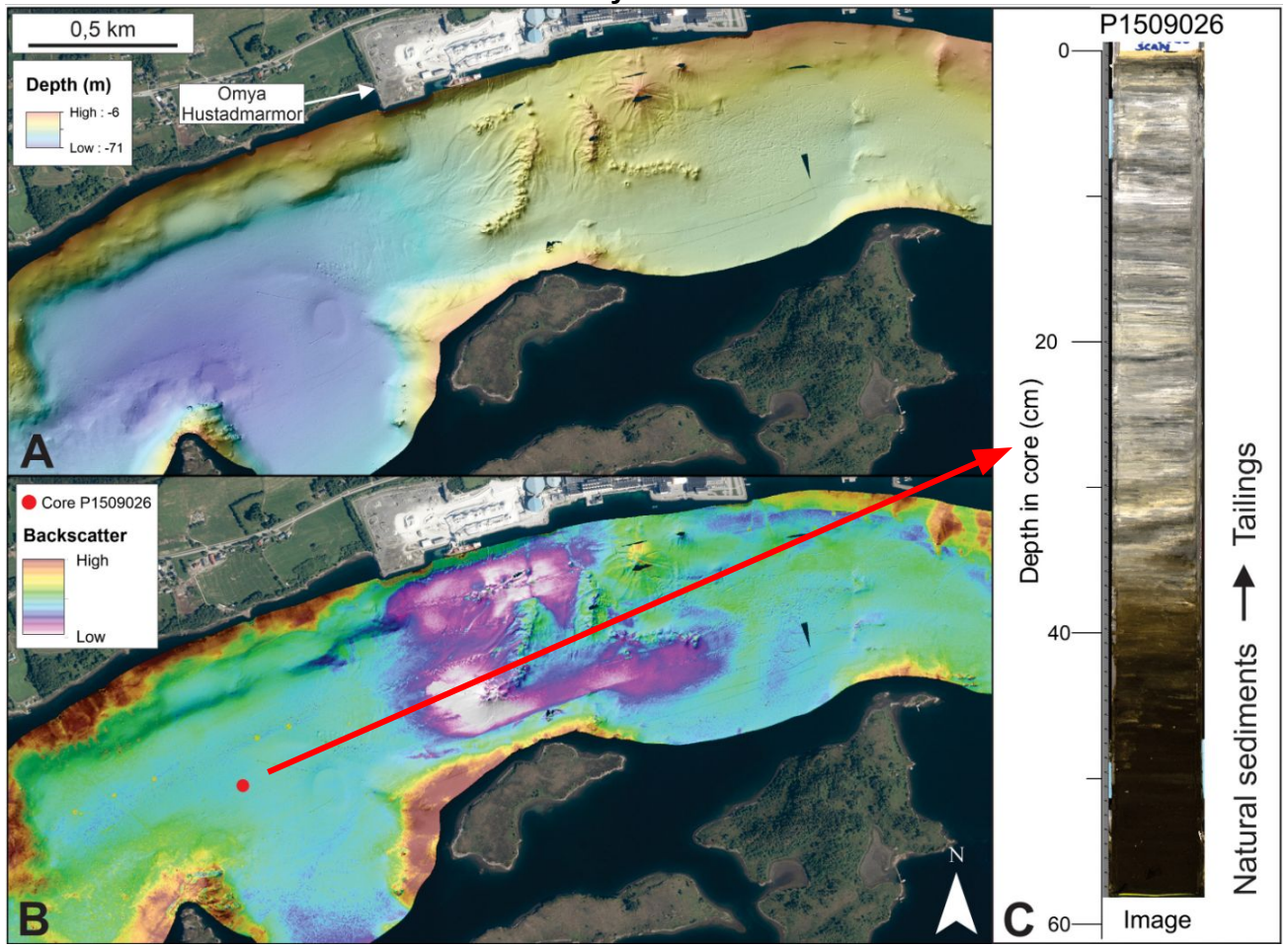



*Ramirez-Llodra, Trannum et al., 2022. Mar. Poll. Bull.*

# Geological mapping and monitoring of the seafloor

- The fjord bathymetry will be permanently altered!
- The dispersal, distribution and stability of submarine tailings are linked to the natural processes operating on the seafloor
- Modern multibeam echosounder technology can provide 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

Frænfjorden

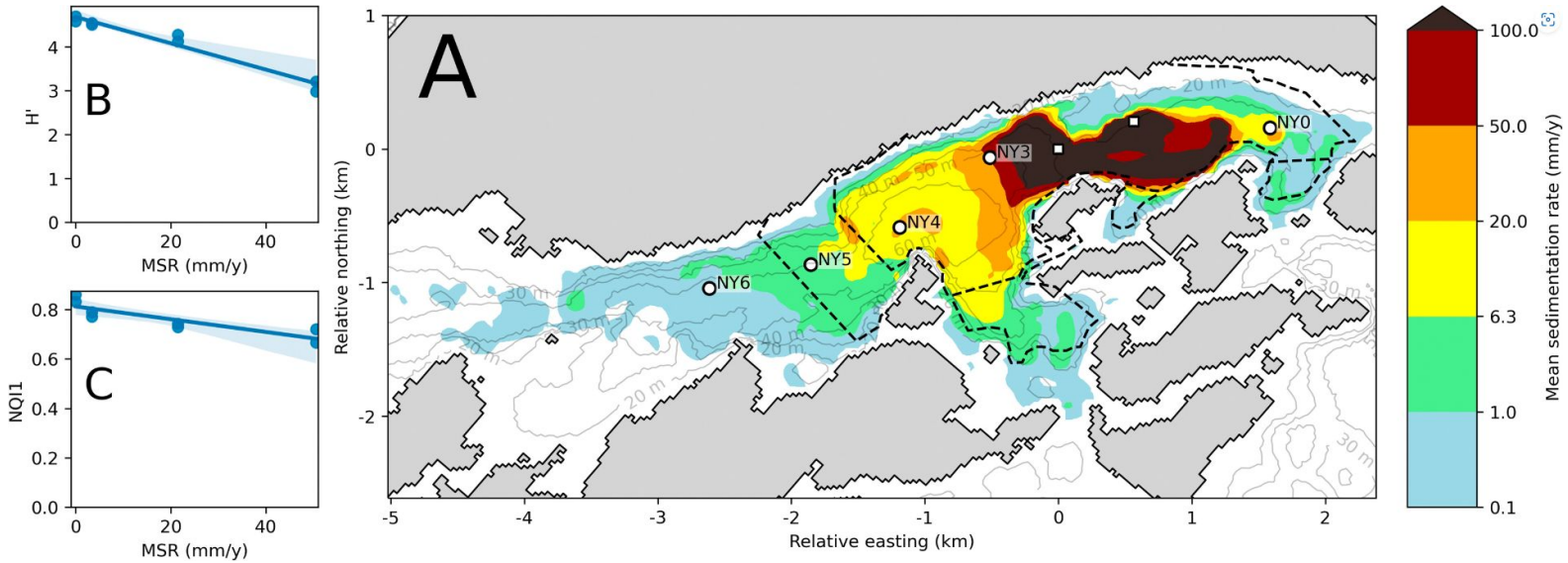



*Baeten et al., 2020, Nor. J. Geol.*

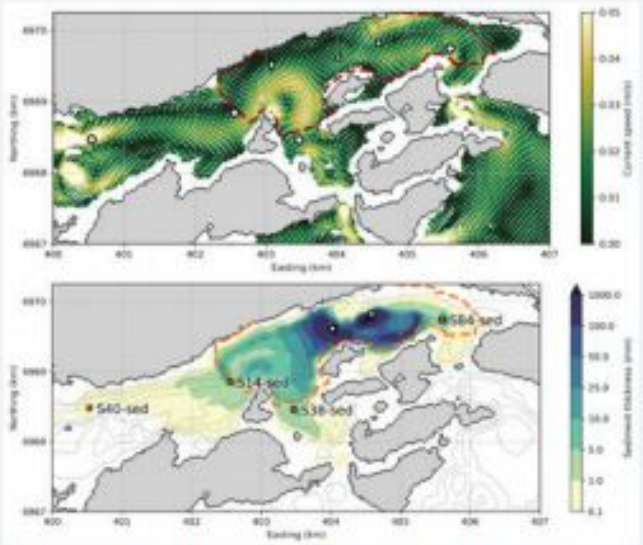
# Modelling and measuring spreading of tailings particles

- A new particle imaging system to directly observe mine tailings flocs in the ocean was developed
- Numerical models that can simulate the spreading and flocculation of tailings particles were developed

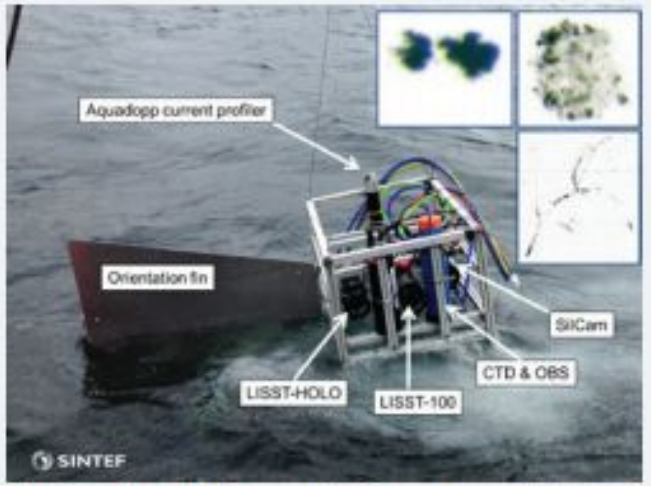
- Model simulations combined with knowledge on biological impacts of tailings can be used to determine environmental risk
- Model simulations can be used to minimize environmental footprint through optimization of the discharge




*Nepstad et al., 2020, Reg. Stud. Mar. Sci.*
*Ramirez-Llodra et al., 2022, Mar. Poll. Bull*




*Results from numerical model simulations. Top: ocean currents in Frænfjorden showing eddy structures at 20 m depth (month average). Bottom: sedimentation rates from a tailings scharge.*




*Floc imaging and supporting instruments being deployed in Frænfjorden.*

# Dynamics of process chemicals pre and post discharge

- In the processing plant: State and mobility of chemicals in tailings mixed with sea water prior to discharge was studied
- In the environment: Transformation products of chemicals were studied, by a novel analytical procedure

- Transformation product of a flotation chemical was detected in sediments, pore water and benthic fauna (holothurians) and blue mussels up to 2 km from the discharge outlet
- A suite of biomarkers measured in the mussels indicated a clear stress response

- The methodology developed revealed a large potential to develop advanced monitoring strategies and to understand how process chemicals in mine tailings migrate and transform in the environment.

*Sediment samples from Frænfjorden (left) where taken using a Gemini corer (right). Photo: E. Ramirez-Llodra (NIVA).*

*Deployment of mussels in a fjord recipient to study environmentally relevant impacts of the tailings to mussel health and chemical bioaccumulation.*

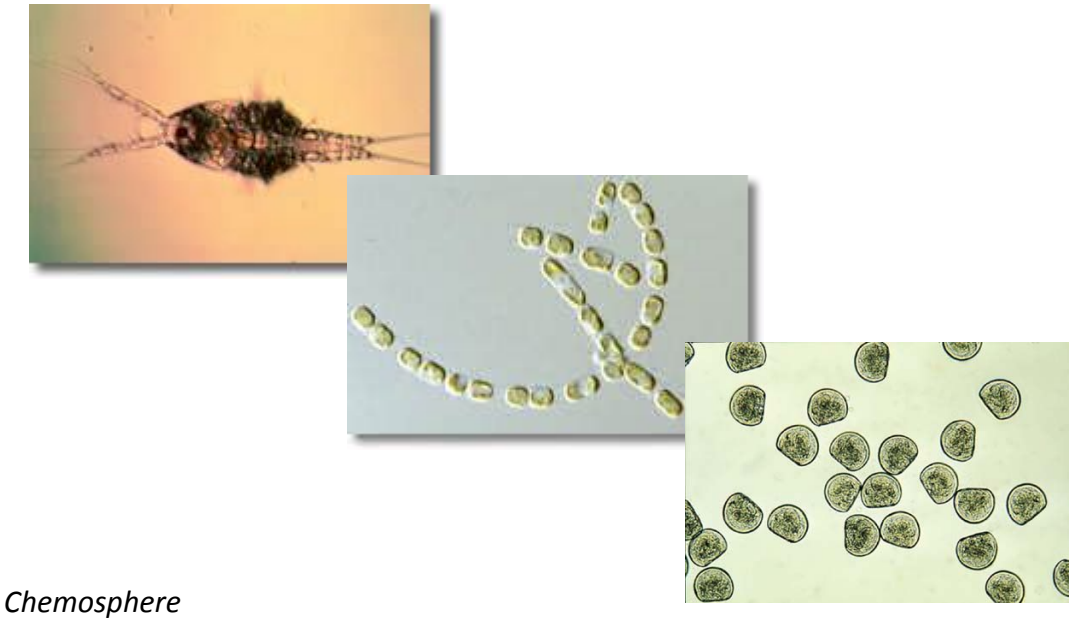
*Sea cucumbers sampled in Frænfjorden being prepared for analysis of process chemicals. Photo: C. Escudero (NIVA).*

*Ibragimova and Kleiv, 2018*
*Brooks et al., 2018, Mar. Environ. Res.*

# Ecotoxicology

- Ecotoxicity assessments (algae, Crustacea, and Mollusca) with different tailings
  - Sibelco (no chemicals)
  - Sydvaranger (flocculation chemicals)
  - Omya Hustadmarmor (flotation chemicals, very fine sediment)

- Differences in particle and waterborne toxicity between the mine tailings
  - Sibelco tailings were most toxic based on waterborne exposures
  - Hustadmarmor tailings were most toxicity based on sediment exposures




*Brooks et al., 2019, Chemosphere*

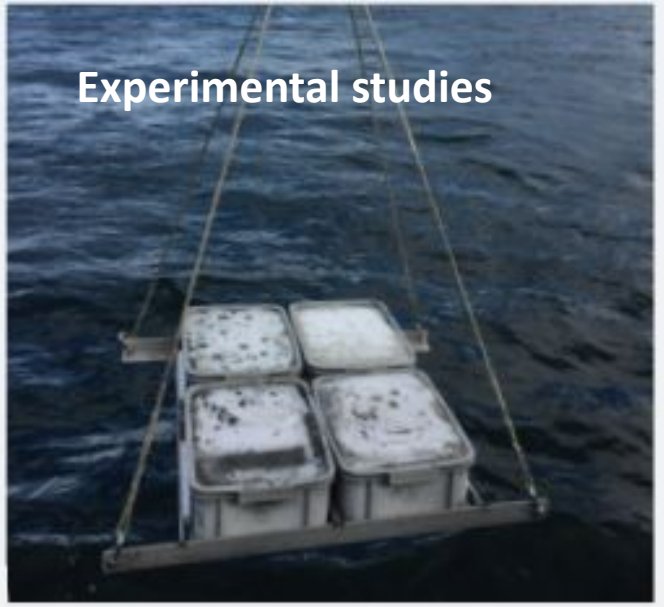
# Effects on benthic fauna

- Responses were studied at the benthic community level (structure & function) with the three different tailings
- The experimental studies showed:
  - Significant effect of all tailings > 2 cm
  - Most pronounced effects of fine-grained tailings with flotation chemicals (Hustadmarmor)
  - Rapid initial colonization
- The field studies showed:
  - The infauna close to the tailings outflow was dominated by tolerant species, indicating a community shift
  - The abundance of epifauna showed a stronger reduction close to the tailing outflow than the infauna

***In situ* (Frænfjorden - Hustadmarmor)**



*Trannum et al., 2018; 2019; 2020*

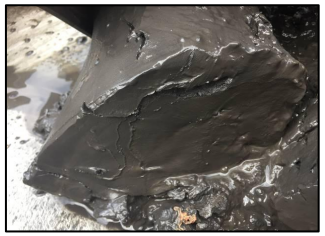



*Recolonization experiment where sediments capped with thin layers of tailings are subject to colonization of benthic fauna. Photo H.C. Trannum*

*Mesocosm experiment where benthic fauna is exposed to mine tailings. Photo H.C. Trannum*

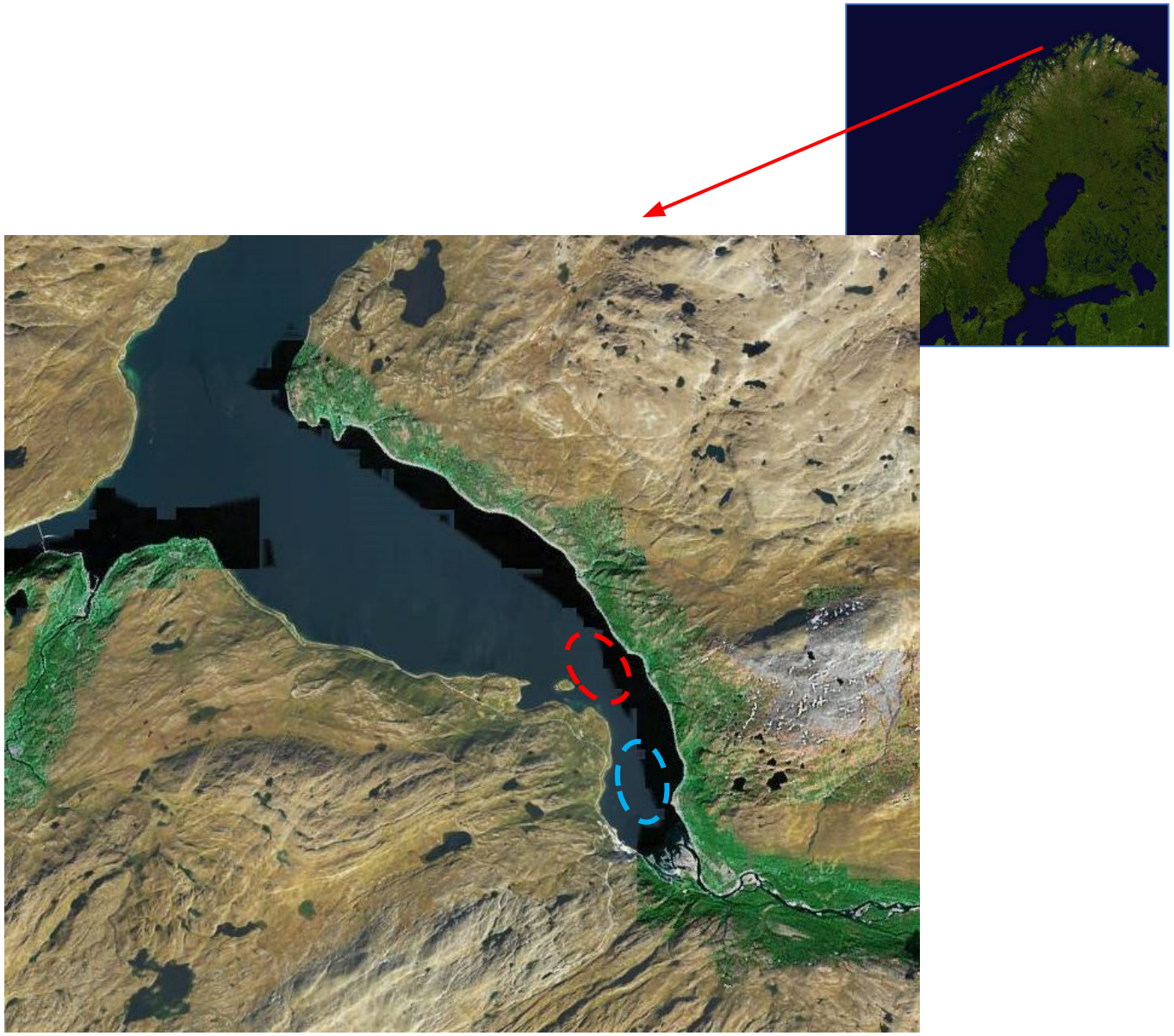
Repparfjorden (Nussir)

Old (and new) sea deposits
Sulfide tailings



Jøssingfjorden (Titania)

# Repparfjorden – past and present

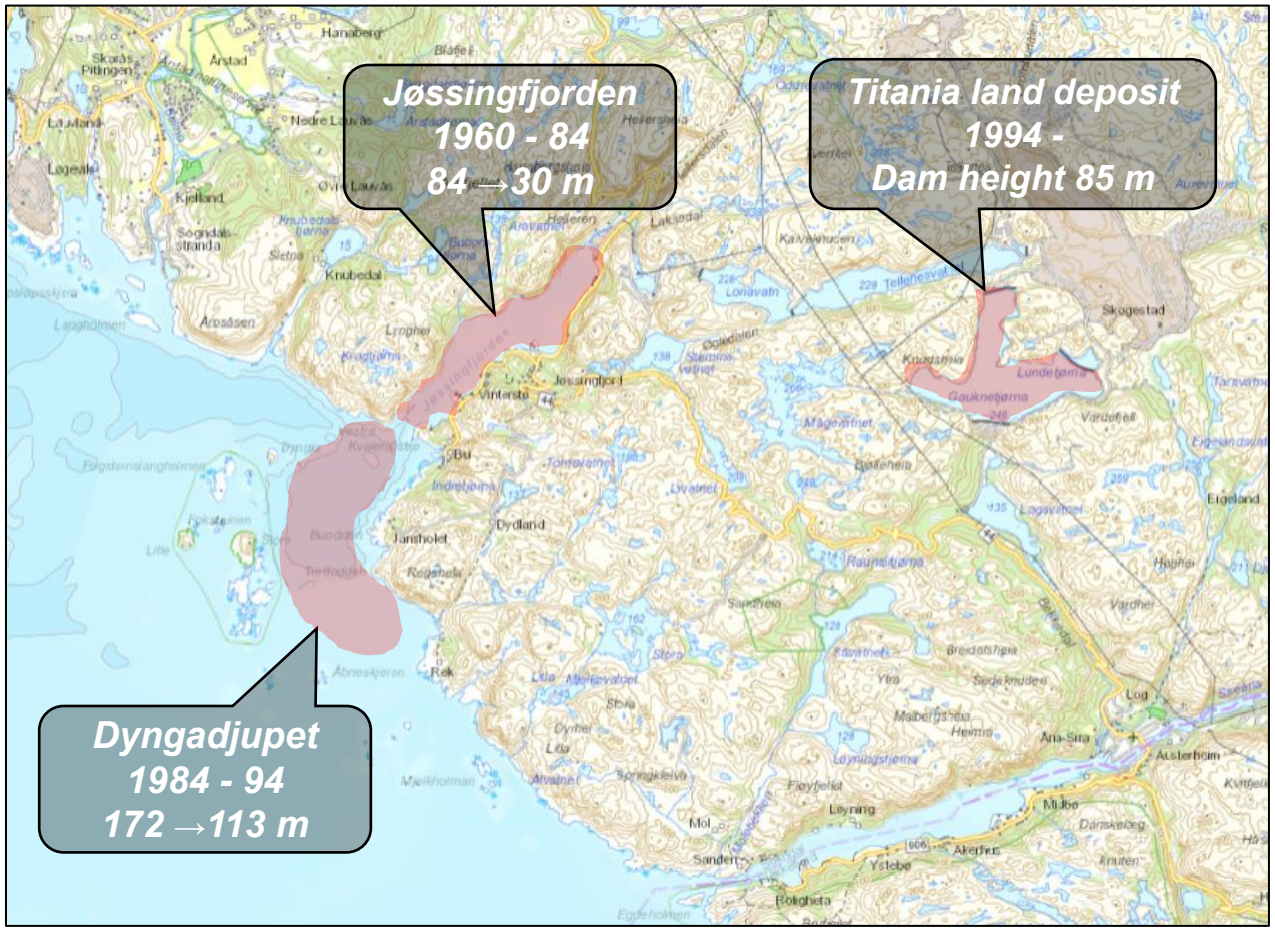


## Disposal of mine tailings

1972-1978: Disposal of approx. 1 million ton of copper-mine tailings

2019: Permit for new disposal
Operating period ~30 years
1-2 million ton mine tailings pr year

# Jøssingfjorden – past and present




## Disposal of mine tailings

1960 - 1994: Sea disposal

1994 - present: Land deposit

Future disposal where?

# Mesocosm experiment: Nussir and Titania tailings

**Method:** Mesocosm – multispecies test

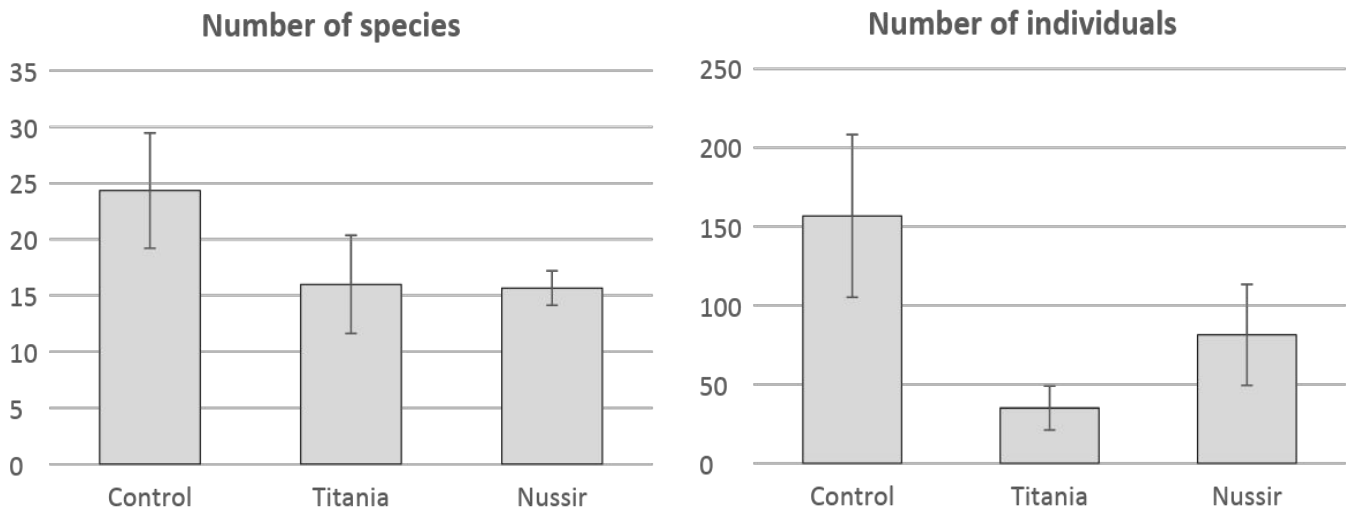
**Treatments:**

- Control
- Titania tailings (2 cm)
- Nussir tailings (2 cm)

**Duration:** 4.5 months

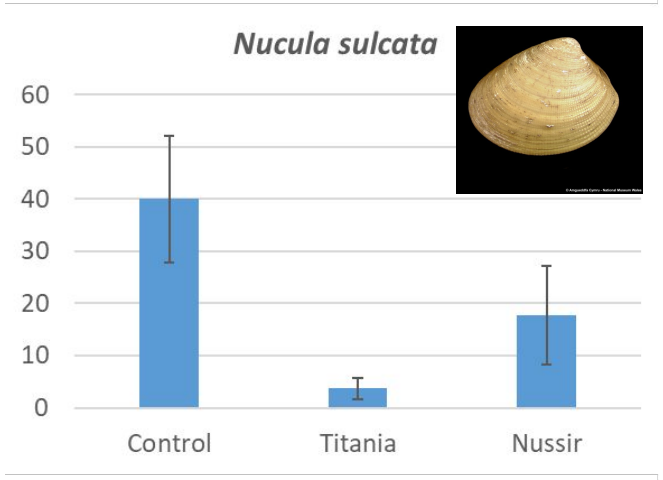
**Samples:** Macrofauna, sediment parameters, trace metal concentrations

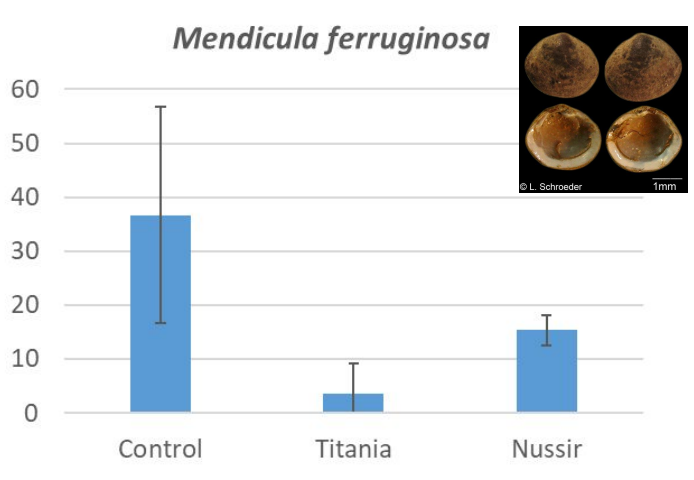
# Mesocosm: Mine tailings affected sediment communities










**Main findings:**

- Mortality in both tailings treatments
- High metal levels in tailings treatments

*Trannum & Schaanning, 2017;*
*Schaanning & Trannum in prep.*

# Repparfjorden colonisation experiment

**From seabed to defaunation and manipulation to seabed**

**Location:** Repparfjorden – close to new deposit site

**Method:** Experimental trays, Repparfjorden tailings

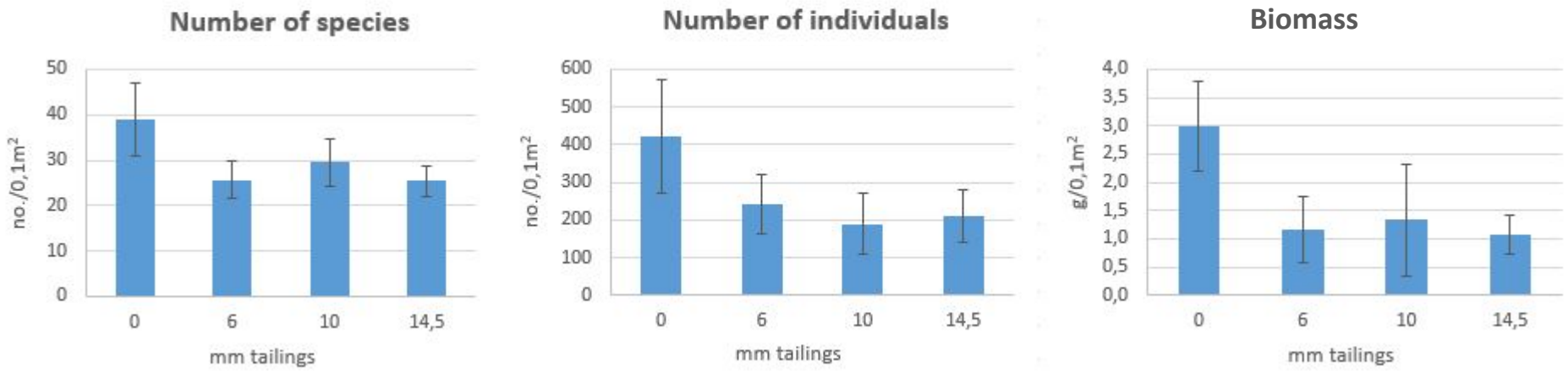
**Treatments:**

- Control
- 6 mm tailings
- 10 mm tailings
- 14.5 mm tailings

**Duration:** 15 months

**Samples:** Macrofauna, sediment parameters, trace metal concentrations

# Mine tailings negatively affected colonization of marine species

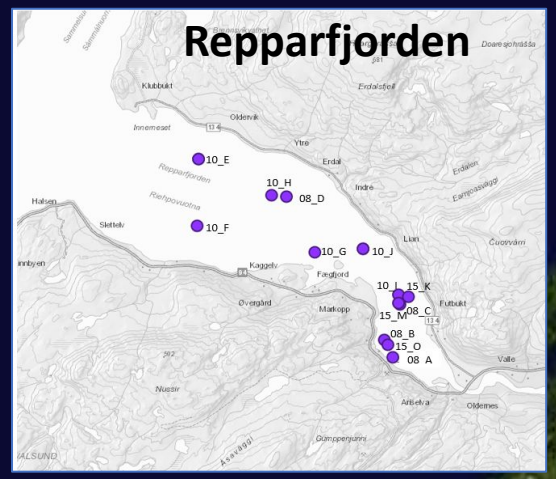



**Main findings:**

- Rapid initial colonization
- Reduced colonization at a scale of mm
- Changed substrate and/or toxic effect?

*Trannum et al., 2023, J. Sea Res.*

# The seafloor is still affected by the old deposits





Main findings:

- Tailings from the old deposit are still present and enriched in metals
- The fauna obtains class «good», according to the WFD, altough there are signs of stress
- Full community recovery and normalisation of metal leakage rates may take several decades, despite an initial rapid colonization

- Capping may prevent long-lasting effects

*Schaanning, Trannum et al., 2019, Mar. Poll. Bull*
*Trannum et al., 2023, J. Sea Res.*

# Impact mechanisms of mine tailings

- Common for all mine tailings:
  - Hypersedimentation (-> food dilution)
  - Allochtonous material in the marine environment
  - Chrushing and grinding increase the surface area and the reaction rates
- Depending on the ore and process plant:
  - Size (often very small)
  - Shape (freshly grinded, sharp edges, needles)
  - Reactive minerals (e.g. sulphides)
  - Remnants of process chemicals (flotation & flocculation)
- Fine-grained tailings with flotation chemicals were most harmful

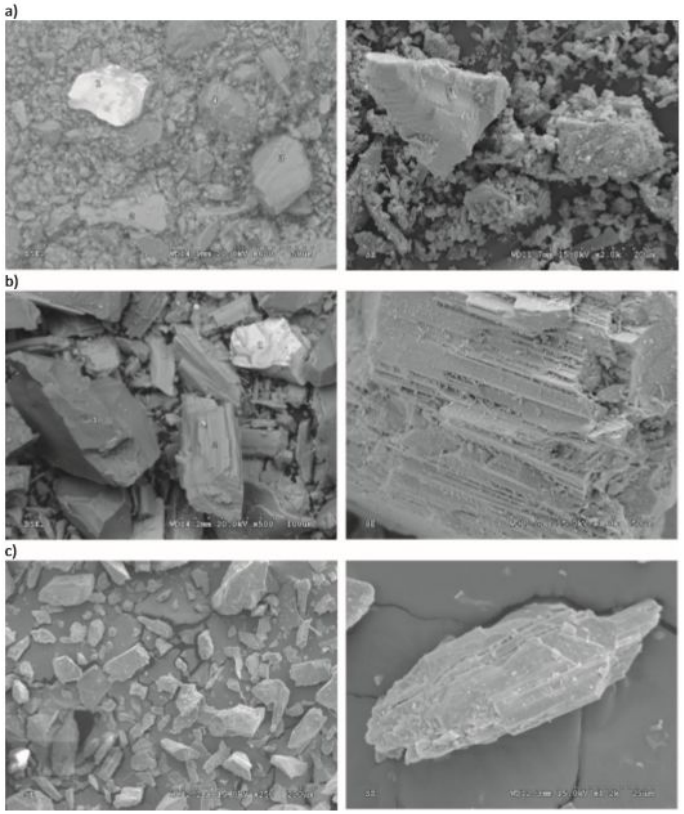
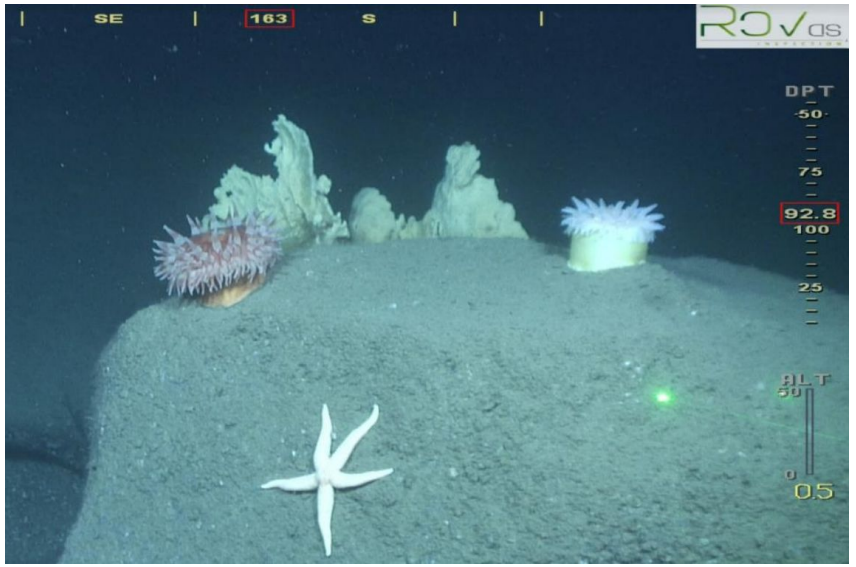



Fig. 1. SEM pictures acquired at two magnifications of tailings from a) Hustadsmarmor, b) Sibelco and c) Sydvaranger.

*Trannum et al., 2018. Sci. Tot. Env.*

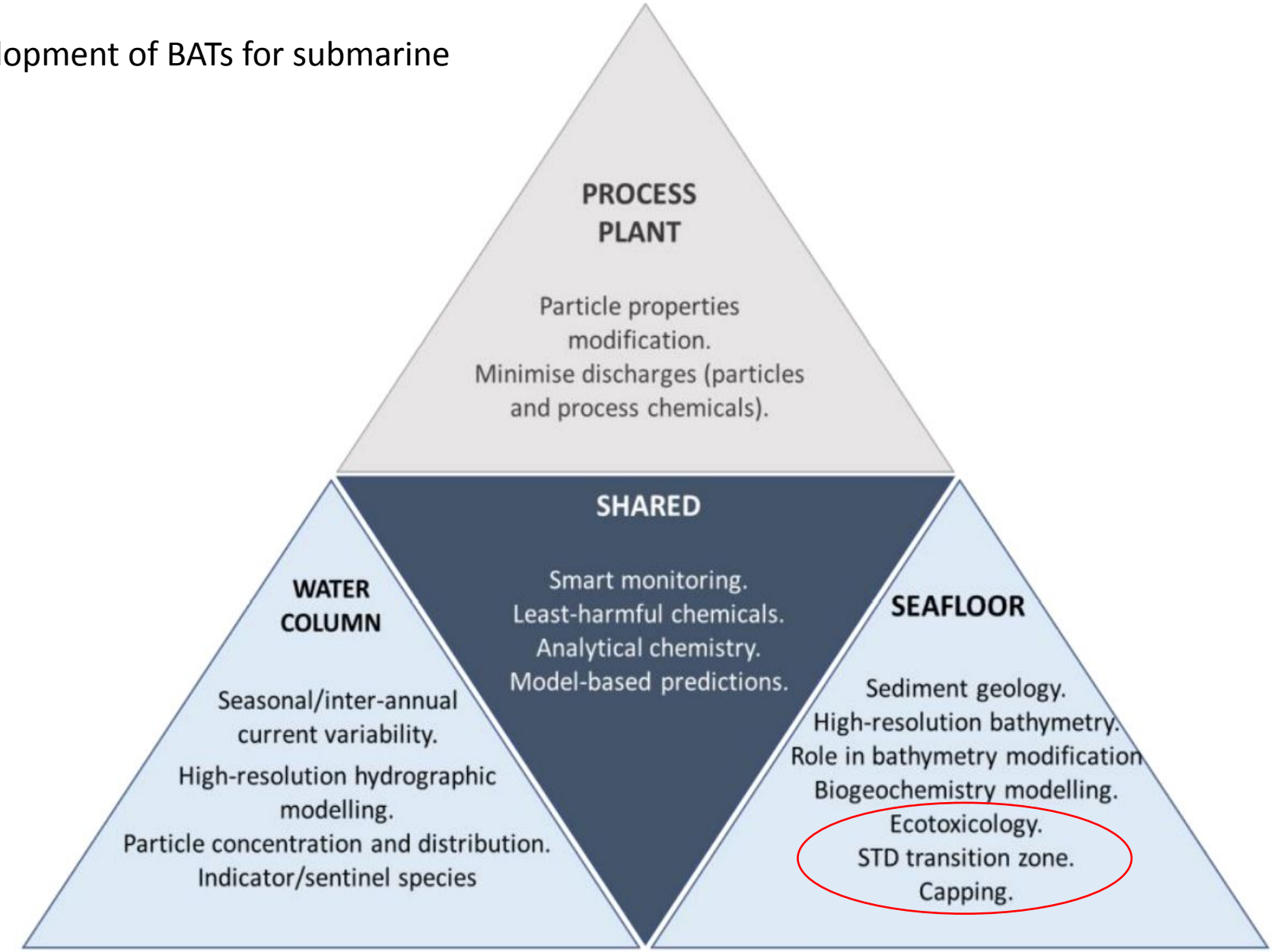
# “Biological” knowledge gaps

- Better understanding of
  - effects on the pelagic community
  - effects on hard substrate/sessile fauna
  - the particular impact mechanisms and effects of particle shape and size in particular
  - the potential for accumulation and trophic transfer of tailings-associated contaminants (metals and chemicals) in biota
- Development of ecological indicators and thresholds to identify serious harm
- Cumulative impacts with other stressors (climate change, other industry, …)



# Development of BATs

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




*Ramirez-Llodra, Trannum et al., 2022. Mar. Poll. Bull.*

# FURTHER READING

Science of the Total Environment 644 (2018) 1056–1069



Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

## An integrative biological effects assessment of a mine discharge into a Norwegian fjord using field transplanted mussels

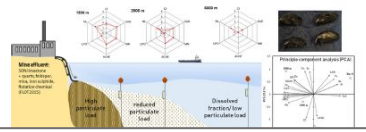
S.J. Brooks [a,*], C. Escudero-Oñate [a], T. Gomes [a], L. Ferrando-Climent [b]

[a] Norwegian Institute for Water Research (NIVA), Gaustadalléen 21, NO-0349 Oslo, Norway
[b] Trace Technology Department, Oil and Gas Section, Institute for Energy Technology, P.O. Box 40, NO-2027 Kjeller, Norway

HIGHLIGHTS

- Transplanted mussels used to discover biological effects of suspended mine tailings
- Biomarkers and chemical body burden measured in field transplanted mussels
- Detection of MTA a chemical marker for flotation chemical (FLOT2015) in mussels
- Link between MTA, metals and biomarker responses with distance from discharge point
- IBR and PCA linked chemical exposure

GRAPHICAL ABSTRACT



Science of the Total Environment 630 (2018) 189–202



Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

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

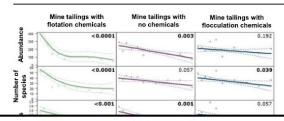
Hilde C. Trannum *, Hege Gundersen, Carlos Escudero-Oñate, Joachim T. Johansen, Morten T. Schaanning

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

HIGHLIGHTS

- Dose and response of 3 types of mine tailings studied in a soft-bottom mesocosm
- Apparent effect threshold at 2 cm layer thickness
- All tailings affected the fauna through more factors than hypersedimentation.
- Most severe effects of fine grained $CaCO_3$ with remnants of flotation chemicals.

GRAPHICAL ABSTRACT




Marine Pollution Bulletin 141 (2019) 318–331



Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

## Benthic community status and mobilization of Ni, Cu and Co at abandoned sea deposits for mine tailings in SW Norway

Morten Thorne Schaanning*, Hilde Cecilie Trannum, Sigurd Øxnevad, Kuria Ndungu

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ARTICLE INFO

Keywords:
Mine tailings
Sea deposit
Metals
DGT
Macrofauna
Jøssingfjord

ABSTRACT

During 1960–94 tailings from an ilmenite mine in southwest Norway were placed in sea deposits in a sheltered fjord and a more exposed coastal basin. In 2015 both deposit sites were sampled to assess the state of metal contamination and macrobenthic communities 20–30 years after deposition was ended. The results showed that nickel and copper still exceeded environmental quality standards in sediment and pore water from the 0–1 cm layer, and fluxes of nickel, copper and cobalt to the overlying water was high compared to adjacent reference stations. Fauna communities were classified as *good*, but moderate disturbance was recorded along an environmental gradient defined by depth and tailings-induced parameters such as particle size and copper. The

Marine Pollution Bulletin 97 (2015) 13–35



Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Review

## Submarine and deep-sea mine tailing placements: A review of current practices, environmental issues, natural analogs and knowledge gaps in Norway and internationally

Eva Ramirez-Llodra [a,*], Hilde C. Trannum [a], Anita Evenset [b], Lisa A. Levin [c], Malin Andersson [d], Tor Erik Finne [d], Ana Hilario [e], Belinda Flem [d], Guttorm Christensen [b], Morten Schaanning [a], Ann Vanreusel [f]

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[d] Geological Survey of Norway, Postboks 6315 Sluppen, 7491 Trondheim, Norway
[e] Departamento de Biologia & CESAM, Universidade de Aveiro, Portugal
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ARTICLE INFO

Article history:
Received 26 March 2015
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Accepted 24 May 2015
Available online 3 June 2015

ABSTRACT

The mining sector is growing in parallel with societal demands for minerals. One of the most important environmental issues and economic burdens of industrial mining on land is the safe storage of the vast amounts of waste produced. Traditionally, tailings have been stored in land dams, but the lack of land availability, potential risk of dam failure and topography in coastal areas in certain countries results in increasing disposal of tailings into marine systems. This review describes the different submarine tailing



Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

## An ecotoxicological assessment of mine tailings from three Norwegian mines

Steven J. Brooks*, Carlos Escudero-Oñate, Adam D. Lillicrap

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HIGHLIGHTS

- Differences in particle and waterborne toxicity between the 3 mine tailings.
- Sibelco tailings were the most toxic based on waterborne exposures.
- Elevated metal concentrations in the Sibelco tailings were responsible for the toxicity.
- Fine particles (Hustadmarmor) showed highest toxicity when in contact with sediment.

ARTICLE INFO

Article history:
Received 2 April 2019
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31 May 2019
Accepted 1 June 2019
Available online 4 June 2019

ABSTRACT

The study assessed the environmental toxicity of three Norwegian mine tailings from Omya Hustadmarmor, Sydvaranger, and Sibelco, which are all released into a seawater recipient. Ecotoxicity assessments were performed on the overlying water extracted from the mine tailings, the transformation/dissolution waters obtained from the mine tailings, and whole sediment assessment using a suite of marine organisms including algae, Crustacea, and Mollusca. Overall, based on the toxicity evaluation of the transformation/dissolution data, Sibelco tailings resulted in the highest toxicity albeit at relatively

Marine Pollution Bulletin 149 (2019) 110560



Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

## Epifaunal and infaunal responses to submarine mine tailings in a Norwegian fjord

Hilde C. Trannum [a,b,c], Gunhild Borgersen [a], Eivind Oug [a], Tormod Glette [c], Lucy Brooks [c], Eva Ramirez-Llodra [a]

[a] Norwegian Institute for Water Research, Gaustadalléen 21, NO-0349 Oslo, Norway
[b] Center for Coastal Research, University of Agder, NO-4604 Kristiansand, Norway
[c] DNV GL, Veritasveien 1, NO-1363 Høvik, Norway

ARTICLE INFO

Keywords:
Mine tailings
STD
Biological traits analysis
Functional diversity
Infauna
Epifauna

ABSTRACT

Disposal of mine tailings in marine shallow water ecosystems represents an environmental challenge, and the present paper reports results from a field study in Frænfjorden, Norway, which is subject to such disposal. Structural and functional responses of benthic infauna and epifauna were investigated along a gradient from heavy tailings deposition to reference conditions. The tailings clearly impacted the faunal composition, with lowered species number close to the outfall. Total abundance of infauna increased in the most impacted area due to dominance of opportunistic species, whereas the epifauna was reduced and represented by a few scattered specimens only. In the most impacted area functional responses included an increase in mobile carnivores/

Science of the Total Environment 708 (2020) 134866



Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

## Macrofaunal colonization of mine tailings impacted sediments

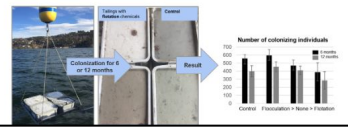
Hilde C. Trannum [a,b,*], Rita Næss [a], Hege Gundersen [a]

[a] Norwegian Institute for Water Research, Gaustadalléen 21, NO-0349 Oslo, Norway
[b] University of Agder, Center for Coastal Research, NO-4604 Kristiansand, Norway

HIGHLIGHTS

- Effects of mine tailings on benthic colonization were experimentally studied.
- All sediments capped with mine tailings were successfully colonized within 6 months.
- Abundances of annelids were lower, while mollusks were higher in tailings treatments.
- Fine-grained tailings with remnants of flotation chemicals had most

GRAPHICAL ABSTRACT




Marine Pollution Bulletin 174 (2022) 113150



Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Review

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

Eva Ramírez-Llodra [a,b,*], Hilde Cecille Trannum [a,c], Guri S. Andersen [a], Nicole J. Baeten [d], Steven J. Brooks [a], Carlos Escudero-Oñate [a,1], Hege Gundersen [a], Rolf Arne Kleiv [a], Olga Ibragimova [a], Alvo Lepland [a], Raymond Nepstad [a], Roar Sandøy [a], Morten Thorne Schaanning [a], Tracy Shimmield [b], Evgeniy Yakushev [a], Laura Ferrando-Climent [i], Per Helge Høgaas [f]

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ABSTRACT

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 envi-

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## Recolonization and recovery of an Arctic benthic community subject to mine-tailings deposits

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ABSTRACT

Deposition of large volumes of mine tailings takes place in several Norwegian fjords, but the impacts on marine ecosystems have received relatively little scientific attention. At a 40 + year old tailing deposition area for a copper mine in the Arctic fjord Repparfjorden, we investigated both short-term colonization of mine tailings-contaminated sediments through a field experiment, and the present faunal state in the old deposit area. Copper-concentrations at the old deposition site were still high (up to 291 mg/kg dry weight (dw)), and exceeded the Norwegian environmental-quality threshold (84 mg/kg dw). Furthermore, copper was identified as a significant structuring factor for the fauna in the fjord, although faunal diversity was relatively high and the community not severely disturbed. In the colonization experiment, experimental boxes filled with defaunated sediment capped with mine tailings were subject to colonization for 15 months. Benthic macrofaunal communities were successfully established in all boxes, but the boxes with tailings showed lower species richness, abundance and biomass than the controls. Mine tailings continue to have local impacts on seafloor communities decades after deposition, and even low levels of metal-rich sediments can affect faunal recruitment. These results have implications for submarine deposition of mining waste and the impacts they have on coastal ecosystems.

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## High-resolution numerical modelling of a marine mine tailings discharge in Western Norway

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ABSTRACT

Waste from mining operations includes mine tailings, a slurry of fine-grained mineral particles and processing chemicals that remains after the desired compounds have been extracted from the ore. In some cases, the method of disposal is to place tailings into the marine environment; this is known as Submarine Tailings Placement (STP). To understanding the environmental impact of releasing large amounts of mine tailings into the marine system, multiple processes must be well characterised, including those relating to the transport and fate of the disposed material.

We applied a set of high-resolution models for wind, hydrodynamics, and sediment transport to simulate a submarine mine tailings discharge in a Norwegian fjord. The transport model includes processes to account for the effect of flocculation on mine tailings transport and fate. We calculated the mean tailings sedimentation rate in the fjord, which is closely related to the environmental footprint of the STP. Comparisons with measurements of winds, currents, turbidity, and sedimentation rates were made to evaluate the model, and we found overall reasonable agreement. We investigated discharge scenarios during 2013 and identified a strong wind event around November 17, which caused increased particle dispersal. The increased mixing caused by the strong winds were seen in elevated turbidity measurements, as well as increased modelled suspended sediment concentration.



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## Equilibria and Kinetics of Flotation Chemical Sorption Reactions in Tailings-Seawater Systems

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ABSTRACT

Submarine tailings placements (STPs) is a viable alternative to land-based waste disposal. The potential environmental impacts of STPs are the results of oceanographic, biochemical, ecological conditions of the site, while the technical conditions of mineral processing has the incredible importance. In order to justify the application of STPs it is crucial to evaluate the tailings as non-toxic materials at the point of disposal. The properties of the tailings are affected by comminution and separation processes, but there is a considerable potential for improving these characteristics through novel approaches to dewatering and flocculation, as well as the recycling of process water and process chemicals. When collector molecules bound to a mineral surface by physical adsorption and exposed to seawater with its much higher ionic strength, significant desorption can occur (Schwarzenbach et al., 2003). By investigating the desorption characteristics of the adsorbed collectors, important information regarding their mobility could be obtained and facilitate improved solutions for chemical recycling or immobilisation. By using a second thickening step, a significant amount of the dissolved collector could be concentrated in a relatively small volume. In process

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## Marine mine tailings disposal at Lillebukt, Stjernsundet, North Norway: distribution, sedimentary processes and depositional impacts

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Sibelco Nordic's mine on Stjernøya, North Norway, disposes mine tailings into the fjord Stjernsundet. The tailings, discharged at the shoreline in the bay of Lillebukt, comprise c. 85% fine silt to medium-grained sand (0.01–0.5 mm). Upon discharge of the mine tailings into the fjord, they are redistributed by slides and density currents along major channels with pronounced levees. Multibeam echosounder data show sand waves in the channels, while seabed samples and cores document sand ripples and layers of mud between the sand layers. Mud accumulates outside of the channels on the seabed in Lillebukt and as a thin veneer along the shores to the east and west. The bathymetry data show partly buried slide escarpments and slide deposits, while smaller slide scars are evident in the levees. Three slide events in the tailings are documented of which the most recent occurred 9th October 2017. Comparison of bathymetry data collected in 2016 and 2018 show changes in bathymetry in the channels of ± 3 m. Slides are partly initiated along fine-grained layers and caused by hypersedimentation. From 60 m depth, one single channel continues down to 300 m, where the sediment transport is along a gully in the steep (45°) bedrock slope down to c. 400 m depth. A sand-dominated submarine fan has accumulated at the foot of the slope, extending to c. 463 m depth. Bathymetric data, seismic data and core analysis show that the fan has a radius of up to 1500 m and covers an area of c. 1.5 km$^2$. Comparison of bathymetry data collected in 1998 and 2016 shows that a large part of the tailings disposed of in that 18-year period (4 million tons) have accumulated on the submarine fan.

*Keywords: Submarine tailings placement, Submarine slide, Submarine fan, Seabed morphology, Sedimentary environment, Environmental impact*

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