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

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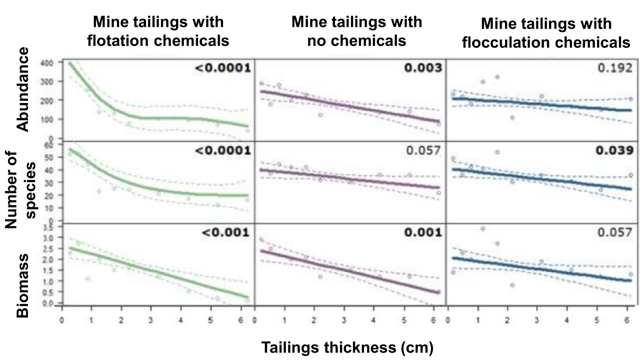
## HIGHLIGHTS

- 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.
- Indications were found on *in situ* biodegradation of flotation chemicals.

## GRAPHICAL ABSTRACT

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## ABSTRACT

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



## 1. Introduction

The mining sector is growing in parallel with societal demands for minerals (Ramirez-Llodra et al., 2015). Historically, the mining industry has been a vital economic driver, and the industry remains necessary for the global economy as it contributes jobs, social benefits, infrastructure, wealth, and the vast array of goods that are part of everyday modern life (Hudson-Edwards, 2016). At the same time, the mining activity produces large volumes of unwanted waste and profitless materials (including rock, sediment, tailings, metallurgical wastes, dusts, ash, and processing chemicals) that are found at or near mine sites in virtually every country in the world (Lottermoser, 2010). Traditionally, tailings have been stored in land dams, and only 0.6% of industrial-sized mines deposit the tailings in the marine environment (Vogt, 2013). However, the lack of land availability, potential risk of dam failure, and

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complex topography in coastal areas result in increasing interest of disposal into marine systems. In Norway, several mines are located in rugged terrain making land-based tailing storage unsuitable. Since these mines are also situated close to fjords, sea disposal has been practiced in Norway (Ramirez-Llodra et al., 2015). Currently, Norwegian tailing discharges are taking place in Frænfjorden (Omya Hustadmarmor, western Norway), Ranfjorden (Rana Gruber, northern Norway) and at Stjernøy (Sibelco, Arctic region), and new deposits have been granted permits in Førdefjorden (Nordic mining, western Norway) and Repparfjorden (Nussir, Arctic region).

The sedimentation caused by mine wastes into the marine environment may be huge; up to several million tons of tailings per year with an accumulated layer up to tens of meters thick (Ramirez-Llodra et al., 2015). Thus, the soft bottom fauna is the ecosystem compartment which will be most severely affected by such discharges. In the most extreme cases of hyper-sedimentation, most benthic fauna can disappear and large areas may be barren (Ramirez-Llodra et al., 2015). In less impacted areas, such as in transitional zones outside the main deposit area, the community may still be impoverished and dominated by opportunistic species (Brooks et al., 2015). The effects may be significant also in time. After cessation of the mining activity, the initial colonization may be fast, but the reestablishment of a faunal community similar to the original state may take several decades (Burd, 2002; Josefson et al., 2008; Olsgard and Hasle, 1993), or probably never happen in cases where the bathymetry has been severely modified.

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

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

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

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

## 2. Materials and methods

### 2.1. Test materials

The experiment included three types of tailings:

1) Without process chemicals (delivered from Sibelco Nordic AS, denoted S);
2) With flocculation chemicals (delivered from Sydvaranger Gruve AS, denoted V);
3) With flotation chemicals (delivered from Omya Hustadmarmor AS, denoted H).

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

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

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

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