ImpTail: Improved Submarine Tailing Placements (STPs) in Norwegian Fjords

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Abstract
This paper presents preliminary results from a new project that aims to improve the practice of submarine tailings placements (STPs) in the Norwegian fjords. STPs are tailings in marine waters deposited directly to the seafloor without contact with the euphotic zone. The use of STPs is common and permitted, but controversial practice of tailings disposal in Norwegian waters. We are developing data and methods to reduce the environmental impacts and improve ecosystem recovery of STPs. These include 1) the fate and toxicity of STPs in Norwegian fjords, 2) testing organic enrichment of inert tailings to stimulate faunal recolonization and ecosystem recovery, 3) using seafloor baffling structures to limit tailing suspension into the water column, and to supply organic material to the STPs as artificial reefs, and 4) testing which areas are essential to protect to maintain marine ecosystems and to maximize recovery of sediments following submarine mine tailings placements. The project's industry-partners, Sydvaranger Gruver AS, Nordic Mining ASA, Rana Gruber AS and Titania AS, are contributing to and learning from this project, and will be in a unique position as leaders in terms of more environmentally friendly and cost-efficient management for STP deposits.

Introduction
Norway is rich in minerals and metals and mining has been in operation since the 1500s. The mineral resources are situated close to the Norwegian coastline and currently provide employment for around 5000 people (NGU, 2009). In 2008, total annual revenue through these activities equaled 931 million Norwegian kroner (NOK) for metallic ores and 2,900 million NOK for industrial minerals and this out of a total of 11,400 million NOK from the entire Norwegian mineral industry (NGU, 2009).

Tailings, fine-grained, waste rock produced during mining processes, are the main waste product following the extraction of valuable minerals and metals from ores. The proximity of mineral resources to vulnerable water bodies creates a real environmental challenge worldwide. STPs imply tailings deposited directly on the seafloor without contact with the euphotic zone (Ellis et al., 1995; Moody, 2000; Coumans, 2002; Ellis, 2008), and Norway currently allows the environmentally controversial technique in existing projects and are considering it for new projects (Agard & Bjørlykke, 2007). STPs are and have been used in fjords in Canada and Greenland in addition to Norway, in the anoxic deep waters of the Black Sea and in open waters in tropical countries, but many of these deposits are not done with Best Available Techniques (BAT) (Ellis, 2008). The OSPAR Convention, Annex II, Article3, 2(b) states that ”inert material of natural origin, that is solid, chemically unprocessed geological material the chemical constituents of which are unlikely to be released into the marine environment” are exempt from the ban on placement in Norwegian fjords. There are 23 existing fjord- or near-coastal sites in Norway where mining tailings have been deposited, including six STPs which are currently in operation (Kvassnes et al., 2009). Norwegian STPs range from 300,000 tons/year (NCM Stjernøya, Finnmark) to 7 million tons (Sydvaranger Gruver A/S in Finnmark). The ‘Riverine Inputs and Direct discharges’ (RID) program, where the OSPAR-countries track the discharges to common waters, reported 1,291 million tons of suspended matter in fjords from Norwegian industries in 2005 (Sydvaranger Gruver A/S re-opened in 2009). In the pending project at Engebøfjellet in Førdefjorden, the pending application asks for 4 to 7 million tons/year to be deposited over 40 years, and Sydvaranger Gruver is considering an application to increase the discharge from 7 to 14 million tons/year to the Bøkfjord.

The main benefit of STPs, besides it being less costly than land-based options, is the reduction of acid mine drainage (AMD) even in tailings with small amounts (<1%) of sulfides. Titania AS was made to abandon their STP in the 1990s, and the new self-draining dam now discharges nickel to the surrounding waters, causing a new environmental problem. By submerging reactive tailings permanently under water, AMD is reduced or, at least restricted, to the top centimeter of an often 50-m thick deposit (Pedersen et al., 1991; Arnesen and Iversen, 1993; Vigneault et al. 2001). However, this AMD-reduction has so far only been demonstrated in fresh waters in Norway. Although AMD-reduction is thought to also occur in saltwater because of permanent water cover and the natural buffering capacity of seawater (Ellis, 2008), Norwegian fjords are often heavily populated by deep-bioturbating and irrigating fauna, such as thalassinid shrimp (Christiansen, 1993). These animals are capable of building deep burrows (i.e., 1-3m) and contribute significantly to sediment resuspension (Rowden et al., 1998). Therefore, recolonization of reactive sulfide tailings over time may facilitate water and oxygen reactions with reactive tailings at the seafloor. Despite the potential for AMD and heavy metal leaching from STPs in Norwegian fjords, we know of no studies that have attempted to quantify their full impact on marine ecosystems and the potential for mobilization of metals or release of chemicals from STPs into fjords. It is therefore vitally important that the degree of AMD and toxic metal leaching from STPs are quantified in fjords where reactive STPs have been carried out.

All types of STPs, including inert placements, are likely to completely decimate the benthic environment and the ecosystem functions or services they provide through smothering. It has been shown that benthic fauna are capable of recolonizing STPs as early as three years after the termination and decommissioning of an STP, but the benthos can only be characterized as at an early stage of recovery (i.e., composed of small opportunistic species) and remains largely impoverished (Burd, 2002). If true for Norwegian STPs, the smothering could have persistent negative consequences for marine ecosystems as benthic fauna provide critical ecosystem services, such as feeding fish as well as regenerating nutrients through organic matter mineralization that are used in primary production. Ecosystem functioning is therefore largely affected in the fjord system with an STP. Surprisingly, despite the potential for STPs to critically impair seafloor ecosystems over long periods of time, we know of no studies in Norway or elsewhere that have assessed how long benthic ecosystem functioning is impaired following the termination of a STP. Likewise, how the STP deposits can be artificially rehabilitated, thereby speeding up recovery of natural (i.e., pre-STP) ecosystem functioning and services is not known. In addition, although an STP is defined to a given permit area, it is not understood how sediment resuspension from a STP can be limited to that area.

STPs have been known to fill in the entire length of a fjord (Poling, 1995; Ibrekk, et al., 1989) or may be deposited across a fjord, creating an artificial sill (Skei et al., 2009). STPs may form a physical barrier to benthic fauna dispersal, especially those that lack a free-swimming or planktonic larval stage. The change in hydrodynamics caused by modified bottom topographies may combine to significantly hinder biological recovery and rehabilitation of the deposit afterwards. Furthermore, if STPs cover a genetic source population or cut dispersal corridors between source and sink populations, the potential for biodiversity loss is high as water exchange and gene flow between fjords is known to be very limited (Le Goff-Vitry et al., 2004). If additional stressors are involved (e.g., aquaculture-based operations, industrial pollution), the loss may be even more devastating. Therefore, it is important to appropriately site STPs so they do not smother source populations, impede gene-flow, and cut off dispersal corridors potentially creating biodiversity loss. If these procedures are followed, rehabilitation of the impacted marine environment following mine closures will be given every chance of success. STP disturbance to fjord ecosystems is not limited to benthic organisms alone. Pelagic and demersal fauna may be affected by suspended fine-grained material from the tailings discharge site, and STPs will potentially increase turbidity leading to reduced visual-predator feeding success (Eiane et al., 1999), as well as interfering with faunal respiration (Dale et al., 2008). Persistent effects may therefore bar the co-existence of STPs and local fisheries, and as such, it is essential for the industry that cost-efficient methods are developed for the preservation of marine life during STP operations. However, despite the potential for extreme genetic diversity-loss as a result of STPs in Norwegian fjords and significant damage to pelagic fauna, there is a lack of studies that have assessed best practices of an STP.

Effective management of existing and future STP sites throughout the Norwegian coastal zone implies balancing both the negative and positive impacts. Furthermore, successful, environmentally friendly coastal-management strategies need to be able to sensibly site STP deposits along the coastline. This approach is particularly important today given that the mining industry is growing and new STPs may be required. Suitable management policies require a detailed understanding of where to locate STPs, including how they modify seafloor sediment chemistry and ecosystem functioning. Also, one must understand how to reduce STPs impact during the deposition process and stimulate ecosystem recovery following mine closure as previous rehabilitation methods have simply been to decommission an STP by stopping discharge of tailings. This project will satisfy all of the above criteria, and, in doing so, provides an improved basis from which to design coastal-management schemes for the Norwegian coastal zone.

The IMPTAIL project is divided into four closely related work phases (WP's). as listed below:

1) investigate the fate and toxicity of STPs in Norwegian fjords,
2) use knowledge from WP1 testing the use of organic enrichment of inert tailings to stimulate faunal recolonization and ecosystem recovery,
3) investigate the use of seafloor baffling structures to both limit tailing suspension into the water column, as well as to supply organic material to the STP by functioning as artificial reefs, and
4) identify which regions of a fjord are genetic 'source-populations' and which are genetic 'sink populations' in order to estimate which areas are essential to protect to maintain marine ecosystems and for the potential for rapid recovery from submarine mine tailings placements.

Through this project we will develop methods to reduce environmental impacts and improve ecosystem recovery of STPs and increase the knowledge base that may be implemented worldwide to reduce the effects of mine waste in the marine area.

Preliminary Results and discussion

All work phases were initiated in 2011. WP2 has worked on design and performed a pilot, thus results are not available now. Preliminary results from the other work phases are available at this time.

WP1: The Fate of existing STPs in Norwegian Fjords

In this study we focused on defining how the tailings deposited in Norwegian fjords have developed over time, not just in terms of biological activity, but also in terms of inorganic geochemical leaching reactions between the deposits and the seawater and pore water. It is important for the industry to understand how the different kinds of materials will react in the oceanic environment, beyond simple biodiversity-studies and whole-sediment chemistry. We have studied how potentially reactive tailings deposited in a Norwegian fjord have developed over time, not just in terms of biological activity but also in terms of geochemical leaching reactions between the deposits and the seawater and pore water in the tailings. We have explored whether AMD in the STP in Ballangfjorden (Nordland) is currently active in the tailings. The tailings are the waste from an old copper-mine that closed in 1964, where the tailings simply were discharged to the local river and filled up an estuary. The now land-based part of the deposit was covered and capped by tailings dominated by olivine, in the 1970s and -80s, greatly reducing the AMD in the river. The intertidal and subtidal areas still consist of tailings with high levels of copper and lead (Berge, 1997). If the marine tailings are nearly non-reactive in seawater, as the BAT for the use of STPs states (Ellis, 2008), there should not be significant AMD recorded in the pore water chemistry and thus no leaching to the ambient water above the deposit for the different types of tailings.

We sampled the tidal and subtidal tailings with a custom piston-corer from the University of Bergen. Each of the cores was split and pore water was extracted in distinct horizons of the core halves. The corresponding tailings were sampled for analysis for metal-analyses and organic content. The wave-rippled intertidal-zone was inspected, and we found abundant mounds from digging worms, possibly Polychetaes (Figure 1), mussels including yearlings (*Mytilus Edulis)* (Figure 2) and seaweed. Each mound could be as tall as 17 cm, and appear to overprint the ripples indicating that they are fresh features. The oxidized zone was found to be 10-30 cm deep into the tailings, and the digging worms also dug into the anoxic zone, as indicated by the blue-gray of some of the mounds.

Figure 1: The intertidal tailings are heavily populated by digging worms. Backpack for scale.

Figure 2: *Mytilus Edulis* on the tailings.

WP3: The use of baffling-structures for sediment redistribution control and artificial reefs around STPs.

Tailings may not be the ideal dwelling site for newly established organisms as explained in WP1 and. STPs may be vast, open, low in organic C, and very compact sediment flats where larvae find it difficult to settle. While providing sediment control, the baffling-structures in Task 3.2 may act as artificial reefs, which are known to provide dwelling-sites for organisms in the marine environment (Jensen et al., 2000; Jensen 2002). Marine artificial reefs elsewhere in northern Europe (Jensen et al., 2000) have developed long term and biologically diverse epibiotic communities (Ardizzone et al., 2000). Reef structures placed on distal portions of a deposit during placement and over an entire STP following decommissioning may collect detrital material through biofouling as well as stimulate organic enrichment (and fauna recolonization) of the deposit from fecal deposition from reef associated communities. In addition, the reef will provide a structure that may allow free-swimming or planktotrophic larvae to settle out and onto an STP enhancing recolonization and ecosystem rehabilitation (Christie, 2007). Thus, we expect to see increased biological activity around artificial reefs on an STP. We deployed three “Runde Habitats” (RH) on an inert tailings deposit in Langfjorden, near Kirkenes, Northern Norway. The deposit is not active at the moment, but strong currents were expected to cause re-suspension of tailings in the area. The “habitats” consist of a cylindrical concrete center made filled with rocks and radial tubes made of PEH plastics. This gives the 3 meter tall “habitat” a surface area of 300 m^2. The purpose of the placing of the habitats is to fertilize the tailings below by the secondary production of animals that settle on the habitat. The habitats were placed in water 25 meters deep, and can therefore be inspected by divers. The sediments around the habitats was inspected and sampled upon deployment and after two months. Preliminary results indicate that a lot of sediments settle on top of the habitats and small opportunists are settling below the tubes where there are no sediments. This indicates that the “habitats” act as baffling-structures for sediment redistribution and they will be monitored again in the following two summers.

WP4: Genetic connectivity between fjord benthic habitats.
A serious consequence of mine tailing deposition in Norwegian fjords is the potential for extreme biodiversity loss through smothering of source populations and production of obstacles to dispersal of benthic fauna, especially those species that lack a free-swimming or planktonic larval stage. In terms of metapopulations, local fjord-populations may be more or less isolated from each other, depending particularly on their means of dispersal. The significance of connectivity between soft-bottom communities in fjord basins is unknown, including exchange with shelf communities. Depending on the degree of isolation, genetic diversity within local populations is expected to be variable, and some populations may be dependent on recruitment from outside for long-term maintenance (source-sink populations). Larval-dispersing species are expected to have well-mixed gene pools, while brooding species are expected to occur in more or less isolation and thus make up differentiated populations. STPs may impede dispersal between the outer and inner parts of the fjord system cutting off populations from one another, and if deposited over source populations, may lead to biodiversity loss if additional stressors decimate any remaining populations. It is therefore important to identify areas normally home to source, as well as sink populations, so that STPs can be suitably sited. A variety of other human activities are likely to also affect metapopulation dynamics by reducing habitat continuity and blocking dispersal routes (e.g. coastal development and aquaculture). Hence, this work has management implications beyond the tailing deposition problem.

The project gives a general picture of the source – sink population dynamic in fjords. A large STP may potentially be deposited in the inner fjord studied. For species with low dispersal rates we will study the bivalve *Astarte sulcata* and the crustacean *Leucon nasica*. None of these species have pelagic larvae, they are common in Norwegian fjords and their movement across the sea bottom is slow. For comparison, similar analyses of genetic diversity and gene flow will be made for a species with efficient dispersal. One such candidate is *Munida sarsi*. (Crustacea), which is common in fjords and disperses by pelagic larval stages that settle only after drifting with currents for days or weeks (e.g., Zeldis 1985). All target taxa has been sampled from the shelf and in each basin by bottom trawling. No population genetic markers have been available for these species, and our study includes the development of microsatellite markers for these species. In the coming year we will sample the outer shelf and multiple (but at least three) individual fjord basins of the Førdefjord in western Norway for species that have fundamentally different means of dispersal using standard methods. The established markers will be used to characterise genetic diversity, heterozygosity and level of inbreeding in populations sampled in selected basins as well as the shelf outside. Importantly, these data will also allow for estimates of effective gene flow between the source and sink populations.

Conclusion

The project Imptail is, as the first independent research project in Norway, seeking to better the practise on depositing tailings in the marine environment. WP1 investigate the fate and toxicity of STPs in Norwegian fjords, WP2 use knowledge from WP1 to test the use of organic enrichment of inert tailings to stimulate faunal recolonization and ecosystem recovery, WP3 investigate the use of seafloor baffling structures to both limit tailing suspension into the water column, as well as to supply organic material to the STP by functioning as artificial reefs, and WP4 identify which regions of a fjord are genetic ‘source-populations’ and which are genetic ‘sink populations’ in order to estimate which areas are essential to protect to maintain marine ecosystems and for the potential for rapid recovery from submarine mine tailings placements. The project will run until the end of 2013.

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