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Research paper

Waste sites from mines in Norwegian Fjords

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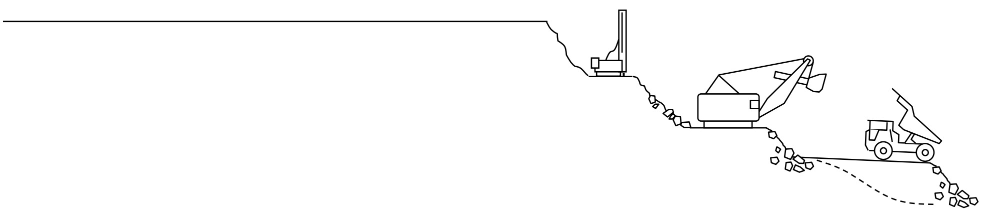
ABSTRACT

We present an overview of sites where tailings and other mine waste can be found in seawater along mainland Norway. While modern mines manage their waste sites, earlier sites were often spills or uncontrolled- or poorly-designed discharges. In Norway today (2013) there are seven sites where tailings are discharged to the sea, of which two are large in size (2-3 million tonnes/year), two are medium (~300 000 tonnes/year) and three are small (10 000-30 000 tonnes/year). At least 26 historic sites exist, where all are large total discharges and/or discharges with high levels of potentially toxic metals. These are therefore significant contributors to the geologic record and may be influencing the environment of each fjord. We do not include waste from other activities like road construction and the processing industry. Discharge of waste in significant amounts into a water body will modify its environmental condition. We discuss how the scientists and the industry may use the nature of tailings and fjords to improve the environmental outcome of the ocean when tailings are discharged to the fjords.



1. INTRODUCTION

1.1 Mining in Norway

Mineral resources in Norway have been exploited since the 1500s (Wii, 1991), and there are thousands of sites with evidence of mining (http://www.miljostatus.no). In 2012, the Norwegian minerals industry had total annual revenues of 13 billion NOK, which is a record (Neeb and Brugmans, 2013). The Norwegian Geological Survey (NGU) has estimated the value of known mineral resources throughout the mainland to be ~1400 billion NOK (Boyd et al., 2012). A thorough mapping program, the MINN and MINS-programs of the Norwegian Geological Survey (http://www.ngu.no), is currently underway to promote increased activity, and new search permits covering 15 559 km2 were issued in 2012. Thus, the mining industry is growing very rapidly in Norway.

Table 1. Waste sites for marine tailings in Norway listed from north to south. (Iversen and Johannesen 1997, http://www.miljøstatus.no, Ibrekk 1989, Iversen 2007. Jensen 2008) *:As reported by the pollution authority at www.norskeutslipp.no. **: Note that the "Type of ore" does not correlate to the chemical types of tailings as the characteristics of all tailings in Norway have not been studied.

#	Fjord area and County	Mine	Type	Comment	Active?	Type of ore **
1	Langfjorden, Finnmark	AS Sydvaranger	Deposit in the fjord built to the water surface	"Slambanken". Terminated in 1976.	No	Iron ore
2	Bøkfjorden, Finnmark	AS Sydvaranger and Sydvaranger Gruve AS	Deposit in the fjord	Permit: 4 000 000 tonnes/year, 2 633 000 tonnes discharged in 2012*	Yes	Iron ore
3	Stjernsundet, Finnmark	Sibelco Nordic, division Stjernøya	Deposit in the fjord	Permit: 300 000 tonnes/year, 216 000 tonnes discharged in 2012.*	Yes	Nepheline syenite with bioitite
4	Kåfjord, Finnmark	Altens Kobberverk	Beach deposit	Mine terminated in 1909.	No	Sulfide ore
5	Repparfjorden, Finnmark	Folldal Verk	Deposit in the fjord	A total of ~1 000 000 tonnes over seven years.	No	Copper sulfides ores in carbonate
6	Ballangsfjorden, Nordland	Bjørkåsen Gruver	Beach deposit/estuary fill	Mine terminated in 1964. "Ballangsleira"	No	Copper sulfide ore with quartz
7	Ballangsfjorden, Nordland	Nikkel og Olivin	Deposit in the fjord	Deposit at Forneset	No	Nickel sulfide with olivine
8	Bergsfjorden, Troms	Skaland Graphite AS	Deposit in the fjord	Permit: 40 000 tonnes/year, 21 000 tonnes discharged in 2012. *	Yes	Graphite ore
9	Bergsfjorden, Troms	Senjens Nikkelverk i Hamn	Deposit in the fjord	1872-1886.	No	Nickel ore
10	Fauskevika, Nordland	Sulitjelma gruber	Tailings and ore-spill in the bay	Mine terminated in 1991.	No	Sulfide ore
11	Ranfjorden, Nordland	Rana Gruber	Deposit in the fjord	Permit of 1 250 000 tonnes/year pending new permit of 2 500 000 tonnes/year. 2 080 000 tonnes discharged in 2012* (on exemption).	Yes	Iron ore with carbonate

Table 1 continued. Waste sites for marine tailings in Norway listed from north to south. (Iversen and Johannesen 1997, http://www.miljøstatus.no, Ibrekk 1989, Iversen 2007. Jensen 2008) *:As reported by the pollution authority at www.norskeutslipp.no. **: Note that the "Type of ore" does not correlate to the chemical types of tailings as the characteristics of all tailings in Norway have not been studied.

#	Fjord area and County	Mine	Type	Comment	Active?	Type of ore **
12	Ranfjorden, Nordland	Mofjellet Gruber	Deposit in the fjord	Mine terminated in 1987.	No	Sulfide ore
13	Ranfjorden, Nordland	Bleikvassli gruber	Deposit in the fjord	Mine terminated in 1997.	No	Sulfide ore with lead, copper and zinc
14	Ranfjorden, Nordland	Båsmoen gruver	Beach deposit	Mine terminated in 1937.	No	Sulfide ore
15	Tysfjord, Nordland	The Quartz Corp AS (former: Norwegian Crystallites)	Deposit in the fjord	Permit: 30 000 tonnes/year (production volume) of which 70% may be tailings.*	Yes	Quartz
16	Tysfjord, Nordland	Norcem AS Kjøpsvik	Deposit in the fjord	Small. Reduced from ~10 000 tonnes/year in 2009 to 3 000 tommes/year in 2012.	Yes	Calcium carbonate
17	Kongsmoen at Follafjorden, N-Trøndelag	Kongsmoen	Shipping area for Skorovas grube	Waste from the docks	No	Sulfides with copper
18	Trondheimsfjorden, N-Trøndelag	Verdalskalk AS	Deposit in the fjord	Small. Terminated in 2009.	No	Calcium Carbonate
19	Ytterøya at Levanger, N-Trøndelag	Hokstad Kisgruber	Deposit in the fjord	Mine terminated ca. 1918.	No	Sulfide ore
20	Beitstadfjorden, N-Trøndelag	Fosdalens Bergverk / Nye Fosdalen Bergvrk	Deposit in the inner fjord	Mine terminated in 1997.	No	Iron ore
21	Ilsvika in Trondheimsfjord, S-Trøndelag	Killingdal Grubeselskap	Deposit in the fjord	Mining from 1674-1986.	No	Copper sulfide ore
22	Hommelvika, S-Trøndelag	Meråker Gruber (N-Trøndelag)	Shipping area for the mine	Waste from the docks	No	Copper sulfide ore

Table 1 continued. Waste sites for marine tailings in Norway listed from north to south. (Iversen and Johannesen 1997, http://www.miljøstatus.no, Ibrekk 1989, Iversen 2007. Jensen 2008) *:As reported by the pollution authority at www.norskeutslipp.no. **: Note that the "Type of ore" does not correlate to the chemical types of tailings as the characteristics of all tailings in Norway have not been studied.

#	Fjord area and County	Mine	Type	Comment	Active?	Type of ore **
23	Frænfjorden, Møre og Romsdal	Hustadmarmor AS	Deposit in the fjord	Permit on criteria of acceptable conditions in the fjord. 327 000 tonnes discharged in 2012.*	Yes	Calcium carbonate
24	Åheimsfjorden, Møre og Romsdal	AS Olivin	Deposit in the fjord	Reports indicate plans for fjord deposit in 1977 (Tryland 1977). Exact data are missing.	No	Olivine
25	Førdefjorden, Sogn of Fjordane	Svanøy Gruve		Waste from the docks	No	Copper sulfide
26	Lonevågen at Osterøy, Hordaland	Hosanger Nikkelverk	Shipping area at Lonevåg	Waste from the docks	No	Sulfide ore with nickel
27	Sagvågen, Hordaland	Stordø kisgruber	Shipping area at Sagvåg	Mining from 1908-1968. Waste from the docks.	No	Sulfide ore
28	Lyklingfjorden, Hordaland	Goldmines at Bømlo	Unclear	Waste into the sea	No	Sulfide ore
29	Hardangerfjorden, Hordaland	Gravdal Kisgruve	Deposit in the fjord	Mining from 1864-1964.	No	Sulfide ore
30	Hardangerfjorden, Hordaland	Varaldsøy	Shipping area for the mine	Waste from the docks	No	Sulfide ore
31	Vigsnesbukta/Føynfjorden, Rogaland	Vigsnes Kobberverk	Unclear	Waste from the docks	No	Sulfide ore, copper rich
32	Jøssingfjorden Rogaland	Titania AS	Deposit in the fjord	Depositing from 1964-1984..	No	Ilmenite ore
33	Dyngadjupet, Rogaland	Titania AS	Deposit in the fjord	Deposit from 1984-1994.	No	Ilmenite ore

1.2 Submarine tailings placement

The processing of ore from mining causes fine-ground waste called tailings. This waste has commonly been placed in Norwegian Fjords during the last 100 years or more (Table 1, modified from Kvassnes et al. 2009). These waste management impoundments are commonly called Submarine Tailings Placements (STP) (Ellis 2008). STPs have been known to fill in the entire length of a fjord (Poling and Ellis 1995, Ibrekk 1989) or may be deposited across a fjord, creating an artificial sill (Nordic Mining 2009). The current use of STPs in Norway is permitted on a case-by-case basis (Miljødirektoratet 2011). The practice remains controversial internationally in ocean waters (Ellis et al. 1995, Moody, 2000, Coumans 2002, Ellis 2008, Aagard and Bjørlykke 2007). STPs are and have been used in fjords in Canada and Greenland, in the anoxic deep waters of the Black Sea, and in open waters in tropical countries. Many of these deposits are not done with Best Available Techniques (BAT) (Ellis 2008). Internationally, due to the lack of fjords, the so-called Deep Sea Tailings Placements (DSTP) practice has been used, where the tailings are released to very deep (>100 mbsl) areas along the continental margin from deep pipelines (Ellis 2008). This is different from the Norwegian practice.

In Norway today, there are seven active STP sites (2013), while two sites (in the Førdefjord and the Repparfjord) are still in their planning stages. These latter two will therefore not be discussed here. We are also not including discharges from other industries, roadworks or tailings from imported ore. However, mining waste is found in an additional 26 deposits (Table 1). Many of the old sites were accidental in terms of poor management, and some are very small in volume (i.e. < 10k's of tons per year), but all the small older sites listed have significantly elevated levels of potentially toxic metals. We therefore infer that all of these should be detectable in the geologic record of the fjord sediments. The modern sites are larger and managed and may involve millions of tons of waste per year. However, compared to international mines, Norwegian STP's are small. The Island Copper Mine waste facility in Canada managed approximately 25 million tons of tailings per year (Ellis et al. 1995). There are currently no Norwegian STPs in operation that have significant concentrations of potentially toxic metals in the tailings.

1.3 Why design marine deposits in the first place?

The land-scarcity and rugged topography along the Norwegian coast makes the design of safe and efficient land deposits difficult. The local rainy climate conditions makes land-deposits challenging as dams may burst if overstressed by floods. The impending climate change may increase precipitation even more and may make new regions more prone to heavy rains (Caroletti and Barstad 2010, Jaedicke et al., 2009). Some land deposits with tailings of sulfidic and potentially toxic compositions will generate runoff that needs to be managed or contained. The necessary land deposits (impermeable impoundment dams) will generally have perpetual and costly maintenance needs. Marine deposits, on the other hand, placed on the slopes or at the base of a fjord are not likely to slide due to rainfall. In addition, marine deposits have less visual pollution than land deposit.

2. REGULATIONS

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 discharge into Norwegian fjords.

The discharges are regulated under a number of Norwegian laws, the most important being “Plan og Bygningsloven”, regulating the EIA-process, Chapter 17 of “Avfallsforskriften”, the Norwegian transposition of the Mine Waste Directive (2006/21/EC), defining “inertness” for the different tailings and of the EC (2006/21/EC), and “Vannforskriften” which is the Norwegian transposition of the Water Framework Directive (2000/60/EC). “Naturmangfoldsloven” protects rare nature types and species. The definition for “inertness” from Avfallsforskriften has been made for managerial purposes and is only valid for freshwater management. Most STPs in operations should under Vannforskriften be classified as candidates for Heavily Modified Water Bodies (cHMWB).

3. MINE WASTE AND THE INFLUENCE ON THE MARINE ENVIRONMENT

3.1 Physical effects of tailings in the marine environment

All tailings will have common potential physical effects on the marine environment. The main problems are hyper-sedimentation and the smothering of seafloor ecosystems. In addition, physical harm by particles on pelagic animals and plants caused by abrasions due to angular and/or low sphericity particles. Natural glacifluvial sediments in fjords are generally of a higher angularity than for example those found in rivers, and on beaches and in deserts. Likewise, mechanical crushing of ore will most likely cause the tailings grains to have high angularity. The roundness of the grains (measured in sphericity), however, are dependent on the minerals in the waste. Minerals that naturally have cross-cutting cleavage are more likely to form low sphericity needles known to be harmful to fauna (Dale et al., 2008). The effect of angularity of grains with higher sphericity is not as explored in terms of particle effects in the marine environment.

3.2 Chemical effects of tailings in the marine environment

3.2.1 Acid rock drainage management

On land it is well known that mine waste may produce very acidic conditions (pH <3) when the sulfide-containing rocks react with water and oxygen to produce sulfuric acid (Acid rock drainage, ARD). The acidic pore-water in the waste leach metals into the percolating water releasing them to waterways downstream. In order to overcome this problem, acid-producing tailings are often submerged under water in Norway (Iversen and Johannessen 1987). The procedure is thought to reduce, or at least restrict, ARD to the top centimeter of an often 50-m thick deposit (Pedersen 1984, Arnesen and Iversen 1993, Vigneault et al. 2001). Due to steep topography and heavy rains giving rise to concerns of geotechnical stability, and conflicts on land-use, tailings have been deposited in the fjords in Norway, rather than building impermeable impoundment dams.

Tailings in the marine environment do not act the same geochemically as they would on land. It has been shown that sulfate-reducing bacteria form in marine sediments, and the bacteria may fixate heavy metals in secondary sulfides in-situ in the sediments (Perry, 1995). In addition, the higher pH of the ocean (pH ~7,9), together with the high content of SO_4^{2-} ions in the seawater provide a buffering effect on the tailings (Pedersen 1984) improving the outcome compared to land based water covered containment facilities. In the project Imptail (NRC# 204033) it was demonstrated that while copper and lead concentrations in the sampled tailings were up to 275 times higher than the limit between good and poor chemical state in terms of “Vannforskriften”, the pore waters had low concentrations of metals. Nickel, however, had a poor chemical state both in the tailings and pore water (Gravdal, 2013). While there are many and standardized freshwater leaching tests for tailings, there are no standardized tests to predict whether tailings are safe for the marine environment.

We propose that there should be three categories for tailings in terms of the marine environment: inert, sulfidic and potentially toxic tailings.

3.2.2 Inert tailings

Inert tailings do not contain sulfides and/or natural or added chemicals in significant concentrations to potentially react chemically with- and harm the marine environment. The main environmental problems associated with “inert” tailings in the marine environment are the physical effects described in chapter 3.1.

3.2.3 Sulfidic tailings

In terms of the marine realm, the second type of tailings is those that do contain sulfide minerals in significant amounts, but that do not contain high concentrations of heavy metals. Alternatively, the toxic metals present are bound in sulfide-minerals that do not readily dissolve in seawater. Such tailings may have less total chemical impact on the environment if placed under a stable water cover than when exposed to atmospheric water and air. The main environmental problems associated with sulfidic tailings in the marine environment are the physical effects described in chapter 3.1.

3.2.4 Potentially toxic tailings

The third type of tailings in the marine environment has a make-up that renders them potentially toxic to marine organisms. The toxicity may be due to significant levels of toxic metals in minerals that dissolve readily into seawater, the waste may contain potentially toxic processing-chemicals, or both. Left uncovered on the sea-floor, potentially toxic tailings may keep releasing toxins to the environment for an extended amount of time (Christensen et al., 2011), unless the management of the tailings includes the provision of clean cover as a part of the decommissioning. Potentially toxic tailings deposits left uncovered are not likely to be in compliance with "Vannforskriften".

While there are ample freshwater and acid tests for tailings, we cannot separate between the "Inert tailings" and "Sulfidic tailings" that do not leak toxins and the "Potentially toxic tailings" with standardized and meaningful tests today. It is imperative that such tests are developed.

4. DESIGN

4.1 Current practices for waste management

While an official Best Available Techniques policy for marine tailings management has not been implemented in Norwegian law, there are several documents that suggest how to best deposit this material. The Norwegian Environmental Agency (Miljødirektoratet) has published a report on the practice in Norway and internationally (Miljødirektoratet 2011), where a "best practice" has been suggested. In addition, Ellis (2008) and Shimmield (2010) have suggested best practices for the design of these waste sites. In general, these publications agree that:

1. The tailings should not interact with the euphotic (i.e. light influenced) zone in the water body they are placed into. This can be done by:

a) Transportation of tailings below the euphotic zone through a pipeline at a depth preferably below a halocline, providing a barrier to resuspension to the surface.

b) Avoiding fjords that have an annual complete turnover of the water masses (Poling and Ellis 1995).

c) Transporting the tailings as thick slurry with water of similar salinity as the water body it is being deposited into to prevent gravitational rise of the water to the upper water masses.

d) De-aerating the pipeline, so that air-bubbles do not transport the tailings back up to the euphotic zone.

2. The sea area impacted should not have specific ecological- or economic interest.

Design of the STP must therefore involve the entire waste-management, from tailings design in the processing plant, thickening, pipe design and knowledge of the water body that the tailings are discharged into.

4.2 What are the major concerns for marine deposits?

For all tailings hypersedimentation and smothering will eradicate in-fauna in the main deposit area. If the nature of the watermasses of the fjord is poorly understood, it may be challenging to keep the waste in one area due to currents. Therefore, the distal zone of the deposit may be larger than intended (Miljødirektoratet, 2011). There are no immediate ways of controlling or inspecting the deposits. If problems arise, then the deposit will need to be fixed using costly underwater technology. Valuable seafloor areas (e.g breeding grounds, genetic source populations) and threatened species may be disturbed. 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). Either way, potentially toxic tailings will also harm marine life through the release of toxins (Miljødirektoratet, 2011) for a longer time, with concomitant impacts on other industries (e.g. fisheries).

4.3 How can the marine waste sites be designed better?

While regulations give general guidelines to follow and targets to meet, it is imperative that good designs based on scientific methods show how the practice can be more environmentally friendly than it has previously been in the historic sites.

The anthropogenic pressures on marine systems in Norway are plentiful, and mine STPs come in addition to influences like local sewage discharges, rock material from roadworks and sludge from dredging of polluted sites and harbor management, commercial fishing activities, aquaculture and other industrial discharges.

In order to design the best possible tailings waste site, it is important to do thorough baseline analyses of the current pollution status and activities within the entire fjord, placing the STPs into an environmental context. Ocean currents and ecosystems that make up fjords and their ecosystem functioning must first be assessed for each case. Fjords do have the most diverse deep-sea ecosystems in the world. Generalized baselines for the marine environments in Norway are difficult to establish since most fjords are impacted due to various human activities mentioned above. Moreover, most environmental investigations are done under the “Polluter Pays” principle, meaning that little is known about ecosystems outside of immediately impacted areas. This provides a sample bias towards polluted sites. In addition, Norwegian fjords range from temperate systems in the south of Norway to Arctic fjords in the north, so the different ecologies of these different fjord types may respond to STP associated stress (e.g. water column turbidity and darkening) in different ways.

Only if the STPs are designed to follow the natural processes in the fjord systems, can the outcome be improved from earlier practices.

5. CONCLUSION

We have presented the 33 known Norwegian marine deposits that contain significant discharged waste from mining. While seven are currently operating under governmental regulations, the older sites are assumed to be significant enough to be recorded in the sedimentary records of the fjords. While there are ample freshwater and acid tests for tailings, we cannot separate between the “Inert tailings” and “Sulfidic tailings” that do not leak toxins and the “Potentially toxic tailings” with standardized and meaningful tests today. It is imperative that such tests are developed. The future of the practice depends largely on designing waste management impoundments that have an overall better environmental outcome, if it is on land or in the sea. Only by designing the STP to work with nature instead of against it, one will be create a waste management impoundment that is a better solution than a land-based impoundment.

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