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SHORT AND LONG TERM ENVIRONMENTAL EFFECTS OF MARINE TAILINGS AND WASTE ROCK DISPOSAL FROM A LEAD/ZINC MINE IN GREENLAND

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ABSTRACT

During its active operation from 1973 to 1990 the Black Angel Mine in West Greenland disposed its tailings in seawater slurry to a fjord. During the disposal between 10 and 30 tons of lead and between 30 and 55 tons of zinc dissolved annually in the receiving sea water. This resulted in a significant pollution of the surrounding marine environment. Other pollution sources, particularly waste rock dumps and dust from the ore crusher and concentrate handling, also were important. After closure of the mine in 1990 a waste rock dump was excavated and partly deposited on top of the tailings on the fjord bottom below 60 m water depth.

The heavy metal pollution at the site has been monitored while the mine was operating, but also after mine closure in 1990, after which significant improvements of the environment has been observed in sea water and marine organisms. Analyses of the sea water after mine closure indicate that from the undisturbed tailings and waste rock deposited on the fjord bottom 0.1 tons lead and 5 tons zinc dissolve annually. The experience from this operation is that marine disposal of mining waste, which in some cases seems to work satisfactory, also can be a risky operation. Systematic testing of the waste is important before a decision is made to dispose mine waste to the ocean.

INTRODUCTION

Disposal of tailings is a major issue of concern both for new and old mines. In cases where a mine is located near the sea or a fjord, marine waste disposal often is an option mine owners and regulators will consider. From the review of Ellis, Poling and Baer (1995) of marine tailings disposal and its environmental impacts world-wide, it can be concluded that these operations both have succeeded and failed in terms of their impacts.

In this paper we present and discuss the environmental impacts of marine waste disposal at a lead- zinc mine, the Black Angel, at Maarmorilik in West Greenland. The emphasis in this presentation is on mechanisms affecting the release and transport of heavy metals from tailings and waste rock to seawater during mining and after mine closure. For further details on environmental impacts we refer to Johansen and Asmund (1999) and Johansen et al. (1991).

THE MINE AND THE POLLUTION SOURCES

The zinc/lead mine "The Black Angel" at Maarmorilik in West Greenland operated from the fall of 1973 to the summer of 1990. The ore body was situated at an altitude of 600 meters. Crushed ore was transported across the fjord, Affarlikassaa by a cable car system to the mill and concentrator in Maamorilik. The outline of the operation is shown in Figure 1.

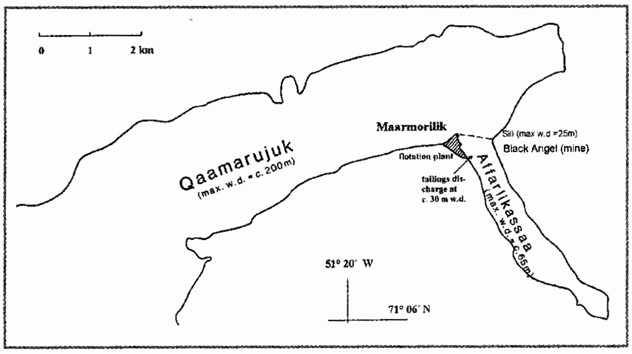

Figure 1. Map of the Maarmorilik area.

Ore production varied between 600 000 and 735 000 tons per year. Mineral particles were separated in a flotation plant, where on average 135 000 tons of zinc concentrate and 35 000 tons of lead concentrate were produced annually. The mountainous topography surrounding the ore deposit prevented the design of a land based tailings disposal system, and the decision was made to dispose of the tailings at depth in the 70 m deep and 4 km long Affarlikassaa Fjord. This fjord is separated by a 25 m sill from the neighbouring Qaamarujuk fjord (Figure 1). At the time the decision to dispose of the tailings directly into the fjord was made, no serious environmental problems were anticipated, or foreseen.

The chemical composition of ore and waste varied over the years of the operation. A typical example from 1988 is shown in Table 1.

	Ore	Tailings	North Face Dump
Zn %	10.53	0.4	2.7
Pb %	3.58	0.23	0.89
FeS %	13.66	16.1	8.4
Cd mg/kg	484	27	129
Cu mg/kg	303	101	
Ag mg/kg	26.1	3.5	
As mg/kg	121	93.3	
Hg mg/kg	16.0	0.67	

Table 1. Composition of ore, tailings and waste rock. 1988.

Tailings and waste rock

The tailings were discharged from a pipeline at a depth of 25 m and occupied eventually an area estimated to be at least 0.3 km^2 inside the sill between the two fjords. This behaviour was as anticipated and planned when the discharge system was constructed. The only major change made in the original design was an addition of a de-aeration system (Mathisen et al., 1982). It was a advantage for the discharge system to the fjord that seawater was used in the flotation plant. The performance of the system further was improved by keeping the density and salt content of the discharge water as high as possible and by adding of flocculants, aluminium sulphate and lime to the tailings water.

A second important source of pollution is waste rock dumps. During the first 10 years of operation, disposal of waste rock outside the underground mine workings was not regulated, and 2-3 million tons of waste rock with 0.1 to 0.8% lead and 0.3 to 2.3% zinc was left in four dumps on the slopes of steep mountains in the area. Metals are released to the sea mainly in form of sulphide particles in rain and melt water from glaciers. An average annual input of 8 tons of lead has been estimated from this source. Most of this, however, settles close to the river outlet in the fjord.

One of the waste dumps was located directly at the Qaamarujuk Fjord, partly in and below the coast line. This caused a high mobilisation of lead and zinc from the waste, which was in direct contact with seawater and was exposed to wave and tidal action. The highest lead and zinc levels in seaweed and blue mussels were found at this dump. As part of a plan to mitigate metal pollution in the area after mine closure, this dump was removed to the extend possible as described below.

Chemical properties of tailings and waste rock

When it was realised that lead and zinc from the tailings and waste rock partly dissolved in the seawater, studies of the chemical properties of the ore and tailings was started. It was concluded that a small but significant part of the galena and sphalerite in the ore was weathered. The exact composition of the weathering products was not established, but it is believed that the weathering products predominantly were composed of carbonates, as they were soluble in acetic acid, and slightly soluble in fresh water and sea water. Practical ways to minimise the dissolution of lead was tried. The most effectfull was to minimise the dispersion of tailings particles in sea water by securing a fast settlement on the bottom of the fjord, as the amount of lead, that dissolved were directly proportional to the amount of water the tailings was in contact with.

While the tailings disposal took place the receiving bottom water of the fjord Affarlikassa was contaminated by 100 to 1000 µg L^{-1} of both zinc and lead (Asmund, 1980). Natural levels are about 1 µg L^{-1} for zinc and 0.01 µg L^{-1} for lead.

Dust

A third significant source of metal pollution was dust. An annual input to the environment of 2 tons lead and 5 tons zinc from all dust sources has been estimated during the last years of the mine operation (Johansen *et al.,* 1997). The main source of dust was the ore crusher, and because it was located ca. 600 m above sea level, dust and metals from it could be dispersed over long distances. Another important source of dust was the conveyor belt transporting concentrates from the concentrate storage building to the bulk carriers. Other pollution sources also existed, e.g. mine water and ventilation from the mine and the concentrate storage building. However, these sources do not seen to be important compared to tailings, waste rock dumps, and dust from the ore crusher (Greenex environmental Action Plan, see Asmund et al., 1994).

IMPACTS ON BIOTA

Brown seaweeds and blue mussels have been used as biological indicators of the lead and zinc pollution in space and time. The main results for seaweed are shown in Figure 2. Seaweeds from a large part of the coast of the fjords have elevated zinc and lead concentrations and these levels have decreased over the monitoring periode, particulary for lead. Nevertheless, zinc levels have remained high after mine closure.

Lead levels in blue mussels increased significantly in all three fjords at the mine after the start of mining operations. Lead concentrations above 3000 µg g^{-1} (on a dry weight basis) were observed at the most affected sites. This is more than 3000 times higher than the concentrations found in unaffected areas. For many years it has been recommended not to collect and eat blue mussels in an area up to 30 km from the mine site, because of high lead concentrations. After mine closure lead levels in blue mussels have decreased, but slowly because the mussels do not depurate some of the lead originally taken up (Riget et al., 1997).

A number of marine fish species and a prawn species have been monitored regularly and no elevated zinc in these has been observed. Lead levels in the meat have remained low whereas in liver and bone tissues elevated levels have been found in many cases. The lead levels in fish and prawns have generally decreased since the mid 1980´s and particularly after mine closure.

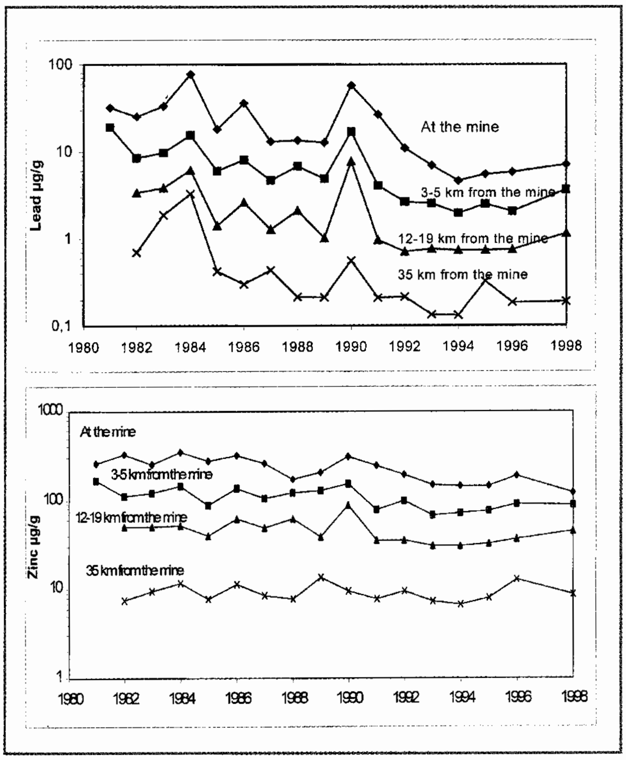

Figure 2. Lead and zinc concentrations (µg g^{-1} dry weight) in brown seaweed at Maarmorilik from 1981 to 1998.

Figure 3 shows lead concentration in the liver of shorthorn sculpin, a rather stationary fish species. After closure lead levels in sculpin remained high, and only fish living 4-5 km from the mine site showed a significant decrease.

The most common seal species (the ringed seal) and five marine bird species (common eider, Iceland gull, glaucous gull, and black guillemot) also have been studied. Metal levels were not elevated in blubber, meat, liver, and kidney of the seals. In the most recent bird study (1991) elevated lead levels were only found in bone tissue of the birds and not in meat, liver, or kidney as in earlier studies performed during active mining. Lead concentrations in seals, birds, and in fish meat have all been below guidelines for human consumption.

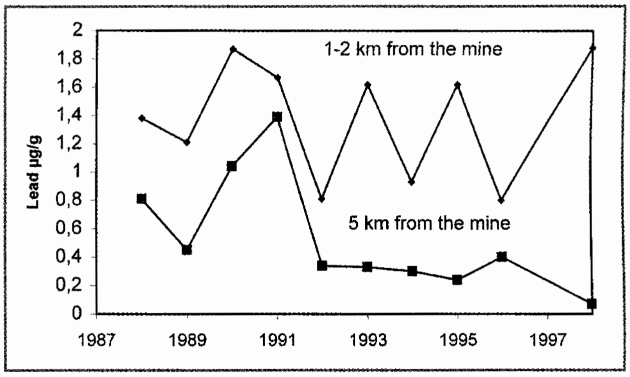

Figure 3. Lead concentrations (µg g^{-1} dry weight) in liver of shorthorn sculpin at Maarmorilik from 1988 to 1998.

QUANTIFICATION OF METAL RELEASE FROM TAILINGS

At 5 stations, 2 in Affarlikassaa and 3 in Qaamarujuk water was sampled at 0, 10, 20, 30, 40, 50, 75, 100, 150 and 200 meters if the depth allows it. The samples were then analysed for lead and zinc (Asmund, 1992 b). The highest concentrations found were in the bottom water of Affarlikassaa where tailings settled. Figure 4 is a plot of dissolved zinc and lead in the 29.1 million m^3 sea water below 30 m water depth in this fjord.

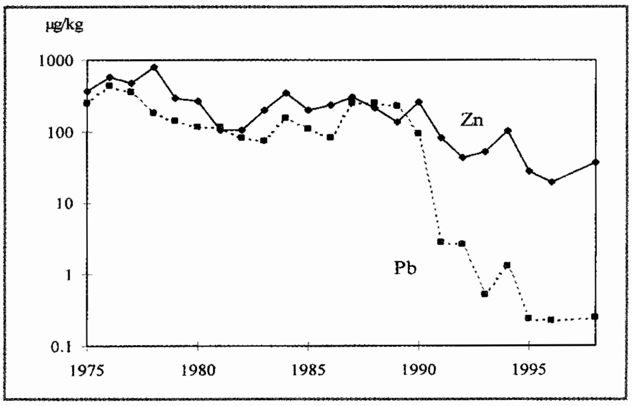

Figure 4. Dissolved lead and zinc in the bottom water (30 – 60m) of Affarlikassaa.

During mining

Metal was primarily released from the tailings/seawater jet and took place while the tailings settled on he fjord bottom. Measurements after closure, in 1990, made it possible to estimate the release rate from the deposited tailings and waste rock, and from the tailings jet of suspended tailings solids in sea water. The calculation used the inventory of dissolved metals, the change in the ratio between dissolved zinc and lead, combined with knowledge about the hydrography. Based on this it was estimated that between 10 and 30 tons/year of lead and between 30 and 55 tons/year of zinc dissolved during the active life of the mine, primarily from the tailings in suspension in sea water between the discharge point and the sea floor (Asmund, 1992a).

After closure

During the first year after the closure of the mine, the amount of dissolved lead and zinc was monitored regularly, and an estimate of the release rate for these elements was made. In this year it was found that 18 to 33 kg zinc per day were released whereas lead was either absorbed by the tailings and waste rock on the fjord bottom ore released at a slow rate. The release rate for lead was estimated to be between –1 and +0.5 kg per day (Asmund, 1992a).

The metal concentrations in the seawater have now been monitored in 8 years after the closure, and a more exact picture has been obtained. Table 2 shows the dissolution rate determined by multiplying the amount of dissolved metal in the beginning of September in the two fjords by a calculated time constant of 2.38 y^{-1} (Asmund, 1992a).

Year	Zinc kg/day	Lead kg/day
1975-1981	151	86
1982-1987	81	33
1988-1990	70	53
1991	18 to 33	-1 to 0.5
1992	13	0.92
1993	18	0.23
1994	26	0.40
1995	8.2	0.124
1996	6.1	0.131
1998	11.3	0.121

Table 2. Estimates of dissolution rate of lead and zinc from the marine tailings discharge and the deposited tailings and waste rock. The mine closed in 1990.

For the years after 1991 the calculations are based on studies of Affarlikassaa only and an assumption of similar hydrographic conditions as before 1991, a time constant for Affarlikassa and Qaamarujuk combined of 2.38 y^{-1}, as in the previous years. Furthermore it has been assumed that the metals in Affarlikassaa in September, where the measurements were done, constitute 63% of the total amount of metals dissolved in the two fjords (average 63%, standard deviation 12%). This simplification, based on experience from the period 1972 to 1990, is necessary because the determination of metals dissolved in Qaamarujuk after 1991 was quite uncertain because concentrations approached background concentrations, which were difficult to determine.

QUANTIFICATION OF METAL RELEASE FROM A WASTE ROCK DUMP

During mining (the dump partly in the tidal zone)

The North Face Dump released dissolved metals due to dissolution in rain and melt water and due to direct action of seawater waves and tidal action. The mining company measured the release of dissolved zinc to 6.3 kg/day and of lead to 0.14 kg/day and of particulate zinc to 19 kg/day and particulate lead to 7 kg/day (Pedersen, 1989). This is substantially less than released from the tailings jet, but the release of dissolved metals are probably underestimated because the metal release caused by waves and tidal action was not taken into account. Because the metals were concentrated in the surface waters, where the photosynthesis and most of the biological activity takes place, the effect of metals released from this source may be comparable to the effects of the tailings which were released to the bottom water. However the biological effects of the tailings and of the waste rock could not be distinguished satisfactory from each other.

After mining (the dump on the sea floor)

In 1990 after the closure of the mine, the North Face Dump was excavated to the extend possible and partly placed on top of the tailings at the bottom of Affarlikassaa on 50 to 60 meters of water depth. Some of the dump material was placed in an old marble quarry on land.

Leaching tests in the laboratory on samples of waste rock placed undisturbed in cylinders flushed with sea water gave a dissolution rate that was inversely proportional to the square root of time (Asmund 1992, b). Multiplying the dissolution rate determined in the laboratory with the surface area of the deposited waste rock, 0.1 km^2, gave the anticipated dissolution rates in Table 3.

It is seen hat these rates are smaller that the measured release rate from the combined tailings and waste rock at the fjord bottom.

Year	Zinc kg/day	Lead kg/day
1991	0.81	0.066
1992	0.57	0.046
1993	0.46	0.038
1996	0.36	0.029
1998	0.30	0.025

Table 3. Dissolution rate from 0.1 km^2 marine deposited waste rock based on laboratory measurements.

LESSONS LEARNED

Environmental studies at the Black Angel Mine have showed that marine disposal of tailings can cause serious environmental impacts. It has also been demonstrated that placement of mine waste in the tidal zone seriously may affect the sea. The adverse effects by the operations could have been avoided or significantly reduced, if appropriate tests on tailings and waste rock had been conducted before the mine started operation.

Test procedures necessary for a decision about marine tailings disposal is outlined by Ellis et al. (1995). The proposed tests which are base on experience from several mines including the Black Angel would have predicted the basic environmental problems experienced at Maarmorilik. Here bioaccumulation tests, leaching tests, and toxicity tests would have been the most important. Such tests would have identified the existence of soluble lead compounds and would have warned the decision-makers that marine waste disposal in this case was unacceptable with the design chosen, and that waste rock should not be disposed of in the tidal zone.

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