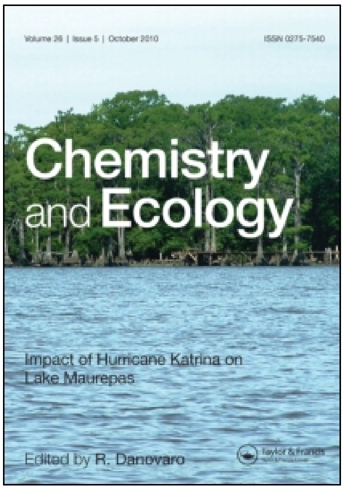

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DISPOSAL OF MINE WASTES CONTAINING Pb AND Zn NEAR THE OCEAN: AN ASSESSMENT OF ASSOCIATED ENVIRONMENTAL IMPLICATIONS IN THE ARCTIC

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INTRODUCTION

The past two decades have witnessed an increase in the exploration for, and development of, mineral resources at Arctic latitudes. Such effort has resulted in the commencement of production at a number of different localities in close proximity to the ocean. Since proximity to a source of transportation for the conveyance of concentrates to the market is a primary requirement governing the economic decisions for the mine to proceed, it is logical that ore deposits near a coastline are primary targets for development.

Closely tied to coastal mining developments is the need to dispose of tailings and waste rock in the most economical manner. Prior to the advent of heightened public awareness and environmental concern, and the enactment of pollution legislation, disposal practices were largely based upon convenience. Currently, however, proposed disposal and operating practices receive closer scrutiny, with a view to providing adequate protection for aquatic resources and habitat.

This paper summarizes some of the features of three Arctic mines, wastes from which enter the marine environment, and compares the disposal practices used at each to measures of environmental change as indicated by metal concentrations in various media.

Maarmorilik

Tailings and waste rock containing lead and zinc have been disposed of at several locations in the Arctic. At Maarmorilik in Greenland (Figure 1), mining for zinc and lead commenced in 1973. Ore production has varied between 600,000 and 735,000 tonnes per year. Mineral particles are separated by flotation with yearly production of approximately 120,000 tonnes per year of zinc concentrate, 30,000 tonnes per year of lead concentrate and 450,000–600,000 tonnes per year of tailings. The mountainous topography surrounding the ore deposit prevented the

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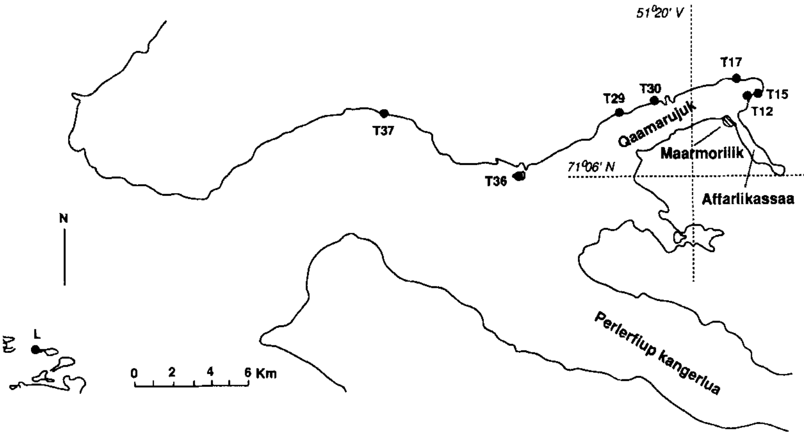

Figure 1 Location of the Maarmorilik mine and sampling stations.

design of a land based tailings disposal system, and the decision was made to dispose of the tailings at depth in Affarlikassaa Fjord, a 4 km long fiord with a sill at its mouth. At the time the decision to dispose of the tailings directly into the fiord was made, it was not anticipated that serious environmental problems would subsequently arise. However, environmental studies four months after the commencement of mining illustrated that concentrations of lead and zinc in the sea water close to the mine had increased from preoperational values of 1 μg/kg to around 1000 μg/kg. It was also discovered later that several species of marine biota (bivalves, shrimp, *Fucus*) were contaminated, especially with lead (Johansen *et al.*, 1985; Asmund, 1986; Asmund *et al.*, 1988a; Johansen *et al.* 1990).

At several places around Maarmorilik, waste rock containing lead has been disposed of on the mountain slopes. In one case, the North Face Dump, the waste rock extends right to the shore of the fiord. Unconfined disposal of lead containing waste rock contributes singificantly to marine pollution of the area (Asmund *et al.*, 1988b). Further it has been estimated that each year approximately 3 tonnes of lead are spread as dust from the mine, the dumps, the mill, and the shiploading facility (Asmund *et al.*, 1988c).

Nanisivik

The Nanisivik lead and zinc mine is located on the northern tip of Baffin Island, N.W.T., Canada (Fig. 2). This mine commenced milling operations in the autumn of 1976. After considerable debate over the best option for disposing of mine tailings in the most economical and environmentally safe manner, the decision was made to dispose of tailings into West Twin Lake. Preoperational investigations in this lake revealed that it was not inhabited by any fish species and had only limited populations of benthic invertebrates and plankton. While considerable additional costs were associated with the acquisition, installation and operation of pumps and piping needed to transport the tailings vertically over the hill to West Twin Lake (rather than letting them flow by gravity down the hill to be discharged at depth in Strathcona Sound), the increased costs were considered

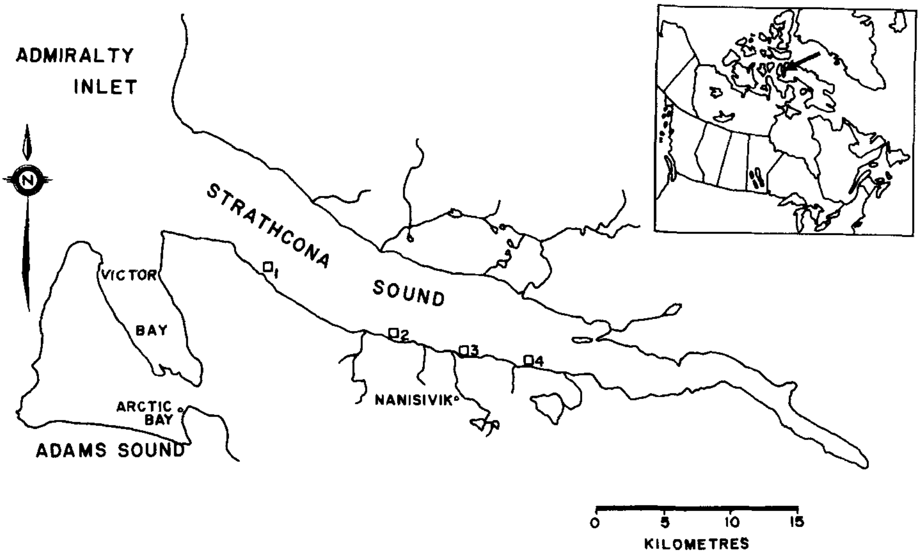

Figure 2 Location of the Nanisivik mine and sampling stations.

to be offset by the benefit of having the tailings physically contained over the life of the mine, and subsequent to abandonment. The recent extension to the initially anticipated life of the mine has, however, raised the problem of where to dispose of tailings once the capacity of West Twin Lake is totally utilized.

Pre and post-operational studies were conducted in Strathcona Sound in an effort to document the extent to which concentrations of lead and zinc in the sediments, the bivalve mollusc *Mya truncata* and the seaweed *Fucus vesiculosus* changed over time. Concentration changes were considered to provide an indication of the extent to which metallic contaminants associated with mining activities at Nanisivik had entered the marine ecosystem in Strathcona Sound.

Ivittuut

Mining for cryolite in southern Greenland started on a small scale in 1854. In the 1920's when the production of aluminium accelerated, mining for cryolite was undertaken on a larger scale. Waste rock has been used for landfill in Arsuk Fjord to create a work area close to the cryolite deposit (Fig. 3). The work area is approximately 700 m long by 50 m wide with an average depth of 5 to 10 m. The land fill consists of stones of all sizes up to 1 m^3 and contains several minerals including galena (lead sulphide). In the <0.5 cm fraction, which constitutes 7% of the land-fill, the lead content was measured to be 0.15%. The land-fill is of an open structure which allows the tidal movements in the fiord to saturate it with sea water. Samples of the interstitial sea water from the land-fill have been analyzed and found to contain 9-5460 μg Pb/kg. The tidal movements transport the lead polluted sea water from the land-fill to the adjacent Arsuk Fjord where it results in increased concentrations of lead in sea water, sediments, *Fucus*, and *Mytilus* (Hansen and Asmund, 1983).

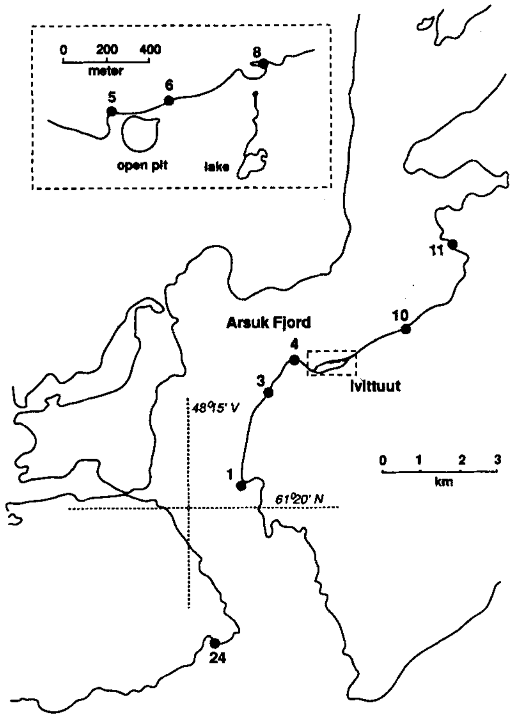

Figure 3 Location of the Ivittuut mine and sampling stations.

Table 1 Basic data concerning the lead-zinc mines at Maarmorilik, Greenland and Nanisivik, Canada.

		Maarmorilik Greenland	*Nanisivik Canada*
Northern latitude		71°	73°
Annual precipitation (cm/yr)		10	14.4
Start of production		1973	1976
Ore processed (tonnes/yr)		700,000	575,000
Ore composition	Zn (%)	10	14 (10.1)[a]
	Pb (%)	3	1.4 (0.3)[a]
Flotation recovery	Pb (%)	87	84
	Zn (%)	94	96
Tailings composition	Zn (%)	0.2–0.5	0.4–0.6
	Pb (%)	0.1–0.2	0.1–0.2
	Cd (mg/kg)	20–40	10
	FeS_2 (%)	20–50	90
	(Ca, Mg) CO_3 (%)	50–75	10
Disposal of tailings		To the sea	In a lake basin
Disposal of waste rock		On land, partly on shore	Very little waste rock
North Face Dump tonnes		400.000	
North Face Dump Pb (%)		0.8	

[a] Average grade of remaining ore.

Table 1 provides a comparison of various features of the Nanisivik and Black Angel Mines (Maarmorilik). As illustrated in the Table, the two mines are situated at similar latitudes, process similar quantities of ore each year and process ore with roughly similar quantities of zinc. The Maarmorilik ore has approximately 2% more lead than the ore at Nanisivik. Annual precipitation at the two mines is similar, hence, the metallic input to the ocean as a consequence of leaching related to precipitation would be expected to be similar if the amounts of exposed mineralization and waste rock were similar. Mining at Nanisivik results in minimal amounts of waste rock production (some waste rock has been used in connection with road construction) due to the relatively uniform distribution of the ore in the host rock, whereas at Maarmorilik and Ivittuut waste rock has been disposed of along the ocean shoreline.

METHODS

Maarmorilik and Ivittuut

Sea water samples were collected using a Hydrobios reversing water sampler. The samples were filtered through 0.4 μm Nucleopore filters, acidified and analyzed by A.S.V. Sediments were analyzed by AAS subsequent to treatment with hydrofluoric acid and aqua regia. *Fucus* and *Mytilus* were frozen after collection, dry ashed, dissolved in nitric acid and analyzed by AAS (Loring and Asmund, 1989).

Nanisivik

Sea water samples were obtained using a Go-Flo bottle and subsequently filtered in the laboratory through a 0.4 μm Nucleopore filter and acidified. Metal concentrations were determined by AAS after freon extraction (Thomas *et al.*, 1983). The *Mya truncata* results obtained by Thomas *et al.*, (1983), were determined by AAS after teflon bomb dissolution. The sediments, *Mya* and *Fucus* from Nanisivik were analyzed using methods described by Fallis, (1982).

RESULTS

Sea water

In all three cases, particularly at Maarmorilik, extensive studies of metal levels in sea water have been performed (Loring and Asmund, 1989, Asmund *et al.*, 1988c). In order to compare the three mining situations, surface sea water analyses have been selected and average concentrations calculated where several measurements existed for the upper five metres at a station. The results are presented in Table 2 and the lead concentrations are plotted in Figure 4. In all three cases, the average concentrations are highest close to the mine, with values generally decreasing with increased distance from the mine. The concentrations of dissolved metals in sea water close to Maarmorilik are notably higher in the winter as compared with the summer. Summer sea water concentrations are generally higher at Maarmorilik than at Ivittuut and Nanisivik. The high winter

Table 2 Analytical results for surface sea water samples collected in the vicinity of the three mines.

	Zn *μg/kg*	*Pb* *μg/kg*	*Distance from the mine (km)*	
	3.43	0.50	0.2	
	0.65	0.096	1.3	Nanisivik
	0.45	0.116	2.6	summer
	0.33	0.050	4.4	1982[a]
	0.86	0.085	7.0	
	41	18.2	0.2	
	5.5	2.1	0.8	Ivittuut
	2.4	0.6	1.4	summer
	1.3	0.5	2.4	1982
	2.5	0.3	3.6	
summer	4.7	3.2	0.2	
winter	66	42		
summer	5.7	2.12	2.6	Maarmorilik
winter	27	16.2		Average 1980–88
summer	6.0	1.91	2.9	
winter	23.5	9.4		
summer	3.0	1.05	5.2	
winter	14.8	5.9		

[a] Data from Thomas *et al.*, 1983.

sea water concentrations at Maarmorilik are attributed to the mixing of bottom water with the surface water in Affarlikassaa Fjord. This results in the polluted sea water at the bottom (which receives the tailings) being spread over a much greater area than just the small recipient fiord (Møller, 1984).

At Ivittuut, most of the pollution arises from the land-fill activities. The metals are released directly into the surface sea water. At Nanisivik, the situation is somewhat similar, decant from the tailings pond being released directly into Twin Lakes Creek which empties into the surface waters of Strathcona Sound. Concentrates spilled during the loading of ships also enter the surface sea water in Strathcona Sound. Table 3 summarizes the estimated quantities of metals which are released annually to the ocean at each of the mine sites.

From Table 3 it can be seen that the contact of sea water with the waste rock and tailings at Ivittuut results in considerable quantities of lead and zinc becoming dissolved in the surface sea water when compared with the concentrations in the fresh water contacting the North Face Dump at Maarmorilik and the concentrations in the ocean close to the point of entry of Twin Lakes Creek which transports the decant from the tailings pond at Nanisivik. The data in Table 3 for the North Face Dump at Maarmorilik only include the dissolved metals transported by fresh water. The dump reaches the sea, and through contact with sea water considerable amounts of metals are dissolved and dispersed to the fiord where they mix with metals originating from the adjacent marine tailings disposal.

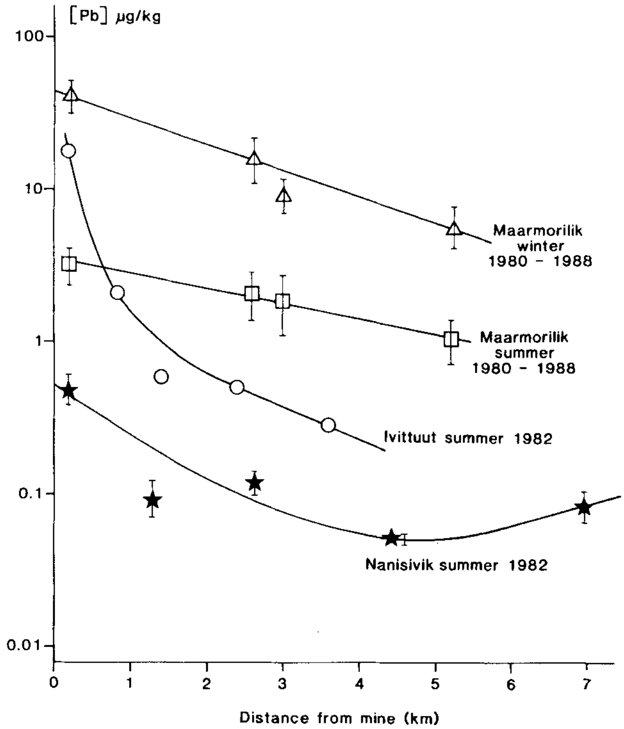

Figure 4 Semilogarithmic plots of mean lead concentrations (µg/kg) in surface sea water in the vicinity of the Maarmorilik, Ivittuut and Nanisivik mines. Bars indicate the standard deviation of the mean.

Sediments

Detailed sediment studies have been performed at Maarmorilik, (Pedersen, pers. comm.; Loring and Asmund, 1989) Ivittuut, (Bondam and Asmund, 1986) and Nanisivik (Bornhold, 1976; Fallis, 1982; Thomas *et al.*, 1983).

Table 4 summarizes the concentrations of lead and zinc in the <1 mm fraction of sediments obtained from the ocean floor in the vicinity of the three mines. Lead concentrations in the sediments close to the mine at Maarmorilik were almost six times greater than the concentrations present in sediments close to the mining operations at Nanisivik and Ivittuut when post operational concentrations were compared. Prior to mine development, lead concentrations in sediments at Maarmorilik and Ivittuut were quite similar. However, lead concentrations at Maarmorilik increased to levels almost ten times background concentrations, whereas at Ivittuut, lead concentrations increased only two and a half times relative to background concentrations. Zinc concentrations in sediments at Nanisivik and Maarmorilik provide an interesting comparison—levels at Nanisivik increased about seven times relative to background concentrations, while at Maarmorilik, zinc concentrations in sediments closest to the mine only increased two and one half times relative to preoperational concentrations. This comparison

Table 3 Estimated quantities of metals (kg/yr) released from deposited wastes.

	Zn	*Cd*	*Pb*	*Receiving water*
Maarmorilik				
Waste rock below sea level Tailings jet in marine suspension	8000–16,000	50–120	6000–12,000	sea water
Ivittuut				
Waste rock below sea level 600,000 tonnes	1000–2500	4–10	400–1000	sea water
Maarmorilik				
Waste rock above sea level Data from North Face Dump, 400,000 tonnes[a]	176	0.15	4	fresh water
Nanisivik				
Tailings deposited under fresh water 724,050 m^3 water/year	78.7	3.88	70.2	fresh water

[a] Knud Pedersen, pers. comm.

Table 4 Lead and zinc concentrations (mg/kg) in the <1 mm fraction of surface sediments (0–2 cm).

Distance from mine. (km)	*Zn (mg/kg)*	*Pb (mg/kg)*
Maarmorilik, Average 1984–1987		
1	500	390
3	300	190
5	240	140
Background (1972, 1973)	200	40
Ivittuut, 1983		
0.8		70
1.2		80
1.5		61
1.6		55
2.6		56
3.0		35
5.2		42
10.4		31
Background (before 1900)		30
Nanisivik, Average 1979–1981		
1	509	73.2
4.5	42	9.8
5.8	111	25.9
15	19	5.4

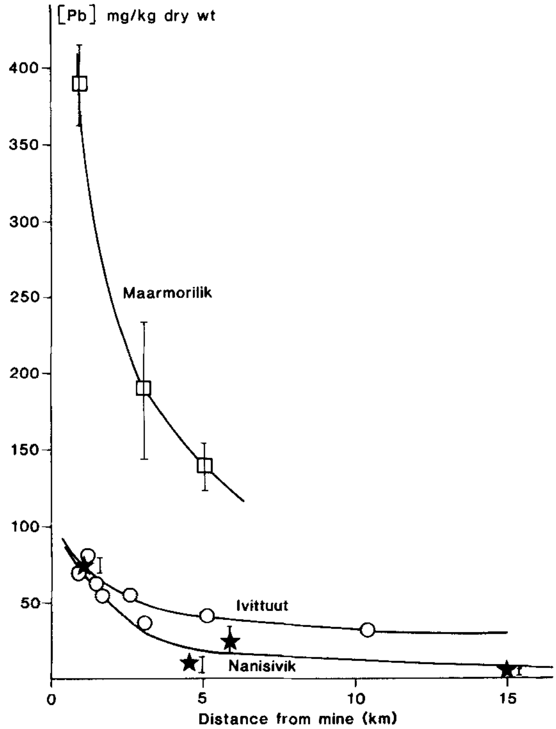

Figure 5 Mean lead concentrations (mg/kg) in the <1 mm fraction of surface sediments collected in the vicinity of the Maarmorilik, Ivittuut and Nanisivik mine sites. Bars indicate the standard deviation of the mean.

includes only sediment samples outside the main tailings sedimentation area at the bottom of Affarlikassaa Fjord, which may account for the magnitude of difference between the two mine sites. The surface sediment lead concentrations are plotted against distance from the mine in Figure 5. The metal distribution patterns for the sediments were similar to those observed in the surface sea water (Table 3).

Bivalves

Table 5 summarizes the concentrations of lead and zinc in bivalve molluscs collected from the ocean in the vicinity of each of the mine sites. As was the case of sediments, the lead concentrations were highest in the molluscs collected close to the Black Angel mine at Maarmorilik, followed by molluscs from Ivittuut. The lowest values were found at Nanisivik. Zinc concentrations in molluscs from the three sites displayed a similar pattern, with concentrations at Maarmorilik being greater than those at Nanisivik and Ivittuut. The zinc concentration in molluscs close to the mine at Nanisivik were, however, greater than the concentrations in molluscs close to the mine at Ivittuut. The higher zinc values at Nanisivik may reflect the difference in the species analyzed, or indicate the contribution of spilled concentrate to the zinc loading in bivalves at Nanisivik. The *Mya truncata*

Table 5 Lead and zinc concentrations (mg/kg) in the total soft tissues of bivalves.

Location stn.	*Distance from mine (km)*	*Concentration (mg/kg) Zn*	*Pb*	*Comments*
Ivittuut				
6	0	259	907	*Mytilus edulis*
8	0.6	281	706	Shore disposal
4	1.1	105	79	of waste
10	2.7	88	19.3	rock
3	3.3	84	10.3	
11	5.3	108	13.1	
24	9	84	4.0	
Maarmorilik				
12	0	700	1300	*Mytilus edulis*
17	1.7	350	400	1985–1987
30	4.3	400	300	Marine tailings disposal
36	11	350	220	Shore disposal of
37	18	270	130	waste rock (at Stn. 12)
L	38	150	7	
Nanisivik				
3	1	437	65.4	*Mya truncata*[a]
2	4.5	137	6.3	1980 and 1981
4	5.8	193	22.1	Lake disposal of tailings
1	15	114	2.7	No waste rock on shore
3	1	388	2.28	1979
2	4.5	118	1.00	
4	5.8	288	6.96	
1	15	124	1.42	
DS1	5.2	408	0.72	*Mya truncata*[b]
DS2	4.0	407	1.21	
DS3	0.3	584	5.38	
DS4	4.0	180	1.31	
DS5	0.2	388	2.53	
DS6	∞	273	2.46	

[a] B. W. Fallis (unpublished).
[b] D. J. Thomas *et al.*, 1983.

analyzed from Nanisivik and the *Mytilus edulis* analyzed from Ivittuut are both filter feeders and were considered to have similar metal uptake patterns, barring minor differences in filtering rates.

The data in Figures 6 and 7 for the Maarmorilik and Ivittuut sites are model calculated estimates for a standard sized mussel (1.8 g dry wt. soft tissue) based on several years' results for several size groups (Asmund *et al.*, 1988c). The standard deviation for the estimates of lead and zinc in *Mytilus* and *Fucus* at Maarmorilik and Ivittuut were between 5% and 10%. The data for Nanisivik represent averages of analytical results for molluscs of various sizes taken from Thomas *et al.*, (1983) or Fallis (unpublished).

Seaweed

The analytical results for the new growth of the seaweed *Fucus vesiculosus* are directly comparable for the three sites as shown in Table 6 and Figures 8 and 9.

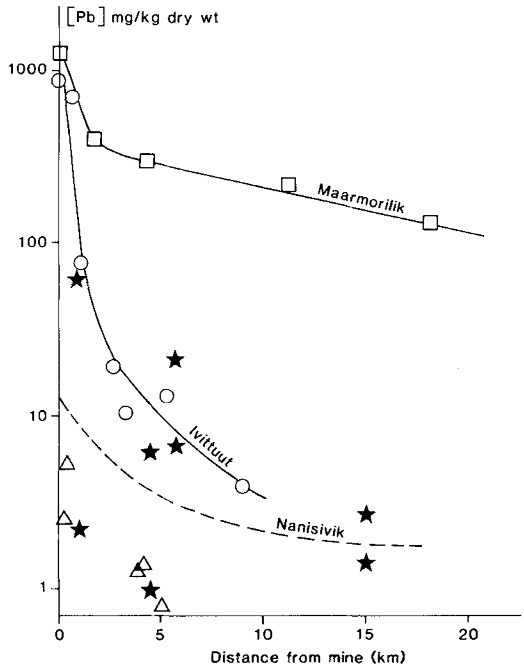

Figure 6 Semilogarithmic plots of the mean lead concentrations (mg/kg dry wt.) in the soft tissues of bivalve molluscs collected in the vicinity of the Maarmorilik, Ivittuut and Nanisivik mines. Nanisivik data depicted with stars are from Thomas *et al.*, 1983.

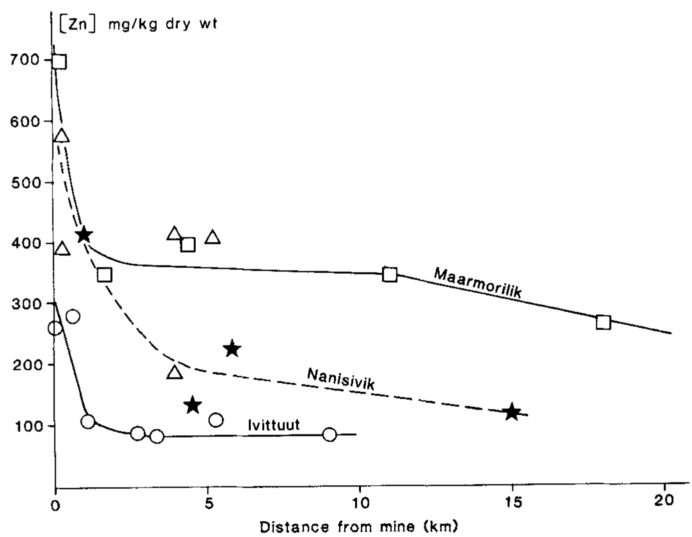

Figure 7 Mean zinc concentration (mg/kg dry wt.) in the soft tissues of bivalve molluscs collected in the vicinity of the Maarmorilik, Ivittuut and Nanisivik mines. Nanisivik data depicted with stars are from Thomas *et al.*, 1983.

Table 6 Lead and zinc concentrations (mg/kg dry wt.) in the new growth portion of *Fucus vesiculosus* collected in the vicinity of the three mine sites.

Stn.	*Distance from mine (km)*	*Zn (mg/kg)*	*Pb (mg/kg)*
Ivittuut (1986–87–88)			
6	0	234	69.3
5	0.33	232	70.1
4	0.83	42.4	4.51
3	1.9	21.4	1.02
1	4.9	20.6	0.68
Maarmorilik (1985–86–87)			
12	0.1	445	55
15	1.8	283	14.3
17	2.1	177	9.26
30	3.45	120	7.81
29	5.35	120	7.81
36	10.5	69.1	2.53
L	35	9.2	0.32
Nanisivik (1979–80–81)			
3	1	348	20.7
2	4.5	80	1.7
4	5.8	130	3.8
1	15	79	0.97

Lead and zinc concentrations were markedly higher close to the mines and decreased with distance from the mine sites. The increase in concentrations at 5.8 km (Nanisivik) is believed to reflect the input of metals leached from areas of mineralization into a creek which enters Strathcona Sound at this point. Zinc concentrations in *Fucus* at Maarmorilik and Nanisivik were higher than at Ivittuut, whereas lead concentrations close to Ivittuut exceeded those at both Maarmorilik and Nanisivik.

DISCUSSION

Comparison of lead and zinc concentrations in sea water and in tissues of molluscs from the vicinity of the mines at Maarmorilik, Ivittuut, and Nanisivik indicates wide variations in the quantities of metals present in media at different sites. The data presented reveal that there is a positive relationship between the concentrations of lead and zinc present in the sea water and the concentrations in the tissues of molluscs. A similar relationship was observed by Pentreath, (1973) and by Phillips, (1976*a*, *b*). Gault *et al.*, (1983), who studied mussels off the coast of Ireland, proposed that contamination of the marine environment could be detected by subtle changes in the concentrations of metals in mussels, and that mussel condition could be adversely affected by metal contamination. The present study adds support to the theory that metal concentrations in molluscs can serve as barometers of environmental contamination. If the value of 1 μg/g Pb as suggested by Goldberg *et al.*, 1983, and by Hansen (pers. comm.) based upon

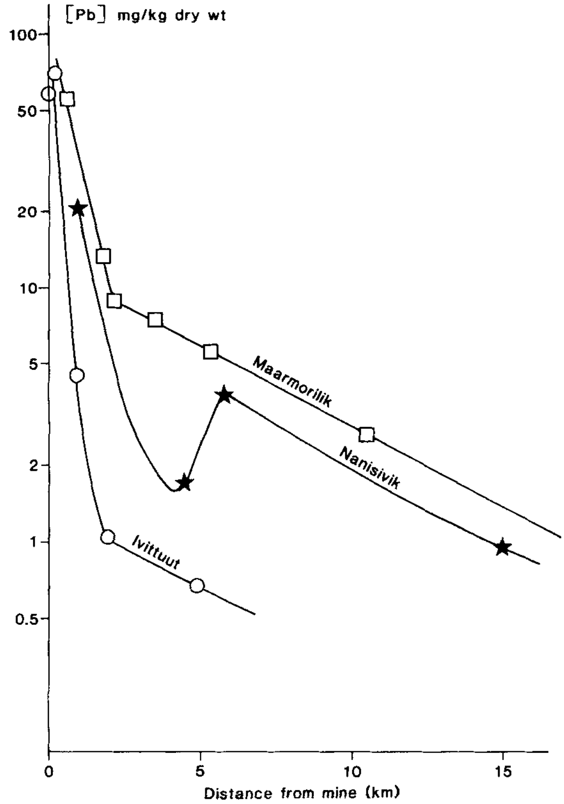

Figure 8 Semilogarithmic plots of the mean lead concentrations (mg/kg dry wt.) in the new growth portion of *Fucus vesiculosus* collected in the vicinity of the Maarmorilik, Ivittuut and Nanisivik mines.

studies at other locations in Greenland, is taken as the upper limit for naturally occurring lead concentrations in mussels; it is readily seen that the concentrations in bivalve molluscs close to the source of pollutant inputs at the mines, reported on here, consistently exceed the assumed "natural" concentration.

Based upon the data presented for the three arctic mines which all handle wastes enriched with lead, it is concluded that the environmental effects were least at Nanisivik where tailings are deposited into a freshwater lake under controlled conditions and a minimum of waste rock is produced.

At Ivittuut, where waste rock was deposited on shore, considerable impact occurred in the tidal zone. At Maarmorilik, where both waste rock deposition on shore and tailings disposal at depth in the ocean are practiced, the environmental impact was even greater.

The long term implications of disposal options for tailings and waste rock associated with the development of mines in arctic latitudes should be thoroughly evaluated prior to development. The results reported here indicate that in order to minimize environmental contamination, waste rock and tailings should be placed in areas which in so far as possible confine solids and restrict exposure to runoff and tidal action.

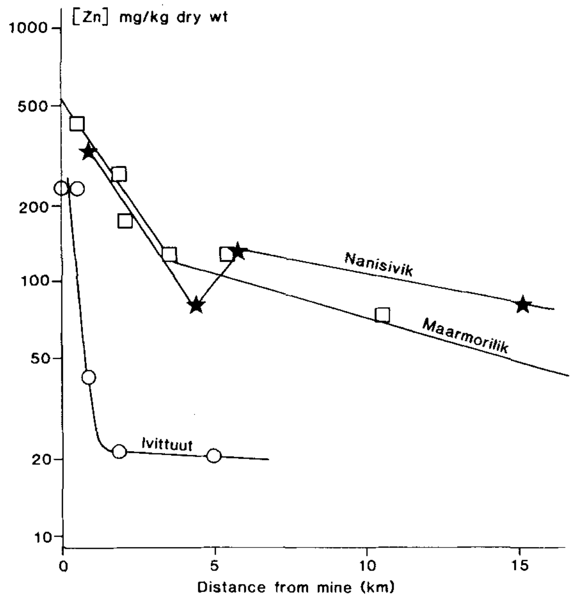

Figure 9 Semilogarithmic plots of the mean zinc concentrations (mg/kg dry wt.) in the new growth portion of *Fucus vesiculosus* collected in the vicinity of the Maarmorilik, Ivittuut and Nanisivik mines.

SUMMARY

A comparative assessment of tailings and waste rock disposal practices at two Pb/Zn mines; one in the Canadian Arctic and one in Greenland, and at a cryolite mine in Greenland was carried out. Changes in metal concentrations in sea water, sediments and biota were used to evaluate the impact of disposal practices on the neighbouring environment. The disposal options examined included:

(a) Direct disposal to the marine environment at depth
(b) Disposal on land close to the ocean shore
(c) Disposal into a lake basin with subsequent discharge of effluent to an ocean tributary

Examination of the ocean environment close to each mine site revealed that disposal of tailings in a manner which provides for containment of solids results in the release of lower quantities of available metals, as shown by metal concentrations in marine sediments and biota close to the sites of deposition.

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