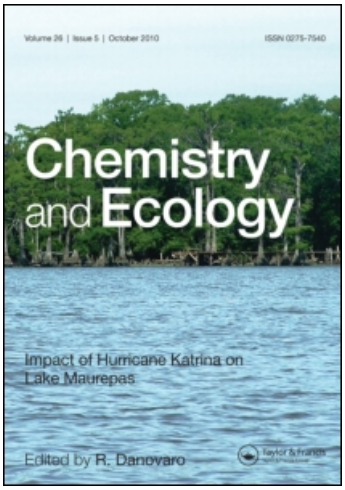

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MARINE ORGANISMS AS INDICATORS OF HEAVY METAL POLLUTION—EXPERIENCE FROM 16 YEARS OF MONITORING AT A LEAD ZINC MINE IN GREENLAND

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(5 July 1990)

KEY WORDS Indicator species, Fish, Prawn, Seaweed, Mussel, Sea water, Heavy metal, Lead, Zinc, Cadmium, Copper, Mine pollution

INTRODUCTION

In monitoring the impact of a lead-zinc mine in Greenland, species of fish, prawns, seaweed and mussels have been analysed for cadmium, copper, lead and zinc for several years. These metals have been released to the marine environment in significant amounts from the mining operation.

The underground mine is located at Maarmorilik in mid West Greenland, in the inner of a large fiord system with great water depths and steep high mountains. The operator of the mine is the company Greenex. Since mining started in 1973, the annual ore production has been c. 735,000 tonnes.

The ore is massive sulphide hosted in a light coloured marble and is composed mainly of pyrite, sphaelerite, and galena. Crushed ore is treated in a flotation plant and separated into a zinc concentrate, a lead concentrate, and c. 600,000 tonnes of tailings per year. Tailings from the plant are discharged into a small fiord (Affarlikassaa), where solids settle, as a sill at the mouth of the fiord prevents tailings from flowing into the adjacent larger fiord (Qaamarujuk), see Figure 1. However, a small but significant part of lead, zinc, and cadmium in the tailings dissolves in the bottom water of the fiord, reaching concentrations of typically 200 μg/kg Zn, 100 μg/kg Pb and 2 μg/kg Cd. Winter mixing of fiord water then causes transport of polluted water to the upper water masses of the fiord and further into Qaamarujuk.

The main pollutants are lead and zinc, but copper, cadmium, arsenic, silver, and mercury are also released to the environment. The main constituents of the ore are marble, c. 60% (Ca, Mg)CO_3, and pyrite, c. 30% FeS_2. The metal content of ore and tailings is shown in Table 1. The largest metal source is the tailings

Information in this paper is based upon studies by the authors and information from the mining company Greenex A/S.

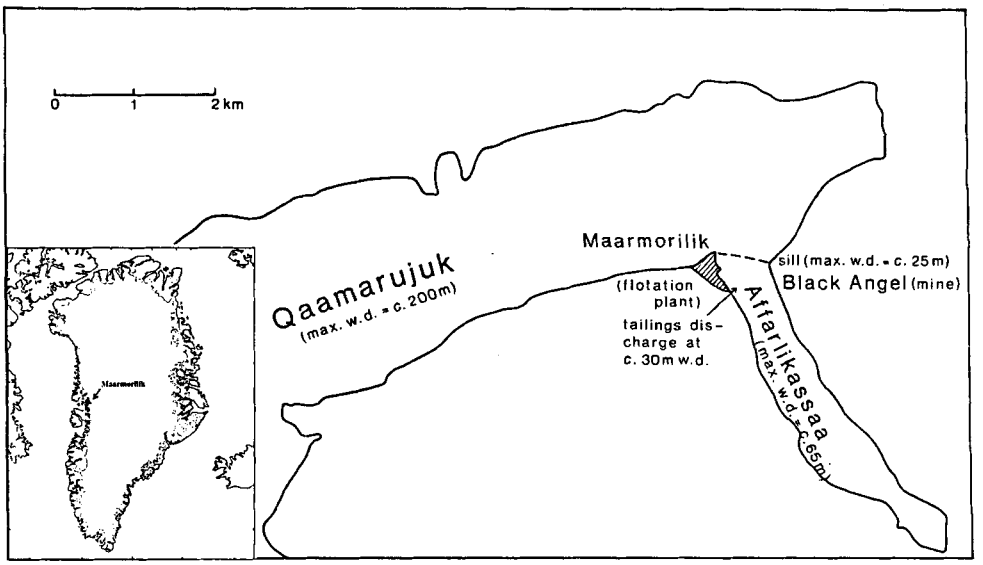

Figure 1 Map showing the location of Maarmorilik in Greenland and the Maarmorilik area (max. w.d. = maximum water depth).

discharge, but metals from waste rock and dust also contribute. The annual inputs to the larger fiord (Qaamarujuk) from all sources are several tonnes of zinc and lead. Further details about composition, quantities, and transport of pollutants are given in Johansen *et al.* (1985), Asmund *et al.* (1988a), Asmund *et al.* (1988b), and Loring and Asmund (1989).

Environmental studies in connection with the mining operation were initiated in 1972, when baseline studies were conducted. These studies continued in 1973 before the start of the operation in the fall of 1973. Since then monitoring studies have been carried out on sea water, sediments, lichens and a variety of marine organisms. This paper concentrates on presenting the results from the monitoring of sea water, fish, prawns, seaweed and mussels. Monitoring has also included sediments, marine birds, and ringed seal, but the results from these studies are not presented here. The results of the environmental studies carried out from 1972 to 1988 are presented in Asmund *et al.* (1988c).

Table 1 Composition of ore and tailings of the Black Angel mine 1988.

	Ore	*Tailings*
Pb	3.58%	0.23%
Zn	10.53%	0.40%
Fe	13.66%	16.10%
Cu	303 mg/kg	101 mg/kg
Cd	484 mg/kg	27.0 mg/kg
Ag	26.1 mg/kg	3.5 mg/kg
As	121 mg/kg	93.3 mg/kg
Hg	16.0 mg/kg	0.67 mg/kg

MATERIALS AND METHODS

Sample Types and Sampling Methods

A variety of sample types has been collected over the years to monitor temporal and spatial trends and to ensure the quality of the marine products as human food.

Water sampling was initiated on a regular basis in 1978. Samples have been taken routinely each month at several fixed depths at two fixed positions, one close to the tailing outlet in Affarlikassaa and one in the adjacent fiord Qaamarujuk. Twice per year since 1976 samples have been collected at three further stations in the two fiords and at stations outside the fiords. Samples were collected with a Hydro Bios TPN water sampler (all plastic).

Six species of fish were monitored. Capelin (*Mallotus villosus*) was sampled with a landing net while the fish were spawning at the coastline in June or early July. Samples have been collected at Maarmorilik in the period 1978 to 1988, and samples from reference sites have been collected in 1978, 1983 and 1988. Greenland halibut (*Reinhardtius hippoglossoides*) and spotted wolf-fish (*Anarhichas minor*) were caught by long line fishing at depths of c. 100–200 metres. Cod (*Gadus morrhua*) and in some instances Greenland cod (*Gadus odac*) were caught in gill nets at the surface and on long lines from deep water. Samples have been collected at Maarmorilik once per year, in some cases twice per year, and in reference sites in West Greenland within the period 1973 to 1988. Shorthorn sculpin (*Acanthocottus scorpius*) was caught with gill nets or long lines at depths of c. 5 to c. 30 metres. Regular sampling at Maarmorilik has taken place since 1984 and samples from a reference site were collected in 1984.

Deep sea prawns (*Pandalus borealis*) have been sampled each year since 1976 at Maarmorilik close to the mine and c. 5 km away. In 1984 sampling also took place c. 10 km and c. 40 km from the mine, and in 1983 at five reference sites in West Greenland. The prawns were caught by trawling and by setting traps at depths of c. 200 metres.

Seaweed and blue mussels (*Mytilus edulis*) from the intertidal zone have been sampled at a number of fixed stations close to the mine and up to 40 km from the mine from 1976 to 1988. The seaweed species sampled were mainly *Fucus vesiculosus*, in a few cases *Fucus distichus*. Samples were collected by hand at low tide. In 1984 an experiment was set up in which blue mussels were transplanted from a highly polluted site near the mine to a clean site c. 40 km from the mine and vice versa. Subsamples of resident and transplanted mussels from the two sites have been taken annually from 1984 to 1988.

Field Preparation of Samples and Storage

Water samples were filtered through a 0.45 μm Nucleopore filter and conserved with 1 ml/l suprapure nitric acid. For analysis, the conserved samples were shipped to the Danish Isotope Center, the Water Quality Institute, the Geological Survey of Greenland, or the Greenland Environmental Research Institute. Analytical methods used were anodic stripping voltammetry, potentiometric stripping or atomic absorption spectrometry.

All biological samples were frozen as quickly as possible after sampling and shipped to the laboratory without thawing.

Capelin was frozen whole. All other fish species were dissected at the field laboratory (on board a ship or at the environmental laboratory of the mining company in Maarmorilik). Samples included muscle, liver and bone tissue, except for cod where only muscle and liver tissue were sampled. Length, weight, liver weight, sex and stomach content of the fish were recorded in most instances. In some cases otoliths for age determination were collected.

Deep sea prawns were pooled in size groups according to carapace length, each group consisting of normally c. 20 individuals. In the field laboratory, each size group, except the smallest, was split into two subsamples consisting of meat and the remaining parts (heads and shells).

During all sampling years one sample of seaweed consisting of entire plants has been taken at each station. From 1982 this sample was supplemented with two further samples consisting of growth tips. These samples represent seaweed plants growing a few metres apart at the station. The samples of growth tips were prepared at the field laboratory. Growth in the Arctic is slow, and the age of the growth tips cannot be determined accurately. Growth tips were collected in September and are expected to represent the growth of the last 1–3 years. All seaweed samples were washed in distilled water prior to freezing.

Blue mussels were pooled in size groups according to shell length, each pool normally consisting of c. 20 individuals. In the field laboratory the shell length of each individual was measured to nearest millimetre, and the shells were cut open and allowed to drain. Individuals contaminated with sediment were discarded. The soft parts were cut out and frozen in polyethylene plastic bags.

Sample Preparation for Analysis

Capelin was analysed whole, and each individual was homogenized prior to analysis.

From other fish species subsamples of the tissues were taken for analysis. Samples of muscle and liver were cut out well below the original sample surface. In muscle sampling major blood vessels or bone and skin tissue were excluded from the material for analysis. Bone samples were removed from the backbone, and attached muscle tissue was removed as far as possible prior to analysis.

The prawn samples (meat, shells or whole prawns), seaweed and mussels were homogenized prior to analysis.

Chemical Analyses

Until 1987 biological samples were analysed by the Centre for Industrial Research (SI), Oslo, Norway or by B.C. Research (BCR), Vancouver, Canada. In 1988 the samples were analysed at the laboratory of Greenland Environmental Research Institute (GERI).

At SI, samples were dried and subsequently ashed at 450°C. The ash was dissolved in nitric acid and high concentrations of metals were measured in the solution by flame AAS (Perkin–Elmer 303, 460 or 503). For analysing low concentrations the metals were extracted using APDC (ammonium pyrrolidine-

dithiocarbamate) and MIBK (methyl isobutyl ketone). The MIBK phase was analysed by flame AAS. The ashing involves a risk for loss of volatiles, and in this study lead is the most volatile element. The quality of the lead analysis was checked by analysing spiked and unspiked samples of NBS no. 1577, Bovine liver, and NBS no. 1571, Orchard leaves. No losses were found.

At BCR samples were homogenized and dried and subsequently digested with concentrated nitric and perchloric acids. Cadmium, copper and zinc were determined in the diluted liquid digests by flame ASS (Perkin–Elmer Model 306). Lead was analyzed by graphite furnace AAS.

At GERI the samples were dissolved in nitric acid using teflon bombs (Berghof). High concentrations were determined using flame AAS (Perkin–Elmer 3030) and low concentrations using graphite furnace AAS (Perkin–Elmer Zeeman 3030).

Results were expressed on a dry weight basis.

Statistical Analyses

Sea water. The fiords at Maarmorilik have been sampled twice per year at 5–9 stations and at standard water depths (0, 10, 20, 30, 50, 75, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800 metres and above sea bottom). Figures 2–4 show the analytical values multiplied by the relevant volume of sea water. In addition, two stations have been sampled every month by the mining company. The results from the stations in Qaamarujuk were used to calculate average surface concentrations (0 and 10 metres) and average bottom water concentrations (50, 75, 100, and 2 m above sea bottom).

Biological samples. For all biological analyses logarithmic transformation of metal concentrations and biological covariates such as length, weight or liver weight were used.

The statistical treatment of the data has the primary aim of determining time trends and differences between sampling areas and were based on analysis of variance. Parameters such as year, sampling locality and sex were defined as class variables while biological covariables were included as regression variables.

In some data sets a consultant to the mining company (B.C. Research, Canada) analysed samples in addition to the samples analysed by the Centre for Industrial Research. In order to obtain the broadest possible data base, the laboratory was included in these cases as a class variable to take account of possible systematic laboratory differences in analyses. The analysis of variance as presented here was used to compute values normalized to a specific set of conditions (e.g. length, weight, sex or laboratory). Also 95% comparison intervals were computed for the normalized values (i.e. values adjusted for significant biological covariates). The method used is approximate and is due to Gabriel (see Sokal and Rohlf, 1981). Normalized values whose intervals do not overlap are significantly different. The statistical analyses were performed using the GLM procedure (General Linear Model) of the SAS software system.

In the analysis of variance of capelin data, length was included as a covariate. In the analysis of variance of other fish data the significance of length, weight, liver weight and sex was determined for each species and tissue separately. In the final analysis, determining time trends and differences between sampling areas,

only parameters found to be significant in the first analysis were included as covariates/class variables.

In the presentation of the prawn data the metal concentration in whole prawns of each size group was computed. Mean weight was used as a covariate in the analysis. In mussels the results are expressed as concentration in the soft parts. Mean weight of the group was used as a covariate. In the analysis of seaweed data, seaweed species was used as a class variable. In the data treatment in this paper whole plants as well as growth tips were included in the analysis. The type of material was defined as a class variable.

RESULTS

Sea Water

Zinc, lead, and cadmium in sea water of the fiords at Maarmorilik have been monitored for several years. The highest concentrations of metals were found during the first 4 years after the start of the operation, when up to 1000 μg/kg Zn and Pb and 5 μg/kg Cd were found in the bottom water of Affarlikassaa. In the neighbouring larger fiord Qaamarujuk zinc or lead concentrations higher than 20 μg/kg are observed rarely. The total volume of the two fiords is $1.40 \cdot 10^9$ m^3. Using this figure and the concentrations measured, the tonnage of dissolved metals present has been computed as shown in Figures 2, 3, and 4. A significant decrease is seen in 1979, when the mining company initiated an intensive environmental program.

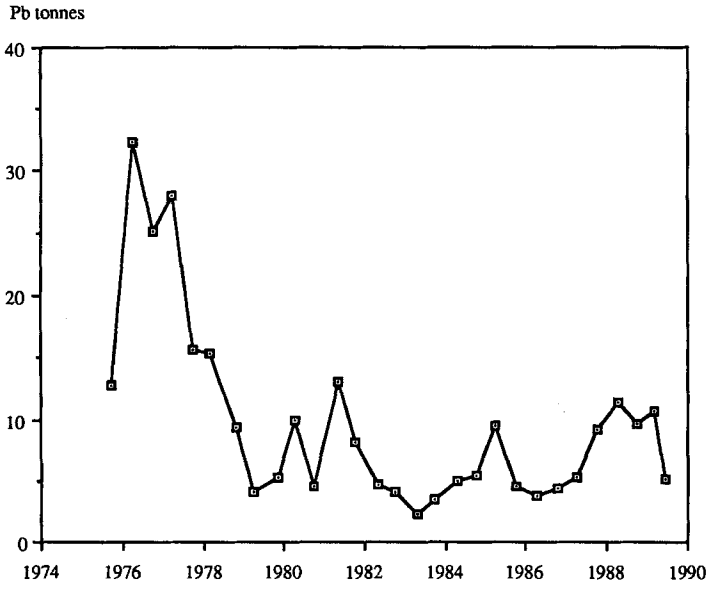

Figure 2 Total amount (tonnes) of lead present in Affarlikassaa and Qaamarujuk.

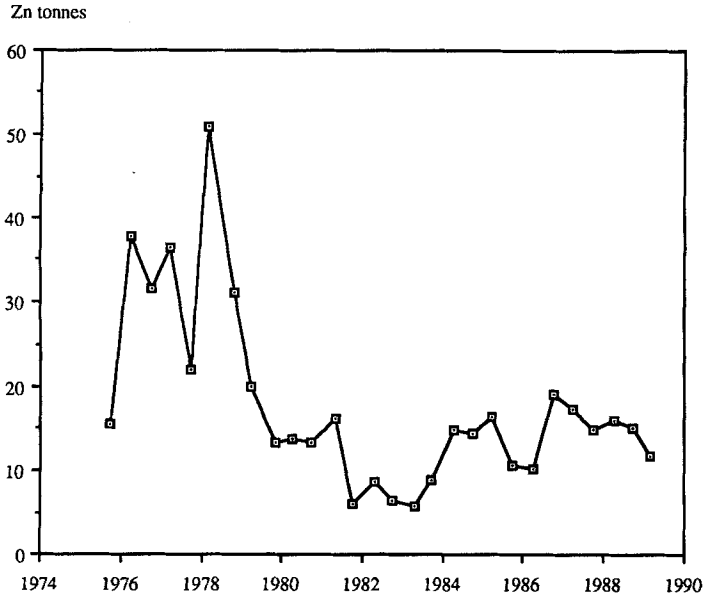

Figure 3 Total amount (tonnes) of zinc present in Affarlikassaa and Qaamarujuk.

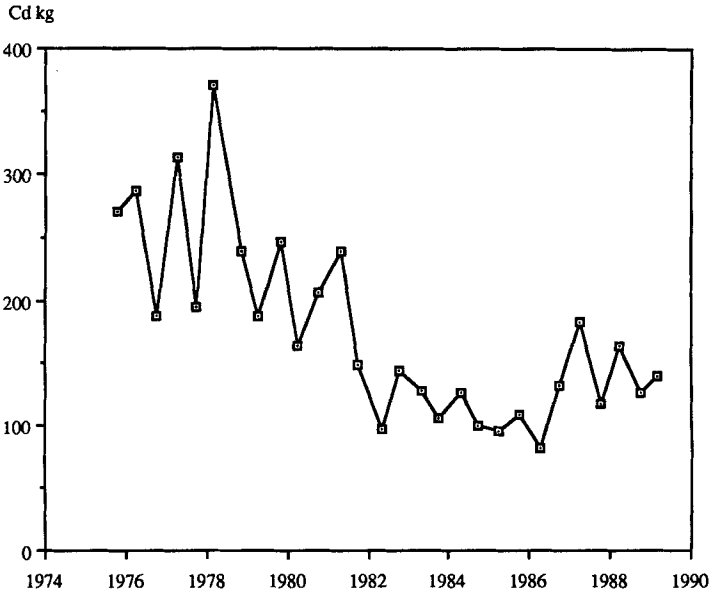

Figure 4 Total amount (kg) of cadmium present in Affarlikassaa and Qaamarujuk.

Fish

By comparing the results from fish sampled near the mine with results from reference areas in Greenland, it appears that only lead levels are clearly elevated in fish from Maarmorilik, and not the levels of cadmium, copper and zinc. Therefore only the lead results are presented.

Capelin. The estimated values and 95% comparison intervals of lead in whole capelin sampled at Maarmorilik in the period 1978–1988 and at three reference sites in West Greenland are shown in Figure 5. Lead values are significantly higher (2–13 fold) at Maarmorilik than at reference sites (using the highest value from reference sites).

Greenland halibut, spotted wolf-fish, shorthorn sculpin, Greenland cod and cod. No differences between the lead level in meat from fish at Maarmorilik and those from reference sites have been detected, except the level in shorthorn sculpin. The lead concentration in fish meat is very low, normally less than the detection limit of 0.05 μg/g (dry weight basis).

No differences between the lead level in liver and bone from Greenland halibut and in liver from cod sampled at Maarmorilik and the level at reference sites have been detected, and in most instances this is also the case for the level in liver and bone from Greenland cod.

The lead values and 95% comparison intervals in liver and bone from spotted wolf-fish and shorthorn sculpin are shown in Figures 6 to 9. The lead level is elevated 3–10 fold in liver of both species, 2–4 fold in bone from wolf-fish and 4–15 fold in bone from shorthorn sculpin. Furthermore, in shorthorn sculpin

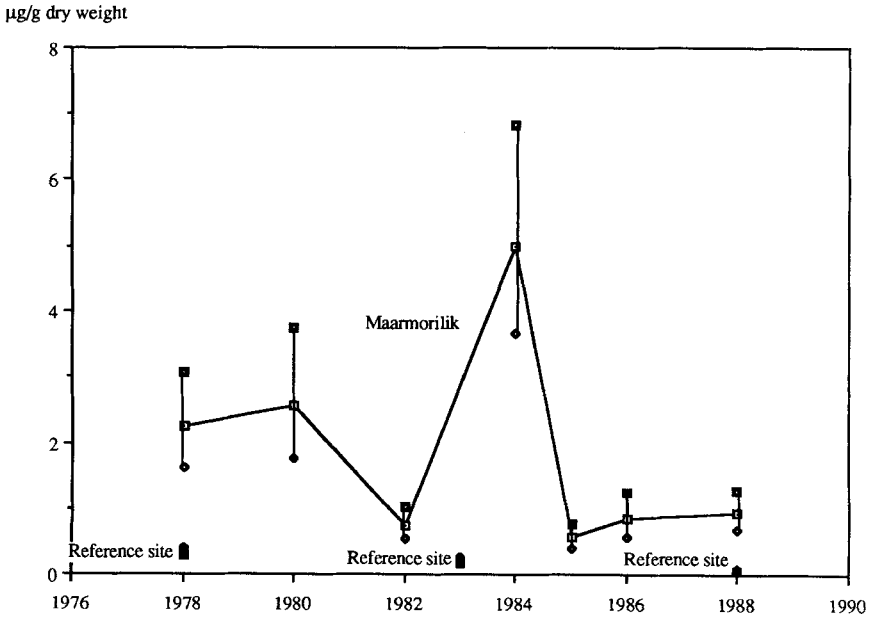

Figure 5 Estimated lead concentration (μg/g dry weight) in capelin from Maarmorilik and from reference sites in West Greenland. 95% comparison intervals are shown as bars.

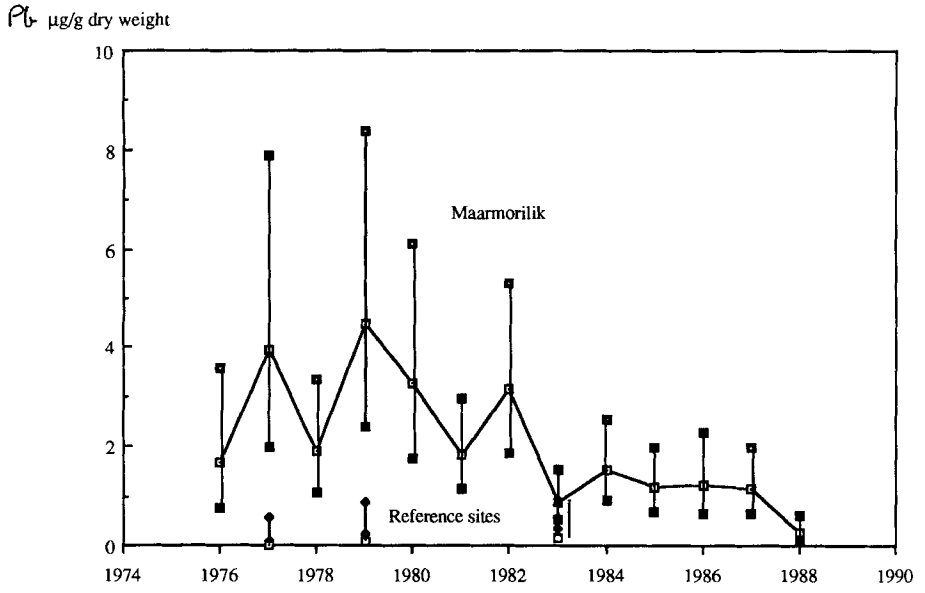

Figure 6 Estimated lead concentration (µg/g dry weight) in spotted wolf-fish liver from Maarmorilik and from reference sites in West Greenland. 95% comparison intervals are shown as bars.

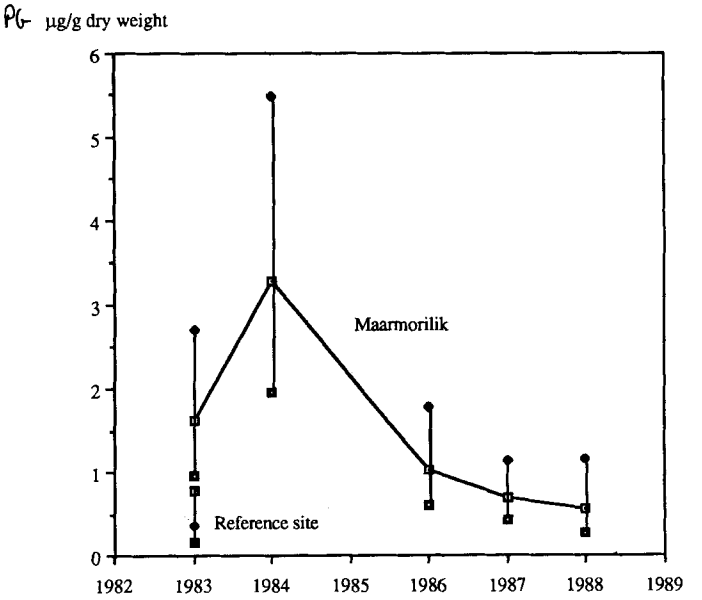

Figure 7 Estimated lead concentration (µg/g dry weight) in spotted wolf-fish bone from Maarmorilik and from a reference site in West Greenland. 95% comparison intervals are shown as bars.

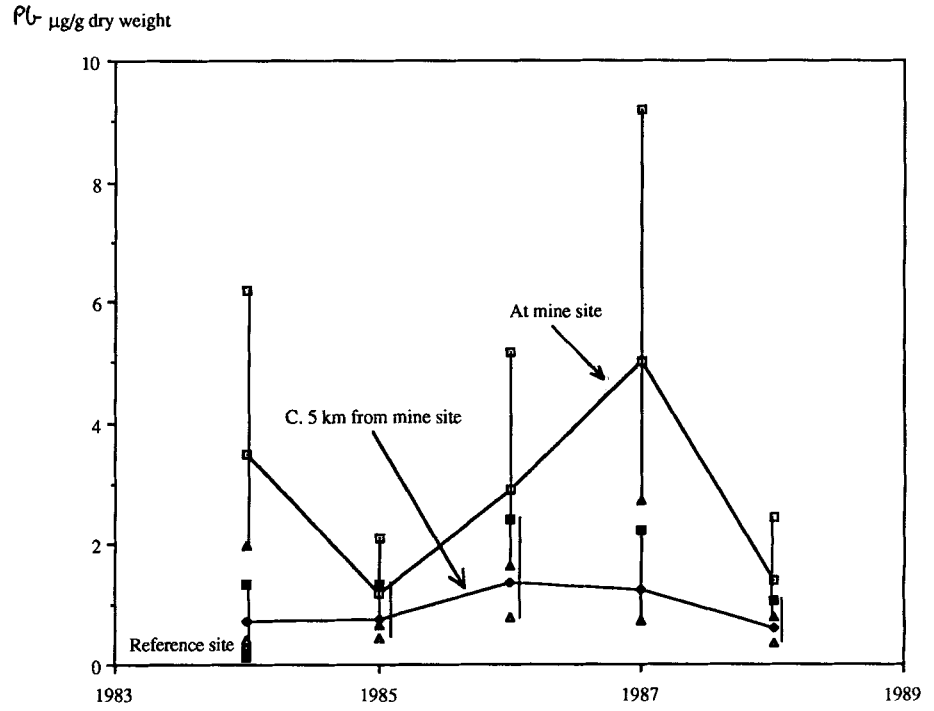

Figure 8 Estimated lead concentration (μg/g dry weight) in shorthorn sculpin liver from Maarmorilik and from a reference site in West Greenland. 95% comparison intervals are shown as bars.

sampled close to the mine (1–2 km from Maarmorilik) the lead level in liver and bone is c. twice (liver) and c. 3 times (bone) higher than the level found c. 5 km from the mine. The general pattern is that the Maarmorilik values in all years differ significantly from the reference site values. If only 95% comparison intervals for the same year are compared, no overlap is found apart from the values in spotted wolf-fish liver in 1983 (Figure 6).

Prawns. Estimated values of cadmium, copper, lead and zinc in whole prawns and meat from individuals sampled close to the mine, c. 5, c. 10, and c. 40 km from the mine are shown in Table 2. Estimated lead values and 95% comparison intervals close to the mine from the period 1976–1988 and from reference sites in West Greenland are shown in Figures 10 and 11.

As in the case for fish, only lead levels are significantly elevated at Maarmorilik and not cadmium, copper and zinc when compared to levels found at reference sites. There is a clear geographical trend for lead in the prawn (Table 2), as values decrease with an increasing distance up to 40 km from the mine. The metals are found mainly in heads and shells of prawns. Table 2 shows that Cd-values increase with increasing distance from the mine.

Seaweed. Cadmium values do not show any trends in the study area, indicating no cadmium uptake in seaweed above background levels. Values in whole plants and growth tips do not differ significantly. Cadmium concentrations normally vary around 1 μg/g on a dry weight basis.

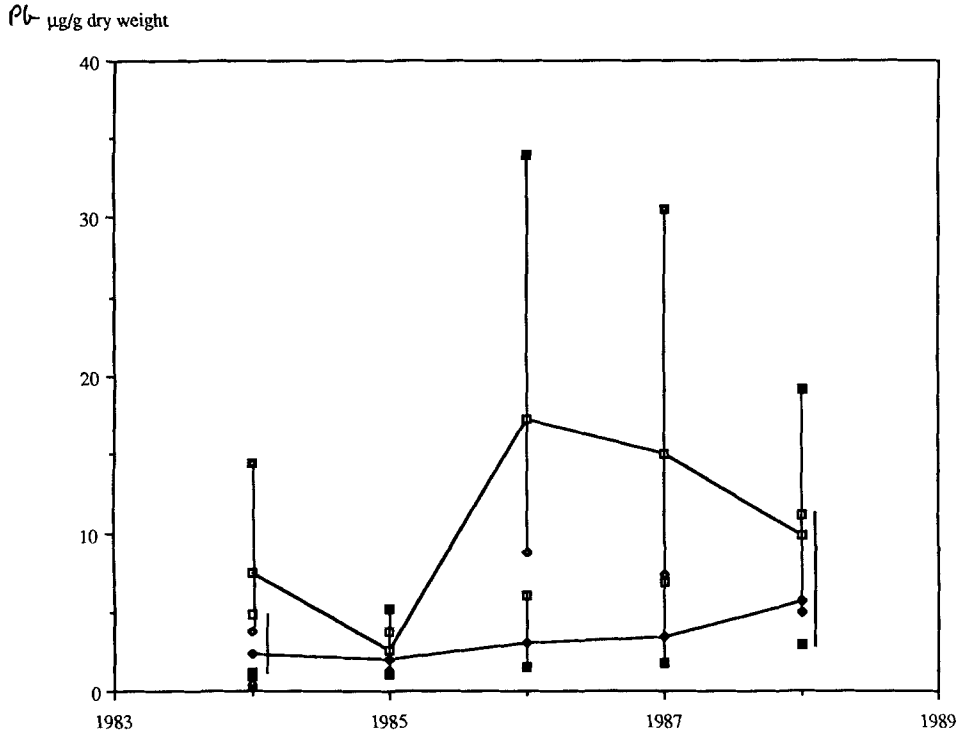

Figure 9 Estimated lead concentration (µg/g dry weight) in shorthorn sculpin bone from Maarmorilik and from a reference site in West Greenland. 95% comparison intervals are shown as bars.

Copper values are elevated only slightly very close to the mine. Values in whole plants and growth tips differ significantly, on the average 23% lower in growth tips than in whole plants. Outside the area affected, copper concentrations normally are around 4 µg/g on a dry weight basis.

In contrast to cadmium and copper, lead and zinc values are elevated to high

Table 2 Estimated values (µg/g dry weight) of Cd, Cu, Pb and Zn in deep sea prawns from the Uummannaq area 1984.

Distance (km) from Maarmorilik	*Cd*	*Cu*	*Pb*	*Zn*
		Whole prawn		
1–2	2.73	68.6	5.73	69.3
4–5	4.15	78.0	4.46	71.1
10	4.63	72.3	1.78	67.3
38	5.40	85.6	0.81	69.5
		Meat		
1–2	0.14	13.3	1.06	47.2
4–5	0.08	18.2	1.42	44.9
10	0.11	18.1	0.57	44.9
38	0.15	18.4	1.02	46.6

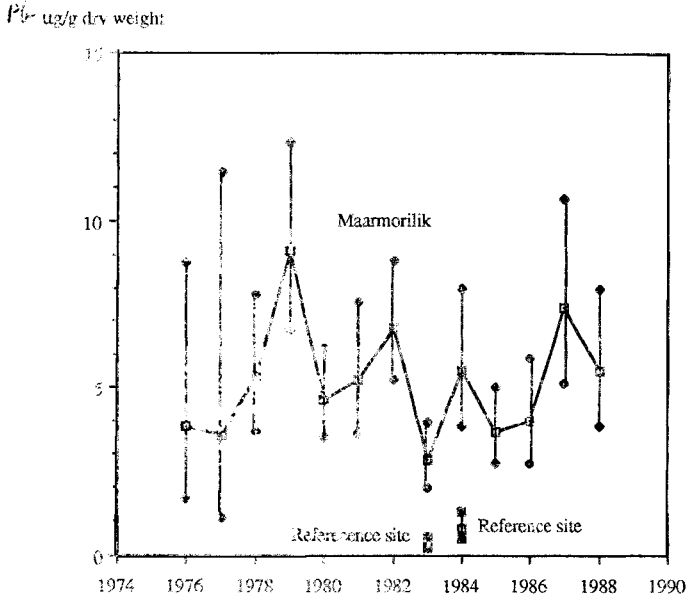

Figure 10 Estimated lead concentration in whole prawn (µg/g dry weight) from Maarmorilik and from reference sites in West Greenland. 95% comparison intervals are shown as bars.

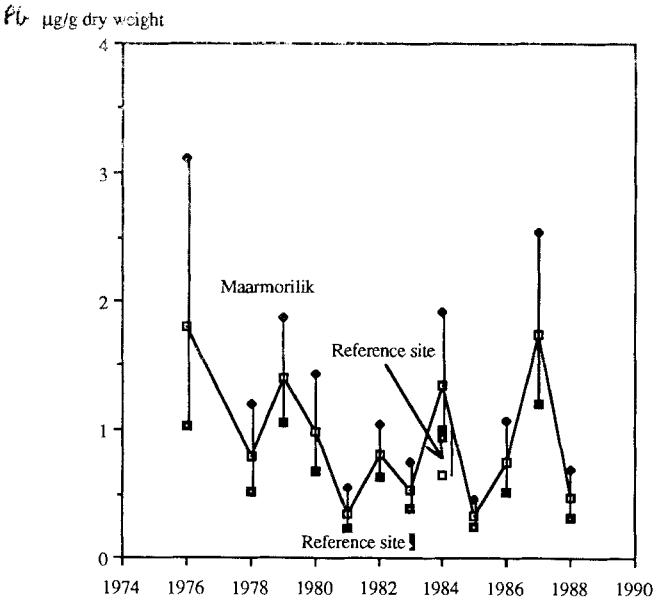

Figure 11 Estimated lead concentration (µg/g dry weight) in prawn meat from Maarmorilik and from reference sites in West Greenland. 95% comparison intervals are shown as bars.

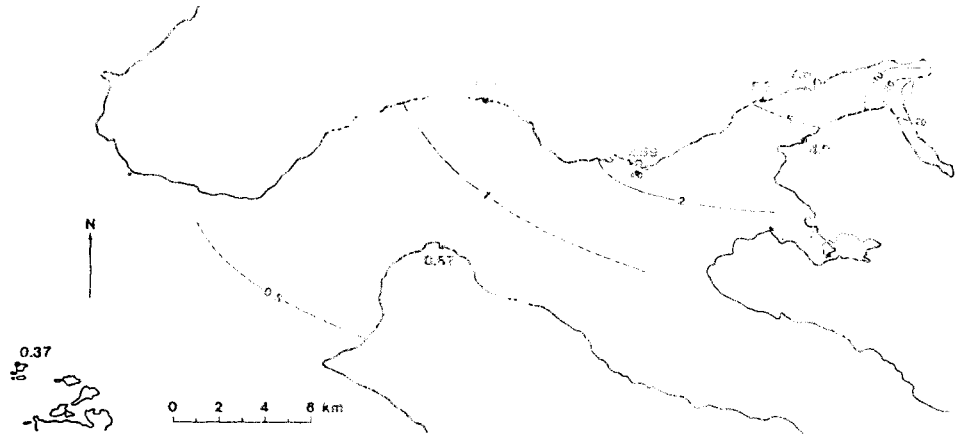

Figure 12 Estimated lead concentration (μg/g dry weight) in growth tips of seaweed.

levels in a wide area up to 30 km from the mine. Values in whole plants and growth tips differ significantly, on the average 44% lower in growth tips for lead and 36% lower for zinc than in whole plants. The geographical distributions of lead and zinc in growth tips of seaweed are shown in Figures 12 and 13. The values are averages of observations from 1986 and 1987. It can be seen that growth tips of seaweed reflect the dispersion of lead and zinc from the sources at the mine.

Blue mussel. Cadmium values are elevated only slightly very close to the mine. Outside this area, cadmium concentrations are between 2 and 5 μg/g on a dry weight basis.

Copper values do not show any trends in the study area, indicating no copper uptake in blue mussels above background levels. Copper concentrations vary between 6 and 10 μg/g on a dry weight basis.

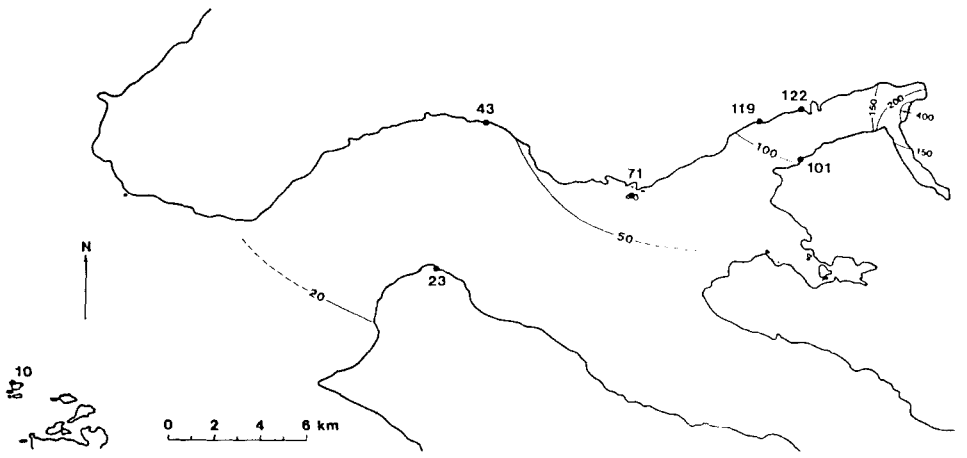

Figure 13 Estimated zinc concentration (μg/g dry weight) in growth tips of seaweed.

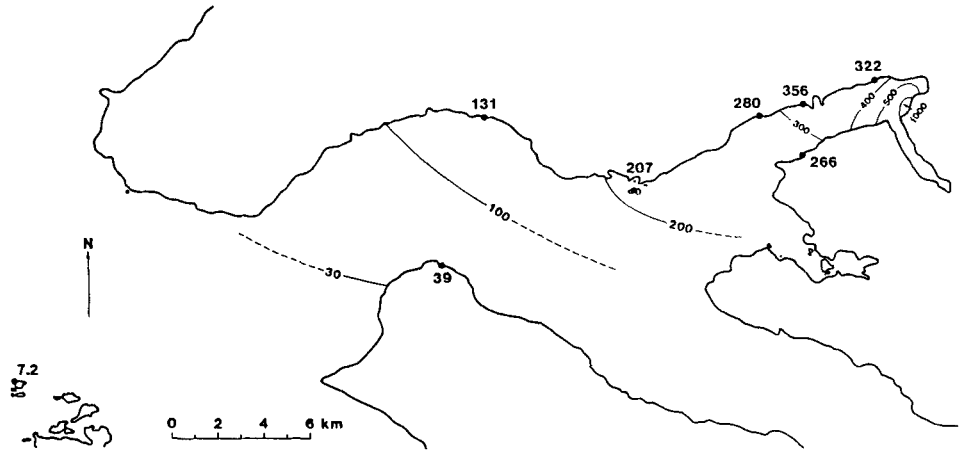

Figure 14 *Estimated lead concentration (μg/g dry weight) in blue mussel.*

As is the case for seaweed, zinc and especially lead are elevated in a wide area, up to 30 km from the mine. The geographical distribution of lead and zinc in blue mussels is shown in Figures 14 and 15. The values are averages of observations from 1986 and 1987. It is seen that there is a clear geographical trend for lead, which is elevated 100–1000 times above background level close to the mine. The same trend is found for zinc, but levels are elevated only 2–10 fold.

Release rates of lead and zinc in the blue mussel have been studied by transplanting mussels from a highly polluted site close to the mine to a clean area c. 40 km from the mine, and uptake rates have been studied by transplanting mussels from the clean area to the highly polluted area. Transplanted and resident populations have been sampled annually since mussels were transplanted in 1984. The metal content of a mussel of a specific size was computed.

Figure 16 shows that the lead content in mussels transplanted from the highly

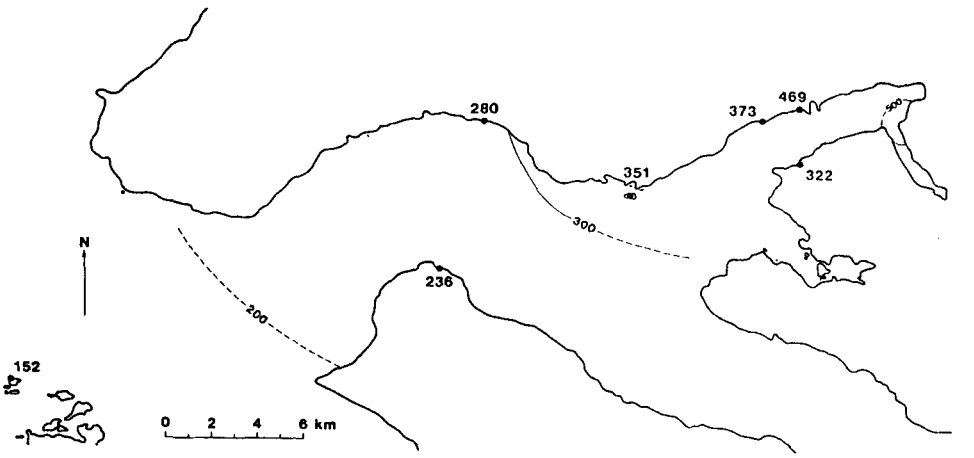

Figure 15 Estimated zinc concentration (μg/g dry weight) in blue mussel.

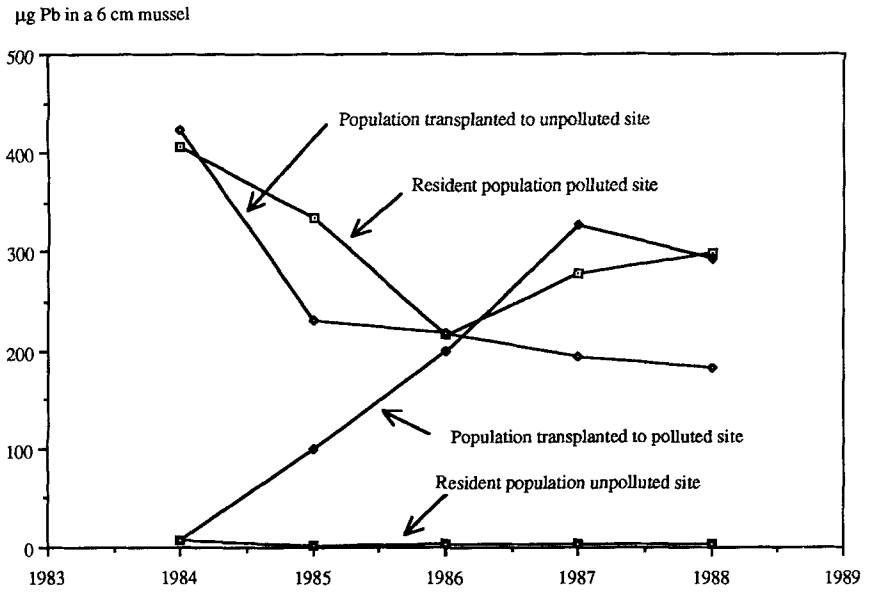

Figure 16 Estimated lead content (µg Pb in a mussel of 6 cm shell length) in transplanted and resident populations of blue mussel. The relative standard deviation of the estimated lead content is between 5 and 10%.

polluted area to the clean area within one year fell to about 55% of the content one year earlier. During the following three years the decrease was much slower, from 6% to 12% per year. Mussels transplanted from the clean site to the highly polluted area gradually took up lead and reached the level of the resident population the second year after transplantation. Similar, but not so clear results, were found for zinc.

DISCUSSION

The purpose of analysing indicator organisms is to identify differences in contaminant levels. These differences can be between areas (spatial trends) and in time (temporal trends).

The quality of an organism as a quantitative indicator depends on the ability of the organism to reflect the changes in the levels of contaminants in the environment. It is fairly easy to identify the ideal properties of a perfect indicator (Phillips, 1980). However, no single species fulfils the ideal properties, and the problem therefore is to determine the organism, which under different circumstances, can provide meaningful information.

In this study, time trends as well as spatial trends have been investigated. Because changes in contaminant levels from year to year normally are small, the quantification of time trends is more difficult than that of spatial trends. This is particularly true in the Maarmorilik case where the mine is the only man-made source of metals in a large area, creating a substantial gradient in metal

concentrations as a function of distance from the mine. The following discussion of our results therefore first focusses on identifying the organisms which reflect the expected differences between sampling sites, demonstrating the monitoring capabilities when differences are large, and then looks in more detail on their qualities as time trend indicators.

By comparing the results from fish sampled near the mine with results from reference areas in Greenland, it appears that only lead levels are clearly elevated in fish from Maarmorilik, but not the levels of cadmium, copper and zinc. This may seem surprising knowing that the fish are exposed to an annual input from the mining operation of 5 to 10 tonnes of lead, 5 to 10 tonnes of zinc, 0.5 to 1 tonnes of copper, and 100 to 200 kg of cadmium (see Figures 2–4). Since lead concentrations are elevated in some species, some fish must have remained in the polluted area for some time, and it therefore is concluded that zinc and cadmium are not accumulated in the fish tissues analysed in this study.

Lead concentrations at Maarmorilik exceed those of reference sites in tissues of spotted wolf-fish (Figures 6 and 7), capelin (Figure 5), and especially shorthorn sculpin (Figures 8 and 9), but not in tissues of cod or Greenland halibut. This is attributed to the migratory behaviour of the different species. Cod and Greenland halibut are considered to migrate to an extent that they remain too short a time in the polluted area to accumulate lead significantly. Spotted wolf-fish and shorthorn sculpin are considered to be rather stationary, lending to these species the ability to reflect environmental lead levels. Shorthorn sculpin even show differences in lead concentration within a few kilometres. As this species has a very wide geographical distribution, and is usually numerous and easy to catch, it seems to be a useful indicator fish species.

Capelin also have higher lead concentrations at Maarmorilik than at reference sites, but with large and unsystematic variations between years. The migratory behaviour of capelin in the area is not known, but there is a possibility that the very high concentrations may be caused by uptake of metals from shore sediment during spawning.

As is the case for fish, lead is the only element that is significantly elevated in prawns at Maarmorilik compared to levels found at reference sites. As seen in Table 2, the lead concentration in prawns exhibits a clearly decreasing trend with increasing distance from the mine, and therefore this organism seems to be a useful indicator for lead. For cadmium in whole prawns an interesting phenomenon is observed: the concentration increases with increasing distance from the mine. Since elevated levels of cadmium are found in sea water near the mine this is surprising. However, other factors may be more important for the uptake of cadmium by biota. A similar observation has been made in seaweed and blue mussels sampled in the unpolluted Godthåb Fiord, Southwest Greenland. In algae, as well as mussels, a gradient in the cadmium concentrations was found with lowest concentrations at the head of the fiord and highest concentrations near the open sea. These data suggest that higher cadmium concentrations may be found in the more "oceanic" sampling localities. The reason for this is not known.

Blue mussels and seaweed are normally sampled at the same stations in the intertidal zone. Both sample types reflect the pollution with lead and zinc, but not with cadmium. For lead the geographical distribution and the gradients are similar. The concentrations of zinc also are highest near the mine and have a

clearly decreasing trend out through the fiord system. However, the gradients are not as steep as the gradients observed for lead, and rather different in mussels and seaweed. The zinc gradient in seaweed resembles the lead gradients in mussels and seaweed. In mussels, the zinc gradient is very flat, probably due to a physiological regulation of the internal zinc concentration in mussels. Consequently seaweed seems to be a good indicator for environmental concentrations of lead and zinc, while the blue mussel seems to be a good indicator for lead but not for zinc. One should, however, be aware, as shown in the transplantation experiment, that part of the lead taken up by the mussels is excreted very slowly. This means that the blue mussel is not very useful to monitor decreasing lead exposure, at least over time spans that are short compared to the age of the mussels.

In conclusion, the geographical comparisons of metal levels have shown that liver and bone of some fish species reflect expected trends in lead concentration (shorthorn sculpin and spotted wolf-fish). Other fish species (cod, Greenland halibut) seem to be mobile to an extent that they cannot be used as monitors for pollution within areas where pollution does not extend beyond say 20 kilometres. Prawns, seaweed and mussels show geographical trends for lead that are expected. Seaweed and to a less extent mussels reflect expected trends in zinc concentrations. Mussels, however, cannot be recommended for zinc monitoring. Neither fish nor prawns indicate environmental zinc gradients.

It is notable that none of the analysed biota reflect the elevated cadmium concentrations in the sea water, which indicates that monitoring for cadmium using biological indicators in some cases will not work. This may be due to a competitive effect of zinc, which chemically is rather similar to cadmium. A further explanation may be that cadmium concentrations in sea water at Maarmorilik are not elevated as much as lead and zinc. In September 1986 for example, in the inner part of Qaamarujuk Fiord, lead in sea water was elevated 50 fold, zinc 100 fold, but cadmium of 2 fold compared to typical coastal waters. Birds and mammals are known to accumulate cadmium in the kidneys, and this could also be the case for fish kidneys which have not been analysed at Maarmorilik. However, analyses of 25 shorthorn sculpin from an area in East Greenland not affected by any local sources of pollution gave geometric mean cadmium values of 0.003 mg/kg wet weight in muscle, 0.651 mg/kg in liver and 0.082 mg/kg in kidney, indicating that in fish liver rather than kidney accumulates cadmium.

Even if a species reflects major differences in element levels, as is the case for the geographical differences discussed above, it is not necessarily an efficient monitor of small differences such as time trends, without more detailed analysis of the monitoring data. To study this, comparisons between time trends have been made in cases where the geographical comparisons demonstrated indicator capabilities of the species.

If one compares the time series of lead in sea water (Figure 2) with that of lead in the liver of spotted wolf-fish (Figure 6), the correlation is not convincing.A closer examination of the data reveals that the lead concentration in the livers of wolf-fish sampled at Maarmorilik often falls into two distinct groups, one resembling the reference site, in which the lead concentration was between 0.14 and 0.86 μg/g, and the remaining observations which fall into a larger concentration range from 1 to 50 μg/g. This indicates that the fish stock in the fiord consists

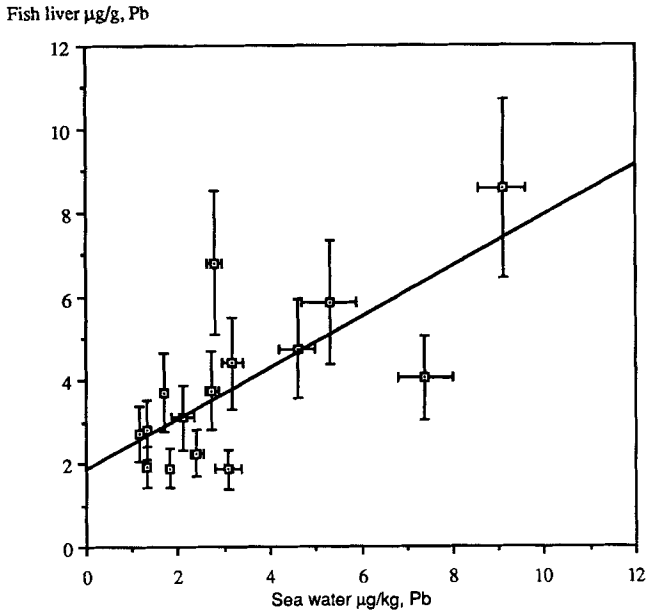

Figure 17 Estimated lead concentration (μg/g dry weight) in spotted wolf-fish liver above 0.86 μg/g plotted against mean sea water lead concentration (μg/kg) below 50 metres 6 months before fish sampling. Mean values have been computed only if more than 10 fish had a lead concentration higher than 0.86 μg/g. Standard deviations are shown as bars.

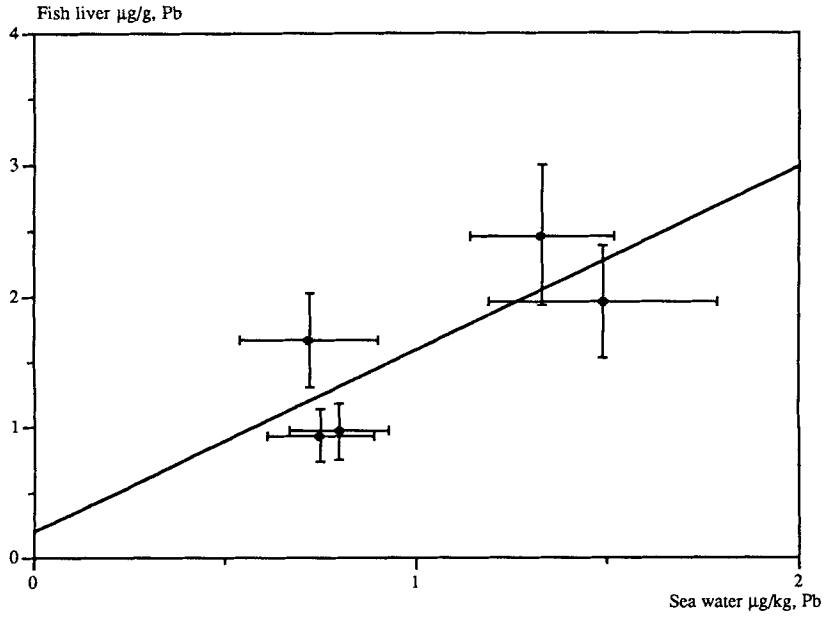

Figure 18 Estimated lead concentration (μg/g dry weight) in shorthorn sculpin liver plotted against mean sea water lead concentration (μg/kg) in 0 and 10 metres of Qaamarujuk at the time of fish sampling. Standard deviations are shown as bars.

of one part that has arrived recently to the polluted area and therefore cannot be distinguished from fish from the reference site, and one part that has stayed a longer period in the polluted area. Consequently, all values at Maarmorilik below the highest value from the reference site (0.86 μg/g) have been omitted, and a lead value of the remaining observations has been calculated and plotted against the dissolved lead concentration in sea water for depths greater than 50 metres over a period of 6 months before sampling of the fish (Figure 17). This results in a better correlation between lead concentration in sea water and wolf-fish liver. On a logarithmic basis, the omission of the values below 0.86 μg/g increases the correlation coefficient R from 0.46 to 0.68. The concentration factor between sea water and wolf-fish liver is c. 1000.

The lead concentration in the liver of shorthorn sculpin close to the mine and in sea water also has been compared. In this case a reasonable correlation was obtained using the lead concentration in surface water at the time of sampling, see Figure 18. The concentration factor between sea water and shorthorn sculpin liver is c. 1500 with a correlation coefficient R of 0.77. There is no indication that fish migration has to be taken into account as for wolffish when interpreting results for sculpin.

A closer examination of lead concentrations in seaweed and blue mussel compared to lead concentrations in sea water also has been made. Here the lead

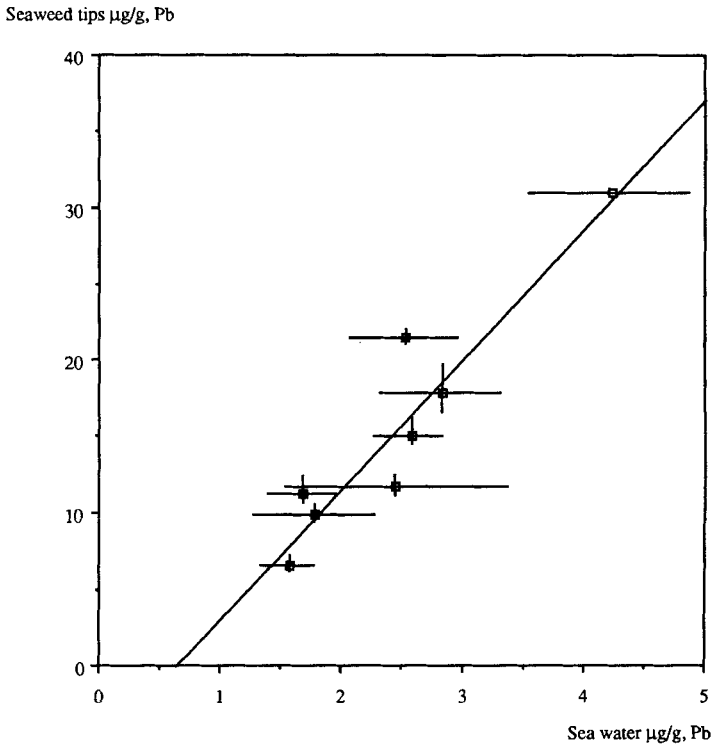

Figure 19 Estimated lead concentration (μg/g dry weight) in growth tips of seaweed (*Fucus vesiculosus*) close to the mine site plotted against mean sea water lead concentration (μg/kg) in 0 and 10 metres in June to September prior to seaweed sampling in September. Standard deviations are shown as bars.

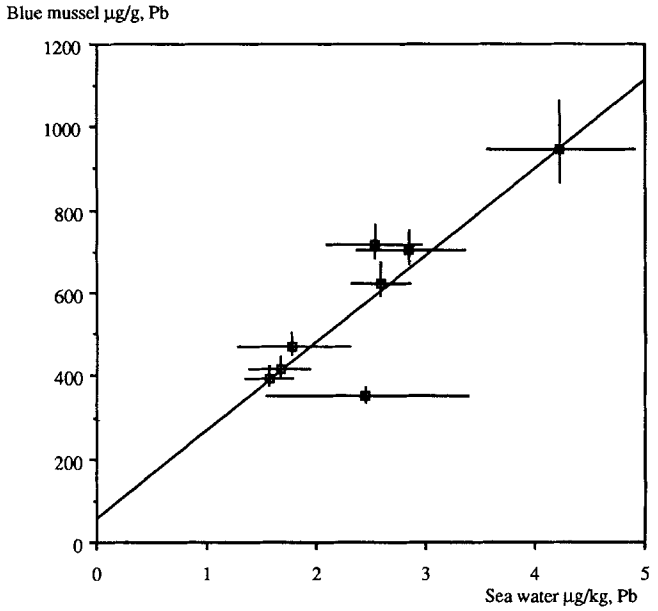

Figure 20 Estimated lead concentration (μg/g dry weight) in blue mussel (*Mytilus edulis*) close to the mine site plotted against mean sea water lead concentration (μg/kg) in 0 and 10 metres in June to September prior to mussel sampling in September. Standard deviations are shown as bars.

concentration in growth tips of seaweed and blue mussels collected close to the mine has been plotted against the mean dissolved lead concentration in sea water samples from 0 and 10 metres in June to September, as the seaweed and the mussels have been exposed to metal uptake in this period (the growing season) prior to sampling in September. As shown in Figures 19 and 20 the correlation is reasonably good ($R = 0.93$ for seaweed and $R = 0.88$ for the blue mussel). The concentration factor between growth tips of seaweed and sea water is c.6200 and c. 220,000 for the blue mussel.

In conclusion, those species that have indicator capabilities for the geographical distribution of lead also reflect changes in exposure over time, although there seems to be larger variability when time trends are considered. In some cases, assumptions or considerations about heavy metal data and the biology of the species will have to be made when interpreting data.

SUMMARY

In West Greenland a lead-zinc mine has operated since 1973. Significant amounts of cadmium, copper, lead and zinc are released to the marine environment from the mining operation.

Monitoring of these metals in sea water, marine algae, molluscs, shrimps and fish has taken place since 1972. The monitoring studies have revealed large differences in metal levels from species to species and from tissue to tissue and have found to what extent metal levels are elevated above background levels.

The monitoring results are presented and discussed in order to select the species (and tissues) best reflecting spatial and temporal trends in metal levels of their environment. It is demonstrated that seaweed, mussels and prawns as well as liver and bone from sculpin and wolf-fish appear to be good indicators for lead. Seaweed is also a good indicator for zinc.

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