ENVIRONMENTAL MONITORING AT THE FORMER LEAD-ZINC MINE IN MAARMORILIK, NORTHWEST GREENLAND, IN 2009

NERI Technical Report no. 775 2010

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Data sheet

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Abstract: In 2009 environmental monitoring was carried out at the former lead-zinc mine which closed in 1990. Samples of lichens and blue mussels were analyzed. The study shows, that after mine closure an impact from the previous mining operation can still be seen. The pollution with dust on land seems to continue with no signs of a decrease, while the pollution in the sea is decreasing.

Keywords: Lead, zinc, mining, Black Angel, Greenland

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Contents

Summary 5

Eqikkaaneq 7

Resume 9

1 Introduction 11

2 Sampling 13

3 Analytical methods and quality control 16

3.1 Biological samples 16
3.2 Detection limits 16
3.3 Quality control 16

4 Results and discussion 19

4.1 Lichens 19
4.2 Blue mussel 23

5 Conclusion 28

6 References 29

Annex 1. Metal analyses of lichens in 2009 transplanted from Saatut in 2008 30

Annex 2. Metal concentration in transplanted blue mussels 2009 31

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Summary

From 1973 to 1990 lead and zinc ore was mined at Maarmorilik in the region of Uummannaq by the mining company Greenex A/S. The ore was primarily found in the mountain called "Black Angel". It was mined at an altitude of about 600 metres above sea level and transported in cable cars across the Affarlikassaa fjord to a processing plant in Maarmorilik. The produced lead and a zinc concentrate was loaded on ships and transported in bulk to smelters in Europe.

During mining different sources of pollution were identified. Ore crushing and transport of concentrate created dust that was dispersed into the environment. Waste rock dumps were another source for dust but also for the release of lead and zinc to the aquatic environment (e.g. the surrounding fjords). The most important pollutant source, however, was the mine tailings that were discharged into the Affarlikassaa fjord and settled there. In addition, after mine closure, a waste rock dump was excavated and dumped into the Affarlikassaa Fjord on top of the tailings.

Since 1972, environmental studies have been conducted in the vicinity of the mine and the fjords around Maarmorilik by monitoring lead and zinc contents in seawater, sediments and biota (seaweed, mussels, fish, prawns and lichens). This report presents and assesses the results of the environmental studies conducted in 2009.

The lead and zinc dispersal with dust around Maarmorilik were monitored using the lichen *Cetraria nivalis*. It is a good indicator for dispersal of metals in the atmosphere, since it takes up water, nutrients and contaminants via its surface. Lichens, transplanted in 2008 from a reference site to locations near Maarmorilik, showed increased levels of lead and zinc in 2009. Clearly elevated lead concentrations were found in lichens from sampling sites in Affarlikassaa, Qaamarujuk and at Qeqertanguit about 12 km west of Maarmorilik with levels between about 2 to 10 µg/g dry weight above background. Zinc concentrations were not elevated to as high levels as lead and were elevated only within a short distance from Maarmorilik. There is no indication that the dispersal of lead and zinc with dust has changed since 1996, when we introduced the lichen transplantation study to evaluate temporal changes of the dust pollution.

Blue mussels were used to monitor metal pollution in the marine environment since they take up and accumulate metals from seawater, sediment and food particles. In 2008, blue mussels from an unaffected site were transplanted to 8 sites at different distances from Maarmorilik. These were sampled one year later in 2009. The lead content in transplanted mussels was elevated in Affarlikassaa, Qaamarujuk and at Qeqertanguit. Zinc concentrations were elevated in a much smaller area and only close to Maarmorilik. After mine closure the lead contamination in transplanted mussels has decreased significantly, on average by 5.5% per year, with decreases ranging from 2.2% to 8.6% dependent on locality.

As an overall conclusion it is observed, that after mine closure in 1990 an impact from the previous mining operation can still be seen in 2009. The pollution with dust on land seems to continue with no signs of a decrease, while the pollution in the sea is decreasing.

Eqikkaaneq

Maarmorilimmi Uummannap eqqaaniittumi aatsitassarsioqatigiiffik Greenex A/S 1973-imiit 1990-imut aqerlussamik zinkissamillu qalluinermik ingerlataqarpoq. Aqerlussaq zinkissarlu annermik nassaasaavoq qaqqami Inngili Qernertumik taaguutilimmi. Qaqqami tassani aatsitassaq 600 meterinik qatsissusilimmiit piiarneqarpoq Affarlikassaanullu silaannakkut ikaartaassuit atorlugit Maarmorilimmut suliarinneqarfissaanut aqqussorneqartarluni. Aqerloq zinkilu akuiakkat umiarsuarnut usiliussuunneqartarput Europamilu aatsiterivinnut ingerlanneqartarlutik.

Aatsitassarsiorfiup ingerlanerata nalaani mingutsitsineq qassiinik aallaaveqarpoq. Akuiagassap aserorterneqarneratigut akuiakkallu angallanneqarneratigut avatangiisit pujoralatserneqartarput. Aserorternerlukuttaaq pujoralatsitsisuusarput, aammali aqerlumik zinikimillu imermut taratsumullu seeritsisarlutik. Mingutsitsinerpaajuppulli akuiarnerlukut ”tailings”-inik taaneqartartut Affarlikassaanut eqqarneqartartut immamullu kiviorartartut. Aatsitassarsiorfik matummat aserorternerlukut qallorneqarput Affarlikassaanilu akuiarnerlukut ”tailingit” qaavinut iliorarneqarlutik.

Kangerlunni Maarmorillup eqqaaniittuni avatangiisit 1972-imiilli misissuiffigineqartarput taratsup, marraap, naasut uumassusillillu assigiinngitsut (qeqqussat, uillut, raajat, aalisakkat ujaqqallu naaneri qillinerit) misissuagassanik katersuiffigisarnerisigut. Nalunaarusiami matumani saqqummiunneqarput misissuinernit 2009-imi ingerlanneqartunit paasisat.

Aqerlup zinkillu aatsitassarsiorfimmiit pujoralatserinikkut siammarsimanerat misissorneqartarpoq tamatuma eqqaani qillinerit (ujaqqat naaneri) *Cetraria nivalis* aqerlumik zinkimillu akoqarnerinik misissuiffigiumallugit katersortarnerisigut misissoqqissaartarnerisigullu, taakkumi imeq, inuussutissat minguillu qaamikkut tigoorartarpaat. Qillinerit 2008-imi mingutsitaanngitsumiit Maarmorillup eqqaannut nuunneqartut 2009-imi aqerlumik zinkimillu akoqarnerulersimapput. Affarlikassaani, Qaamarujummi Qeqertannguanilu erseqqivissumik aqerlumik akoqalersimapput, tassa akoqanngitsunut naleqqiullutik grammimut 2 aamma 10 mikrogrammit (panerlutik oqimaassusii) akornanni akoqalersimasaramik. Zinkimik akui taama qaffasitsiginngillat Maarmorilimmullu qanittumi taamaallaat akoqarnerulersimallutik. Pujoralatsigut mingutsitsinerup allanngoriartornera paasilluarumallugu 1996-imiit qillinernik nuussisalernermiit allanngorsimaneranik malunnartoqanngilaq.

Uillut ulluttagaaniittut immamiit taratsumik, uumassusilinnik sunillu mikisuaqqanik tigooraasaramik immap mingutsitaasimaneranik uuttuinermut atorneqarsinnaapput. 2008-mi uillut sunnigaasimanngitsut sumiiffinnut arfineq-pingasunut Maarmorilimmiit assigiinngitsunik ungasissulimmut nuussorneqarput. Taakku 2009-imi misiligutissanik tigooraavigineqarput. Uillut nuussat aqerlumik akui Affarlikassaani, Qaamarujummi aammalu Qeqertannguani ukiup ataatsip ingerlanerani qaffariarsimapput. Zinkimik akuat sumiffimmi annikitsuaraannarmi taamaallaallu Maarmorilimmut qanittuararsuarmi alleriarsimavoq. Uillut aqerlumik akoqassusiat aatsitassarsiorfiup matunerata kingorna appariarsimaqaaq, ukiumut agguaqatigiissillugu 5,5%, tassa sumiinnerat apeqqutaalluni 2,2%-imiit 8,6% allanngorarluni.

Tamakku tamaasa ataatsimut isigalugit paasinarpoq 2009-imi suli aatsitassarsiorfiusimasoq 1990-imi unissimasoq sunniusimasimasoq. Pujoralatserineq nunami suli takussaavoq allannguuteqarneranik malunnaateqarani, imaanili mingutsitsineq annikilliartorsimalluni.

Resume

Fra 1973 til 1990 blev der brudt bly-zink malm ved Maarmorilik i Uummannaq regionen af mineselskabet Greenex A/S. Malmen fandtes hovedsagelig i det fjeld, som kaldes "Sorte Engel". Den blev brudt i omkring 600 meters højde og transporteret i en tovbane over fjorden Affarlikassaa til et opberedningsanlæg i Maarmorilik. Her blev der produceret et bly- og et zinkkoncentrat, som blev lastet på skibe og transporteret til smelteværker i Europa.

Mens minedriften fandt sted, blev der identificeret en række forureningskilder. Malmknusning og transport af koncentrater skabte støv, som blev spredt til omgivelserne. Såkaldte gråbjergsdumpe var også en støvkilde, men var også en kilde til forurening af fjorden. Den vigtigste forureningskilde var imidlertid affaldet fra opberedningen, såkaldt "tailings", der blev udledt til fjorden Affarlikassaa, hvor det bundfældede. Endnu en kilde var en gråbjergsdump, som efter minens lukning blev gravet op og dumpet i Affarlikassaa ovenpå den "tailing", som allerede lå der.

Der er siden 1972 udført miljøundersøgelser omkring minen og i fjordene ved Maarmorilik ved at undersøge og overvåge bly- og zinkindholdet i havvand, sedimenter og en række organismer (tang, muslinger, rejer, fisk og lavplanter). Denne rapport viser resultaterne at de miljøundersøgelser, som blev udført i 2009.

Bly- og zinkforureningen med støv omkring Maarmorilik blev overvåget ved hjælp af lavarten *Cetraria nivalis*. Den er en god indikator for spredning af metaller i atmosfæren, da den optager vand, næringsstoffer og kontaminanter fra sin overflade. Lavplanter, som i 2008 blev transplanteret fra et referenceområde til flere områder ved Maarmorilik, havde i 2009 forhøjede bly- og zinkkoncentrationer. Der fandtes tydeligt forhøjede blykoncentrationer i Affarlikassaa, Qaamarujuk og ved Qeqertanguit med niveauer mellem omkring 2 til 10 µg/g (tørvægt) over baggrundsniveau. Zinkkoncentrationerne var ikke forhøjet i samme grad som for bly og kun indenfor kort afstand fra Maarmorilik. Der er ikke tegn på, at mængden af bly- og zinkspredt støv har ændret sig siden 1996, da vi indførte metoden med at transplantere lav for at kunne vurdere ændringer over tid af støvspredningen.

Blåmuslinger er anvendt til overvågning af metalforureningen i det marine miljø, da de optager og akkumulerer metaller fra havvand, sediment og fødepartikler. I 2008 blev der transplanteret blåmuslinger fra et område, som ikke er påvirket af minen, til 8 områder i forskellig afstand fra Maarmorilik. Prøver af disse muslinger blev indsamlet i 2009. Blyindholdet i transplanterede muslinger var efter et år forhøjet i Affarlikassaa, Qaamarujuk og ved Qeqertanguit. Zinkindholdet var forhøjet i et meget mindre område og kun tæt ved Maarmorilik. Efter minens lukning er blyforureningen af muslingerne faldet væsentligt, i gennemsnit 5,5% pr år varierende fra 2,2% til 8,6% afhængigt af område.

Alt i alt kan det konkluderes, at der stadig i 2009 kan ses en påvirkning af den tidligere mineaktivitet, som ophørte i 1990. Støvforureningen på land ser ud til at fortsætte uden tegn på ændringer, mens forureningen i havet er faldende.

1 Introduction

From 1973 to 1990 zinc and lead ore was mined at Maarmorilik in Northwest Greenland in the inner part of a large fjord system. The closest community, Ukkussissat, is about 25 km to the west. The main town, Uummannaq, is about 80 km away from Maarmorilik (Figure 1.1).

The ore was primarily mined in the "Black Angel" mountain at about 600 meters altitude and transported with cable cars across the Affarlikassaa fjord to a flotation plant in Maarmorilik. Here zinc and lead concentrates were produced, loaded into ships and transported in bulk to European smelting plants. The company Greenex A/S operated the mine.

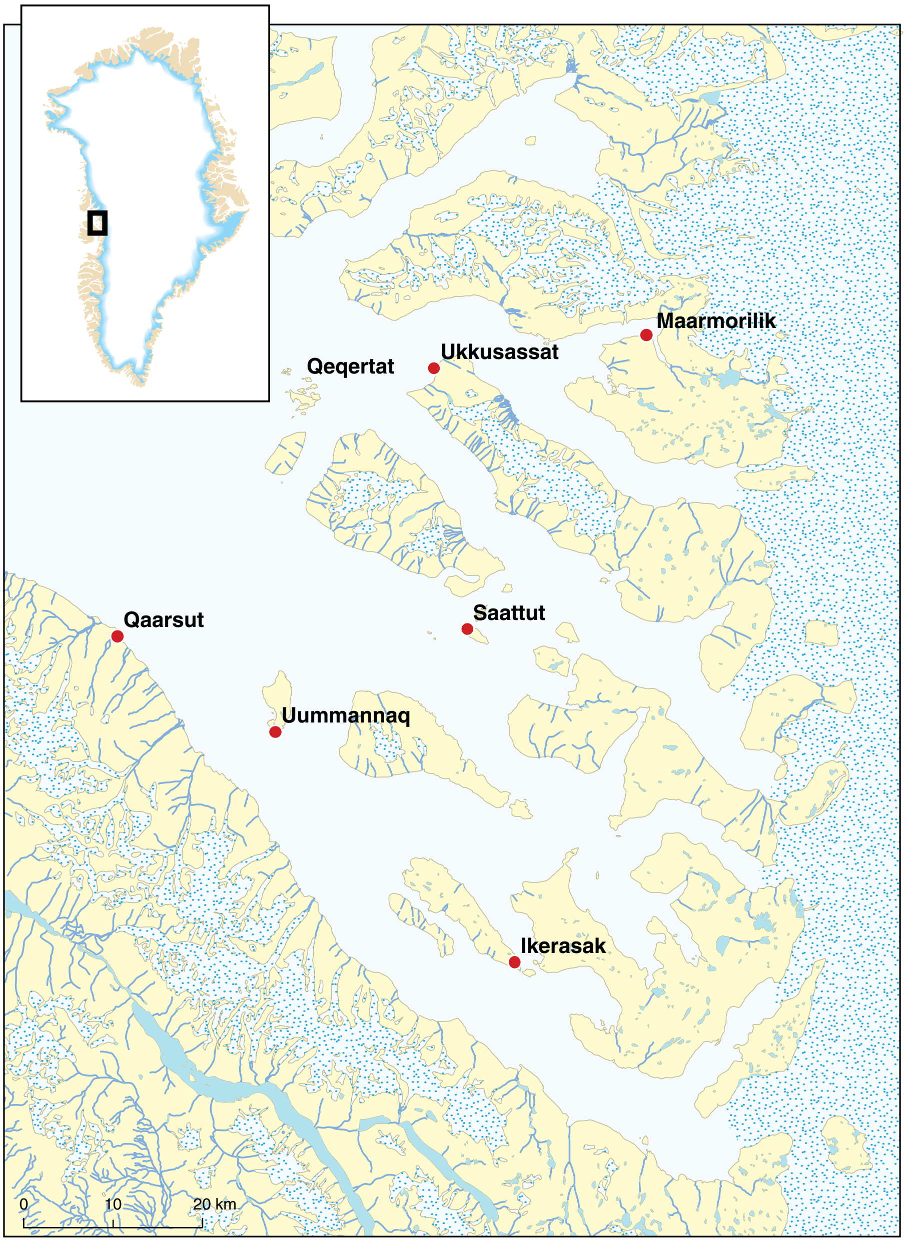


Figure 1.1. Location of the Maarmorilik mine (Northwest Greenland) and nearby settlements.

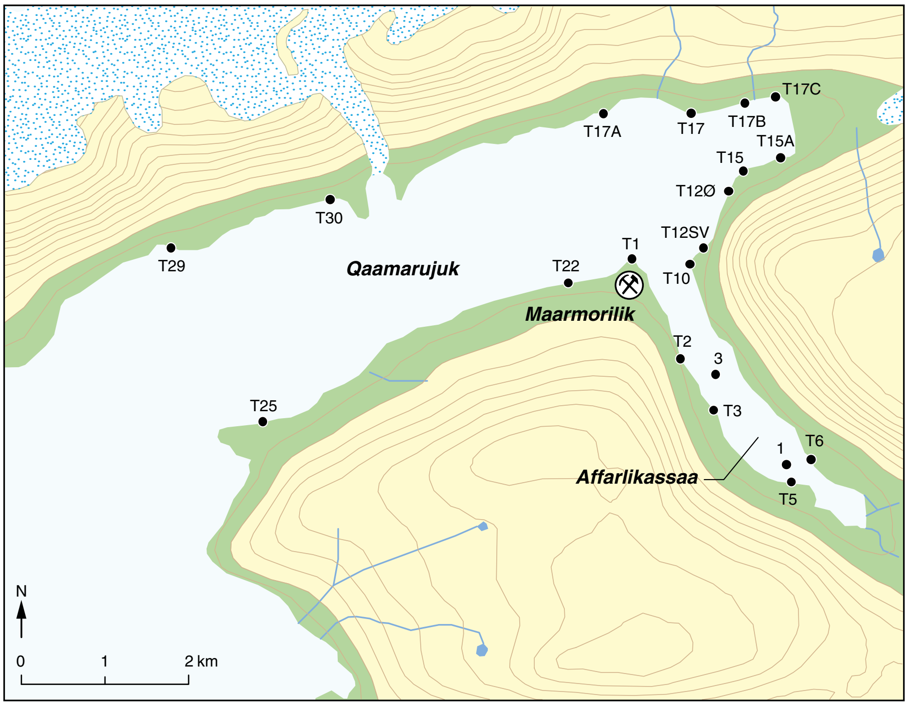
During the operation of the mine, so-called tailings resulting from ore-processing were discharged into the Affarlikassaa fjord, where they settled. Several tons of lead and zinc were annually discharged as tailings into the fjord, leading to serious pollution of the marine environment. Other pollution sources were dispersal of dust due to ore crushing, handling of concentrates and from waste rock dumps left on the steep slopes of the mountains. These waste rock dumps contain several hundred thousand tons of rock with elevated concentrations of lead and zinc. One of the dumps, "The Old Waste Rock Dump", was a particularly strong pollution source in the area. In the summer 1990, this dump was removed to the extent possible and the material dumped into the Affarlikassaa fjord on top of the tailings and on land in the former concentrate storage building.

The pollution from the mining operation was monitored while mining took place and continued after mine closure. The monitoring comprises regular (in most of the years annually) sampling and chemical analysis of seawater and biota (seaweed, mussels, fish, prawns and lichens) and with longer intervals marine sediments and the benthic fauna (Johansen et al. 2006, Josefson et al. 2008). The most recent results of the regular monitoring carried out in 2008 were published by Schiedek et al. (2009). The present report presents results from field work carried out in 2009.

2 Sampling

Sampling was carried out from 18-25 August 2009 with the assistance of local boat charter from Uummannaq and Ukkusissat. Gert Asmund and Jens Søndergaard from NERI and Aron Skade from Ukkussissat carried out the field work.

In 2008, lichens (*Cetraria nivalis*) were transplanted from Saatut, which is known to be unaffected by pollution from the mining operation, to different monitoring stations in Affarlikassaa, Qaamarujuk, Perlerfiup Kangerlua, the islands Qeqertat, and inside the Maarmorilik area (Figure 1.1, 2.1 and Annex 1).



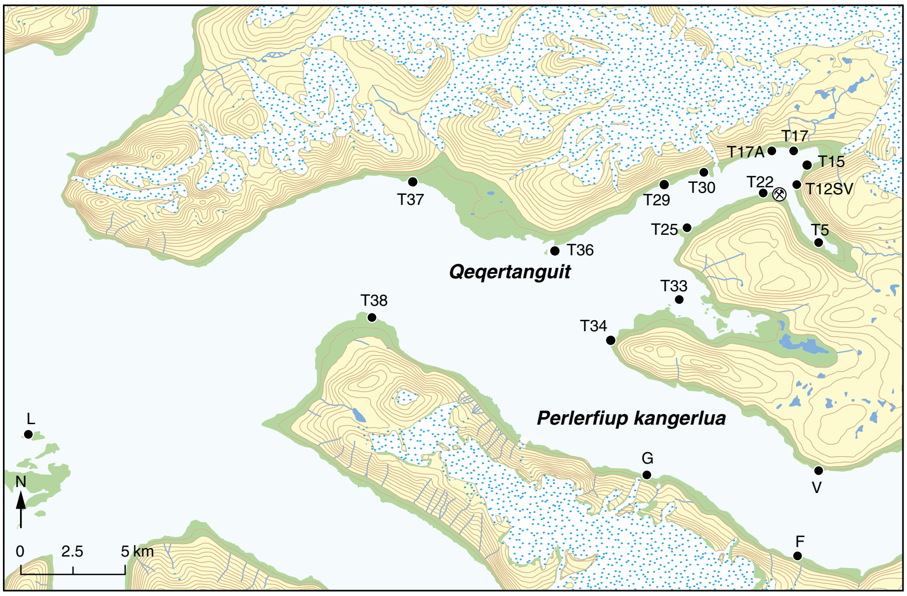


Figure 2.1. Sampling stations close to Maarmorilik (upper map) and further away (lower map). Numbers 1 and 3 refer to the seawater sampling stations. Letters (with and without number) indicate sampling stations for lichens, seaweed and blue mussels.

In 2009, lichens from these stations (a total of 16) were sampled as well as from a reference site near Uummannaq (Annex 1). We have compiled this detailed description of the transplantation sites inside the Maarmorilik area (see also Figure 2.2):

- Locality 1: About 8 meters above the road along Affarlikassaa, about 70 meters from dolphin 1 towards Maarmorilik, 7 meters north of concrete pill.
- Locality 2: About 40 meters directly above new terminal of new cableway.
- Locality 3: At a vertical marble wall at the road approximately at the site of the old ball mill, above the flotation plant.
- Locality 4: Just above and north of the flotation plant at a large stone (2x1x1 m).
- Locality 5: At a marble wall and a heap of roadstones to the right further along the road passing the flotation plant.
- Locality 6: At light no. 6 of the heliport.

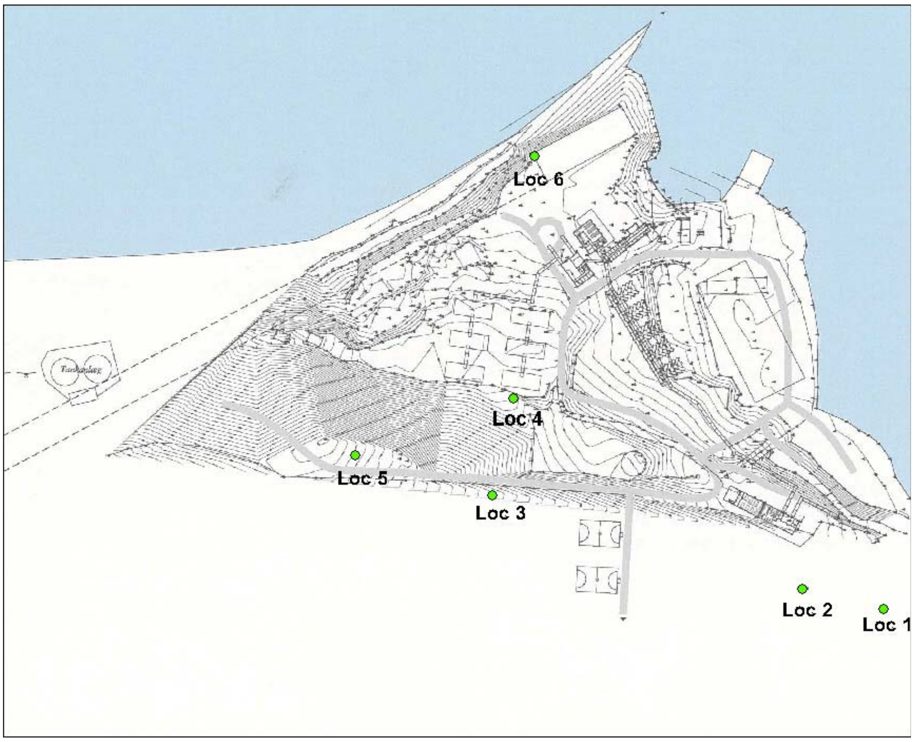


Figure 2.2. Sampling stations within Maarmorilik

Only fresh living lichens growing on dead organic matter were collected. Samples were kept in paper bags.

Blue mussels (*Mytilus edulis*), which had been transplanted in 2008 from Qeqertat (station L) were collected at 5 stations in the Affarlikassaa, Qaamarujuk, Perlerfiup Kangerlua fjords and at Qeqertat (Figure 1.1 and 2.1 and Annex 2). Blue mussels collected at each station were divided into two or three size classes according to their shell length: 4-5 cm, 5-6 cm etc. The adductors of the mussels were cut and the shells were opened. The mussels were allowed to drain before the soft parts were cut out with a stainless steel scalpel. The soft parts of each size group were pooled (number of specimens is seen in Annex 2) and then deep-frozen. New mussels from Qeqertat were transplanted to the fjords at Maarmorilik.

3 Analytical methods and quality control

3.1 Biological samples

At the laboratory of the Department of Arctic Environment at NERI (NERI-DAE), mussel samples were initially freeze-dried and then grounded in an agate mortar. The dry weight was determined by weighing before and after freeze-drying.

The lichen samples were sorted in the laboratory, to remove all foreign material, and subsequently dried at 60ºC for 24 hours.

A 0.3 g sub sample of the dried samples was dissolved with 4 ml concentrated Merck suprapure nitric acid and 4 ml MilliQ water in Teflon bombs under pressure in an Anton Paar Multiwawe 3000 Microwave Oven. After digestion, the samples were transferred to polyethylene bottles with MilliQ water and lead and zinc were measured in these solutions. Zinc concentrations were determined using flame AAS (Perkin Elmer AAnalyst 300 and lead concentrations were determined using graphite furnace AAS (Perkin Elmer AAnalyst 800).

3.2 Detection limits

The detection limit for a method is the concentration below which the uncertainty for the results obtained it too high. The detection limit depends on the method used, the pre-treatment and dilution of the samples. The detection limit applied in this report is the concentration that gives an analytical signal that is 3 times the standard deviation of the blind value.

In biological samples the detection limits are 0.02 µg/g dry wt for lead and 0.8 µg/g dry wt for zinc.

3.3 Quality control

The analytical methods were checked by regularly analyzing the certified reference materials Dorm-1, Dolt-3 and Tort-2.

The analytical methods were also checked independently, as NERI-DAE participates in the intercalibration program QUASIMEME organized by the European Union. In this program a sample with an unknown concentration of e.g. lead and zinc is analyzed by many laboratories. Based on the results, the organizers of QUASIMEME compute a so called "assigned value" for the concentration of – in this case – lead and zinc in the sample. Figure 3.1 shows the result of NERI-DAE's participation in QUASIMEME. In the figure, NERI-DAE's results are shown as the relative deviation from the "assigned value" plotted against the concentration.

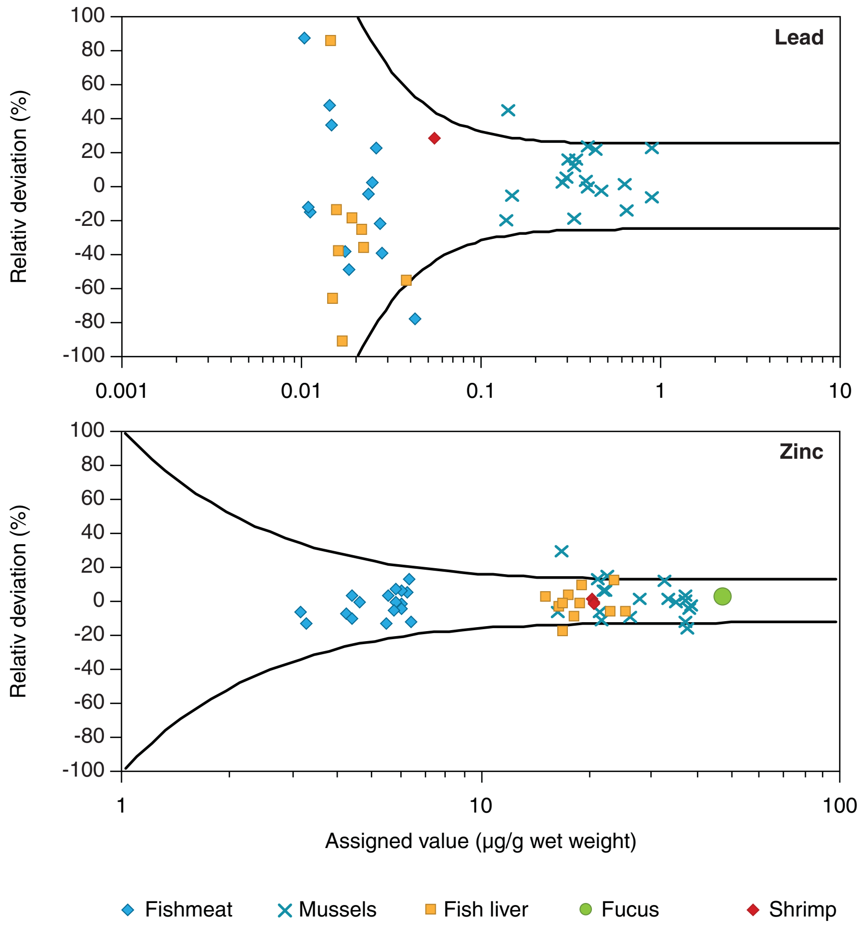


Figure 3.1. Results for lead (upper graph) and zinc (lower graph) from NERI-DAE's participitation in the QUASIMEME laboratory study programme. The lines represent the 95% confidence limit (see text). Concentrations are on a wet weight bases except for Fucus that are on a dry weight basis.

It is seen that for lead the uncertainty by NERI-DAE is about 25% for samples with concentrations higher than 0.05 µg/g wet weight. For biological samples with concentrations lower than 0.02 µg/g wet weight, QUASIMEME only designated so called "indicative assigned values". In these cases, NERI-DAE found lower concentrations than the "indicative assigned values". For zinc the uncertainty by NERI-DAE is in almost all cases within 12.5% (Figure 3.1). The lines in Figure 3.1 represent the 95% confidence limits calculated as the sum-uncertainty of the detection limit and the relative uncertainty seen in the table below:

	Zinc	Lead
Constant error (detection limit), mg/kg dry weight	0.8	0.02
Proportional error (%)	12.5	25

Finally, the analytical methods were checked by analyzing the same sample twice (same ID# but different nitric acid digestions).

In this study a lichen sample and a mussel sample were analysed twice with the results shown below:

	Pb	Pb	Zn	Zn
Mussel	9.070	9.044	218	207
Lichen	1.964	3.747	34.6	40.4

It is seen that for the homogenized sample (the mussel) the deviation between the two samples is 5% for zinc and 4% for lead which is within the analytical uncertainty. But for lichen samples the two 0.3 gram samples analyzed had quite different lead concentrations, differing by almost a factor of 2. This probably is because the lichen samples have not been homogenized.

When a sample has been analyzed twice, we have used the average in further calculations.

4 Results and discussion

4.1 Lichens

Lichens are known to accumulate atmospheric pollutants and are abundant in the Arctic. The lack of roots, a large surface area and a long life span enable them to effectively bioaccumulate air contaminants (Bari et al. 2001). In many studies it has been shown that lichens are good indicators for various kinds of air pollution including those caused by mining activities (Naeth & Wilkinson, 2008).

The lichen species *Cetraria nivalis* is common in Greenland and thus suited as an indicator of metal pollution via the atmosphere. The species grows primarily on dead organic matter and takes up nutrients (and contaminants) from its surface. Once accumulated in the lichens, metals are only released from the plants at a very slow rate – if at all.

At Maarmorilik, the dispersal of metals via the atmosphere has been monitored over many years by sampling lichens at a number of stations close to the mine and in the region to the west. To assess year to year variations of the air quality, lichens were collected at Saatut (Figure 1.1) and transplanted to different locations at Maarmorilik and further away in 2008. The lichens from Saatut had a lead concentration of 0.69 µg/g dry wt and a zinc concentration of 12.6 µg/g dry wt.

In 2009 – after one year of transplantation – lichens were collected again and analyzed for lead and zinc. The results are shown in Annex 1 and the spatial trends are illustrated in Figure 4.1, 4.2 and 4.3.

Figure 4.1. Lead concentrations (µg/g dry weight) in lichens (*Cetraria nivalis*) from sampling stations close to Maarmorilik (upper graph and further away (lower graph).

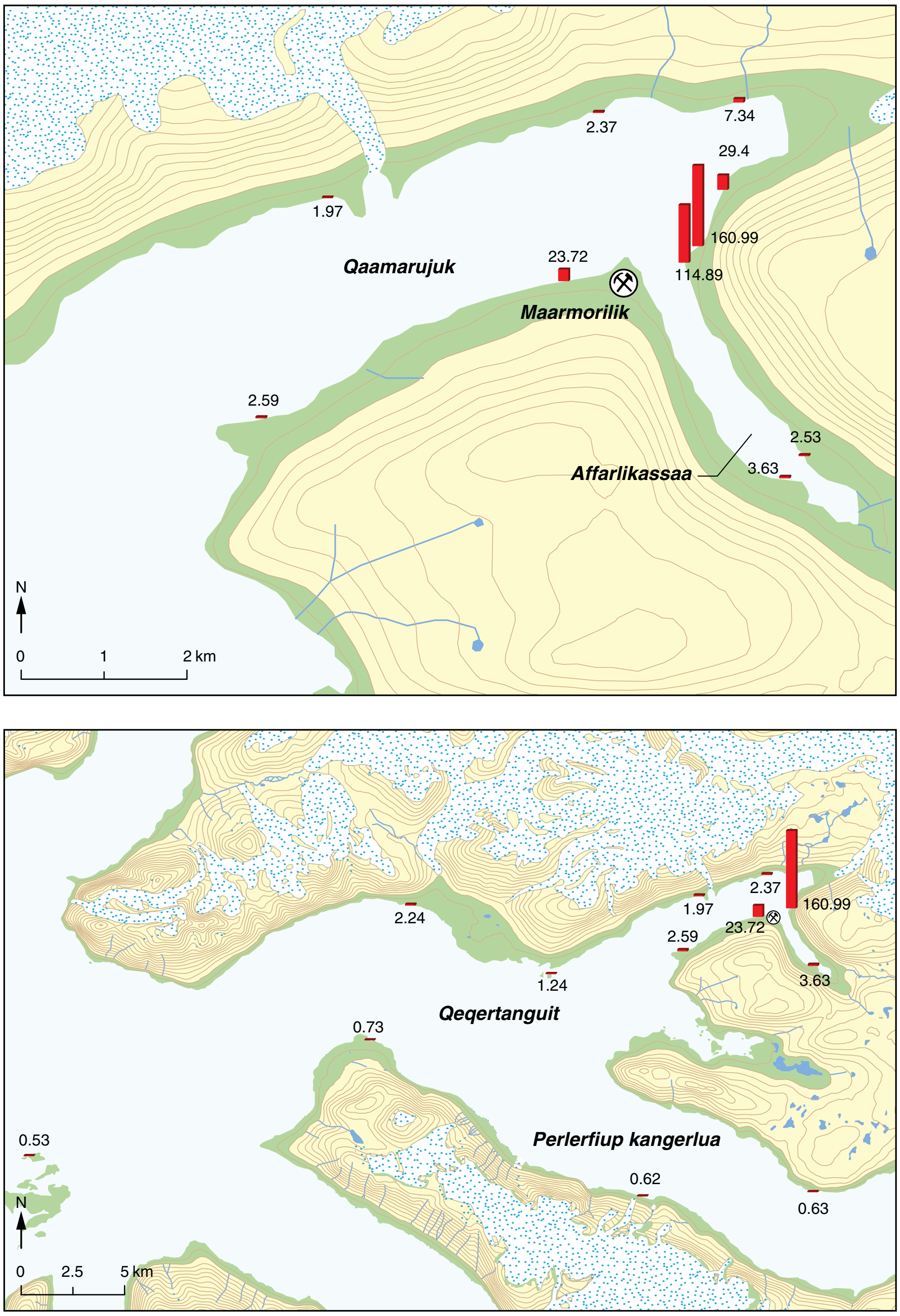
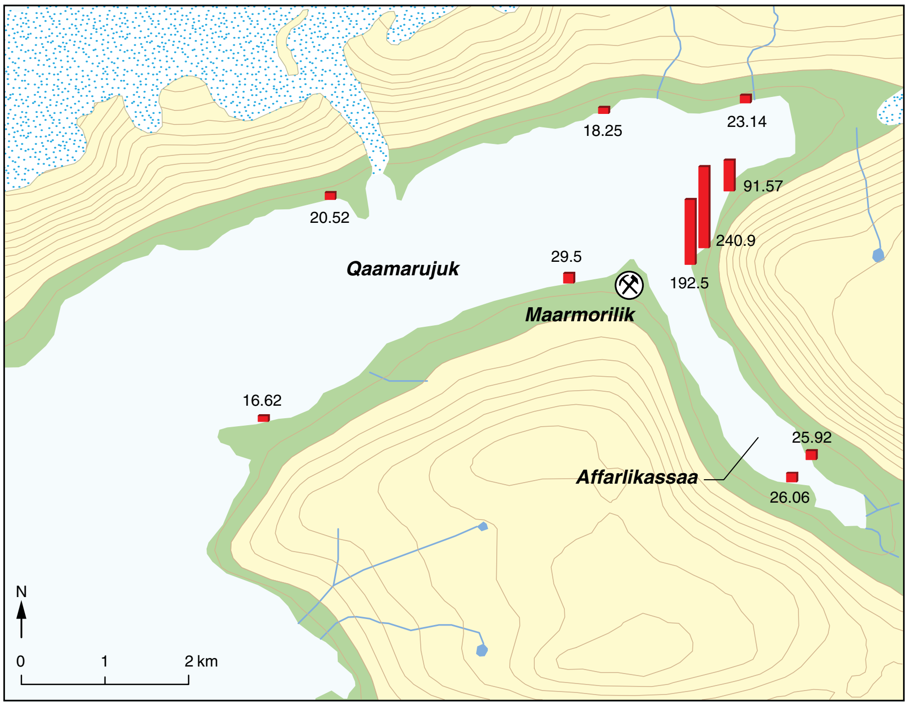


Figure 4.2. Zinc concentrations (µg/g dry weight) in lichens (*Cetraria nivalis*) from sampling stations close to Maarmorilik (upper graph) and further away (lower graph).



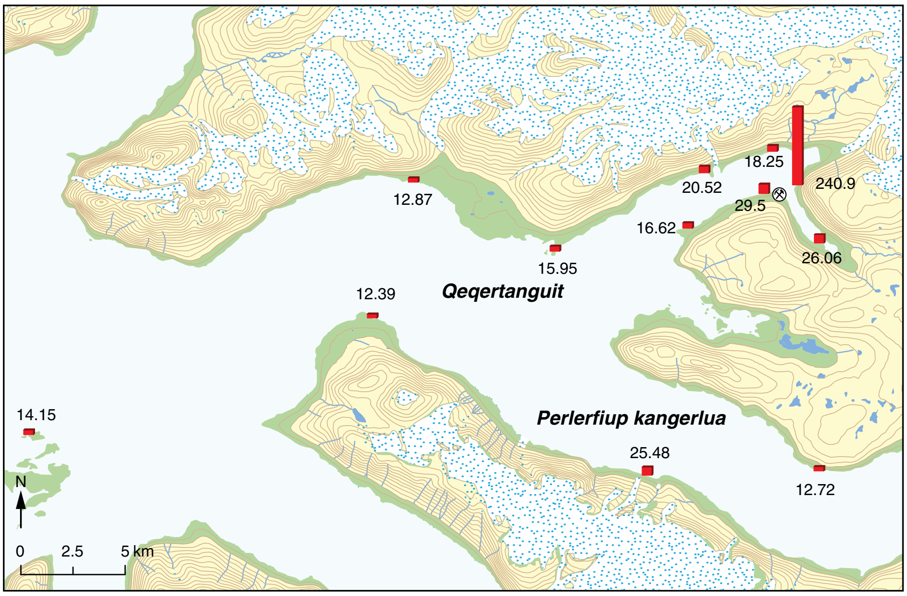
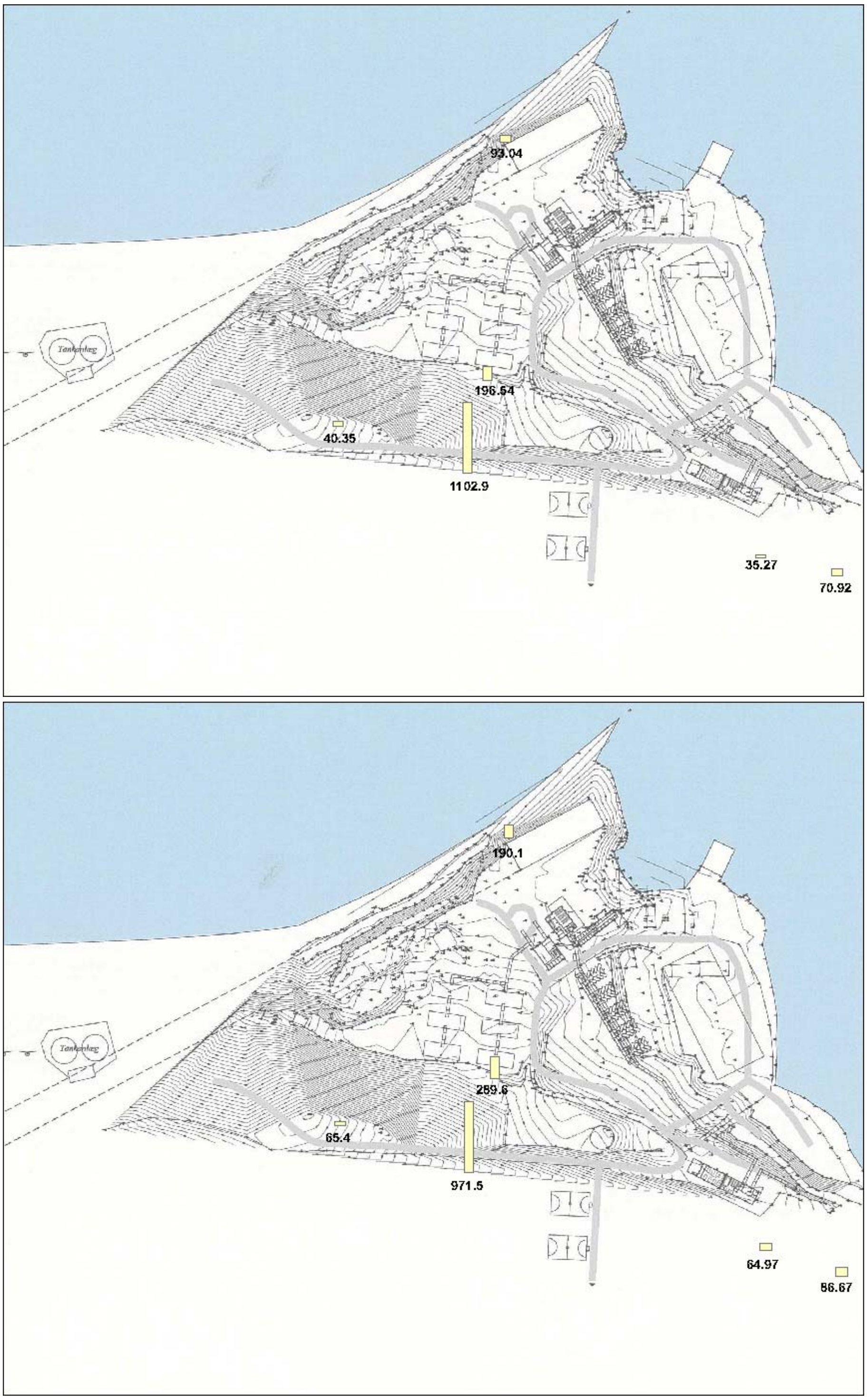


Figure 4.3. Lead (upper graph) and zinc concentrations (lower graph) in lichens (µg/g dry weight) transplanted in 2008 and sampled within the Maarmorilik area in 2009.



4.1.1 Spatial trends

Clearly elevated lead concentrations were found in lichens from Affarlikassaa, Qaamarujuk and Qeqertanguit with levels between 2 to 1000 times higher than background level. The highest concentrations were found in Maarmorilik and in lichens sampled below the Black Angel Mountain (Figure 4.1 and 4.2). Remains of waste rock dumps with elevated lead and zinc concentrations are still found below this mountain. This indicates that a main source of dust dispersal is the waste rock dumps and their remains left on the slopes of the Black Angel Mountain. The high lead and zinc concentrations found within Maarmorilik (Figure

4.3) show that there are also dust sources left here. The dust probably comes from remains of ore and concentrate left at the mine site.

Zinc concentrations were not elevated as much as lead and only within a short distance (2-3 km) from Maarmorilik.

In the lichens collected at Saatut, on Qeqertat and in the inner part of Perlerfiup kangerlua concentrations are low and in the same range as found in other areas in Greenland unaffected by local sources. At reference sites used to the monitor the impact of mining activities at Nalunaq, Seqi and Maarmorilik, concentrations between 0.3-1 µg/g lead and 9-18 µg/g zinc were found in *Cetraria nivalis* (Glahder et al. 2009, Asmund et al. 2009, Johansen et al. 2006). Interestingly, in the samples collected 2-3 km from Uummannaq the lead and zinc concentration appears elevated by a factor of about 2 compared to these background levels. This indicates that the town of Uummannaq is creating heavy metal pollution. A possible source is the waste incinerator in Uummannaq.

4.1.2 Temporal trends

Since 1996 lichens have been transplanted from a reference site to different sites in Affarlikassaa, Qaamarujuk, Perlerfiup kangerlua and Qeqertat and left for one year (except in 2002, when they had been left for two years) before being sampled and analyzed. The results are summarized in Table 4.1.

No systematic apparent temporal trend (increasing or decreasing) was found at any of the sites. Lead levels were varying by a factor of 2 to 10 at the same site and variations were highest closest to Maarmorilik. The zinc levels varied less. The large variations are probably a result of interannual differences in wind patterns and other climatic parameters.

Table 4.1. Metal concentrations (µg/g dry weight) in the lichen *Cetraria nivalis* at different sites (see Figure 2.1) one year after transplantation, except in 2002, when the transplantation period was two years.

	Pb						Zn					
Site	**1997**	**1999**	**2002**	**2005**	**2008**	**2009**	**1997**	**1999**	**2002**	**2005**	**2008**	**2009**
L	0.35	0.26	0.38	0.32	0.31	0.53	6.88	10.6	10.9	11.5	12.3	14.1
V	0.63	0.32	0.35	0.30	1.01	0.63	10.1	6.57	15.8	10.0	11.0	12.7
G	0.23	0.32	0.53	0.31	1.48	0.62	14.3	16.9	13.5	14.6	23.7	25.5
T6	3.23	1.09	2.42	10.3	4.73	2.52	16.2	14.5	22.2	21.4	20.6	25.9
T12SVW	89.2	27.9	80.4	110	165	161	146	79.5	51.1	176	268	241
T12E	18.2	16.4	17.3	51	52.6	29.4	35.8	61.4	29.7	96.3	85.8	91.6
T17A	3.91	4.28	5.01	1.86	4.50	2.37	19.1	22.6	17.7	16.5	16.8	18.3
T17B	7.68	11.4	19.8	10.0	10.1	7.34	19.0	72.6	28.6	34.1	25.3	23.1
T22	7.62	4.03	35.6	7.53	11.3	23.7	21.0	21.3	40.2	23.1	21.6	29.5
T25	1.89	1.75	1.34	0.76	2.78	2.59	13.7	18.7	14.4	5.80	13.6	16.6
T30	2.93	2.80	2.33	0.94	2.97	1.97	16.6	18.5	11.4	12.7	19.1	20.5
T36	2.12	1.28	1.98	0.81	2.24	1.24	14.1	18.7	10.1	9.80	16.1	15.9

4.2 Blue mussel

Blue mussels (*Mytilus edulis*) have been widely used to monitor heavy metal pollution in the marine environment. In Maarmorilik they have been an important tool to monitor the impact of the mining operation both during mining and after closure. The monitoring programme has involved sampling of both resident mussels and mussels transplanted from a site unaffected by the mining into the fjords at Maarmorilik.

Sampling of resident mussels, i.e. mussels that have lived all their life at the site at which they were sampled, is mainly conducted to evaluate the spatial extent of the area affected by pollution and to advice on the risk for human health of collecting and eating contaminated mussels.

Transplanting mussels and collecting them a year later allows assessing temporal trends of lead contamination. This method was introduced in Maarmorilik after it was observed that contaminated mussels did not release lead at the same rate as the lead pollution in the surrounding water decreased. In previous studies it was observed that contaminated mussels after living 2-3 years in an uncontaminated area still contained about half of the lead content they had before (Riget et al. 1997). After that period they did not release lead at all. By transplanting mussels from a reference site unaffected by the mine to the fjords at Maarmorilik and analyzing them one year later it provides a measure for the intensity of the exposure for the period of one year.

In 2009, only mussels that had been transplanted in 2008 were collected and the lead and zinc concentrations were measured. The results are shown in Annex 2. Similar transplantation experiments have been performed regularly since 1991. In some cases the bodyweight was lower in the transplanted mussels after one year, resulting in increased lead concentrations in the tissues. In order to compensate for this effect, the lead and zinc content has been estimated and normalized to a standard size, i.e. 6 cm shell length based on available data for length/weight relationship for each location (Riget et al. 1997). This relationship was for station L described as follows

$W = 0.0101 \times L^{2.54}$, $R^2 = 0.95$
L: mean shell length of length group in cm
W: mean soft tissue dry weight in g
R^2: coefficient of determination.

The results from calculating the lead content are shown in Table 4.2. Table 4.3 shows the lead content of the mussels that were transplanted. In most years, particularly in the beginning of the monitoring period, the lead content at Station L about 30 km from Maarmorilik is higher than at Schades Øer further west, indicating that Station L is affected.

Results for zinc have not been computed, as zinc in the transplanted mussels were elevated only locally and to much lower levels than for lead (Annex 2).

Tabel 4.2. Mean lead content (µg Pb per mussel) in transplanted mussels at different monitoring locations (see Figure 2.1) around Maarmorilik. The lead content has been normalized to a mussel with 6 cm shell length.

Transpl. year	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1998**	**2004**	**2007**	**2008**
Sampling year	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1999**	**2005**	**2008**	**2009**
Station T5		21.5	28.6	20.0	27.7	21.9	12.2	9.05		10.3
T12E	188	170	187	79.3		151	94.8			
T12SW				111	170	96.3		82.6		71.9
T17A	20.1	18.1	18.2	15.8	19.0	21.9	16.6	9.55		18.2
T17B	21.7	14.2	22.6	17.3	20.2	23.4	23.4			
T22	18.7	12.2	17.9	14.6	20.0	14.8	11.3	9.45	9.82	13.2
T25	11.3	12.5	11.9	9.39	10.7	7.61	6.30	6.34		
T30	14.7	9.88	10.4	7.71	12.8	6.79	8.05	7.44		
T36	10.2	9.74	7.95	8.15	5.52	5.10	7.27	5.83	4.38	6.30
G				3.76	1.55	2.54	2.76			
V				3.79	2.05	2.04	2.70			

Tabel 4.3. Mean lead content (µg Pb) in mussels being transplanted to different monitoring locations (see Figure 2.1) around Maarmorilik. The lead content has been normalized to a mussel with 6 cm shell length. Schades Øer is located about 70 km northwest of Maarmorilik and about 50 km northwest of Station L.

Station	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1998**	**2004**	**2007**	**2008**
L	3.76	4.21	3.33	4.62				3.77	1.80	1.68
Schades Øer					0.55	1.03	0.86			

After settling for one year at the new locations, in 2009 the lead content in the transplanted mussels was clearly elevated, varying from 71.9 µg Pb below the Black Angel (Station T12SW) to 6.3 µg Pb at station T36 on Qeqertanguit, about 12 km west of Maarmorilik. The lead content in mussels sampled in Affarlikassaa and Qaamarujuk were between 10 and 18 µg. The lead content of mussels from Station L, which is their original location, was 1.7 µg Pb.

As seen in Table 4.2, lead levels have been elevated in all years since 1992 at all stations to which mussels have been transplanted. We have tested if there is a temporal trend in the period 1992-2009. Since the stations T12E and T12SW were not both included in all the years, we have combined data from station T12E and T12SW as there was no indication of a systematic difference in lead levels at these two stations. Before conducting the time trend analysis we have also subtracted the lead content of the mussels being transplanted in order to evaluate the net uptake in one year.

The statistical temporal trend analyses followed the ICES (International Council for the Exploitation of the Sea) temporal trend assessment procedure (Nicholson et al. 1995). The log-mean lead concentration is used as the annual index value. The total variation over time is partitioned into a linear and non-linear component. Linear regression analysis is applied to describe the linear component, and a LOESS smoother (locally weighted quadratic least-squares regression smoothing) with a window width of 7 years is applied to describe the non-linear component. The linear and non-linear components are tested by means of an analysis of variance. The theory behind the use of smoothers in temporal trend analyses is described in detail by Fryer and Nicholson (1999). A significance level of 5% was applied. The results of the temporal trend analysis can be interpreted as follows:

- Both log-linear and non-linear trend components not significant: no temporal trend.
- Log-linear trend significant, non-linear trend not significant: log-linear trend (exponential trend)
- Both log-linear trend and non-linear trend significant: non-linear trend
- Log-linear trend not significant, non-linear trend significant: non-linear trend

The temporal trend analysis also gives the overall annual change estimated from the log-linear regression.

The results of the temporal trend analysis in transplanted mussels are shown in Table 4.4 and Figure 4.4. Over the entire monitoring period lead content in transplanted blue mussels has decreased at all stations. This decrease, ranging from 2.2 to 8.6% per year, is significant ($p < 0.05$) for 4 out of 7 stations and can be described as a log-linear trend, meaning an exponential decrease. In average the annual decrease in lead concentration in transplanted mussels is 5.5%.

Table 4.4. Results of the temporal trend analyses of the increase of lead content in blue mussels one year after being transplanted to the station from station L. Significance at the 5% level is shown by “sign” and non-significance by “–“ for both the log-linear trend and the non-linear trend components. The overall annual change during the period is given.

Blue mussels Pb			
Station/Year	**Log-linear trend**	**Non-linear trend**	**Annual change**
T5, 1993-2005	sign	-	-8.0%
T12, 1992-2009	sign	-	-5.7%
T17A, 1992-2009	-	-	-2.2%
T22, 1992-2009	-	-	-2.7%
T25, 1992-2005	sign	-	-8.6%
T30, 1992-2005	-	-	-5.0%
T36, 1992-2009	sign	-	-6.1%

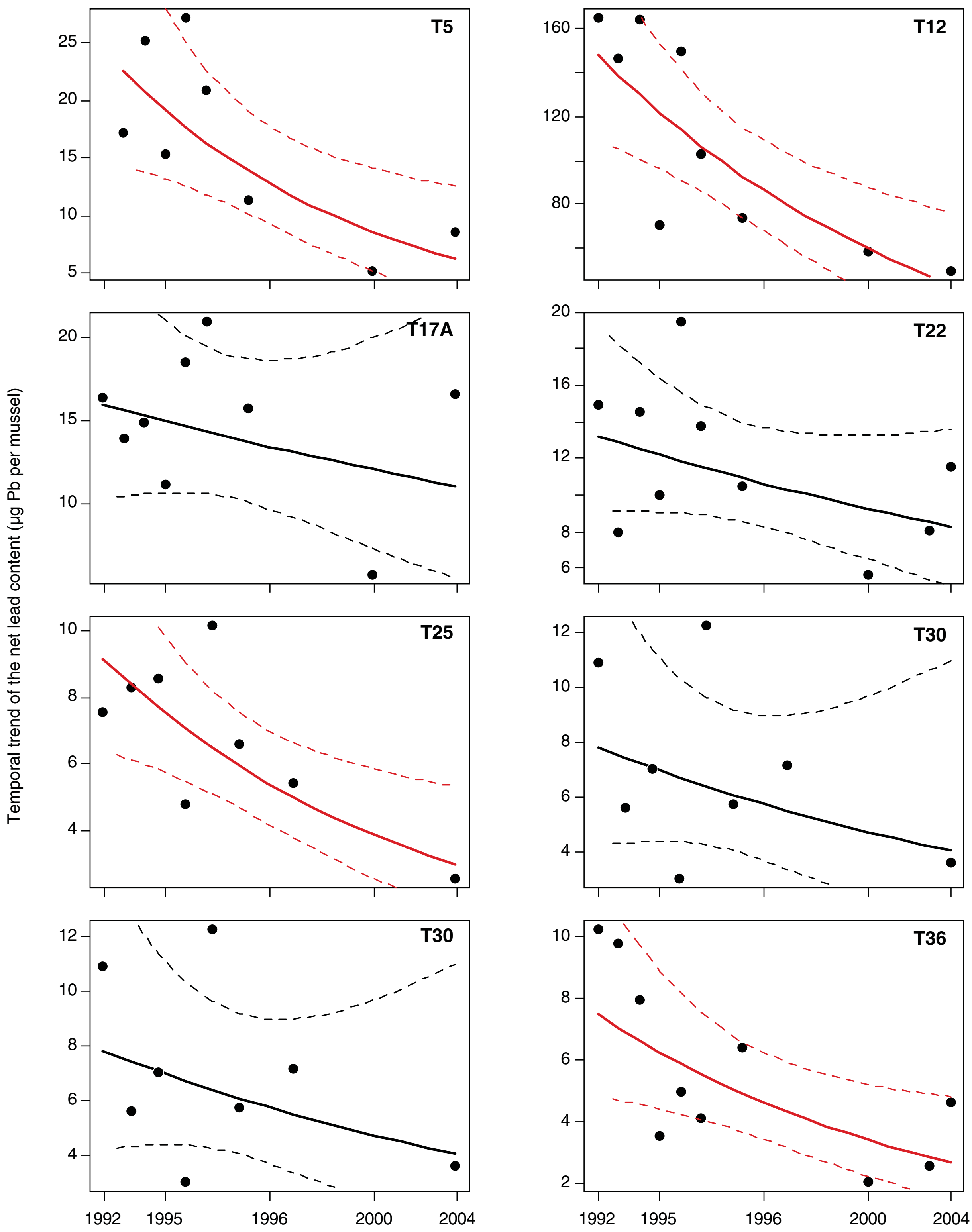


Figure 4.4. Temporal trend of the net lead content (µg Pb per mussel) in transplanted mussels. Points denote annual net content. A solid line together with 95% confidence limits (dashed lines) is shown. A red line indicates a significant trend and a black line that the trend was not significant.

5 Conclusion

Lichens, transplanted in 2008 from a reference site to locations near Maarmorilik, showed increased levels of lead and zinc in 2009. Clearly elevated lead concentrations were found in lichens from sampling sites in Affarlikassaa, Qaamarujuk and at Qeqertanguit about 12 km west of Maarmorilik with levels between about 2 to 10 µg/g dry weight above background. Zinc concentrations were not elevated to as high levels as lead and were elevated only within a short distance from Maarmorilik. There is no indication that the dispersal of lead and zinc with dust has changed since 1996, when we introduced the lichen transplantation study to evaluate temporal changes of the dust pollution.

In 2008, blue mussels from an unaffected site were transplanted to 8 sites at different distances from Maarmorilik. These were sampled one year later in 2009. The lead content in transplanted mussels was elevated in Affarlikassaa, Qaamarujuk and at Qeqertanguit. Zinc concentrations were elevated in a much smaller area and only close to Maarmorilik. After mine closure the lead contamination in transplanted mussels has decreased significantly, on average by 5.5% per year, with decreases ranging from 2.2% to 8.6% dependent on locality.

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Annex 1. Metal analyses of lichens in 2009 transplanted from Saatut in 2008

Results are expressed in µg/g dry weight. Species analyzed is *Cetraria nivalis.* Result from Uummannaq is from lichens being transplanted to other stations in 2009 to be sampled in 2010.

ID No.	Station	UTM coordinates		Pb	Zn
		x	y		
41769	Uummannaq			3.75	34.61
41769	Uummannaq			1.96	40.44
41770	L			0.53	14.15
41771	G			0.62	25.48
41772	V			0.63	12.72
41773	T38			0.73	12.39
41774	T37			2.24	12.87
41775	T36			1.24	15.95
41776	T30			1.97	20.52
41777	T25			2.59	16.62
41778	T22			23.72	29.50
41779	T17B			7.34	23.14
41780	T17A			2.37	18.25
41781	T12SW			160.99	240.9
41782	T12E			29.40	91.57
41783	T10			114.89	192.5
41784	T6			2.53	25.92
41785	T5			3.63	26.06
41786	Maarmorilik loc.1	490253	7891199	70.92	86.67
41787	Maarmorilik loc.2	490151	7891244	35.27	64.97
41788	Maarmorilik loc.3	489934	7891294	1102.90	971.5
41789	Maarmorilik loc.4	489896	7891350	196.54	289.6
41790	Maarmorilik loc.5	489816	7891356	40.35	65.40
41791	Maarmorilik loc.6	At light no. 6 of the heliport		93.04	190.1

Annex 2. Metal concentration in transplanted blue mussels 2009

Soft tissue was analyzed. Results are in µg/g dry weight. Results from station L are from mussels being transplanted to other stations in 2009 to be sampled in 2010.

ID No	Station	Size group	Number of individuals	Mean length (cm)	Mean individual wet weight (g)	Dry wt %	Pb µg/g dry wt	Zn µg/g dry wt
41713	L	4-5 cm				16.83	1.64	143
41714	L	5-6 cm				14.85	3.15	151
41715	L	6-7 cm				14.80	2.82	138
41717	L	7-9 cm				13.45	5.16	179
41716	L	9-10 cm				12.25	4.34	238
41704	T36	4-5 cm	12	4.53	2.28	14.29	9.07	218
41704	T36	4-5 cm	12	4.53	2.28	14.29	9.45	208
41705	T36	5-6 cm	10	5.42	3.71	12.69	9.17	229
41701	T22	4-5 cm	15	4.51	2.27	13.65	20.67	286
41702	T22	5-6 cm	6	5.33	4.01	14.16	15.76	298
41703	T22	6-7 cm	4	6.58	6.98	14.18	14.82	287
41711	T5	4-5 cm	13	4.50	2.80	12.92	14.80	214
41712	T5	5-6 cm	11	5.42	4.46	11.72	15.46	274
41709	T12SW	4-5 cm	12	4.54	2.70	17.10	90.87	394
41710	T12SW	5-6 cm	8	5.51	5.39	14.03	70.35	245
41706	T17A	4-5 cm	17	4.52	2.49	14.09	23.0	276
41707	T17A	5-6 cm	5	5.43	5.22	14.29	17.8	209
41708	T17A	6-8 cm	3	6.76	8.91	13.63	22.4	315

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ENVIRONMENTAL MONITORING AT THE FORMER LEAD-ZINC MINE IN MAARMORILIK, NORTHWEST GREENLAND, IN 2009

In 2009 environmental monitoring was carried out at the former lead-zinc mine which closed in 1990. Samples of lichens and blue mussels were analyzed. The study shows, that after mine closure an impact from the previous mining operation can still be seen. The pollution with dust on land seems to continue with no signs of a decrease, while the pollution in the sea is decreasing.

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